5101-221
Flat-Plate Solar
Array Project

DOE/JPL-1012-76
Distribution Category UC-63b

Summary of Flat-Plate Solar Array Project Documentation

Abstracts of Published Documents, 1975 to 1986

M. J. Phillips

September 1986

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL Publication 82-79, Rev. 1

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Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy through an agreement with the National Aeronautics and Space Administration.

The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the National Photovoltaics Program to initiate a major effort toward the development of cost-competitive solar arrays.

This document reports on work done under NASA Task RE-152, Amendment 419, DOE/NASA IAA No. DE-AI01-85CE89008.

ABSTRACT

This document contains abstracts of final reports, or the latest quarterly or annual, of the Flat-Plate Solar Array (FSA) Project Contractors of Jet Propulsion Laboratory (JPL) in-house activities. At the time of publication, some Contractor final reports have not been received.

Also contained in this document is a list of proceedings and publications, by author, of work connected with the Project.

This work has been conducted under a contract with the U.S. Department of Energy (DOE) as part of the National Photovoltaics Program. The aim of this program has been to stimulate the development of technology that will enable the private sector to manufacture and widely use photovoltaic systems for the generation of electricity in residential, commercial, industrial, and Government applications at a cost per watt that is competitive with utility generated power.

FSA Project activities have included the sponsoring of research and development efforts in silicon refinement processes, advanced silicon sheet growth techniques, higher efficiency solar cells, solar cell/module fabrication processes, encapsulation, module/array engineering and reliability, and economic analyses.

FINAL REPORT ORGANIZATION

The Flat-Plate Solar Array Project Final Report, Volumes I through VIII, JPL Publication 86-31, 5101-289, DOE/JPL-1012-125, October 1986, is composed of an Executive Summary and seven technology reports. Two supplemental reports included in the FSA final report package are:

FSA Project: 10 Years of Progress, JPL Document 400-279, 5101-279, October 1985.

Summary of FSA Project Documentation: Abstracts of Published Documents, 1975 to 1986, JPL Publication 82-79 (Revision 1), 5101-221, DOE/JPL-1012-76, September 1986.

Upon request, the Final Report (JPL Publication 86-31) and the two supplemental reports [JPL Document 400-279 and JPL Publication 82-79 (Revision 1)] are individually available in print from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.
Springfield, VA 22161

or

U.S. Department of Energy
Technical Information Center
Publication Request Section
P.O. Box 62
Oak Ridge, TN 37830

ABBREVIATIONS AND ACRONYMS

AAA	automated-array assembly
ac	alternating current
AM	air mass
APL	Advanced Photovoltaics Laboratory
AR	antireflective
ARCO	ARCO Solar, Inc.
a-Si	amorphous silicon
ASI	ARCO Solar, Inc.
B_F	back surface
BCL	Battelle Columbus Laboratories
BSF	back-surface field
BSR	back-surface reflector
C-V or CV	capacitance voltage
CAST	capillary action shaping technique
CDRL	Contract Data Requirement List
CFH	crucible-free horizontal
CFP	continuous-flow pyrolyzer
CFR	continuous-flow reactor
CG	crystal grower
CLF	continuous-liquid feed
CO	carbon monoxide
c-Si	single crystal silicon
CTS	capacitance transient spectroscopy
CVD	chemical vapor deposition

Caltech	California Institute of Technology
Cz	Czochralski
dc	direct current
DCF	discounted cash flow
DCS	dichlorosilane
DLTS	deep-level transient spectroscopy
DOE	U.S. Department of Energy
DRD	Data Requirement Description
DTA	differential thermal analysis
EBIC	electron-beam-induced current
ECN	Engineering Computer Network
ED	exploratory development
EPDM	ethylene-propylene-diene monomer
EPSDU	experimental process system development unit
ERDA	Energy Research and Development Administration
ESB	electrostatic bonding
ESEA	Energy Systems Economic Analysis
EVA	ethylene vinyl acetate
FAST	fixed-abrasive slicing technique
FBR	fluidized-bed reactor
FSA	Flat-Plate Solar Array (Project)
FSF	front-surface field
FZ	float-zone
GE	General Electric Co.
GRC	glass-reinforced concrete
HEM	heat-exchange method

HF	high frequency
HS	Hemlock Semiconductor Corp.
Hamco	division of Kayex Corp.
I-V	current-voltage
IBM	International Business Machines
IBS	interfacial bonding stability
ID	inside diameter
IEEE	Institute of Electrical and Electronics Engineers
IPEG	Improved Price Estimation Guidelines
IR	infrared
I_{sc}	short-circuit current
JPL	Jet Propulsion Laboratory
KCI	Kinetic Coatings, Inc.
LAPP	Low-Altitude Plume Program
LASS	low-angle silicon sheet
LCG	linear congruential random number generator
LCP	lifetime cost and performance
LMSC	Lockheed Missiles and Space Co., Inc.
LSA	Low-Cost Solar Array (Project) (later became FSA)
LSCAP	light-stimulated capacitance method
LSSA	Low-Cost Silicon Solar Array (Project) (later became LSA)
MBA	MBAssociates (Tracor MBAssociates)
MBE	molecular-beam epitaxy
MBS	multiblade sawing
MEPSDU	module experimental process system development unit
MF	microfiche

MOS	metal-oxide semiconductor
m-Si	microcrystalline silicon
MT	metric ton
MTBF	meantime between failures
MWS	multiwire slurry (sawing)
NASA	National Aeronautics and Space Administration
NDE	nondestructive evaluation
NEC	National Electrical Code
NMA	non-mass analyzed
NOC	nominal operating conditions
NOCT	nominal operating cell temperature
NTIS	National Technical Information Service
OCLI	Optical Coating Laboratory, Inc. (Appied Solar Energy Corp.)
PAG	Price Allocation guidelines
PC	personal computer
PDU	process development unit
PEBA	pulsed electron beam annealing
PELA	pulsed excimer laser annealed
PIM	Project Integration Meeting
PRDA	Program Research and Development Announcement
PROPSM	process research on polycrystalline silicon material
PV	photovoltaic(s)
PVB	polyvinyl butyral
PVC	polyvinyl chloride
PVD	photovoltage decay
QTM	Quantimet Image Analyzing System

R&D	research and development
RBS	Rutherford backscattering
RCA	RCA Corp.
RF	radio frequency
RH	relative humidity
RTP	rapid thermal processing
RTR	ribbon to ribbon
S_F	front surface
SAI	Science Applications, Inc.
SAMICS	Solar Array Manufacturing Industry Costing Standards
SAMIS	Standard Assembly-Line Manufacturing Industry Simulation
SCAP1D	Solar Cell Analysis Program in One Dimension
sccm	standard flow of cubic centimeters per second
SCG	solar cell grade
SCIM	silicon coating on an inverted meniscus
SCS	semiconductor grade silicon
SEM	scanning electron microscope
SERI	Solar Energy Research Institute
SG	semiconductor grade
SIMRAND	SIMulation of Research ANd Development
SIMS	secondary ion mass spectrometer
SOC	silicon-on-ceramic
SPV	surface photovoltage
STC	Silicon Technology Corp.
SUPREMII	Stanford University Process Engineering Model-II
Semix	Semix Corp.

Si	silicon
TCP	transparent conducting polymer
TCS	trichlorosilane
TEM	transmission electron microscope
TGA	thermogravimetric analysis
TJC	tandem junction cell
TSCAP	thermally-stimulated capacitance method
Tyco	Mobil Solar Energy Corp (formerly Mobil Tyco Solar Energy Corp.)
UCC	Union Carbide Corp.
UCLA	University of California at Los Angeles
UCP	ubiquitous crystallization process
UL	Underwriters Laboratories, Inc.
V_{NO}	nominal operating voltage
V_{oc}	open-circuit voltage
VSCAP	voltage-stimulated capacitance method
WO	work order

CONTENTS

ABSTRACTS OF PUBLISHED DOCUMENTS

PROJECT OFFICE
JPL - IN-HOUSE ABSTRACTS

PROJECT OFFICE IN-HOUSE ABSTRACTS

TITLE: Energy Research and Development Agency LSSA Project. Proceedings of the First Task Integration Meeting
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1976
REPORT NO: ERDA-JPL 1012-76/1, and 5101-2
AVAILABILITY: NTIS, PC A16/MF A01; 1

ABSTRACT: The LSSA Project convened the first LSSA Task Integration Meeting at JPL on January 13, 14 and 15, 1976. The primary objectives of this first Task Integration Meeting were: To provide an overview of LSSA Project technical plans, progress, and problems for all Project participants; and to further identify and establish the technical interfaces within and between LSSA Project tasks. The purpose of this document is to disseminate, as quickly as possible, the material that was presented at the meeting. This includes summaries of the second day task sessions as presented by each task manager during the review. The document consists of the vugraphs used in the presentations, a brief summary from each contractor, and a brief summary of the meeting.

TITLE: Energy Research and Development Agency LSSA Project. Proceedings of the 2nd PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 1976
REPORT NO: ERDA JPL 1012 76/4, and 5101 5
AVAILABILITY: NTIS, PC A11/MF A01; 1

ABSTRACT: The LSSA Project convened its second PIM (the first meeting was called Task Integration Meeting) at the California Institute of Technology campus in Pasadena, California, on April 27-28, 1976. (An ERDA/JPL in-house review and critique of the previous two-day session was held on April 29.) The primary objectives of this meeting were to integrate the LSSA Project technical plans and activities, to further identify and establish the technical interfaces, and to provide an overview of Project technical plans and status. The purpose of this document is to disseminate the material that was presented at the meeting, including summaries of the second day task sessions as presented by each task manager. The document includes view graphs used in the presentations, technical progress summaries from the contractor; and a brief summary of the meeting.

TITLE: Proceedings of the 3rd PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 1976
REPORT NO: ERDA-JPL 1012-76/7, and 5101-8

ABSTRACT: The PIM of the LSSA Project was conducted July 28 and 29, 1976, at the California Institute of Technology; some technology development task meetings were held during the preceding two days as well. The PIM began with a general introductory session, in which the current status of the ERDA Photovoltaic Program, the LSSA Project, other Program elements, recent solar-cell module test experience at JPL, cost analysis methods developed by the Battelle contract with the Encapsulation Task were briefly reviewed. These are summarized in Section II of these proceedings. Next, the participants were divided, and in each of two periods three Intratask or Intertask sessions were conducted. The Silicon Material Task 1 held an Intratask session and participated in an Intratask session with the Large Area Silicon Sheet Task 2. Task 2 had an Intratask Meeting prior to the PIM, and participated in Intertask sessions with Task 1 (above) and with Encapsulation (Task 3) and Automated Array Assembly (Task 4). Task 3 also held pre-PIM Intratask Meetings, and participated in the 2-3-4 session. Large Scale Production, Operations, and Engineering held one Intertask session among themselves and another with Task 3. These are summarized, sometimes from the perspective of more than one participating Task, in Section III. Finally there was a concluding general session, which included statements of summary status, conclusions, and action items by the Task 1-5 Managers and the Project and Program Managers. The Task Summaries are included in Section III; the Management conclusions and action items are given in Section I.

TITLE: First Annual Report, January 1975 to March 1976
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 9, 1976
REPORT NO: ERDA-JPL 1012-76/5, and 5101-3
AVAILABILITY: NTIS, HC

ABSTRACT: The LSSA was established to greatly reduce the price of solar arrays by the improvement of manufacturing technology, by adaptation of mass production techniques, and by helping achievement of user acceptance. The Project's approach included the development of technology, its transfer by industry to commercial practice, the evaluation of the economics involved, and the stimulation of market growth. The activities and progress of the LSSA Project during its first year are described in this document which covers all project activities, with primary emphasis on the technical plans and accomplishments. The development of manufacturing technology is now and will continue to be performed principally by industries and universities. To date, 24 contractors are working on new Si-refinement processes, Si-sheet-growth techniques, encapsulants, and automated assembly studies. Nine more contractors have been selected to perform additional technology investigations and their contracts are being negotiated. Additional Contracts will be issued in the future as promising ideas appear.

TITLE: Quarterly Report, April to June 1976
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 8, 1976
REPORT NO: ERDA-JPL 1012-76/6, and 5101-7
AVAILABILITY: NTIS HC A08/MF A01

ABSTRACT: Activities and progress of the LSSA Project during April, May, and June 1976 are described. This involved the awarding of additional contracts, an evaluation and clarification of plans and working relationships with contractors, the receipt of initial technical results, and an expansion of activity in the evaluation and improvement of the solar cell modules that are included in the project's first procurement (46 kW). For the most part, the new manufacturing technology is being developed under contract by industries and universities. It includes the consideration of new Si-refinement processes, Si sheet growth techniques, encapsulants, and automated assembly production. During this report period analytical and experimental accomplishments resulted from day to day activities that are the early efforts of a long range plan. Thirty-one contracts have been awarded and two more are being negotiated. Five companies have delivered 20 kW out of a total purchase of 46 kW of "off-the-shelf" modules that will be used in ERDA's Test and Demonstration Activities. The same five companies have just been awarded contracts for the purchase of 130 kW of semistandardized modules at an average selling price of $15.50/W.

TITLE: Quarterly Report 2, July to September 1976
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1976
REPORT NO: ERDA-JPL 1012-77/1, and 5101-10
AVAILABILITY: NTIS, PC A08/MF A01

ABSTRACT: The potential for future widespread use of PV systems for the generation of electric power was the motivation for the establishment, in January 1975, of the PV conversion program by ERDA's division of solar energy. The program's activities are planned to develop and to promote the use of PV systems to such an extent that the private sector will produce and utilize cost-competitive PV systems. As part of the ERDA program, the LSSA was

established in January 1975. The project objective is to develop the national capability to produce low-cost, long-life PV arrays at a rate greater than 500/megawatts/yr and a price of less than $500/kW peak by 1986.

TITLE: Quarterly Report 3, October to December 1976
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1976
REPORT NO: ERDA-JPL 1012-77/2, and 5101-24
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: The potential for future widespread use of PV systems for the generation of electric power was the motivation for the establishment, in January 1975, of the PV conversion program by ERDA's Division of Solar Energy. The program's activities are planned to develop and to promote the use of PV systems to such an extent that the private sector will produce and utilize cost-competitive PV systems. As part of the ERDA program, the LSSA was established in January 1975. The activities and progress of the LSSA Project during the months of October, November, and December 1976 are described. The Project objective is to develop the National capability to produce low-cost, long-life PV arrays at a rate greater than 500 megawatts/yr and a price of less than $500/kW peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years. The approach is to reduce the cost of solar cell arrays by improving solar array manufacturing technology and by increasing solar array production capacity and quantity. Forty seven contracts have been awarded to date, to industrial firms and university and independent laboratories for experimental work, process development and analysis, technology assessment, and the production of solar array modules. Approximately 58 kW of state-of-the art modules have been delivered; design development is under way for a second block of moderately advanced modules, and planning for subsequent module procurements has begun.

TITLE: Direct Conversion Technology Si Cell
AUTHOR: Ralph Lutwack
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1977
REPORT NO: DOE JPL 01647
AVAILABILITY: NTIS-01647

ABSTRACT: The major block to the employment of PV conversion systems for terrestrial power generation is economic. Scientific and engineering efforts to supply the requisite technology and programs to insure the high volume production of suitably low-cost PV arrays are necessary to achieve commericial practicability. A technical assessment of a program to develop PV conversion systems technology for large scale terrestrial energy applications was performed. The set of conclusions and recommendations from this assessment included: (1) The primary PV system candidate is single crystal Si. The program for developing the technology for low cost and high volume production should be comprised of tasks for solar cell grade Si, large area single crystal Si, automated array fabrication, array encapsulation, and improved conversion efficiency, (2) Thin film solar cells of CdS/Cu_2S, polycrystal Si and GaAs as well as organic and other novel materials and devices should be placed in a category of candidates whose technical capabilities are yet to be proven. The development programs for these systems should be for the development of practical devices, (3) A concerted effort will be necessary to provide the information base for the design of PV systems for power generating installations, and (4) National laboratories should be instituted for the collection, processing, and dissemination of insolation data and for conducting independent tests and evaluations of materials, devices and systems. The assessment also included a management plan and a recommended budget for the implementation of the overall program. The single crystal Si cell is the primary candidate in the program to develop PV conversion systems due to these attributes: the theory and technology are well developed, the energy conversion efficiency is high, the base material is abundant, the technical goals to achieve terrestrial utilization are well defined, and the attainment of commericial practicability has a high probability. Si modules for terrestrial use are presently priced at about $30/W_p$. A reduction in price to $5/W_p$ would require and extensive development program, the crucial element being the perfection of a means for the continuous production of single crystal Si in large area at high volume. The EFG which has been under development for more than 2 yr, has great potential but it must still be converted into an automated, continuous process to be utilizable.

TITLE: Proceedings of the 4th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1976
REPORT NO: 5101-11

ABSTRACT: The 4th PIM was held October 27-28, 1976 at Caltech, with attendance restricted to technical representatives from all organizations that are or will be working on the LSSA Project. A JPL/ERDA in-house review of the two-day meeting was held the evening of October 28. The objectives of the PIM were to integrate the LSSA Project technical plans and activities, with special presentations on automated solar cell manufacturing assessments and economic analyses of Si sheet growth and ingot cutting, to further identify and establish the technical interfaces, to exchange technical data, and to provide an overview of LSSA Project technical plans and status.

TITLE: Proceedings of the 5th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1977
REPORT NO: 5101-18

ABSTRACT: The Fifth PIM was held January 17 and 18, 1977 at the San Diego Hilton Hotel, held in sequence with the ERDA Semiannual National Solar Photovoltaic Review. The objectives of the Fifth PIM were to integrate the LSSA Project technical plans and activities, to assess Project activities in the areas of higher efficiencies, costs, economics, and manufacturing; to exchange technical data at the working level and provide an overview of LSSA Project technical plans and status. The two major topics covered were cost versus efficiency and manufacturing processes for solar cells and solar arrays.

TITLE: Quarterly Report 4, January to March 1977
CORPORATE AUTH: Jet Propulsion Laboratory
REPORT NO: DOE JPL 1012-77/3, and 5101-32
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: This report describes the activities of the LSSA Project during the period January through March 1977. The LSSA Project is assigned responsibility for advancing Si solar array technology while encouraging industry to reduce the price of arrays to a level at which PV electric power systems will be competitive with more conventional power sources early in the next decade. Set forth here are the goals and plans with which the Project intends to accomplish this, and the progress that was made during the quarter. The Project objective is to develop the national capability to produce low cost, long-life PV arrays at a rate greater than 500 megawatts per year and a price of less than $500/kW peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 yr.

TITLE: Proceedings of the 6th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 4-5, 1977
REPORT NO: 5101-29

ABSTRACT: The Sixth LSSA PIM was held May 4 and 5, 1977, on the campus of the California Institute of Technology.

Invitation controlled attendance included Project participants form JPL and all LSSA Contractors, together with representatives of the ERDA Program Office and many agencies participating in the Program, as well as the new Director of the Solar Energy Research Institute and special invitees. The general objectives of the PIM were to integrate the LSSA Project technical plans and activities, with specific emphasis on a review of ingot technology relative to meeting Project goals of $2/W (1982) and $0.55/W (1986); to discuss and strengthen the technical interfaces within the LSSA Project tasks and between the LSSA Project and other ERDA Photovoltaic Program elements; to exchange technical data, and to provide an overview of LSSA Project technical plans and status. A special review of ingot technology in the light of interim cost goals was conducted at this meeting, as well as the normal task-level reviews, intertask sessions, and general discussions.

TITLE: Quarterly Report 5, April to June 1977
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1977
REPORT NO: DOE-JPL 1012-77/4, JPL Pub. 78-9, 5101-46
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The activities of the LSSA Project during the period April through June 1977, are described. The LSSA Project is assigned responsibility for advancing Si solar array technology while encouraging industry to reduce the price of arrays to a level at which PV electric power systems will be competitive with more conventional power systems early in the next decade. Set forth here are the goals and plans with which the project intends to accomplish this, and the progress that was made during the quarter. The project objective is to develop the national capability to produce low cost, long-life PV arrays at a rate greater than 500 megawatts per year and a price of less than $500 (in 1975 dollars)/kW peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years. The LSSA Project contractors and their technology areas are tabulated and discussed.

TITLE: Quarterly Report 6, July to September 1977
CORPORATE AUTHOR: Jet Propulsion Laboratory
DATE: 1977
REPORT NO: DOE JPL 1012-78/2, JPL Pub. 78-83, 5101-55
AVAILABILITY: DEP. NTIS, PC A07/MF A01

ABSTRACT: The activities of the LSSA Project during the period July through September 1977 are described. The LSSA Project is assigned responsibility for advancing Si solar array technology while encouraging industry to reduce the price of arrays to a level at which PV electric power systems will be competitive with more conventional power sources early in the next decade. Set forth there are the goals and plans with which the Project intends to accomplish this, and the progress that was made during the quarter. The Project objective is to develop the national capability to produce low cost, long-life PV arrays at a rate greater than 500 megawatts/yr at a price of less than $500/kW peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 yr.

TITLE: Proceedings of the 7th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 10-11, 1977
REPORT NO: 5101-37

ABSTRACT: The Seventh LSSA PIM was held August 10 and 11, 1977, at Caltech. Invitation-controlled attendance included Project participants from JPL and all LSSA contractors, together with representatives of the ERDA Solar Program Office and many other agencies participating in the Program. The objectives of this PIM were to review recent technical advances in light of the 1982 and 1986 goals; to orient the participants in this somewhat new state of the art in order to maintain direction toward the requirements of the 1982 and 1986 goals; to discuss and strengthen technical interfaces within and among LSSA Project elements and between the LSSA Project and other ERDA Photovoltaic Program elements, and to exchange technical data and to invite challenges to this data that may only effectively occur during face-to-face meetings. A special review of progress relative to the 1982 goal of $2/W was conducted at this meeting, as well as task-level reviews, inter-task sessions, and general discussions.

TITLE: Quarterly Report 7, October to December 1977
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1977
REPORT NO: DOE-JPL 1012-78/13, JPL Pub. 78-97, 5101-81
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: This report describes the activities of the LSSA Project during the period October through December 1977. The LSSA Project is assigned responsibility for advancing Si solar array technology while encouraging industry to reduce the price of arrays to a level at which PV electric power systems will be competitive with more conventional power sources early in the next decade. Set forth here are the goals and plans with which the Project intends to accomplish national capability to produce low-cost, long-life PV arrays at a rate greater than 500 megawatts/yr and a price of less than $500/kW peak by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 yr.

TITLE: Proceedings of the 8th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 7-8, 1977
REPORT NO: 5101-52

ABSTRACTS The 8th LSA PIM was held December 7 and 8, 1977, at Caltech. Invitation-controlled attendance included Pro ject participants from JPL and all LSA contractors, together with representatives of the DOE Division of Solar Technology and other agencies participating in the Program. The following highlights were noted at this PIM: (1) Technology developments required for the production of $2/W modules, (2) Si sheet progress, (3) SAMICS, (4) Field performance of Block I and II modules, (5) Environmental tests for uncovering potential failures modes for modules installed in the field, and (6) Elimination or control of the photon-induced instability phenomenon.

TITLE: Proceedings of the 9th PIM
CORPORATE AUTHOR: Jet Propulsion Laboratory
DATE: 1978
REPORT NO: 5101-67
AVAILABILITY: NTIS, PC A21/MF A01

ABSTRACT: Invitation-controlled attendance at the meeting included Project participants from JPL and LSA Project contractors, together with representatives of the DOE Division of Solar Technology and other agencies participating in the PV program. The status of the JPL LSSA Project is described in detail. The report includes the following sections: (1) Project Analysis and Integration, (2) Technology Development Area (Si Material Task, Large Area Si Sheet Task, and Encapsulation Task), (3) Production Process and Equipment Area, (4) Engineering Area, and (5) Opera tions Area.

TITLE: Quarterly Report 8, January to March 1978
DATE: 1978
CORPORATE AUTH: Jet Propulsion Laboratory
REPORT NO: DOE-JPL 1012-2, JPL Pub. 79-14, 5101-88
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: This report describes progress made by the LSSA Project during the period January through March 1978. It includes task reports on Si material processing, large area

Si sheet development, encapsulation materials testing and development, Project engineering and operations, and manufacturing techniques, plus the steps taken to integrate these efforts.

TITLE: Quarterly Report 9, April to June 1978
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1978
REPORT NO: DOE-JPL 1012-3, JPL Pub. 79-15, 5101-99
AVAILABILITY: NTIS, PC 04/MF A01

ABSTRACT: Progress made by the LSSA Project during the period April through June 1978 is described. It includes reports on Si material processing, large-area Si sheet development, encapsulation materials testing and development, project engineering and operations activities, and manufacturing techniques, plus the steps taken to integrate these efforts.

TITLE: Proceedings of the 10th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 16-17, 1978
REPORT NO: 5101-86

ABSTRACTS: The 10th PIM was held August 16 and 17, 1978, at Caltech. Invitation-controlled attendance included Project participants from JPL and LSA Project contractors, together with representatives of the DOE Division of Solar Technology and other agencies participating in the PV Program. A Metallization Workshop was held on Tuesday, August 15. Presentations were made on recent work in established technologies such as plated and thick film techniques and on novel methods.

TITLE: Quarterly Report 10, July to September 1978
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1978
REPORT NO: DOE-JPL 1012-4, JPL Pub. 79-16, 5101-100
AVAILABILITY: NTIS, HC A04/MF A01

ABSTRACT: This report describes progress made by the LSSA Project during the period July through September 1978. It includes reports on Si material processing, large-area Si sheet development, encapsulation materials testing and development, Project engineering and operations activities, and manufacturing techniques, plus the steps taken to integrate these efforts.

TITLE: Quarterly Report 11, October to December 1978 and Proceedings of the 11th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1978
REPORT NO: DOE-JPL 1012-26, and 5101-109

ABSTRACT: This report describes progress made by the LSA Project during the period October through December 1978. It includes task reports on Si material processing, large-area Si sheet development, encapsulation materials testing and development, Project engineering and operations, and manufacturing techniques, plus the steps taken to integrate these efforts. It also includes a report on and copies of viewgraphs presented at the PIM held December 13-14, 1978.

TITLE: Project Development Plan
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1, 1979
REPORT NO: 5101-17, Rev. A

ABSTRACT: The scope of this document includes a discussion of currently planned LSA Project activities covering the period October 1, 1977 through September 30, 1986. Technical management information is emphasized.

TITLE: Progress Report 12, January to April 1979, and Proceedings of the 12th PIM
CORPORATE AUTHOR: Jet Propulsion Laboratory
DATE: 1979
REPORT NO: DOE-JPL 1012-27, and 5101-112
AVAILABILITY: NTIS, PC A15/MF A01

ABSTRACT: This report describes progress made by the LSA Project during the period January through April 1979. It includes reports on Project Analysis and Integration; Technology Development in Si Material, Large-Area Sheet Si, and Encapsulation; Production Process and Equipment Development; Engineering and Operations, and a discussion of the steps taken to integrate these efforts. It includes a report on, and copies of viewgraphs presented at the PIM held April 4-5, 1979.

TITLE: Progress Report 13, April thru August 1979, and Proceedings of the 13th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1979
REPORT NO: DOE-JPL 1012-29, JPL Pub. 79-88, 5101-133
AVAILABILITY: NTIS, PC A20/MF A01

ABSTRACT: This report describes progress made by the LSA Project during the period April through August 1979. It includes reports on project analysis and integration; technology development in Si material, large-area sheet Si, and encapsulation; production process and equipment development; engineering and operations, and a discussion of the steps taken to integrate these efforts. It includes a report on, and copies of viewgraphs presented at, the PIM held August 22-23, 1979.

TITLE: Low Cost Solar Array Project (LSA) Resources Management Manual, Revision 3
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 15, 1979
REPORT NO: 5101-63

ABSTRACT: This document covers the Project general administrative practices and procedures, an overview of the system for resources management, Project planning reporting and control applications.

TITLE: Progress Report 14, August to December 1979, and Proceedings of the 14th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1979
REPORT NO: DOE JPL 1012-42, JPL Pub. 80-21, 5101-142
AVAILABILITY: NTIS, PC A23/MF A01

ABSTRACT: This report describes progress made by the LSA Project during the period August through November, 1979. It includes reports on project analysis and integration; technology development in Si material, large-area sheet Si, and encapsulation; production process and equipment development; engineering, and operations, and a discussion of the steps taken to integrate these efforts. It includes a report on, and copies of the visual materials presented at, the PIM held December 5-6, 1979.

TITLE: Progress Report 15, December 1979 to April 1980, and Proceedings of the 15th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1979
REPORT NO: DOE JPL 1012-44, JPL Pub. 80-27, 5101-151
AVAILABILITY: NTIS, PC A17/MF A01

ABSTRACT: This report describes progress made by the LSA Project during the period December 1979 to April 1980. It includes reports on project analysis and integration; technology development in Si material, large-area Si sheet and encapsulation; production process and equipment development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the PIM held April 2 and 3, 1980.

TITLE: Progress Report 16, April to September 1980, and Proceedings of the 16th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1980
REPORT NO: DOE-JPL 1012-51, JPL Pub. 80-100, 5101-160
AVAILABILITY: NTIS, PC A21/MF A01

ABSTRACT: This report describes progress made by the LSA Project during the period April to September 1980. It includes reports on project analysis and integration; technology development in Si material, large-area Si sheet and encapsulation; production process and equipment development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the PIM held September 24 and 25, 1980.

TITLE: Progress Report 17, September 1980 to February 1981, and Proceedings of the 17th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1981
REPORT NO: DOE-JPL 1012-54, JPL Pub. 81-35, 5101-172
AVAILABILITY: NTIS, PC A22/MF A01

ABSTRACT: This report describes progress made by the LSA Project during the period September 1980 to February 1981. It includes reports on project analysis and integration; technology development in Si material, large-area Si sheet and encapsulation; production process and equipment development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the PIM held at Pasadena, Calif, on February 4 and 5, 1981.

TITLE: Progress Report 18, February to July 1981, and Proceedings of the 18th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1981
REPORT NO: DOE-JPL 1012-58, JPL Pub. 81-94, 5101-186
AVAILABILITY: NTIS, PC A25/MF A01

ABSTRACT: This report describes progress made by the LSA Project during the period February to July 1981. It includes reports on project analysis and integration; technology development in Si material, large-area Si sheet and encapsulation; process development; engineering, and operations. It includes a report on, and copies of visual presentations made at, the PIM held at Pasadena, California, on July 15 and 16, 1981.

TITLE: Electricity from PV Solar Cells LSA Project. Displayed at the 15th IEEE Photovoltaic Specialists Conference, May 1981
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 1981
REPORT NO: 5101-178C

ABSTRACT: This is a copy of all display material.

TITLE: Progress Report 19, July to November 1981, and Proceedings of the 19th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1981
REPORT NO: DOE-JPL 1011-67, JPL Pub. 82-11, 5101-194
AVAILABILITY: NTIS, PC A17/MF A01

ABSTRACT: This report described progress made by the FSA Project (formerly the Low-Cost Solar Array Project) during the period July 10 November 1981. It includes reports on project analysis and integration; technology research in Si material, large area Si sheet and environmental isolation; cell and module formation; engineering sciences, and module performance and failure analysis. It includes a report on, and copies of visual presentations made at, the 19th PIM held at Pasadena, California, on November 11, 1981. This PIM was a one day meeting consisting primarily of parallel technology sessions. Two limited-attendance workshops were conducted on the day before the PIM: one on Si materials and crystal-growth technology, and one on solar-cell and module technology. A two-day short course on SAMICS was held following the PIM.

TITLE: Progress Report 20, November 1981 to April 1982, and Proceedings of the 20th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1982
REPORT NO: DOE-JPL 1012-71, JPL Pub. 82-48, 5101-209

ABSTRACT: This report describes progress made by the FSA Project during the period November 1981 to April 1982. It includes reports on project analysis and integration; technology research in Si material, large area Si sheet and environmental isolation; cell and module formation; engineering sciences, and module performance and failure analysis. It includes a report on, and copies of visual presentations made at, the 20th PIM held at Pasadena, California, on April 21 and 22, 1982. This report also contains the presentations made by various speakers during the plenary session.

TITLE: Summary of FSA Documentation Abstracts of Published Documents, 1975 to June 1982
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 15, 1982
REPORT NO: DOE-JPL 1012-76, JPL Pub. 82-79, 5101-221
AVAILABILITY: NTIS, PC A16/MF A01

ABSTRACT: Provided are abstracts of final reports and latest quarterly reports of JPL and contracted efforts that have constituted JPL-FSA, formerly LSA. Included are abstracts of Project Office reports, and of reports covering project analysis and integration, Si material, Si sheet (large-area Si sheet) encapsulation (environmental isolation), production process and equipment (process research), engineering (engineering sciences), and operations (module performance and failure analysis).

TITLE: Progress Report 21, April 1982 to January 1983, and Proceedings of the 21st PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1983
REPORT NO: DOE-JPL 1012-88, JPL Pub. 83-48, 5101-222
AVAILABILITY: NTIS, PC A22/MF A01; 1

ABSTRACT: This report describes progress made by FSA during the period April 1982 to January 1983. It includes reports on polysilicon refining, thin-film solar-cell and module technology development, central-station electric utility activities, Si sheet growth and characteristics, advanced PV materials, cell and processes research, module technology, environmental isolation, engineering sciences, module performance and failure analysis, and project analysis and integration. It includes proceedings of, and copies of visual presentations made at, the 21st PIM held at Pasadena, California, on January 12 and 13, 1983.

TITLE: Progress Report 22, January to September 1983, and Proceedings of the 22nd PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1983
REPORT NO: DOE-JPL 1012-94, JPL Pub. 84-2, 5101-242
AVAILABILITY: NTIS, PC A99/MF A01; 1

ABSTRACT: This report describes progress made by FSA during the period January to September 1983. It includes reports on Si-sheet growth and characterization, module technology, Si material, cell processing and high-efficiency cells, environmental isolation, engineering sciences, module performance and failure analysis and project analysis and integration. It includes a report on, and copies of visual presentations made at, the 22nd PIM held at Pasadena, California, on September 28 and 29, 1983.

TITLE: Progress Report 23, September 1983 to March 1984, and Proceedings of the 23rd PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1984
REPORT NO: DOE-JPL 1012-99, JPL Pub. 84-47, 5101-250
AVAILABILITY: NTIS, PC A22/MF A01; 1

ABSTRACT: This report describes progress made by FSA during the period September 1983 to March 1984. It includes reports on Si sheet growth and characterization, module technology, Si material, cell processing and high-efficiency cells, environmental isolation, engineering sciences, module reliability and project analysis and integration. It includes a report on, and copies of visual presentations made at, the 23rd PIM held at Pasadena, California, on March 14 and 15, 1984.

TITLE: Progress Report 24, March to October 1984, and Proceedings of the 24th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1984
REPORT NO: DOE-JPL 1012-104, JPL Pub. 85-27, 5101-259
AVAILABILITY: NTIS, PC A99/MF A01; 1

ABSTRACT: This report describes progress made by FSA during the period of March 1984 to October 1984. It includes reports on Si sheet growth and characterization, Si material, process development, high-efficiency cells, environmental isolation, engineering sciences, and reliability physics. It includes a report on, and copies of visual presentations made at, the 24th PIM held at Pasadena, California, on October 2 and 3, 1984.

TITLE: Progress Report 25, October 1984 to June 1985, and Proceedings of the 25th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1985
REPORT NO: DOE-JPL 1012-119, JPL Pub. 86-4, 5101-271

ABSTRACT: This report describes progress made by FSA during the period October 1984 to June 1985. It includes reports on Si sheet growth and characterization, Si material, process development, high-efficiency cells, environmental isolation, engineering sciences, and reliability physics. It includes a report on, and copies of visual presentations made at, the 25th PIM held at Pasadena, California, on June 19 and 20, 1985.

TITLE: Progress Report 26, July 1985 to April 1986, and Proceedings of the 26th PIM
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 1986
REPORT NO: DOE-JPL 1012-124, JPL Pub. 86-23, 5101-286

ABSTRACT: This report describes progress made by FSA during the period July 1985 to April 1986. It includes reports on Si sheet growth and characterization, Si material, process development, high efficiency cells, environmental isolation, engineering sciences, and reliability physics. It also includes technical and plenary presentations made at the 26th Project Integration Meeting held at Pasadena, California, on April 29, 30, and May 1, 1986. This 26th and final Project Integration Meeting was divided into three specific areas: (1) April 29 consisted of an overview of the progress and the significance of the results of 11 years of progress to the PV manufacturers, users, and community; (2) April 30 provided detailed summaries of the progress of the FSA contractors and in-house work since the 25th PIM; and (3) May 1 offered an opportunity for industry and users to explain their continuing participation in the manufacture and use of crystalline Si PV.

SILICON MATERIAL
JPL - IN-HOUSE ABSTRACTS

SILICON MATERIALS IN-HOUSE ABSTRACTS

TITLE: Research Priorities for PV Si Technology
AUTHOR: K.M. Koliwad, G.D. Cumming, and T.G. Digges, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1976
REPORT NO: DOE-JPL 01652
AVAILABILITY: NTIS-01652

ABSTRACT: It is the intent of this paper to define the necessary areas of research and assign appropriate priorities in PV Si technology. The problems discussed include wafering for the ingot yielding processes such as Cz, float zone and casting; die interaction and/or seeding for the ribbon processes like EFG, Stepanov and web dendritic; substrate/nucleation problems for the thick film techniques such as CVD and dip coating; and high temperature mechanical properties for hot forming processes. Conclusions of the analysis indicate the need for funda mental research in the areas of nucleation, crystallization, solidifications, heat flow dynamics, high temperature mechanical properties and Si-contact material interactions.

TITLE: Modeling of Fluidized-Bed Si Deposition Process
AUTHOR: K. Kim, G. Hsu, R. Lutwack, and A. Praturi
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1977
REPORT NO: JPL Pub. 77-25, and 5101-50

ABSTRACT: Modeling of the fluidized bed for Si deposition is described. The model is intended for use as a means of improving FBR design and for the formulation of the research program in support of the contracts of the Si Material Task for the development of the fluidized bed Si deposition process. A computer program derived from the simple modeling is also described. Results of some sample calculations using the computer program are shown.

TITLE: CVD of Si from Silane Pyrolysis
AUTHOR: A. K. Praturi, R. Lutwack, and G. Hsu
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 1977
REPORT NO: JPL Pub. 77-38

ABSTRACT: The four basic elements in the CVD of Si from silane are mass transport of silane, pyrolysis of silane, nucleation of Si and Si crystal growth. These four elements are analytically treated from a kinetic standpoint. Rate expressions that describe the various conceivable steps involved in the CVD of Si are derived from elementary principles. Applications of the rate expressions for (1) modeling and the simulation of the Si CVD process and (2) the analysis of experimental data on Si CVD are discussed. The lack of an experimentally established mechanism of the Si CVD process and established values for various constants involved in the rate expres sions is the major impediment to the modeling of the CVD process. Experimental data are needed to determine the equilibrium adsorption coefficients for silane, hydrogen and Si vapor and the activation energies and frequency factors for the various rate processes involved in the Si CVD.

TITLE: Si Formation by Pyrolysis of Silane. Interim Report of the Continuous Flow Pyrolyzer Study
AUTHOR: H. Levin
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1978
REPORT NO: 5101-87

ABSTRACT: A study of the formation and growth of Si was conducted in which silane was converted to Si in a continuous flow pyrolyzer. The study employed a set of four experiments, factorially designed for a high and low level of gas-stream temperature and for the presence and absence of Si seed particles in the gas stream. The study was undertaken to support and complement those Project programs which utilize pyrolysis technology in the production of Si. In most of these programs, the form and size of the Si are important elements in the success of the program.

TITLE: In-House Study Fluidized-Bed Silane Pyrolysis
AUTHOR: R. Hogle, G. Hsu, and R. Lutwack
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 1978
REPORT NO: 5101-89

ABSTRACT: As part of the Task I in-house support effort, low-cost Si production by silane pyrolysis is being studied using a 2-in. inside diameter FBR. The reactor as well as a quartz fluidization column were constructed and instrumented with electronic pressure transducers, and a computer data acquisition system to study general Si fluidization along with the silane chemistry.

TITLE: Modeling of Si Particle Growth. A Progress Report
AUTHOR: A.K. Praturi, G.C. Hsu, and R. Lutwack
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 1979
REPORT NO: DOE-JPL 1012-20, and 5101-105
AVAILABILITY: NTIS, PC A03/MF A02

ABSTRACT: Efforts at JPL toward the production of pure polycrystalline Si are centered on the concept of Si particle growth in a FBR and a CFP. The CFP possibly can provide the seed particles which will be grown to longer sizes in the FBR. In both the reactors polycrystalline Si is obtained from the pyrolysis of silane. A part of the JPL effort is to develop a model of Si particle growth for the purpose of predicting particle growth rates and product particle size distributions in the FBR and the CFP. This report describes the mathematical models of Si particle growth in the FBR and the CFP.

TITLE: On the Modeling of Silane Pyrolysis in a Continuous Flow Reactor
AUTHOR: A.K. Praturi, G.C. Hsu, and R. Jain
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 1979
REPORT NO: DOE-JPL 1012-21, and 5101-106
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Silane pyrolysis in a CFP is a simple process that is currently being developed for producing solar cell grade Si. The process involves complex phenomena, however, including thermal decomposition of silane, nucleation and growth of Si particles, and mass and heat transfer. Modeling the effects of transport phenomena on silane pyrolysis in a CFP is discussed in this report. One- and two-dimensional models are developed to predict velocity, temperature, and concentration profiles in the reactor. The one dimensional model has been implemented as a computer code.

TITLE: Purification of Si by the Si Fluoride Transport Process: A Thermochemical Study
AUTHOR: R.A. Rhein
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 1979
REPORT NO: DOE-JPL 1012-18, and 5101-107
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: A computer-assisted thermochemical equilibrium analysis was conducted for the Si transport reaction: $Si(s) + SiF_4(g) = (intermediates) = Si(s) + SiF_4(g)$. The calculations indicated that a substantial transport rate should be possible at temperatures of 1700 K and one atmosphere pressure. Computations were made to determine whether the elemental impurities present in metallurgical-grade Si would transfer in this process. It was concluded that aluminum, chromium, copper, iron, manganese, molyb-

denum, nickel, vanadium, and zirconium would not transfer, but that boron, magnesium, phosphorus, and titanium would transfer.

TITLE: Si Preparation and Purity from the Reaction of Sodium with Si Tetrafluoride and Si Tetrachloride
AUTHOR: R.A. Rhein
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 1979
REPORT NO: DOE-JPL 1012-19, and 5101-108
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Thermochemical equilibrium computations for the preparation of Si by the reaction between sodium, either liquid or vapor, with Si tetrafluoride and Si tetrachloride are presented. The reactions of a number of impurity elements in Na, during the course of the Na-Si halide reaction, have been described.

TITLE: The Effects of Impurities on the Performance of Si Solar Cells
AUTHOR: K.A. Yamakawa
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1981
REPORT NO: DOE-JPL 1012-57, and 5101-189
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The major factors that determine the tolerable concentrations of impurities in Si feedstock for solar cells used in power generation are discussed in this report.

TITLE: Proceedings of the FSA Workshop on the Science of Si Material Preparation (August 23, 24, and 25, 1982, The Pointe, Phoenix, Arizona)
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1, 1983
REPORT NO: DOE-JPL 1012-81, JPL Pub. 83-13, 5101-228
AVAILABILITY: NTIS, PC A14/MF A01

ABSTRACT: The Science of Si Material Preparation Workshop was held August 23-25, 1982 at The Pointe, Phoenix, Arizona. It was sponsored by JPL-FSA. There were six sessions: Si Production and Purity; Thermodynamics, Kinetics, and Mechanisms; Particle Formation and Growth; Deposition in FBRs; CVD; and Alternative Polysilicon Processes. Twenty-two invited papers were presented. Discussion periods followed the papers and the sessions. These Proceedings are a record of the papers and the discussions.

TITLE: Si Production in a Fluidized Bed Reactor: A Parameter Study
AUTHOR: N. Rohatgi and G. Hsu
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1983
REPORT NO: JPL D-1283, 5101-248

ABSTRACT: This report covers one phase of experimental study sponsored by the DOE, that was carried out by JPL. One of the objectives of FSA is to establish the technology for a low-cost process for producing semiconductor Si to meet the needs for terrestrial PV applications. The starting material for this process is silane gas produced by the Union Carbide Corp. under another FSA development program. The process for converting metallurgical-grade Si to silane is being demonstrated at the pilot-plant scale by the Union Carbide Corp. at Washougal, Washington. The low-cost means of converting silane to semiconductor-grade Si in a FBR is being investigated by JPL and by the Union Carbide Corp. under a contract with JPL. The overall goal of the program is to produce Si at $16-20/kg (1982 dollars).

TITLE: A Review of the Si Material Task
AUTHOR: R. Lutwack
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1, 1984
REPORT NO: DOE-JPL 1012-96, JPL Pub. 84-24, 5101-244
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: The Si Material Task of FSA was assigned the objective of developing the technology for low-cost processes for producing polysilicon suitable for terrestrial solar-cell applications. The Task program comprised sections for process developments for semiconductor-grade and solar-cell-grade products. To provide information for deciding upon process designs, extensive investigations of the effects of impurities on material properties and the performance of cells were conducted. The silane process of the Union Carbide Corp. was carried through several stages of technical and engineering development. A pilot plant was the culmination of this effort. The work to establish silane fluidized-bed technology for a low-cost process is continuing. The advantages of the use of dichlorosilane in a Siemens-type process were shown by Hemlock Semiconductor Corp. The development of other processes is described.

TITLE: An Analysis of the Feasibility of Producing Si for Solar Cells by a Dichlorosilane/Fluidized-Bed Reactor Process
AUTHOR: A. Briglio, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 1984
REPORT NO: DOE-JPL 1012-101, JPL Pub. 84-55, 5101-256
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: An analysis was conducted to evaluate a novel Si production process based on conversion of dichlorosilane to Si in FBRs. Such a process seemed attractive from an economic point of view. The study is part of the effort being supported by FSA for new processes for making low-cost, high purity Si for terrestrial solar cells. It was concluded that the thermodynamics and kinetics should be sufficiently favorable: to allow reasonably high values of conversion efficiency of dichlorosilane to Si, to attain a satisfactory Si deposition rate, and to achieve a suitably high product purity. The Si price is expected to be somewhat higher than that for Si produced by the FBRbased Si via silane process being developed by the Union Carbide Corp. and JPL. Process success ultimately will depend upon finding FBR materials of construction that will withstand the severe corrosive and abrasive environment that is expected to be present.

TITLE: Proceedings of the FSA Workshop on Low-Cost Polysilicon for Terrestrial PV Solar-Cell Applications (October 28-30, 1985, at Las Vegas, Nevada)
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February, 1986
REPORT NO: DOE-JPL 1012-122, JPL Pub. 86-11, 5101-287

ABSTRACT: The Workshop on Low-Cost Polysilicon for Terrestrial PV Solar-Cell Applications was held October 28, 29, and 30, 1985, at the Sahara Hotel, Las Vegas, Nevada. It was sponsored by JPL-FSA. The sessions were: Polysilicon Material Requirements; Economics; Process Developments in the USA; Process Developments, International; and Polysilicon Market and Forecasts. There were two forums dealing with polysilicon process technology and polysilicon markets. Twenty-one invited papers were presented and discussion periods followed the papers. This report contains a record of the papers, the forums, and the discussions.

TITLE: Si Production in a FBR. Final Report
AUTHOR: N. Rohatgi
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 1986
REPORT NO: DOE JPL 1012-123, JPL Pub. 86-17, 5101-296

ABSTRACT: Part of the development effort of the JPL in-house technology involved in FSA was the investigation of a low-cost process to produce semiconductor-grade Si for terrestrial PV cell applications. The process selected was based on pyrolysis of silane in a FBR. Following initial investigations involving 1 and 2-in. dia reactors, a 6-in. dia, engineering-scale FBR was constructed to establish reactor performance, mechanism of Si deposition, product morphology, and product purity. The overall mass balance for all experiments indicates that more than 90% of the total Si fed into the reactor is deposited on Si seed particles and the remaining 10% becomes elutriated fines. Si production rates were demonstrated of 1.5 kg/h at 30% silane concentration and 3.5 kg/h at 80% silane concentration. The mechanism of Si deposition is described by a six-path process: heterogeneous deposition, homogeneous decomposition, coalescence, coagulation, scavenging, and heterogeneous growth on fines. The bulk of the grown Si layer appears to be made up of small diameter particles. This product morphology lends support to the concept of the scavenging of homogeneously nucleated Si. Excellent purity of the Si product was obtained from an FBR equipped with a quartz linear. The product Si had metallic contaminants less than the detection limits of spark source mass spectroscopy (e.g., Fe < 0.6 ppma, Cr < 0.02 ppma, Zn < 0.04 ppma, Co < 0.1 ppma). Solar cells fabricated from this pure Si product showed encouraging results and the data are described in this report.

SILICON MATERIAL
CONTRACTOR ABSTRACTS

SILICON MATERIAL CONTRACTOR ABSTRACTS

TITLE: Final Report. Si Material Task. Part 3
AUTHOR: R.A. Roques and D.M. Coldwell
CORPORATE AUTH: Texas Instruments, Inc.
DATE: January 1977
REPORT NO: ERDA-JPL 954412-77/1
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: The feasibility of a process for carbon reduction of low impurity silica in a plasma heat source was investigated to produce low-cost solar-grade Si. Theoretical aspects of the reaction chemistry were studied with the aid of a computer program using iterative free energy minimization. The computer simulation technique of molecular dynamics was used to study the quenching of product species.

TITLE: Final Technical Report. Determination of a Definition of Solar Grade Si
AUTHOR: H.W. Gutsche and D.E. Hill
CORPORATE AUTH: Monsanto Research Corp.
DATE: September 9, 1977
REPORT NO: ERDA-JPL 954338-77/1

ABSTRACT: This final report gives the effects of the impurities Al, C, Cr, Cu, Fe, Mg, Mn, Na, Ni, O, Ti, V, and Zr on the performance of Si solar cells. A series of experimental Si crystals were prepared containing controlled amounts of these impurities in otherwise SG Si single crystals. Using these crystals, solar cells were prepared and the solar energy conversion efficiencies of these devices were measured against a standard cell provided by JPL.

TITLE: Final Report. Lifetime and Diffusion Length Measurements on Si Materials and Solar Cells
AUTHOR: S. Othmer and S.C. Chen
CORPORATE AUTH: Northrop Corp.
DATE: November 1977
REPORT NO: ERDA-JPL 954614-77/1
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: Experimental methods were evaluated for the determination of lifetime and diffusion length in Si intentionally doped with potentially lifetime-degrading impurities found in metallurgical grade Si, impurities which may be residual in low-cost Si intended for use in terrestrial flat-plate arrays. Results obtained by these methods were compared for mutual consistency. Lifetime measurements were made using a steady-state photoconductivity method, which was compared with a photoconductivity decay technique. Diffusion length determinations were made using short-circuit current measurements under penetrating illumination. This method was compared with a direct measurement of diffusion length using a scanning electron microscope.

TITLE: Final Report. Analysis of Effects of Impurities Intentionally Incorporated into Si
AUTHOR: F.M. Uno
CORPORATE AUTH: Spectrolab, Inc.
DATE: December 1977
REPORT NO: DOE-JPL 954694-77/4
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: A methodology has been developed and implemented to allow Si samples containing intentionally incorporated impurities to be fabricated into finished solar cells under carefully controlled conditions. The electrical properties and spectral responses were then measured for each group processed. All 33 lots of group "C", 14 lots of Group "CM" and 16 lots of Group "F" have been fabricated into cells and tested.

TITLE: Final Report. October 9, 1975 to July 9, 1978. Evaluation of Selected Chemical Processes for Production of Low-Cost Si (Phases I and II)
AUTHOR: J.M. Blocher, Jr. and M.F. Browning
CORPORATE AUTH: Battelle Memorial Institute, Columbus Laboratories
DATE: July 9, 1978
REPORT NO: DOE-JPL 954339-78/11
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: The zinc reduction of Si tetrachloride in a fluidized bed of seed particles to yield a granular product was studied along with several modifications of the thermal decomposition or hydrogen reduction of Si tetraiodide. Although all contenders were believed to be capable of meeting the quality requirements of the LSA Project, it was concluded that only the zinc reduction of the chloride could be made economically feasible at a cost below $10/kg Si (1975 dollars). Accordingly, subsequent effort was limited to evaluating that process. A mini-plant, consisting of a 5-cm-dia BFR and associated equipment was used to study the deposition parameters, temperature, reactant composition, seed particle size, bed depth, reactant throughput, and methods of reactant introduction. Other aspects of the process such as the condensation and fused-salt electrolysis of the $ZnCl_2$ by-product for recycle of zinc and chlorine were studied to provide information required for design of a 50 MT/yr experimental facility, visualized as the next stage in the development. Projected Si costs of $7.35 and $8.71/kg (1975 dollars) for a 1000 MT/yr facility were obtained, depending upon the number and size of the FFBRs and $ZnCl_2$ electrolytic cells used.

TITLE: Final Report. Synthesis of Silane and Si in a Non-Equilibrium Plasma Jet
AUTHOR: H.F. Calcote
CORPORATE AUTH: AeroChem Research Laboratories, Inc.
DATE: October 1978
REPORT NO: DOE-JPL 954560-78/8
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: The original objective of this program was to determine the feasibility of high volume, low-cost production of high purity silane or solar cell grade Si using a non-equilibrium plasma jet. The emphasis was changed near the end of the program to determine the feasibility of preparing PV a-Si films directly using this method. The non-equilibrium plasma jet is produced by partially dissociating hydrogen to hydrogen atoms in a 50 to 100 Torr glow discharge and expanding the H/H_2 mixture through a nozzle. A high flux density of hydrogen atoms is thus produced at concentrations of about 3 mol % with about 30% energy utilization efficiency. The jet is mixed with a second reactant and the reaction proceeds at a temperature of 400 to 600 K to produce products. Yields of SiH_4, $SiHCl_3$, or SiH_2Cl_2 from $SiCl_4$ and $SiHCl_3$ were too low to be economically attractive. However, both amorphous and polycrystalline Si films which strongly adhered to Pyrex, Vycor, aluminum, or carbon were prepared with either $SiCl_4$ reactant were more difficult to prepare; they were prepared by carefully cleaning the aluminum substrate, diluting the SiH_4 with about 90% argon, and forming the glow discharge between the mixing nozzle and the aluminum substrate. Doping such films with P by adding PH_3 reduced the electrical resistivity by two orders of magnitude. The non-equilibrium plasma jet should be further evaluated as a technique for producing high efficiency PV a-Si films.

TITLE: Interim Report. Closed-Cycle Process Development
AUTHOR: R.A. Roques
CORPORATE AUTH: Texas Instruments, Inc.
DATE: December 1978
REPORT NO: DOE-JPL 955006-78/2

ABSTRACT: This program was Phase I of an effort to achieve production of low-cost solar-grade polysilicon from metallurgical-grade Siin a closed-cycle process. Impure Si would be converted to trichlorosilane by reaction with by-product Si tetrachloride, and the trichlorosilane thermally decomposed in a rotary drum reactor. The technical restrictions to development of the program approach were based on minimizing new technology requirements by using existing technology to reduce the timing, risk, and cost of achieving production capability. The deficiencies in the established Siemens polysilicon process were identified and systematically eliminated to achieve a simple, continuous, easily scalable, low-cost process. The process was begun with the design of the two major items of untested equipment, the Si tetrachloride by-product converter and the Rotary Drum Reactor for deposition of Si from trichlorosilane. The design criteria of the initial laboratory equipment included consideration of the reaction chemistry, thermodynamics, and other technical factors. Design and construction of the laboratory equipment was completed. The closed-cycle process appears to have a very likely potential to achieve LSA goals.

TITLE: Final Report. The Production of Solar Cell Grade Si from Bromosilanes
AUTHOR: J. Schumacher
CORPORATE AUTH: J.C. Schumacher Co.
DATE: January 1979
REPORT NO: DOE-JPL 954914-79/5

ABSTRACT: Based upon a chemical engineering analysis of existing semiconductor grade polycrystalline Si processes, Cost Element Objectives for (1) Capital Equipment, (2) Raw Materials, (3) Labor, and (4) Utilities were established to meet the LSA Project Si Materials Task cost objective of $10/kg for SCG Si. A CFR process based on the hydrogen reduction if the bromosilanes $SiBr_4$ and $SiHBr_3$ was proposed by the J. C. Schumacher Co. to meet these cost element objectives. Initial experiments directed at obtaining overall yield data for bromosilane reduction in the CFR were carried out. Further experiments to complete process selection and preliminary process economic evaluation and design are suggested.

TITLE: Final Report. Phases I and II. Feasibility of the Silane Process for Producing Semiconductor-Grade Si, October 1975 to March 1979
CORPORATE AUTH: Union Carbide Corp.
DATE: June 1979
REPORT NO: DOE-JPL 954334-79/10

ABSTRACT: The commercial production of low-cost SG Si is an essential requirement of the LSA Project. A 1000-MT/yr commercial facility using the Union Carbide Silane Process will produce molten Si for an estimated price of $7.56/kg (1975 dollars, private financing), meeting the DOE goal of less than $10/kg. Conclusions and technology status are reported for both contract phases, which had the following objectives: 1) establish the feasibility of UCC's Silane Process for commercial application, and 2) Develop an integrated process design for an Experimental Process System Development Unit (EPSDU) and a commercial facility, and estimate the corresponding commercial plant economic performance. To assemble the facility design, the following work was performed: (a) collection of Union Carbide's applicable background technology; (b) design, assembly, and operation of a small integrated silane-producing PDU; (c) analysis, testing, and comparison of two high-temperature methods for converting pure silane to Si metal; and (d) determination of chemical reaction equilibria and kinetics, and vapor-liquid equilibria for chlorosilanes.

TITLE: Final Report. Composition Measurements by Analytical Photon Catalysis
AUTHOR: D.G. Sutton, et al.
CORPORATE AUTH: The Aerospace Corp.
DATE: September 1979
REPORT NO: DOE-JPL 955201-79/4
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: The object of this research is to assess the applicability of the photon catalysis technique for effecting composition analysis of Si samples. In particular, our technique is to be evaluated as a detector for the impurities Al, Cr, Fe, Mn, Tr, V, Mo and Zr. During the first year we have detected Al, Cr, Fe, Mn, Ti and Si with the photon catalysis method. We have established the best fluorescence lines to monitor and determined initial sensitivities to each of these elements by atomic absorption calibration. In the course of these tests vapor pressure curves for these six pure substances have also been mapped. We have also studied the detection of these impurities in Si matrices. The evaporation process was shown to be congruent; thus, our spectral analysis of the vapor will yield the composition of the bulk sample. In addition to these mainline tasks, much ancillary information was obtained. The emission signatures were determined for several additional elements including As, Bi, B, Ca, Cu, Cr, Ga, Ge, Mg, Na, P and Pb. Ionic emission lines for Ca and Mg were determined to be useful for analysis. Pulsed sample introduction was examined.

TITLE: Final Report. Solar Si via the Dow Corning Process
AUTHOR: L.P. Hunt and V.D. Dosaj
CORPORATE AUTH: Dow Corning Corp.
DATE: October 1979
REPORT NO: DOE-JPL 954559-78/7
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: The process developed under this contract meets the LSA Project objective of demonstrating technical feasibility for high-volume production of solar-cell-grade Si. The process consists of producing Si from pure raw materials via the carbothermic reduction of quartz. This Si was then purified to solar grade by impurity segregation during Cz crystal growth. Commercially available raw materials were used to produce 100 kg quantities of Si during 60-h periods in a Direct Arc Reactor. This Si had impurity concentrations of less than 10 ppmw each, except for Al and Fe (50-100 ppmw). Purification of this material by Cz crystal growth gave Si of semiconductor purity, except for Al (1 ppma), B (7 ppma, 0.1 ohm-cm), and P (0.5) ppma. This Si produced a single crystalline ingot, during a second Cz pull, that was fabricated into solar cells having AM1 efficiencies ranging from 8.2% to greater than 14% (AR-coated). An energy analysis of the entire process indicated a 5-month payback time. A price of $12.15 (1980 dollars, with profit) was estimated for a 3000-MT/yr plant. Further process development is recommended based upon technical success, estimated product cost, and commercially-available technology already existing in the industry that can be applied to process scale-up.

TITLE: Quarterly Report. Development of Model and Computer Code to Describe Solar Grade Si Production Processes
AUTHOR: R. Srivastava and R.K. Gould
CORPORATE AUTH: AeroChem Research Laboratories, Inc.
DATE: December 1979
REPORT NO: DOE-JPL 954862-79/8
AVAILABILITY: NTIS, PC A07/MF A01

ABSTRACT: This report describes models and computer codes which may be used to describe flow reactors in which high purity, solar grade Si is produced via reduction of gaseous Si halides. A prominent example of the type of process which may be studied using the codes developed in this program is the $SiCl_4$/Na reactor currently being developed by the Westinghouse Electric Corp. During this program two large computer codes were developed. The first is the CHEMPART code, an axisymmetric, marching code which treats two phase flows with models describing detailed gas-phase chemical kinetics, particle formation, and particle growth. This code, based on the AeroChem LAPP code can be used to describe flow reactors in which reactants mix, react, and form a particulate phase. Detailed radial gas phase composition, temperature, velocity, and particle size distribution profiles are computed. Also, deposition of heat,

momentum, and mass (either particulate or vapor) on reactor walls is described. The second code is a modified version of the GENMIX boundary layer code which is used to compute rates of heat, momentum, and mass transfer to the reactor walls. This code lacks the detailed chemical kinetics and particle handling features of the CHEMPART code but has the virtue of running much more rapidly than CHEMPART, while treating the phenomena occurring in the boundary layer in more detail than can be afforded using CHEMPART. These two codes have been used in this program to predict particle formation characteristics and wall collection efficiencies for $SiCl/^{Na}$ flow reactors. It is anticipated that an important application of these codes will be their use in finding operation conditions where droplet formation may be minimized and high collection efficiencies may still be realized in reactors of the Westinghouse type.

TITLE: Semiconductor Grade, Solar Si Purification Project
AUTHOR: W.M. Ingle, R.S. Rosler, et al.
CORPORATE AUTH: Motorola, Inc.
DATE: December 10, 1979
REPORT NO: 954442-78/12

ABSTRACT: In February 1976, DOE/JPL funding was initiated for Motorola's low-cost polysilicon program. In the process, SiF_4, a low-cost by-product is reacted with mg Si to form SiF_2 gas which is polymerized. The $(SiF_2)_x$ polymer is heated forming volatile Si_xF_y homologues which disproportionate (CVD) on a Si particle bed forming Si and SiF_4. During the initial phases of the investigation, the Si analysis procedure relied heavily on SSMS and ES analysis. These analysis demonstrated that major purification had occurred and some samples were indistinguishable from semiconductor grade Si (except possibly for phosphorus). However, more recent electrical analysis via crystal growth reveals that the product contains compensated phosphorus and boron. Work on the control or removal of the electrically active donors and acceptors could yield a product suitable for solar application.

TITLE: Final Report. Si Halide-Alkali Metal Flames as a Source of Solar Grade Si
AUTHOR: D.B. Olson and W.J. Miller
CORPORATE AUTH: AeroChem Research Laboratories, Inc.
DATE: January 1980
REPORT NO: DOE-JPL 954777-80/8
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The object of this program was to determine the feasibility of using continuous high-temperature reactions of alkali metals and Si halides to produce Si in large quantities and of suitable purity for use in the production of PV solar cells. Equilibrium calculations showed that a range of conditions were available where Si was produced as a condensed phase but the byproduct alkali metal salt was a vapor. A process was proposed using the vapor phase reaction of Na with $SiCl_4$. Low pressure experiments were performed demonstrating that free Si was produced and providing experience with the construction of reactant vapor generators. Further experiments at higher reagent flow rates were performed in a low temperature flow tube configuration with co-axial injection of reagents. A high temperature graphite flow tube was built and continuous separation of Si from NaCl was demonstrated. A larger-scaled well-stirred reactor was built. Experiments were performed to investigate the compatibility of graphite-based reactor materials of constructions with sodium.

TITLE: Final Report. Analysis of The Effects of Impurities in Si
AUTHOR: J.H. Wohlgemuth and M.N. Giuliano
CORPORATE AUTH: Solarex Corp.
DATE: January 1980
REPORT NO: DOE-JPL 955307/4
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: The purpose of this program was to conduct a solar cell fabrication and analysis program to determine the effects on the resultant solar cell efficiency of impurities intentionally incorporated into Si. The program employed "flight-quality" technologies and quality assurance typical of an experienced solar cell manufacturer to assure that variations in cell performance are due to the impurities incorporated in the Si. A rigid program of documentation and decontamination procedures was instituted.

TITLE: Final Report. Novel Duplex Vapor-Electrochemical Method for Si Solar Cells
AUTHOR: L. Nanis, A. Sanjurjo, et al.
CORPORATE AUTH: SRI International
DATE: March 1980
REPORT NO: DOE-JPL 954471-80/13
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: A process has been developed for the economic production of high purity Si from inexpensive reactants, based on the Na reduction of SiF_4 gas. The products of reaction (NaF, Si) are separated by either aqueous leaching or by direct melting of the NaF-Si product mixture. Impurities known to degrade solar cell performance are all present at sufficiently low concentrations so that melt solidification (e.g., Cz) will provide a Si material suitable for solar cells.

TITLE: Final Report. Use of Glass Reinforced Concrete as a Substrate for PV Modules
CORPORATE AUTH: Tracor MBAssociates (MBAssociates)
DATE: March 1980
REPORT NO: DOE-JPL 955281-80/4
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: MBAssociates developed a substrate for flat plate PV solar panel arrays using a GRC material. The installed cost of this GRC panel (designed, developed and fabricated by MBA) is 30% less than the JPL cost goal of the Near Term Low-Cost Flat Plate PV Program. The 4' x 8' panel is fabricated from readily available inexpensive materials, weighs a nominal 190 lbs., has exceptionally good strength and durability properties (rigid and resists weathering), is amenable to mass production and is easily installed on simple mountings. Solar cells are encapsulated in EVA with Tedlar backing and Korad cover film. The laminates are attached to the GRC substrate with acrylic transfer tape and edge sealed with a silicone RTV adhesive.

TITLE: Final Report. Gaseous Melt Replenishment System
AUTHOR: D.N. Jewett, H.E. Bates, and D.M. Hill
CORPORATE AUTH: Energy Materials Corp.
DATE: August 1980
REPORT NO: DOE-JPL 955269-80/16
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The objective of this program was to demonstrate the operation of a novel, efficient Si production technique. The essentials of the method comprised chemical vapor deposition of Si, by hydrogen reduction of chlorosilanes, on the inside of a quartz reaction vessel having large internal surface area. The system was designed to allow successive deposition-melting cycles, with Si removal being accomplished by discharging the molten Si. The liquid product would be suitable for transfer to a crystal growth process, casting into solid form, or production of shots. Successful, sequential operation of the reverse U-bend trap seal ("U-tube") was also demonstrated. This feature, acting as a 1400°C valve, permits successive deposition-meltout cycles in the reactor. Problems remaining to be solved with the system include: (1) Plugging of the reactor outlet tube by Si halide polymers and by Si monoxide generated during the melt-down. (2) Maximization of regenerative heat exchange between reactants and products, thus improving conversion levels.

TITLE: Final Report. AR Coatings on Large Area Glass Sheets
AUTHOR: E. Pastirik
CORPORATE AUTH: Motorola, Inc.
DATE: September 1980
REPORT NO: DOE-JPL 955339-80/4
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: AR coatings which may be suitable for use on the covers of PV solar modules can be easily produced by a dipping process. The coatings are applied to glass by drawing sheets of glass vertically out of dilute aqueous sodium silicate solutions at a constant speed, allowing the adherent liquid film to dry, then exposing the dried film to concentrated sulfuric acid, followed by a water rinse and dry. The process produces coatings of good optical performance (96.7% peak transmission at 0.540 uM wavelength) combined with excellent stain and soil resistance, and good resistance to abrasion. The process is reproducible and easily controlled.

TITLE: Final Report. Development of Megasonic Cleaning for Si Wafers
AUTHOR: A. Mayer
CORPORATE AUTH: RCA Corp.
DATE: September 1980
REPORT NO: DOE-JPL 955342-79/5
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The major contract goals to develop a cleaning and drying system for processing at least 2500 3-in.-dia wafers/h and to reduce the process cost were achieved. The new system consists of an ammonia hydrogen peroxide bath in which both surfaces of 3/32-in.-spaced, ion-implanted wafers are cleaned in quartz carriers moved on a belt past two pairs of Megasonic transducers. The wafers are dried in the novel room-temperature, high-velocity air dryer in the same carriers used for annealing. A new laser scanner was used effectively to monitor the cleaning ability on a sampling basis.

TITLE: Final Report. October 1, 1975 to February 6, 1981. Process Feasibility Study
AUTHOR: C.L. Yaws, K. Li, et al.
CORPORATE AUTH: Lamar University
DATE: February 6, 1981
REPORT NO: DOE-JPL 954343 81/21
AVAILABILITY: NTIS, PC A20/MF A01

ABSTRACT: This study reports work performed and presents results for process system properties, chemical engineering and economic analyses of the new technologies and processes being developed for the production of lower cost Si for solar cells. Major physical, thermodynamic and transport property data are reported for the following Si source and processing chemical materials: silane, Si tetrachloride, trichlorosilane, dichlorosilane, Si tetrafluoride and Si. The property data are reported for critical temperature, critical pressure, critical volume, vapor pressure, heat of vaporization, heat capacity, density, surface tension, viscosity, thermal conductivity, heat of formation and Gibb's free energy of formation. The reported property data are presented as a function of temperature to permit rapid usage in research, development and production engineering. Chemical engineering analyses involving the preliminary process design of a plant (1000 MT/yr capacity) to produce Si via the technology under consideration were accomplished for the following processes: UCC silane process for Si; BCL process of Si - case A; BCL process for Si - case B; conventional polysilicon process (Siemens Technology); SiI_4 decomposition process and DCS process.

TITLE: Final Report. Development of Processes for the Production of Solar Grade Si from Halides and Alkali Metals, Phase I & II
AUTHOR: C.R. Dickson and R.K. Gould (Phase I); C.R. Dickson, W. Felder, and R.K. Gould (Phase II)
CORPORATE AUTH: AeroChem Research Laboratories, Inc.
DATE: March 1981
REPORT NO: DOE-JPL 955491-81/6
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: Phase I of this program was directed toward the development of processes involving high temperature reactions of Si halides with alkali metals for the production of solar grade Si in volume at low cost. Experiments were performed to evaluate product separation and collection processes, measure heat release parameters for scaling purposes, determine the effects of reactants and/or products on materials of reactor construction, and make preliminary engineering and economic analyses of a scaled-up process. Samples of the Si product were delivered to JPL for evaluation of solar cell performance. The objective of Phase II of the program was to characterize the kinetics and mechanism of the formation and growth of Si particles from the decomposition of silane at high temperatures. The experiments were aimed at determining the rates at which gas-phase species form Si particle precursors, the time required for silane decomposition to produce particles, and the competing rate of growth of Si seed particles injected into a decomposing silane environment.

TITLE: Final Report. For period July 1978 to January 1981. Evaluation of Selected Chemical Processes for Production of Low-Cost Si, Phase III
AUTHOR: J.M. Blocher, Jr., et al.
CORPORATE AUTH: Battelle Memorial Institute, Columbus Laboratories
DATE: March 31, 1981
REPORT NO: DOE-JPL 954339-81/21
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: As a phase of a program to establish the engineering feasibility of the process for producing Si by the zinc vapor reduction of Si tetrachloride, a PDU, which consisted of the four major units of the process, was designed, installed, and experimentally operated. The PDU was sized to 50MT/yr. The deposition took place in a FBR. As a consequence of the experiments, improvements in the design and operation of these units were undertaken and their experimental limitations were partially established.

TITLE: Final Report. Investigation of the Hydrogenation of $SiCl_4$
AUTHOR: J.Y.P. Mui and D. Seyferth
CORPORATE AUTH: Massachusetts Institute of Technology
DATE: April 1981
REPORT NO: DOE-JPL 955382-79/8
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: A two-year R&D program was initiated in April of 1979 to study the hydrochlorination of Si tetrachloride and metallurgical grade (m.g.) Si metal to trichlorosilane. This complementary research and development effort is conducted to supplement the engineering process development activities for the EPSDU under the UCC Contract No. 954334. A laboratory scale pressure reactor was constructed to study this reaction at pressures up to 500 psig. Reaction kinetic measurements were carried out as a function of reactor pressure, reaction temperature and $H_2/SiCl_4$ feed ratio. The conditions for reaction kinetic data collected at 500 psig were specifically designed to complement the engineering design for the hydrochlorination reactor in the UCC EPSDU, silane-to-Si process. The effect of an added copper catalyst on the reaction rate was investigated. Different particle size distributions of the m.g. Si metal were utilized to study the effect of total solid surface area on the rate of the hydrochlorination reaction. Experiments were carried out with the object to study the life of the Si mass bed with and without the presence of a copper catalyst. The effect of a prolonged reaction on the reaction rate was investigated. A corrosion study was made on type 304 stainless steel and Incoloy 800H under the actual hydrochlorination reaction environment.

TITLE: Final Technical Report. Development of a Process for High Capacity Arc Heater Production of Si for Solar Arrays for Si Materials Task
AUTHOR: M.G. Fey
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: May 1981
REPORT NO: DOE-JPL 954589-80/9
AVAILABILITY: NTIS, PC A11/MF A01

ABSTRACT: During the performance of the program, the experimental verification system for the production of Si via the arc heater-sodium reduction of $SiCl_4$ was designed, fabricated, installed, and operated. Each of the attendant subsystems was checked out and operated to insure performance requirements. These subsystems included: the arc heaters/reactor, cooling water system, gas system, power system, control and instrumentation system, Na injection system, $SiCl_4$ injection system, effluent disposal system and gas burnoff system. Prior to introducing the reactants (Na and $SiCl_4$) to the arc heater/reactor, a series of gas only-power tests was conducted to establish the operating parameters of the three arc heaters of the system. Following the successful completion of the gas only power tests and the readiness tests of the sodium and $SiCl_4$ injection systems, a shakedown test of the complete experimental verification system was conducted.

TITLE: Final Technical Report. Study of the Effects of Impurities on the Properties of Si Materials and Performance of Si Solar Cell
AUTHOR: C.T. Sah
CORPORATE AUTH: C.T. Sah Associates
DATE: October 1981
REPORT NO: DOE-JPL 954685-81/5

ABSTRACT: This fifth technical report, also the final report, covers studies on the effect of impurities and defects on the performance of Si solar cells which were not reported in the previous four technical reports. It describes a theoretical study of the effect of defects across the back-surface-field junction on the performance of high-efficiency and thin solar cells, using a developed-perimeter device model for the three dimensional defects.

TITLE: Final Report. Effect of Impurities and Processing on Si Solar Cells
AUTHOR: R.H. Hopkins, J.R. Davis, et al.
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: February 1982
REPORT NO: DOE-JPL 954331-82/13
AVAILABILITY: NTIS, PC A11/MF A01

ABSTRACT: The object of the program has been to investigate the effects of various processes, metal contaminants, and contaminant-process interactions on the properties of Si and on the performance of terrestrial Si solar cells. The study has encompassed topics such as thermochemical (gettering) treatments, base doping concentration, base-doping type (n vs. p), grain boundary-impurity interaction in polycrystalline devices, and long-term effects of impurities and impurity impacts on high efficiency cells, as well as a preliminary evaluation of some potential low-cost Si materials.

TITLE: Final Report. Si Production Process Evaluation, May 18, 1981 to July 30, 1982
CORPORATE AUTH: Texas Research and Engineering Institute, Inc.
DATE: July 30, 1982
REPORT NO: DOE-JPL 956045-82/5
AVAILABILITY: NTIS, PC A09/MF A01

ABSTRACT: Chemical engineering analyses involving the preliminary processes design of a plant (1000 metric tons/year capacity) to produce Si via the technology under consideration were accomplished for two cases of the Hemlock Semiconductor Corp. process. Major activities in the chemical engineering analyses included base-case conditions, reaction chemistry, process flowsheet, material balance, energy balance, property data, equipment design, major equipment list, production labor and economic analysis. The process design package provided detailed data for raw materials, utilities, major process equipment and production labor requirements necessary for polysilicon production in each process. Using detailed data from the process design package, cost analyses for a 1000 metric tons/yr Si plant were accomplished for the processes under consideration. Primary results issuing from the cost analyses included plant capital investment and product cost. The product cost represents all cost associated with producing Si including direct manufacturing cost, indirect manufacturing cost, plant overhead and general expenses. The sales price includes a profit for the company measured in terms of DCF rate of return after taxes on the capital investment that the company spent in going into the business. These cost and profitability results for both cases of the HSC process indicate that this new technology shows promise for producing Si at appreciable lower cost and comprises an alternate process capable of providing a less costly Si material for solar cells.

TITLE: Final Report. Investigation of the Hydrochlorination of $SiCl_4$, July 9, 1981 to April 8, 1983
AUTHOR: J.Y.P. Mui
CORPORATE AUTH: Solarelectronics, Inc.
DATE: April 15, 1983
REPORT NO: DOE-JPL 956061/7
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: The hydrochlorination of Si tetrachloride with hydrogen and metallurgical grade Si (mg-Si) metal, $3\ SiCl_4 + 2\ H_2 + Si \rightarrow 4\ SiHCl_3$ has been shown to be an efficient process to produce trichlorosilane. Trichlorosilane is presently the most widely used raw material for the production of high purity, polycrystalline Si metal used by the electronics industry. It is also the starting material in the Union Carbide, silane-to-Si process and in the Hemlock Semiconductor dichlorosilane CVD process to produce low-cost Si metal for high efficiency solar cells. A research and development program was carried out to study the hydrochlorination reaction over a wide range of reaction conditions. The mechanism of the hydrochlorination reaction was also investigated. A corrosion study was carried out to evaluate various materials of construction for the hydrochlorination reactor at 500°C and 300 psig.

TITLE: Final Report, Phase III. April 1979 to December 1981. Experimental Process System Development Unit for Producing Semiconductor-Grade Si Using the Silane-to-Si Process
CORPORATE AUTH: Union Carbide Corp.
DATE: June 6, 1983
REPORT NO: DOE JPL 954334-21
AVAILABILITY: NTIS, PC A16/MF A01; 1.

ABSTRACT: During Phases I and II (refer to June 1979 Final Report), the basic technology was demonstrated by laboratory experiments that silane can be produced via a closed-loop chemical process and that silane can be pyrolyzed in a free-space reactor to produce polycrystalline Si powder. The three objectives of Phase III for the establishment of the practicality of a process producing SG Si by a two-step process, the preparation of silane and the subsequent pyrolysis of silane to yield high-purity Si, are: (1) The detailed engineering design, fabrication, installation, checkout, and operation of an EPSDU; (2) The performance of a supporting research and development program to provide an information and quality control base usable for the EPSDU and for technological design and economic analyses for potential scale-up of the process; and (3) The performance of iterative economic analyses of the estimated product cost and of large scale plant cost for production of SG Si in an EPSDU capable of 100 MT/Si/yr. Phase III program will not be completed as planned. However, nego-

tiations are underway between UCC and DOE/JPL for UCC with its own funding to complete construction of the EPSDU.

TITLE: Final Report. Preliminary Study of A Radiantly Heated Fluidized Bed for the Production of High Purity Si
AUTHOR: O. Levenspiel
CORPORATE AUTH: Oregon State University
DATE: August 1983
REPORT NO: DOE-JPL 956133-83/1
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: Recently a new low-cost method has been investigated as a means of preparing very pure Si from silane (SiH_4). The fundamental chemical reaction of this technology is SiH_4 (gas) + heat → Si↓ + $2H_2$ (gas). When cold silane gas is heated, it decomposes forming solid Si. The purpose of our research is to explore a still different processing method which uses radiant heating of the particles of a fluidized bed. The process involves heating the particles at the surface of a shallow fluidized bed by radiant heaters located above the surface of the bed. The radiant sources could be cooled by a purge of inert gas which is exhausted with the spent H_2. The hot bed particles would circulate down to the bottom of the bed where they would heat the cold silane gas rising through the distributor plate. Decomposition and deposition of the silane then follow.

SILICON SHEET
JPL - IN-HOUSE ABSTRACTS

SILICON SHEET IN-HOUSE ABSTRACTS

TITLE: Evaluation of Si Ribbon Material for Solar Cell Fabrication
AUTHOR: M. Leipold
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1975
REPORT NO: DOE-JPL 01657
AVAILABILITY: NTIS-01657

ABSTRACT: Experimental analyses on Si ribbon growth by the EFG technique have been done in the following areas: (1) material structure, (2) material electrical performance, (3) diffused p-n junction/solar cell characteristics, and (4) solar cells air mass zero and terrestrial performance. Structural investigations have included Laue x-ray, x-ray diffractometer, x-ray topography, SEM/EBIC, EDAX, IR microscopy and visible metallograph analyses. An abundance of macrostructure and microstructure has been observed and correlated with growth conditions where possible. The impact of these analyses on the development of EFG Si ribbon growth will be discussed. Standard resistivity and Hall coefficient measurements have been made on ribbon samples using the van der Pauw technique. The results of these measurements have been correlated with structural characteristics (e.g., grain boundaries, twin boundaries) and will be discussed. In addition to the four-point resistivity measurements obtained from the van der Pauw samples, two-point spreading resistance probe measurements have been made. The results of resistance probe scans done along the ribbon length, width and thickness dimensions will be discussed in relation of grain-boundaries, twin boundaries and ribbon growth conditions. SPV measurements have been made to determine the minority carrier diffusion lengths in bulk ribbon samples. The data from the SPV measurements are correlated with the afore mentioned electrical data and solar cell measurement data. Solar cells fabricated from ribbon material have been evaluated and the data analyzed. Both dark and light I-V data as well as spectral response data were obtained from these cells and correlated with ribbon structure and bulk electrical properties (e.g., diffusion lengths). Both AMO and terrestrial sunlight efficiencies have been measured and correlated with diffusion length and spectral response data.

TITLE: A Review of New and Old Si Crystal Growth and Processing Techniques for Low-Cost PV Power Generation
AUTHOR: J. A. Zoutendyk
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1976
REPORT NO: DOE-JPL 01649
AVAILABILITY: NTIS-01649

ABSTRACT: Advanced cutting techniques are being studied for slicing ingots into wafers. An inherent cost-saving realized from ribbon or sheet forms over ingots is the elimination of cutting with its attendant loss of crystalline material, plus required lapping and polishing. Ribbon and sheet growth techniques are not nearly as advanced as conventional ingot growth (Cz, FZ) and are therefore difficult to compare in terms of projected cost. Research and development of basic ribbon, sheet, "new" ingot growth and cutting processes is needed. R&D work is being supported by this project at eleven industrial or University laboratories for the study of basic crystal growth and cutting techniques. Commensurate materials and device (solar cell) characterization work is being done at these laboratories and at JPL in support of the basic processes. In all the programs, the aim is to define the key factors which limit growth/cutting parameters and thereby allow for optimization of these parameters. Growth (crystallization) rates of all the processes are of paramount importance. These rates are determined by the inter-relationships which exist between linear growth velocity, thickness (ribbon/sheet) and width (diameter). It is precisely these factors which form the basis for eventual economic viability (low cost). The criterion for economic feasibility of crystal growth and processing is a value-added (exclusive of Si material) of less than $\$18/m^2$. Proof of technical feasibilty must be established for a cAndidate process to be successful. In terms of ribbon or sheet, this generally requires the demonstration of growth rates from a single "machine" in excess of 0.5 m^2/h. In terms of ingot growth, higher growth rates of greater thn 3 m^2/h must be achieved to compensate for additional cutting and processing (lapping, polishing, etching) costs involved. In order to meet the goal of less than $\$1/m^2$ value-added, ingot/cutting processes must be supported by roughly less than $\$10/m^2$ for crystal growth and less than $\$8/m^2$ for cutting and wafer processing. It is anticipated that multiple blade or wire sawing will eliminate theneed for lapping the polishing of wafers. Underlying these rate figures is the proviso that resulting solar cell devices must have efficiencies of at least 12%. With the demonstration of the above general goals (plus more specific goals unique to each process), it is felt that economic feasibility may be demonstrated by engineering development of the experimental growth (cutting) machines to provide sustained, highly reliable operation. An up-to-date review of the technical and economic status of the ribbon/sheet/ingot growth and cutting work in terms of technical and economic goals will be given.

TITLE: Si Crystal Growth for Terrestrial Solar PV Energy
AUTHOR: J.A. Zoutendyk
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1976
REPORT NO: DOE-JPL 01650
AVAILABILITY: NTIS-01650

ABSTRACT: Solar PV power generation has significant potential as a terestrial energy source. Although a wide range of semi-conducting materials are capable of producting solar cells with varying conversion efficiencies, Si is a prime candidate for early development and deployment of solar arrays. The key technical areas under development are Si purification, crystal growth, array production and array encapsulation. The subject of this paper is that of low-cost crystal growth. An overview of research and development efforts now being and anticipated to be pursued for Si crystal growth will be given.

TITLE: Critical Growth Factors for Low-Cost, Large Area Si
AUTHOR: T. Digges, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1976
REPORT NO: DOE-JPL 01651
AVAILABILITY: NTIS-01651

ABSTRACT: The basic attributes of each growth class, ribbon, sheet, and ingot, permit the establishment of models which may be used to predict value-added cost. Functional relationships between cost and critical growth factors may be established. Identification of these fundamental relationships provides an invaluable link between the on-going R&D and engineering design activities (e.g., automated array assembly) in determining the ultimate technical and economic feasibility of each growth process. The identification of such relationships provides a much needed system of checks and balances between the R&D and Production Engineering work in order to prevent premature decisions with respect to either eliminating or sustaining individual candidates. This paper provides a view toward the establishment of these critical factors and their relationship to cost for the 3 growth classes.

TITLE: Structural Aspects of Electrical Behavior in Si Solar Cell Material
AUTHOR: G. Cumming
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1976
REPORT NO: DOE-JPL 01653
AVAILABILITY: NTIS-01653

ABSTRACT: Several potentially inexpensive Si crystal growth processes are being pursued. These processes can be classified as shaped ribbon growth process (such as EFG, Stepanov, web-dendritic, laser zone crystallization) and sheet growth process (such as CVD and dip-coating of Si on inexpensive substrates). We have examined Si material produced by crystal growth processes and present the data showing the manifestation of structural imperfections on the electrical performance of the material. Optical and SEM have been used for delineation of structural defects and the electrical activity of these defects has been investigated by operating SEM in EBIC mode. Minority carrier lifetimes have been measured by MOS C-t, SPV, and EPV techniques and mobility and dopant homogeneity have been measured by Van der Pauw and spreading resistance techniques, respectively. The results of these various measurements, their interdependence and impact on PV device operation will be presented.

TITLE: Role of the Metallurgist in the Solar Energy Program
AUTHOR: T.G. Digges, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1976
REPORT NO: DOE-JPL 01654
AVAILABILITY: NTIS-01654

ABSTRACT: A brief discussion is given concerning how the metallurgist is involved in general crystal growth. The specific requirements of Si solar cells are next related to the methods of crystal growth. The role of the metallurgist is then discussed considering the realtionship between solar energy (PV) and crystal growth methods.

TITLE: Si Crystal Growth for Low-Cost Solar PV Conversion
AUTHOR: T.G. Digges, Jr., and K.M. Koliwad
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1976
REPORT NO: DOE-JPL 01655
AVAILABILITY: NTIS-01655

ABSTRACT: This paper is concerned with shaped ribbon processes which have liquid-solid transformations. The problems associated with shaped ribbon growth are unique and somewhat different than those associated with well developed Cz and FZ techniques. The specific shaped ribbon growth processes to be discussed are: web-dendritic growth, EFG, and ribbon zone growth. The 2 processes that compose the web dendrite growth is explained. The stability of the process is determined in terms of tempera ture gradients. The web growth process is discussed in terms of interface stability, the theory of which is some what contradictory to experimental observations. The development of the EFG process is discussed in terms of the mathematical model developed by Chalmers, et al, at Harvard. The dynamic and static conditions are solved and the total mathematical solution is shown to be the juxta position of the 2 solutions. The practical problems involving the selection of the die are discussed in terms of the wetting angle and constitutional supercooling. The problems associated with Stepanov process are similar to those of EFG except that the Stepanov processes use a non wetting die. For ribbon zone growth, the major problem is controlling the factors that affect the stability of the melt zone. We also discuss the Schmid Viechnicki technique. The role of convection is shown to be minimized by this process and thereby constitutional supercooling is reduced.

TITLE: Progress in Si Crystal Technology for Terrestrial PV Solar Energy Conversion. Conducted as part of the Fourth PIM
AUTHOR: J.A. Zoutendyk
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1976
REPORT NO: 5101-12

ABSTRACT: During the course of the Fourth PIM of the LSA Project, the Large Area Silicon Sheet Task conducted an intramural conference to discuss development progress in various aspects of the technology of preparing Si ribbons, sheets, or wafers for use in the fabrication of solar cells. Brief papers were presented by the eleven contractors to the Task, as well as two by other laboratories and one by JPL.

TITLE: Some Observations on the Characteristics of Low-Cost Si Sheets
AUTHOR: T.G. Digges
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1976
REPORT NO: DOE-JPL 01360
AVAILABILITY: NTIS-01360

ABSTRACT: Crystal growth technology ranges in scope from innovative ingot growth and multislice wafering, to shaped growth techniques, substrate-related processes and hot forming techniques. We report some salient observations on materials resulting from these processes. Included are multiblade wafering induced damaged studies, interface morphology studies on the heat exchanger cast Si, some diffusion length measurements in thin Si layers on ceramic substrates, and results on the "equilibrium structure" found in laser zone ribbon growth.

TITLE: Economic Analysis of Low Cost Si Sheet Production from Cz Grown Material
AUTHOR: G. Cumming
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1976
REPORT NO: DOE-JPL 01361
AVAILABILITY: NTIS-01361

ABSTRACT: Cz crystal growth has long been the work horse of the Si semiconductor industry. High quality 5 to 10 cm dia crystals can be grown today in large production quantities and there are no apparent technical reasons that preclude the growth of similar quality, larger diameter crystals in production diameter slices for starting material. In this study we have made a detailed examination of the manufacturing add on costs for both the Cz ingot growth and the associated slicing. The engineering cost considerations for the growth process include single charge, multiple charge and continuous growth configurations. For each of these situations, parametric studies were carried out to examine the effect of growth rate (cm/h) and solidifica tion rate (kg/h), operating and expendable material costs and maintenance expenditures. Wafering investigations considered both ID and multiblade technologies. Wafer yield per unit length of crystals is developed as a critical parameter. Present slicing throughput has been costed for both technologies, and, where possible, projected cost reductions have been estimated based on machine redesign and/or technology development. For both growth and wafering, the lower limits to manufacturing add-on costs have been developed using physical limitations for process variables and optimistic estimates for material and service related costs. The study shows that the lower limits for manufacturing add-on costs to convert polysilicon to wafers is \$20 to \$30/m^2. This cost limit should be viewed as an asymptote since it is based on multicharge or continuous growth configurations, solidification rates in excess of 2 kg/h, multiblade wafering and a slice plus kerf of .050 cm. It should also be emphasized that the results of this study are based on as-sawn wafers, 100% yields (growth and slicing) and no profit.

TITLE: Ceramics in Si Photovoltaics for Terrestrial Applications
AUTHOR: M.H. Leipold and M.A. Hagan
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1976
REPORT NO: DOE-JPL 01656
AVAILABILITY: NTIS-01656

ABSTRACT: The production of Si solar cells for generation of electric power for terrestrial uses involves a significant number of ceramic products and processes. These range from non-contaminating refractories having good wetting characteristics for use in contact with molten Si to electrical contact materials and environmental protection. The shortcomings of present materials and systems are enumerated and development activities toward alleviation of these shortcomings are given. The high probability for extensive use of ceramics with Si photocells is noted. This high probability is related to the superior environmental stability and thermal expansion compatibility with Si.

TITLE: Development of Low-Cost Si Crystal Growth Techniques for Terrestrial PV Solar Energy Conversion
AUTHOR: J.A. Zoutendyk
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1977
REPORT NO: DOE-JPL 02559
AVAILABILITY: NTIS-02559

ABSTRACT: This paper reviews a U.S. research program aimed at reducing the cost of Si cells by developing new methods of growing Si ribbons and sheet from which high efficiency solar cells can be fabricated. The paper also describes novel techniques for lower cost processes for ingot growth and wafer slicing which are included in this research and development program.

TITLE: Structure Development in Si Sheet by Shaped Crystallization
AUTHOR: M.J. Leipold and R.J. De Angelis
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1977
REPORT NO: DOE-JPL 01859
AVAILABILITY: NTIS-01859

ABSTRACT: Models are presented for the development of a parallel twinned (110) (112) structure in Si ribbons. The models are believed to be mutually compatible and operable. The first model relates the requirements for supercooling during crystallization. The existence of reentrant angles associated with the twin structure is proposed to provide a rough interface to reduce super-cooling. The spacing of the twins is proposed to be limited by the geometrical relationship between the thermal gradient in the liquid and the dimensions of the twinned crystallization front. The second model relates the thermal stress configuration to detail dislocation reactions which would be expected to develop twins. While a specific dislocation mechanism cannot yet be defined, a number of alternatives are pre sented. All of these various dislocation mechanisms would result in the observed crystalline configuration and the choice among them is not critical.

TITLE: On the Thermoelastic Analysis of Solar Cell Arrays and Related Material Properties
AUTHOR: M. Salama and F.L. Bouquet
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1978
REPORT NO: DOE/JPL-33-753
AVAILABILITY: NTIS-33-753

ABSTRACT: Accurate prediction of failures of solar cell arrays requires corresponding accuracy in the computation of their thermally induced stresses. This was accomplished by using the finite element technique. Certain improvements in the previously reported procedures for stress calculation were introduced together with failure criteria capable of describing a wide range of ductile and brittle material behavior. With these improvements and capabilities, the stress distribution and associated failure mech anisms in the N interconnect junction of two JPL solar cell designs were discussed and correlated to previous findings. In such stress and failure analysis, it is essential to know the thermomechanical properties of the materials involved. To complement previous efforts in this direction, new measurements were made of properties of materials suitable for the design of lightweight arrays: namely, the microsheet-0211 glass material for the solar cell filter together with 5 materials for lightweight substrates (Kapton-H, Kapton F, Teflon, Tedlar, and Mica Ply PG-402). The temperature-dependence of the thermal coefficient of expansion for these materials was determined together with other key properties such as the elastic moduli, Poisson's ratio, and the stress-strain behavior up to failure.

TITLE: Multi-Wire Slurry Wafering Demonstrations
AUTHOR: C.P. Chen
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1978
REPORT NO: DOE-JPL 1012-78/7, and 5101-57

ABSTRACT: A series of ten slicing demonstrations on a multi-wire slurry saw, manufactured by Yasunaga Engineering Co. of Japan and distributed by GEOS Corp. of Stamford, Connecticut, was made to evaluate the Si ingot wafering capabilities.

TITLE: Compatibility Studies of Various Refractory Materials in Contact with Molten Si
AUTHOR: T. O'Donnell, M. Leipold, and M. Hagan
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1978
REPORT NO: DOE-JPL 1012-77/6, JPL Pub. 78-18, 5101-53

ABSTRACT: The production of low cost, efficient solar cells for terrestrial electric power generation involves the manipulation of molten Si with a present need for noncontaminating high-temperature refractories to be used as containment vessels, ribbon-production dies and dip-coated substrates. Studies were conducted on the wetting behavior and chemical/physical interactions between molten Si and various refractory materials.

TITLE: Copper Precipitation Effects in Si Used in Solar Cells
AUTHOR: A.M. Salama
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 1978
REPORT NO: DOE-JPL 02572
AVAILABILITY: NTIS-02572

ABSTRACT: Microstructural evaluation tests (e.g., TEM, SEM) were performed on copper-doped p type Si single-crystal wafers before and after the solar cell fabrication. The copper concentration was 10^{15} - 10^{16} atoms/cm^3. It was found that B CuSi precipitates were formed during the growth process. No precipitates or other electrically active defects were detected in the solar cell junction depletion region. The copper precipitation in the bulk diminished the possibility of electrically active interstitial copper occurring in the lattice. These results explain the good electrical characteristics of the Si solar cells under investigation.

TITLE: The Effects of Copper and Titanium on Si Solar Cells
AUTHOR: A.M. Salama
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1978
REPORT NO: DOE-JPL 02573
AVAILABILITY: NTIS-02573

ABSTRACT: Copper-doped n/p Si solar cells fabricated from the Cz grown single-crystal wafers were found to have good electrical characteristics, but the titanium-doped n/p Si solar cells had considerably lower conversion efficiency. In the copper/titanium-doped solar cells, copper seems to mitigate the unfavorable effects of titanium. To explain this behavior, microstructural tests were performed on Si

wafers and solar cells doped with copper, titanium and copper/titanium. Dark forward and reverse I-V measurements were performed on the solar cells to correlate the microstructural defects with the p-n junction properties. It was found that copper precipitates were formed in the copper-doped and copper/titanium-doped wafers and cells. There was a significant voltage drop in the dark reverse I-V measurements of the titanium solar cells. Also, there were some electrically active defects in the depletion region of some titanium-doped cells. Reasons that lead to the above results are given in detail.

TITLE: Growth of Large Si Single Crystals by a Casting Technique
AUTHOR: T.G. Digges, Jr. and F. Schmid
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1978
REPORT NO: DOE-JPL 01359
AVAILABILITY: NTIS-01359

ABSTRACT: This paper reports on the observations of nucleation and growth propagation from the single crystal seed by HEM. Initial attempts to control Si solidification by high temperature gradients in both the solid and liquid (controlled by the heat exchanger and furnace temperature) resulted in epitaxial growth that propagated 1 mm from the seed, followed by interface breakdown. It became evident that liquid and solid thermal gradients were critical for Si solidification. By reducing the thermal gradients in both the solid and liquid by decreasing the furnace temperature, it is now possible to propagate single crystal growth from the seed to the top of the melt. Metallographic and x-ray analyses have revealed highly perfect growth with dislocation densities below $10^4/cm^2$. Polycrystalline grains are still present at the edges of the sample. A contamination problem (SiC inclusions) has revealed an interesting phenomena. Single crystal growth has enveloped the silicon carbide particles, which is contradistinct to Cz growth where SiC particles result in interface breakdown with twin/polycrystalline growth. Single crystal growth has proceeded around the particles with no interface breakdown. A problem that has been identified is the cracking of the sample after solidification. This occurs because the Si forms a strong chemical bond with the silica crucible and contracts much greater due to its large coefficient of thermal expansion.

TITLE: Effect of Multiblade Slurry Saw Induced Damage on Si Solar Cells
AUTHOR: T. Daud
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1978
REPORT NO: DOE-JPL 02889
AVAILABILITY: NTIS-02889

ABSTRACT: It is well known that the performance of the Si solar cells fabricated on sawn wafers improves considerably if the saw-induced damage is removed prior to fabrication. The material loss from this removal impacts on the economic viability of ingot technology to meet the requirements of low-cost Si solar cells. This work was undertaken to measure the optimum etch loss required for good solar cell performance. The amount of material that needs to be removed depends both on the extent and the nature of the damage induced by the sawing process. It has been noted in the past that the characteristics of the sawing process have considerable influence both on the extent and the nature of the damage. Wafers (10 cm. dia) cut from a Varian multiblade slurry saw were used in the experiment. Samples with various amounts of damage removed by chemical etching or chem mechanically polishing were processed into solar cells. Cell performance measurements of light and dark I-V and spectral response characteristics were then made as a function of depth of damage removed. Results are presented.

TITLE: Fracture Strength of Si Solar Cells
AUTHOR: C.P. Chen
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1979
REPORT NO: DOE-JPL 1012-32 and 5101-137

ABSTRACT: In an effort to improve the reliability and lower the cost of solar cells, a test program has been developed to determine the nature and source of the flaw controlling the fracture of Si solar cells and to provide information regarding the mechanical strength of cells. This report contains results obtained in the first phase of a test program to develop improved methods for testing the mechanical strength of cells and to evaluate the fracture strength of typical Cz Si solar cells 76 mm (3 in.) in dia.

TITLE: Characterization of Deliberately Nickel-Doped Si Wafers and Solar Cells
AUTHOR: A.M. Salama
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1979
REPORT NO: DOE-JPL 1012-34, and 5101-139

ABSTRACT: Microstructural and electrical evaluation tests were performed on nickel-doped p-type Si wafers before and after solar cell fabrication. The concentration levels of nickel in Si were 5×10^{14}, 4×10^{15}, and 8×10^{15} atoms/cm^3.

TITLE: Cost of Cz Wafers as a Function of Diameter
AUTHOR: M.H. Leipold, C. Radics, and A. Kachare
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1980
REPORT NO: DOE JPL 1012-37, JPL Pub. 80-25, 5101-146
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: The impact of diameter in the range of 10 to 15 cm on the cost of wafers sliced from Cz ingots is analyzed. Increasing Si waste and decreasing ingot cost with increasing ingot size are estimated along with projected costs. Results indicate a small but continuous decrease in sheet cost with increasing ingot size in this size range. Sheet costs including Si are projected to be \$50 to \$60/m^2 (1980 \$) depending upon technique used.

TITLE: Sensitivity Analysis of the Add-On Price Estimate for the EFG Process
AUTHOR: A.R. Mokashi and A.H. Kachare
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1981
REPORT NO: DOE JPL 1012-55, JPL Pub. 81-37, 5101-171

ABSTRACT: The EFG process is a Si-sheet technology option that is being developed for the LSA Project. This study presents a sensitivity analysis of the process add-on price in terms of cost parameters such as equipment, space, direct labor, materials and utilities, and the production parameters such as growth rate, process yield and duty cycle, using a computer program developed specifically to do the sensitivity analysis with IPEG.

TITLE: Sensitivity Analysis of the Add-On Price Estimate for the Si Web Growth Process
AUTHOR: A.R. Mokashi
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 15, 1981
REPORT NO: DOE JPL 1012-61, JPL Pub. 81-112, 5101-175

ABSTRACTS: The web growth process is a Si-sheet technology option that is being developed for the Project. In order to achieve the price goal of \$0.70/W_p, certain required production rate and sheet quality standards must be met. Based on research and development experience, base case data for the technical and cost parameters that could be achieved for the technical and commercial readiness phase of the FSA project are projected. This study

presents a sensitivity analysis of the process add-on price, using the base-case data in terms of cost parameters such as equipment, space, direct labor, materials and utilities, and the production parameters such as growth rate and run length, using a computer program developed specifically to do the sensitivity analysis with IPEG. The sensitivity analysis is also performed with respect to Si price, sheet thickness and cell efficiency.

TITLE: Effect of Loading Rates on the Strength of Si Wafers
AUTHOR: C.P. Chen
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 15, 1981
REPORT NO: 5101-190

ABSTRACTS: The effect of loading rates on the strength of Si wafers was evaluated under biaxial stress conditions at five loading rates and under four-point twisting at two loading rates and was found to be insignificant. The results showed no indication of time-dependent subcritical crack growth in Si at room temperature in a laboratory environment. The mechanical-strength test of Si solar cells can thus be determined at a rate as fast as a testing machine can respond, without loss of accuracy. This conclusion is important in that it shows that a high-speed solar-cell mechanical proof-testing machine can be sued in solar-cell manufacturing.

TITLE: Proceedings of the Low-Cost Solar Array Wafering Workshop (June 8-10, 1981, The Pointe, Phoenix, Arizona)
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1, 1982
REPORT NO: DOE-JPL 1012-66, JPL Pub. 82-9, 5101-187

ABSTRACTS The Low-Cost Solar Array Wafering Workshop was held on June 8-10, 1981, at The Pointe, Phoenix, Arizona. The Workshop consisted of seven sessions covering all aspects of ingot wafering, including fixed- and free-abrasive sawing, materials, mechanisms, characterization, innovative concepts and economics. Twenty-seven papers were presented.

TITLE: Baseline Solar Cell Fabrication Procedure for Evaluation of Si Sheets
AUTHOR: S. Hyland and F. Uno
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 1, 1982
REPORT NO: 5101-206

ABSTRACT: One step toward the commercialization of low-cost solar modules is the development of low-cost Si sheets. Any evaluation of these sheets for their solar cell potential must include the fabrication and testing of devices. A comparison among the various sheets can be drawn by measuring their response to fabrication by a conservative, baseline process. A baseline process has been developed which consistently yields a 12% AM1 solar cell when the substrate used is high-quality Cz Si. The fabrication procedures for this baseline process are given in four sections: sample preparation: dicing of wafers to 2 x 2 cm blanks; cleaning the blanks; junction formation: phosphine diffusion; removal of back junction; metallization: evaporation of Ti-Pd-Ag; sintering, definition of front grid lines by shadow mask or photolithography, and edge etching; and anti-reflection coating evaporation: evaporation of Ta_2O_5. Also included are definitions of terms, scope, and safety precautions along with lists of materials and equipment necessary for each section.

TITLE: Advanced Cz Si Growth Technology for PV Modules
AUTHOR: T. Daud and A.H. Kachare
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 15, 1982
REPORT NO: DOE-JPL 1012-70, JPL Pub. 82-35, 5101-207
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Large-area Si sheet growth is one of the important elements of PV modules. To reduce the cost of these modules, a number of Si sheet-growth approaches encompassing both ingot and ribbon technology have been developed. Advancement of the Cz growth method has been one of these approaches because of its existing broad technical base. Several economic analyses had indicated that large-diameter, multiple-ingot growth using a single crucible with melt replenishment would be required for Cz growth to be economically viable. Based on the results of these analyses, two liquid-feed and two solid-feed melt-replenishment approaches were initiated. The sequential solid-feed melt-replenishment approach, which demonstrated elements of technical feasibility, is described in detail. Growth results of multiple ingots (10-cm-dia, totaling 100 kg, and 15-cm-dia, totaling 150 kg per crucible) are presented. Solar cells were fabricated and analyzed to evaluate the effects of structure and chemical purities as a result of multiple growth. The results indicate that, with SG Si, feedstock impurity build-up does not seem to degrade cell performance. For polycrystalline cells, the average efficiencies are 15% to 25% lower than those of single crystalline cells. Concerns regarding single crystal yields, crucible quality, and growth speed are indicated, and present status and future research thrusts are discussed.

TITLE: Price Estimates for the Production of Wafers from Si Ingots
AUTHOR: A.R. Mokashi
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 15, 1982
REPORT NO: DOE-JPL 1012-74, JPL Pub. 82-65, 5101-212
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Some PV modules are made from solar cells that use ribbon Si. Most solar cells, however, are produced from wafers sliced from crystalline Si ingots. Unfortunately, the cost of the slicing process is a major part of the cost of producing Si sheet. Any attempt to reduce the cost of PV modules, therefore, must involve the development of less expensive wafering technologies. This study presents the current status (1981) of the ID, MBS, and FAST processes with respect to the estimated price each process adds on to the price of the final PV module. The expected improvements in each process, based on the know ledge of the current level of technology, are projected for the next 2 to 5 yrs and the expected add-on prices in 1983 and 1986 are estimated. Assuming that the projected progress is made, the ID and FAST processes are expected to achieve the price allocation of $\$18.15/m^2$ for square ingots and $\$13.70/m^2$ for circular ingots to conform with the earlier price goal of the FSA of $\$0.70/W_p$ of PV module (price estimates are expressed in 1980 dollars). MBS technology projections, however, indicate that its progress will not be sufficient to achieve the allocated price goal before 1986.

TITLE: Free-Abrasive Slicing, the Results of the FSA Program at Varian Associates
AUTHOR: A.D. Morrison
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1983
REPORT NO: JPL D-795, and 5101-199

ABSTRACT: This report summarizes the contract final report, Slicing of Silicon into Sheet Material, by J.R. Fleming, et al., of Varian Associates, Lexington Vacuum Division, Lexington, Massachusetts. Results are presented of analytical and experimental studies of the free-abrasive multiblade ingot wafering process as it was applied to the slicing of Si into wafers for low cost, solar-cell applications. The analytical effort includes process, blade, and economic analyses; and the experimental program covers apparatus, consumables, process studies, and wafer characterization.

TITLE: Proceedings of the FSA Research Forum on the High-Speed Growth and Characterization of Crystals for Solar Cells
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 15, 1984
REPORT NO: DOE-JPL 1012-95, JPL Pub. 84-23, 5101-238
AVAILABILITY: NTIS, PC A99/MF A01; 1

ABSTRACT: The High-Speed Growth and Characterization of Crystals for Solar Cells Research Forum was held on July 25-27, 1983, at the Sandpiper Bay Hotel in Port St. Lucie, Florida. The Research Forum was arranged into eight interactive sessions and addressed theoretical and experimental phenomena, applications, and characterizations including stress/strain and other problem areas that limit the rate of growth of crystals suitable for processing into efficient, cost-effective solar cells. The meeting was sponsored by JPL-FSA. Thirty-five invited papers were presented. Discussion periods followed each presentation. These Proceedings are a record of the papers and the discussions.

TITLE: A Summary Report on the FSA Workshop on Transparent Conducting Polymers, January 11 and 12, 1985
AUTHOR: R. Kachare and J. Moacanin
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 1, 1985
REPORT NO: DOE-JPL 1012-110, JPL Pub. 85-60, 5101-276
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: This report describes the proceedings and technical discussions of a workshop on TCP for solar cell applications, held in support of the Device Research Task. The workshop was held on January 11 and 12, 1985, in Santa Barbara, California. Participants included university and industry researchers. The discussions focused on the electronic and optical properties of TCP, and on experimental issues and problems that should be addressed for high-efficiency solar cell application.

SILICON SHEET
CONTRACTOR ABSTRACTS

SILICON SHEET CONTRACTOR ABSTRACTS

TITLE: Final Report. Thick-Film Si Growth Techniques
AUTHOR: H.E. Bates
CORPORATE AUTH: Mobil Solar Energy Corp.
(Tyco Laboratories, Inc.)
DATE: April 1975
REPORT NO: DOE-JPL 953365-75/1

ABSTRACT: The development of the edge-defined, film-fed growth process for Si ribbon is described. The selection of die materials is described emphasizing SiC, graphite, SiO_2 and Si_3N_4. Utilizing the graphite die, the process was developed to produce ribbons first 1 cm and then 2.5 cm wide and up to 40 cm long. The electrical quality on the ribbon has increased directly as the result of increasing the graphite die purity. Solar cells made from recent ribbons grown from purified dies have exhibited efficiencies on the order of 75% of control cells made from Cz Si.

TITLE: Final Report. Large Area Cz Si
AUTHOR: S.N. Rea, R.S. Gleim
CORPORATE AUTH: Texas Instruments, Inc.
DATE: April 1977
REPORT NO: DOE/JPL 954475-77/4

ABSTRACT: The major purpose of this program was to determine the overall cost effectiveness of the Cz process for producing large-area Si. The goal of the wafering process was a slice thickness of 0.25 mm with minimal kerf. A slice + kerf of 1.26 mm has been achieved of 12-cm crystal using both 200 grit B_4C and SiC abrasive slurries. Crystal growth experiments were performed at 12-cm diameter in a commercially available puller with both 10 and 12-kg melts. Several modifications to the puller hot zone were required to achieve stable crystal growth over the entire crystal length and to prevent crystallinity loss a few centimeters down the crystal. The maximum practical growth rate for 12-cm crystal in this puller design was 10cm/h, with 12-14cm/h being the absolute maximum, range at which melt freeze occurred. A nugget polysilicon feeder was fabricated, assembled, and successfully tested on several multicharge runs. Excessive oxide and carbon contamination in the nugget melts contributed to crystal growth problems. A number of 12-cm crystals were sawed in the multiblade slurry saw. A 100% of the yield was obtained with B_4C abrasive at a slice + kerf of 1.56 mm and an average cutting rate of 6.1 mm/h. Si carbide abrasive has demonstrated 3-5 mm/h sawing rates on 12-cm crystal, although yields have run lower (73%) than those with B4C at the 0.56 mm dimension. A slightly thicker slice, 0.30 mm, can be sawed with SiC abrasive at 100% yield. Experiments in laser scribing Si wafers into hexagons showed that a 10-W YAG laser can penetrate 0.2 mm at a scribe rate of 10 cm/s. Much higher writing rates on the order of 30-40 cm/s can penetrate 0.05 mm which is sufficient for scribe-and-break of 0.25-mm slices. Cz economics were examined using realistic estimates of technical parameters and a sheet cost in the $\$45/m^2$ area is indicated for a semicontinuous puller in the early 1980 time frame. To impact sheet cost in late 1970's, a multicharge growth mode is all that is technically possible and a sheet cost of $\$55/m^2$ is forecast.

TITLE: Final Report. Si Sheet Growth by the Inverted Stepanov Technique
AUTHOR: K.M. Kim
CORPORATE AUTH: RCA Corp.
DATE: June 1977
REPORT NO: DOE-JPL 954465 77/2
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: The feasibility of growing Si ribbons by the inverted ribbon growth process has been established using both nonwetting boron nitride dies as well as wetting composite dies coated with chemically vapor deposited Si nitride. Growth instabililites are associated primarily with the formation and evolution of the Si monoxide; the escape of the gas causes hysteresis of the contact angle and mechanical vibration of the melt. As a result of this, the meniscus during the ribbon growth is not "pinned" at the die edge but is in constant motion, and growth is difficult to initiate. Although real progress was made, the instabilities have not been suppressed sufficiently to allow for initiation of ribbon growth. Preliminary evaluation of the reactivity of liquid Si with CVD Si_3N_4 and CVD $Si_3O_xN_y$ indicated that these materials are considerably more resistant to reaction with and/or dissolution in Si than other materials examined to date. Solar cells made in the epitaxially deposited Si on a Si ribbon grown by the inverted Stepanov process with the BN flat die had an efficiency of 8.2% (AM1). The stability of the ribbon growth, in terms of the dependence of the ribbon thickness on the change in the meniscus height, is theoretically greater in the inverted Stepanov or inverted EFG than in Stepanov or EFG process. A one-dimensional heat flow model has been developed to simulate numerically the major thermal aspects of the inverted Stepanov growth process.

TITLE: Final Report. Heat Exchanger-Ingot Casting/Slicing Process
AUTHOR: F. Schmid and C.P. Khattak.
CORPORATE AUTH: Crystal Systems, Inc.
DATE: December 1977
REPORT NO: ERDA-JPL 954373-77/4
AVAILABILITY: NTIS, PC A10/MF A01

ABSTRACT: The proof of concept for Si casting by HEM has been established. One of the major hurdles of ingot cracking has been eliminated with the development of graded crucibles. Such crucibles are compatible with the casting process in that the integrity of the container is maintained at high temperature; however, during the cool down cycle the crucible fails, thereby leaving a crack-free boule. Ingots as large as 3.3 kg have been cast using this approach. The controlled growth, heat flow and cool-down cycle has yielded Si with a high degree of single crystallinity. Even when the seed melted out, very large grains formed. Solar cell samples made from cast material have yielded conversion efficiency of over 9% (AM1). Representative characterizations of Si grown has demonstrated a dislocation density of less than $100/cm^2$ and a minority carrier diffusion length of 31 The source of Si carbide in Si ingots has been identified to be from graphite retainers in contact with silica crucibles. Higher growth rates have been achieved with the use of a graphite plug at the bottom of the silica crucible. Excellent surface quality, i.e., surface smoothness and 3-5 μm surface damage, was achieved by multiple wire slicing with fixed diamond abrasive. Tungsten wire was the best core material tested because of its high strength, high Young's modulus, and resistance to hydrogen embrittlement. Diamond costs were reduced by impregnating diamonds only on the cutting areas of the wire. A lighter and longer blade carriage can be used for slicing with wire. This will allow the blade carriage to be reciprocated more rapidly to increase the surface speed. A projected add on cost calculation shows that these methods will yield Si for solar cell application within ERDA/JPL cost goals.

TITLE: Final Report. Delayed Fracture of Si
CORPORATE AUTH: The Regents of the University of California, Los Angeles
AUTHOR: T.J. Chen and W.J. Knapp
DATE: March 1978
REPORT NO: DOE-JPL 954836 78/1
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: Bar specimens were cut from ingots of single crystal Si, and acid-etched prior to testing. Artificial surface flaws were introduced in specimens by indentation with a knoop hardness tester. The specimens were loaded

in four-point bending to 95% of the nominal fracture stress, while keeping the surface area, containing the flaw, wet with test liquids. No evidence of delayed fracture, and, therefore stress corrosion, of single crystal Si was observed for liquid environments including water, acetone and aqueous solutions of NaCl, NH_4OH, and HNO_3, when tested with a flaw parallel to a (110) surface. The fracture toughness was calculated to be $K/_{1C} = 0.591 \times 10^6$ N/M 3/2.

TITLE: Final Report. May 12, 1976 to August 11, 1977. Hot Forming of Si Sheet, Si Sheet Growth Development
AUTHOR: C.D. Graham, Jr., P.D. Pope and S. Kulkarni
CORPORATE AUTH: The Trustees of the University of Pennsylvania
DATE: April 1978
REPORT NO: DOE-JPL 954506-78/1
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT Results of an experimental program investigating the hot workability of polytextucrystalline Si are reported. Uniaxial stress-strain curves are given for strain rates in the range of 10^{-5} to 10^{1-1} and temperatures from 1100 to 1380°C. At the highest strain rates at 1380°C axial strains in excess of 20% were easily obtainable without cracking; although special preparation of the compression platens allows strains in excess of 50%. After deformations of 36%, recrystallization is completed within 0.1 hr at 1380°C. When the recrystallization is complete, there is still a small volume fraction of unrecrystallized material which appears very stable and may degrade the electronic properties of the bulk material. Texture measurements show that the as produced vapor deposited polycrystalline rods have a (110) fiber axis changes to (111) and the direction parallel to the growth direction and no preferred orientation about this axis. Upon axial compression perpendicular to the growth direc tion the former (110) fiber axis changes to (111) and the compression axis becomes (110). Recrystallization changes the texture to (110) along the former fiber axis and (100) along the compression axis.

TITLE: Final Report. Floating Substrate Process
AUTHOR: M. Garfinkel and R.N. Hall
CORPORATE AUTH: General Electric Co.
DATE: June 1978
REPORT NO: DOE-JPL 954350 78/3
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: Supercooling of Si Sn alloy melts was studied. Values as high as 78°C at 1100°C and 39°C at 1200°C were observed, corresponding to supersaturation parameter values 0.025 and 0.053 at 1050°C and 1150°C, respectively. The interaction of tin with silane gas streams was investigated over the temperature range 100 to 1200°C. Single pass conversion efficiencies exceeding 30% were obtained. The growth habit of spontaneously nucleated surface growth was determined to be consistent with dendritic and web growth from singly twinned triangular nucleii. Surface growth of interlocking Si crys tals, thin enough to follow the surface of the liquid and with growth velocity as high as 5 mm/min, was obtained. Large area single-crystal growth along the melt surface was not achieved. Small single crystal surface growth was obtained which did not propagate beyond a few millimeters.

TITLE: Final Report. Si Ribbon Growth by a Capillary Action Shaping Technique
CORPORATE AUTH: IBM Corp.
DATE: June 1978
REPORT NO: DOE-JPL 954144-78/1
AVAILABILITY: NTIS, PC A16/MF A01

ABSTRACT: Ribbon Si produced by CAST yields 11.9% solar cell efficiency. CAST ribbons up to 95mm wide and 0.3mm thick were produced. CAST technology single ribbon, 100mm wide ribbon, 0.3mm thick, 3.8m/h growth rate, solar cell efficiency 13% - has the potential to meet a $50/m^2$ target. This is based upon the availability of $10/kg polycrystalline Si.

TITLE: Third Quarterly Progress Report. Development of Advanced Methods for Continuous Cz Growth
AUTHOR: R.G. Wolfson, C.B. Sibley, and C.P. Chartier
CORPORATE AUTH: Varian Associates, Inc.
DATE: July 1978
REPORT NO: DOE-JPL 954884-78/3

ABSTRACT: Six batch melt-replenishment runs were performed. In the most recent, five crystals were grown with a total throughput of 48 kg. In addition to its stated purpose of developing the growth and recharge process for continuous Si production, this experimentation has served to prove completely both the concept of charging with granular (viz., "niblet") feed and the design of the pellet-feeder/isolation-lock assembly. The design of the prototype Cz puller was begun on schedule. Layouts of all major components have been prepared, and detailing is currently in progress; bills of material for long-delivery items were released to manufacturing in June. Two critical components have already undergone advance trials: the recharging mechanism, which has been in use for four months, and the crystal lift mechanism, which has been bench-tested and is to be mounted on the laboratory Varian 2850 puller. Further, the fabrication of the transducer/control assembly, the automation system, has been accelerated in order to permit testing and preliminary process development on the 2850 furnace prior to the completion of the prototype puller. The SAMICS analysis of ingot growth and wafering has been completely revised and has been extended to 1986.

TITLE: Final Report. Chemical Vapor Deposition Growth
AUTHOR: R.P. Ruth
CORPORATE AUTH: Rockwell International Corp.
DATE: October 1978
REPORT NO: DOE-JPL 954372-78/6

ABSTRACT: The technical objective was to investigate and develop CVD techniques for the growth of large areas of Si sheet on inexpensive substrate materials, with resulting sheet properties suitable for fabricating solar cells that would meet the technical goals of the LSSA Project. Several glasses were found that are compatible with CVD Si growth in an inert atmosphere in the 800-900°C range, although a maximum in the Si deposition rate from SiH_4 pyrolysis in He at about 850°C sets an upper limit on film growth rates. The polycrystalline Si films on glasses showed strong preferred orientation parallel to (100) and, to a smaller degree, (110) planes, depending upon deposition temperature, film thickness, and the glass involved as substrate. Evidence was found of unidentified donor impurities entering the films, presumably from the glass substrates, to affect the electrical properties obtained and possibly set an upper limit on the available hole concentrations achievable in p-type B doped polycrystalline films on these glasses. Low purity alumina and similar ceramics were found not suitable as substrates for growth of CVD Si of uniform quality. High purity aluminas permitted growth of polycrystalline CVD Si layers of controllable quality, highly preferred orientations, and grain sizes that scaled directly with the grain size in the substrate. Refired aluminas that has acquired large individual grains produced locally epitaxial Si grains of corresponding dimensions on those substrate grains that were favorably oriented crystallographically. The aluminas are too costly to be considered for meeting the Project goals. Generally poor PV performance was exhibited by solar cells fabricated in CVD Si sheet grown by SiH_4 pyrolysis directly onto substrates of aluminas, glasses, or even single crystal sapphire. V_{oc} values up to about 80% of those of single crystal Si control cells were obtained, but J_{sc} values only 40 to 70% of those of a control cell were obtained under simulated AMO illumination. Depressed long wavelength response and other per-

formance factors indicated low minority-carrier (electron) diffusion lengths were characteristics of the n/p cell structures made in this Si sheet material by the SiH_4 process. Epitaxial p-type (B-doped) CVD Si sheet grown on single-crystal Si substrates by SiJ_2Cl_2 pyrolysis in H_2 at about 1075°C provided relatively good PV performance in solar cell structures produced by P diffusion to form the p-n junctions. V_{oc} values of about 560 mV, J_{sc} values of about 22 mA cm^2, curve fill factors of about 0.7, and power efficiencies of 6-7% were found in these cells. The presence of a p^+ layer below and adjoining a p-type (B-doped) CVD Si polycrystalline or epitaxial layer (on alumina or sapphire, respectively) enhanced the PV response of solar cell structures formed by P diffusion into the p layer. A comparison of the PV response of P-diffused and P-doped in-situ-grown $n^+/p/p^+$ solar cell structures about 20 μm thick on polycrystalline fine-grained Si sheet, the two were about equal in the structures, for given doping concentrations in the p layer. In all cases the epitaxial cells were much better than the polycrystalline cells, mainly because of current collection effects and junction leakage current effects, and the large-grained polycrystalline cells were better than the fine-grained cells. A comparison of diffused-junction and deposited-junction $n^+/p/p^+$ structutes in three different p-layer thickness ranges on the same three classes of substrate showed a direct increase in PV response with p-layer thickness for the epitaxial cells but less distinct differences for the polycrystalline cells.

TITLE: Final Report. Continuous Cz Process Development
AUTHOR: S.N. Rea
CORPORATE AUTH: Texas Instruments, Inc.
DATE: February 1979
REPORT NO: DOE-JPL 954887-79/5
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: A commercial Cz crystal growing furnace was converted to a continuous growth facility by installation of a small, in-situ premelter with attendant Si storage and transport mechanisms. The premelter was situated immediately over the primary melt and provided a molten Si flow into the large crucible simultaneously as crystal was being grown. The key element in this continuous Cz process is the premelter and a substantial portion of the program involved its evolution into a workable design. The best arrangement tested was a vertical, cylindrical graphite heater containing a small fused quartz test tube liner from which the molten Si flowed out the bottom. Approximately 83 cm of nominal 5-cm dia crystal was grown with continuous melt addition furnished by the test tube premelter. High-perfection crystal was not obtained, however, due primarily to particulate contamination of the melt. Elimination of this oxide buildup will require extensive study and experimentation and the ultimate success of continuous Cz depends on a successful solution to this problem. Economic modeling of the continuous Cz process utilized the IPEG option of SAMICS. The influence of both crystal size and total furnace run size were examined. Results of these studies indicate that for 10-cm dia crystal, 100-kg furnace runs of four or five crystals each are near optimal. Costs tend to asymptote at the 100-kg level so little additional cost improvement occurs at larger runs. For these conditions, crystal cost in equivalent wafer area of around $\$16/m^2$ exclusive of polysilicon and slicing is obtained. Lower crystal costs can be obtained by growing large diameter crystals in the 12 to 15-cm range. The outlook for achieving the overall 1986 wafer cost goals is not optimistic because of high slicing costs. Continuous Cz can, however, meet the near-term cost goals for Si sheet material.

TITLE: Quarterly Report. Laser-Zone Growth in a RTR Process Si Sheet Growth Development
AUTHOR: A. Baghdadi, et al.
CORPORATE AUTH: Motorola, Inc.
DATE: March 1979
REPORT NO: DOE-JPL 954376-79/9

ABSTRACT: Appreciable progress has been witnessed in achieving high efficiency on RTR solar cells, with an average efficiency of 9.1% on the most recent lot. The best cell to date has a measured efficiency of 11.3%. A new technique for growing limited-length ribbons continually has been demonstrated. This "Rigid Edge" technique can be used to recrystallize about 95% of the polyribbon feedstock. A major advantage of this method is that only a single, constant length Si ribbon is handled throughout the entire process sequence; this may be accomplished using cassettes similar to those presently in use for processing Cz wafers. Thus a transition from Cz to ribbon technology can be smoothly affected. The maximum size being considered, 3" x 24", is 1/2 ft^2, and will generate 6 W for 12% efficiency at 1 sun. Si dioxide has been demonstrated as an effective, practical diffusion barrier for use during the polyribbon formation. Two different approaches for using the Si dioxide are being pursued.

TITLE: Final Report. Development of Mullite Substrates and Containers
CORPORATE AUTH: Coors Porcelain Co.
DATE: April 1979
REPORT NO: DOE-JPL 954878-79/5
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The objective of this program was to evaluate mullite in contact with molten Si to be used as a substrate for Honeywell's SOC process and as a container for melting solar grade Si. A further requirement was to fabricate respective substrates and containers. To maintain solar grade Si purity levels, the mullite must generally introduce less than 10^{15} atoms/cc of impurities. To evaluate the mullite-molten Si interaction, a series of bodies were made with variations in density, alumina-silica ratio and glass-crystalline ratio. These materials were tested in a sessile drop technique. None of the variations stood up to extended exposure to molten Si sufficiently to be recommended as a container material. However, directional solidification experiments by JPL suggest that, under proper conditions, contamination of the Si by mullite containers can be minimized. To improve an already good thermal expansion match between mullite and Si, compositional variations were studied. Altering of the alumina-silica ratio was determined to give a continuously varying thermal expansion. Thus, a composition can be selected to give the desired thermal expansion match with Si. Concurrent to this work, a standard mullite composition was selected to be used for fabrication development. The major fabrication development requirements were to make substrates 40 x 4 x .040 in. and slotted substrates. Fabrication of standard mullite composition substrates, nominally 40 x 4 x .040 in., have been made and delivered to Honeywell. Slotted substrates of various configurations and various compositions are regularly being supplied to Honeywell.

TITLE: Final Report. Development and Evaluation of Die and Container Materials
AUTHOR: R.R. Wills and D.E. Niesz
CORPORATE AUTH: Battelle Memorial Institute, Columbus Laboratories
DATE: May 1979
REPORT NO: DOE-JPL 954876-79/6
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: Specific compositions of high purity Si aluminum oxynitride (Sialon) and Si beryllium oxynitride (Sibeon) solid solutions are shown to be promising refractory materials for handling and manipulating solar grade Si into Si ribbon. Well controlled processing schedules were developed for fabricating high purity Sialon and Sibeon materials. Essentially the impurity content of the hot pressed ceramics was due only to impurities from the original starting powders. A ceramic shaping die was successfully formed by diamond machining of a hot pressed blank. Projected manufacturing cost estimate for 10^5 dies/yr is \$5.40/die. Evaluation of the interaction of these

materials in contact with molten Si indicates that solid solutions based upon beta-Si_3N_4 are more stable than those based on Si_2N_2O. Sibeon is more resistant to molten Si attack than Sialon, and both materials should preferably be used in an inert atmosphere rather than under vacuum conditions. This is because removal of oxygen from the Si melt in the form of SiO enhances the dissolution of aluminum and beryllium. The wetting angles of these materials are low enough (37^o for x = 0.75 beta' Sialon and 49^o for x = 0.35 Sibeon) for these materials to be considered as both die and container materials.

TITLE: Final Report. X-Ray Measurements of Stresses and Defects in EFG and Large Grained Polycrystalline Si Ribbons
AUTHOR: C.N.J. Wagner
CORPORATE AUTH: The Regents of the University of California, Los Angeles
DATE: August 1979
REPORT NO: DOE-JPL 954851-79/2
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: The Bond method has been employed to measure the lattice parameter a in the area of 0.4 mm in diameter of EFG Si ribbons to an accuracy of ± 0.00008 A. A Bond goniometer was built which included a goniostat with a special specimen holder to mount ribbons 1 m in length and 75 mm in width which could be rotated about two orthogonal axes, and a Leitz microscope for precision alignment of a particular area into the center of the goniostat and the small primary x-ray beam. The (321) planes were found to be parallel to the surface of the ribbons with an angular spread of about 15^o. The poles of the (111) planes clustered about an angle of 20^o away from the surface normal, again with a spread of 10^o. The lattice parameter of a small piece of ribbon material was found to be a_o = 5.43075 A. Converting the observed strain $(a-a_o/a_o)$ into the sum of the principal surface stresses $\sigma_1 + \sigma_2$ assuming that the tilt angles of less than 15^o can be neglected yielded values of $\sigma_1 + \sigma_2$ which were zero within the accuracy of our measurements of ± 10 MPa, but a maximum stress of 115 MPa was observed in a fractured ribbon which corresponded to the fracture stress of single crystals of Si.

TITLE: Final Report. Web-Dendritic Growth
AUTHOR: R.B. Hilborn, Jr., J.W. Faust, Jr., and C. Rhodes
CORPORATE AUTH: University of South Carolina
DATE: August 1979
REPORT NO: DOE-JPL 954344-78/1
AVAILABILITY: NTIS, PC A09/MF A01

ABSTRACT: This final report gives the results of work performed by the University of South Carolina to develop methods of producing large areas of Si ribbon by the web-dendritic method. A prototype web-dendritic growth machine, on hand at the beginning of the contract, was assembled and activated. A program for investigating the role of the various machine design parameters on the contract. The development of the machine proceeded to the point where ribbons could be reproducibly grown to the lengths of 1 meter, with widths increasing linearly from a minimum, at the initiating seed button, up to 1 cm at the point of termination of growth. Considerable thermal data was collected and evaluations were made of actual seeding and growth for variations in a large number of parameters affecting heat loss. From this we found for achieving suitable growth that the mechanical system should be very rigid and stable, and the tolerances and specifications of the quartz crucibles must be far tighter than normal quart tolerances. The widening rates of the ribbons were found to be a function of the temperature gradient rather than the temperature differences alone. A twin spacing in the seed of 3 - 2 was found to be unfavorable for growth; whereas spacing of .9 - 2 and 8 - 2 were favorable. It was found, however, that the spacing of 8 - 2 sets an upper limit of 4 cm/min on the maximum achievable rate. Extensive thermal modeling studies were carried out to investigate the effect of furnace design parameters on the temperature distributions in melt and the growth of the dendritic-web ribbon. From this study it was found that the pull rate of the ribbon is strongly dependent on the temperature of the top thermal shield, the spacing between this shield and the melt, and the thickness of the growing web.

TITLE: Final Report. Epitaxial Si Growth for Solar Cells
AUTHOR: R.V. D'Aiello, P.H. Robinson, and D. Richman
CORPORATE AUTH: RCA Corp.
DATE: September 1979
REPORT NO: DOE JPL 954817 79/4
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The objectives of this contract were: (1) to determine the feasibility of Si epitaxial growth on low-cost Si substrates for the development of Si sheet capable of producing low-cost, high-efficiency solar cells, (2) to achieve a goal of 12% (AM-0) efficient solar cells fabricated on thin epitaxial layers grown on low-cost substrates and (3) to evaluate the add-on cost for the epitaxial process and to develop low-cost epitaxial growth procedures for application in conjunction with low-cost Si substrates. The basic epitaxial procedures and solar-cell fabrication and evaluation techniques are described, followed by a discussion of the development of baseline epitaxial solar-cell structures, grown on high-quality conventional Si substrates. A description of the crystallographic properties of such layers and the performance of epitaxially grown solar cells fabricated on these materials is given. The major conclusions drawn from this work and recommendations for the further development needed to achieve the ultimate cost goals are given.

TITLE: Final Report. Vitre-Graf Coating on Mullite
AUTHOR: R.C. Rossi
CORPORATE AUTH: Tylan Corp.
DATE: September 1979
REPORT NO: DOE-JPL 954896-79/1
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: A technical and economic evaluation was made of a proprietary glass-like carbon glaze coating applied to mullite and graphite to be used either in thin-film Si manufacture or in container ware applications. Preliminary evaluations had indicated that the glassy carbon coating reacts with molten Si to form a Si carbide reaction layer that may serve as a diffusion barrier to prevent Si reaction with the substrate material. The technical evaluation consisted of manufacturing test samples by varying materials and processing parameters in conformance with a preselected matrix. Various tests, primarily coating appearance, adherence and Si reaction behavior was observed as a function of the test parameter variation. The results of these tests indicated that most graphite and carbonaceous materials used as substrates will produce a visually acceptable coating having excellent adherence over a wide range of processing parameters. However, no set of parameters produced a coating that could withstand the chemical attack from molten Si and prevent reaction with a graphite substrate. The primary consideration of graphite substrates was in container ware applications requiring long-time molten Si exposure. The conclusion of this study suggested that the glassy carbon coating might provide protection for time periods of 30 min or less, and therefore was not suitable for the intended application. The results of standard ceramic formulation indicated that a performance optimization did take place for the application of manufacturing Si film solar arrays. When these optimized parameters were tested on type K mullite developed specifically for the intended application it was found that performance was generally insensitive to processing parameters and the selected parameters were then cost optimized. The economic analysis generated a process based on the selected parameter for coating glassy carbon onto newly developed mullite substrate material. By using the interim standard price estimating equation a projected cost of $\$1.30/m^2$ was cal-

culated based on 1975 dollars. If further development of the type K mullite could eliminate the requirement for HF etch preparation of the substrate surface, a unit cost of $\$1.05/m^2$ is calculated on 1979 dollars. Additionally, if normal advance in the Vitre-Graf technology is assumed, a unit cost of $\$0.85/m^2$ is projected on the 1975 $ basis.

TITLE: Final Report. Slicing of Si into Sheet Material
CORPORATE AUTH: Varian Associates, Inc.
DATE: September 1979
REPORT NO: DOE-JPL 954374-79/10
AVAILABILITY: NTIS, PC A24/MF A01

ABSTRACT: Complete results, from raw data to interpretation to recommendations, of a program to investigate the use of multiblade slurry sawing to produce Si wafers from ingots are presented in this report. During the course of this program, the commercially available state-of-the-art process was improved by 20% in terms of area of Si wafers produced from an ingot. The process was improved 34% on an experimental basis. Production of 20 wafers per centimeter length of 100 mm dia ingot is now possible on a production basis. Economic analyses presented show that further improvements are necessary to approach the desired wafer costs, mostly reduction in expendable materials costs. Tests which indicate that such reduction is possible are included, although demonstration of such reduction was not completed. A new, large capacity saw was designed and tested. Performance comparable with current equipment (in terms of number of wafers/cm) was demonstrated. Improved performance was partially demonstrated, but problems (both mechanical and of unknown origin) precluded full demonstration of improved performance.

TITLE: Final Report. Study Program to Develop and Evaluate Die and Container Materials for the Growth of Si Ribbons
AUTHOR: P.E. Grayson and L.A. Addington
CORPORATE AUTH: Eagle-Picher Industries, Inc.
DATE: December 1979
REPORT NO: DOE-JPL 954877-79/6

ABSTRACT: The Large Area Si Sheet Growth Task objective of lowering the cost of Si PV material requires the development of materials which exhibit improved chemical and dimensional stability in contact with molten Si. These materials may find application as containers and/or shaping dies in processes such as edge-defined film growth. This paper describes the development and evaluation of proprietary coatings of pure Si carbide, Si nitride and aluminum nitride on less pure hot pressed substrates of the respective ceramic materials. Si sessille drop experiments were performed on coated test specimens under controlled oxygen partial pressures. X-ray diffraction and SEM characterized after testing with optical and scanning electron microscopy and Auger electron spectroscopy. Increasing the oxygen partial pressure was found to increase the solid-vapor interfacial free energy. Adsorbed oxygen was also found to increase the degree of attack of molten Si upon the chemical vapor deposited coatings. Prototypic containers and dies were delivered and cost projections show that reasonably priced, coated, molten Si resistant refractory material shapes are obtainable.

TITLE: Final Report. Development and Evaluation of Die Materials for Use in the Growth of Si Ribbons By the Inverted Ribbon Growth Process-Task II
AUTHOR: M.T. Duffy
CORPORATE AUTH: RCA Corp.
DATE: December 1979
REPORT NO: DOE-JPL 954901 79/6
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: Amorphous CVD layers of Si nitride and Si oxynitride are prepared by CVD layers are converted to a- and B-Si_3N_4 with a low B-Si_3N_4 content. The a- phase is then slowly converted to the B phase accompanied by simultaneous decompositon. By contrast, Si oxynitride (SiOxNy) layers are converted predominantly to B-Si_3N_4 with a low a-Si_3N_4 content. In this process, oxygen is evolved, and there is no evidence for the existence of an oxynitride phase in the resulting layers. The analysis also indicates that B-Si_3N_4 is much more resistant to chemical attack by molten Si than a-Si_3N_4. Consequently, CVD Si nitride coatings are useful for shorter exposure times. Crystallographic analysis of Si ribbon test specimens, grown from CVD-coated vitreous carbon dies, indicates that Si carbide inclusions are not present in the ribbon samples. The results of infrared analysis also show that the carbon content of the Si ribbons is below detection level and lower than in the Cz seed material.

TITLE: Final Report. Si Sheet Growth Development
AUTHOR: C.M. Johnson
CORPORATE AUTH: Kayex Corp.
DATE: March 1980
REPORT NO: DOE-JPL 954888 80/12

ABSTRACT: The production of low-cost Si capable of being processed into solar cells yielding efficiencies of 14% AM1 is an essential requirement of the LSA Project. Kayex has developed a process for Cz-type crystal growth that significantly reduces the major cost item (other than the Si itself) involved in state of the art Cz growth - the quartz crucible. The new technology generated under this contract can decrease the add-on cost for Si production from at least $51/kg (present state of the art) to $16.14/kg (Cz #3). This translates into an add-on cost of $0.25/pk watt if the JPL/DOE goal of $14/kg is assumed for the polysilicon material used for the growth of crystal ingots. Conclusions and technology status are reported for both phases of the contract which had the following objectives: The growth of 100 kg of Si single crystal material of 10 cm in dia or greater, utilizing one common Si container material (one crucible). The growth of 150 kg of Si single crystal material of fifteen (15) cm in dia, utilizing one common Si container material (one crucible). The objectives of the project included: (a) Developing a new technology concept that would allow a Hamco CG2000 crystal grower to be recharged with a new supply of polysilicon material while still under vacuum and at temperatures above the melting point of Si. (b) Modifying the Hamco CG2000 crystal grower to: (1) accept large polysilicon charges (up to 30 kg, (2) grow large crystal ingots (to 15 cm dia and 25 kg in weight), and (3) hold polysilicon material for recharging (rod or lump) while, at the same time, growing crystal ingots. (c) Designing special equipment to: (1) recharge polysilicon rods, (2) recharge polysilicon lumps, and (3) handle and store large, hot Si crystal ingots. (d) Developing a new process and procedure for growing Si crystal ingots and recharging polysilicon material without contaminating the furnace or breaking the Si container material (crucible).

TITLE: Final Report. Quantitative Analysis of Defects in Si
AUTHOR: R. Natesh
CORPORATE AUTH: Materials Research, Inc.
DATE: April 1980
REPORT NO: DOE-JPL 954977-79/6
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: The analyses of one hundred and seventy four Si sheet samples, about 1200 square centimeters, for twin boundary density, dislocation pit density, and grain boundary length has been accomplished. One hundred and thirty three of these samples were manufactured by Mobil Tyco, thirty two by Motorola, seven by IBM, one by Honeywell, and one by Wacker. Procedures have been developed for the quantitative analyses of the twin boundary and dislocation pit densities using the QTM-720 Quantitative Image Analyzing System. The QTM-720 system has been up graded with the addition of a PDP 11/03 computer with dual floppy disc drive, a Digital Equipment Writer (111) high speed printer, and a Field-Image Feature Interface Module.

These changes have greatly enhanced the speed and reliability of the QTM-720 System as well as improving the data storage and printout capability. Three versions of a computer program that controls the data acquisition and analysis on the QTM-720 have been written. Procedures for the chemical polishing and etching of Mobil Tyco, Motorola, IBM, and Wacker samples have been developed. This report describes the complete procedures for the effect analysis of Si samples using a QTM-720 Image Analyzing System, and includes chemical polishing, etching, and ATM operation. The data from one hundred and seventy four samples, and a discussion of the data is also included herein. In addition to the above work, comparisons of the capabilities of a variety of powerful analytical techniques in analyzing impurities from four different Si matrix was performed. The Si matrix analyzed were Mobil Tyco (EFG-RH and EFG-RF), Honeywell (SOC), and Motorola (RTR). The techniques used were: neutron activation analysis, spark source mass spectrometry, ion scanning spectrometry, secondary ion mass spectrometry, scanning auger microanalysis, electron spectroscopy for chemical analysis, ion microprobe mass spectroscopy, and optical microscopy.

TITLE: Final Report. Development of Methods of Producing Large Areas of Si Sheet by the Slicing of Si Ingots Using ID Saws
AUTHOR: P. Aharonyan
CORPORATE AUTH: Silicon Technology Corp.
DATE: April 1980
REPORT NO: DOE-JPL 955131-81/2
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: ID. wafering equipment, blades and processes were used to develop methods for producing large areas of Si sheet. Modifications to a 16 in. STC automated saw included: 1) programmable feed system; 2) crystal rotating system and 3) STC Dyna-Track Blade monitoring and control system. By controlling the plating operation and by grinding of the cutting edge, we were able to produce 16 in. ID blades with a cutting edge thickness of .22 mm. Crystal rotation mechanism was used to slice 100 mm dia crystals with a 16 inch blade down to a thickness of .20 mm. Cutting rates with crystal rotation were generally slower than with standard plunge ID slicing techniques. Using programmed feeds and programmed rotation, maximum cutting rates were from 0.3 to 1.0 in./min.

TITLE: Final Report. Effects of Varying Oxygen Partial Pressure on Molten Si - Ceramic Substrate Interactions
AUTHOR: P.D. Ownby, et al.
CORPORATE AUTH: The Curators of the University of Missouri
DATE: April 1980
REPORT NO: DOE-JPL 955415-2
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: The objective of this program was to investigate the interaction of molten Si with various die and container candidate materials under varying oxygen partial pressures. This has been done by making Si sessile drop contact angle measurements on the candidate materials to determine the degree to which Si wets these substances, and subsequently sectioning the post-sessile drop experiment samples and taking photomicrographs of the Si-substrate interface to observe the degree of surface dissolution and degradation.

TITLE: Final Report. Si Solar Cell Fabrication Technology
AUTHOR: O.M. Stafsudd
CORPORATE AUTH: The Regents of the University of California, Los Angeles
DATE: May 1980
REPORT NO: DOE-JPL 954902-80/6

ABSTRACT: The initial program was to assist JPL in the building and expansion of their laboratory and device fabrication facilities. This work consisted of device fabrication which was composed of the following processing procedures: (a) low temperature $POCl_3$ diffusions, (b) metallization of back and front ohmic contacts, (c) mask design and fabrication, and (d) sintering in inert and H_2 atmospheres. These processing steps were varied in accordance with JPL's instructions. The device evaluation was performed at UCLA. and JPL. The results of these measurements were correlated, and they included such tests as: a) dark current vs. voltage and log I vs. voltage, b) light current vs. voltage at AM1 and AM0, c) capacitance vs. voltage, and d) spectral response. The measurements were then interpolated and reduced to determine the material properties such as minority carrier lifetimes (t_n) and diffusion lengths (L_n). The diffusion length determination was accomplished by spectral response measurements at UCLA. Similar measurements of various devices were done by SPV at JPL.

TITLE: Final Report. Slicing of Single Crystal and Polycrystalline Si Ingots Using Multi-Blade Saws
AUTHOR: J.B. Ross
CORPORATE AUTH: Norlin Industries, Inc. (P.R. Hoffman Co.)
DATE: May 1980
REPORT NO: DOE-JPL 955563-80/1

ABSTRACT: This contract was issued by JPL to serve primarily as a feasibility study during which the capabilities of P.R. Hoffman Co., Division of Norlin Industries, Inc., could be evaluated with regard to our ability to satisfactorily provide the research and development effort which would lead to optimization of the MBS wafering technique as a contribution to the realization of the Project goals. In addition to making several wafering runs, we were to provide sufficient data necessary for a complete cost analysis of each of the three types of saws utilized.

TITLE: Quarterly Report. Continuous Liquid Feed Cz Growth
CORPORATE AUTH: Siltec Corp.
DATE: June 1980
REPORT NO: DOE-JPL 954886-80/11

ABSTRACT: The purpose of this phase of the continuous liquid feed program is the design and development of equipment and processes in order to ultimately demonstrate the continuous growth of crystals, by the use of the Cz method, suitable for producing monocrystalline Si for use in solar cells. This involves the growth of at least 150 kg monocrystalline Si ingots, 150 mm in dia, obtained from a single growth container. Our approach to meeting this goal is to develop a furnace with continuous liquid replenishment to the growth crucible. Demonstrations using the Si polyrod feed mechanism continued this quarter providing continuous melt replenishment to the meltdown chamber, subsequent transfer of this melt, and the simultaneous growth of Si ingots in the growth chamber. The frame to the CLF furnace was extended in order to accommodate 50 kg crystal ingots above the gate valve, hence enabling us to accomplish our goal of 150 kg throughput. Development work continued on various aspects of the melt transfer system.

TITLE: Final Report. Low Cost Cz Crystal Growing Technology Near Term Implementation of the Flat-Plate PV Cost Reduction
CORPORATE AUTH: Kayex Corp.
DATE: September 1980
REPORT NO: DOE-JPL 955270-80/6

ABSTRACT: One of the primary requirements of the DOE/JPL Si Sheet Task is to develop a process capable of producing low-cost Si. This Si must be capable of being processed into solar cells which will yield a solar cell efficiency of 14% AM1. The technology generated under this contract was aimed at developing process improvement concepts for lowering the costs of the meltdown and crystal growth functions. A program aimed at improving process automation for increased yield and reduced labor requirement

was also undertaken. The development of the various equipment designs that enable high volume, continuous Cz production to be achieved should be directly transferable to industry. The objectives of the process technology phase was to develop and demonstrate continuous Cz crystal growth. Continuous Cz growth was defined as a throughput of 150 kg of Si crystals of 15 cm dia, utilizing one common crucible with melt replenishment. The conclusions and technology status of the contract as applicable to the objectives of the contract are reported. Cost projections and actual cost achievements have been developed using SAMICS/IPEG formula and are also reported. No investigation and evaluation of the variations of the effects of the physical form of Si feed material on the crystal growth process and impurity build-up in the ultimate crystal produced was undertaken.

TITLE: Final Report. EBIC/TEM Investigations of Defects in Solar Si Ribbon Materials
AUTHOR: D.G. Ast
CORPORATE AUTH: Cornell University
DATE: January 1981
REPORT NO: DOE-JPL 954852-81/4

ABSTRACT: Many of the growth methods which produce Si material for the fabrication of inexpensive solar cells yield material which contains a relative high density of structural defects, such as grain boundaries, twin boundaries and dislocations. Because such defects will, in general, reduce the efficiency of a solar cell, there is a technological incentive to study the formation and structure of such defects, and their influence on the minority carrier lifetime. This report discusses the applications of TEM and EBIC to the study of crystalline defects.

TITLE: Quarterly Report. Si Ingot Casting-Heat Exchanger Method Multi-Wire Slicing-Fixed Abrasive Slicing Technique - Phase IV
AUTHOR: F. Schmid and C.P. Khattak
CORPORATE AUTH: Crystal Systems, Inc.
DATE: February 1981
REPORT NO: DOE-JPL 954373-80/16

ABSTRACT: The crystallinity of large-size ingots has been studied as a function of the heat flow conditions at the bottom of the ingot. The size of the ingot has an important effect on crystallinity. The breakdown in crystallinity across the bottom has been resolved to an area in the vicinity of the melted-back seed. Generally, homogeneous resistivity distribution has been achieved all over the ingot. Electroplating of diamonds on one side of the wirepack has an important effect on slicing performance. However, diamond electroplating must be carefully controlled to have a good seat in the grooved rollers. An in-house electroplating facility is now operational. Good performance was achieved with the initial in-house electroplated wirepacks. Projected add-on cost of HEM ingot casting process has been carried out using IPEG analysis. The value that was obtained is $\$8.65/m^2$ well below the allocation of $\$18.15/m^2$ to meet the 1986 goal.

TITLE: Final Report. Si-on Ceramic Process. Si Sheet Growth and Device Development
AUTHOR: B.L. Grung, J.D. Heaps, et al.
CORPORATE AUTH: Honeywell, Inc.
DATE: March 1981
REPORT NO: DOE-JPL 954356-80/15
AVAILABILITY: NTIS, PC A11/MF A01

ABSTRACT: The objective of this R&D program was to investigate the technical feasibility of producing solar-cell-quality sheet Si to meet the DOE 1986 overall price goal of \$0.70/S. With the SOC approach, a low-cost ceramic substrate is coated with large-grain polycrystalline Si by unidirectional solidification of molten Si. This R&D effort was divided into several areas of investigation in order to most efficiently meet the goals of the program. These areas include: 1) dip-coating; 2) continuous coating-designated SCIM-coating; 3) material characterization; 4) cell fabrication and evaluation; and 5) theoretical analysis.

TITLE: Final Report. Si Solar Cell Process Development/ Fabrication/Analysis
AUTHOR: J.A. Minahan
CORPORATE AUTH: Spectrolab, Inc.
DATE: March 1981
REPORT NO: DOE-JPL 955055-81/6
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: Solar cells have been fabricated from unconventional Si materials in the second and final phase of the contract. In the most recent period of work, EFG, web, HEM, and continuous Cz Si materials were fabricated into solar cells, measured and analyzed. Current-voltage measurements under AM1 conditions, in addition to those under AMO conditions, were introduced in Phase II. Several low-cost fabrication steps were included in that phase. Both Hem and Continuous Cz Si were found to be superior to that which had been provided in Phase I. Correlation between quality of starting materials and cell conversion efficiency was observed for Hem-grown Si. Correlation between position in the crystal growth sequence and cell quality was observed for continuous Cz.

TITLE: Final Report. Si Web Process Development
AUTHOR: C.S. Duncan, R.G. Seidensticker, et al.
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: October 1981
REPORT NO: DOE-JPL 954654-80/13
AVAILABILITY: NTIS, PC A08/MF A01

ABSTRACT: Si dendritic web is a single crystal Si ribbon material with unique advantages for the manufacture of low cost solar cells. Shaped by the interplay of natural crystallographic and surface tension forces, rather than by potentially contaminating dies, the web produces solar cells with excellent conversion efficiency. For example, the maximum demonstrated AM1 efficiency, 15.5%, is so far the highest value reported for a ribbon material. The web process also conserves expensive Si. Because impurities are rejected from the ribbon during crystal growth, it is feasible to use cheaper, less pure "solar" grades of Si as feedstock for the web process. Moreover, long flexible web strips facilitate automation of both crystal growth and the subsequent cell-manufacturing operations. Taken together, these characteristics have made the web process a leading candidate to achieve or better the 1986 Project cost objectives of $70¢/W_p$ (1980 \$) of PV output power.

TITLE: Final Report. Enhanced ID Slicing Technology for Si Ingots.
CORPORATE AUTH: Siltec Corp.
DATE: December 1981
REPORT NO: DOE-JPL 955282-81/8
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: To bring ID slicing technology to a higher performance level by demonstrating a significant increase in the number of usable slices per centimeter over industry practice through the reduction of both blade and slice thickness, a combination of three key technologies was investigated: ingot rotation with minimum exposed blade area, dynamic cutting edge control, and the use of prefabicated blade inserts. Prefabricated blade inserts promise great potential for increasing the blade lifetime while decreasing kerf. Results have been encouraging, however, more fundamental work in the materials area of the bond is required before these blades become an effective production tool. An alternative solution of etched core construction permitted low kerf slicing, but further refinement for greater lifetime is necessary. Economic modeling of the enhanced ID slicing process utilized the IPEG II option of SAMICS. A comparison of slicing with

ingot rotation and plunge cutting has shown that simultaneous multiple ingot feed will improve the present cost picture of ID slicing significantly.

TITLE: Final Report. Analysis of Defect Structure in Si
AUTHOR: R. Natesh, M. Mena, et al.
CORPORATE AUTH: Materials Research, Inc.
DATE: April 1982
REPORT NO: DOE-JPL 955676-1

ABSTRACT: The analyses of one hundred and ninety-three (193) Si sheet samples, approximately 880 cm^2, for twin boundary density, dislocation pit density, precipitate density, and grain boundary length has been accomplished in the past contract period. One hundred and fifteen (115) of these samples were manufactured by Crystal Systems, Inc., using their HEM, thirty eight (38) by Mobil Tyco using EFG, twenty-three (23) by Honeywell using the SOC process, and ten (10) by Westinghouse using the Dendritic Web process. Seven (7) solar cells were also step-etched to determine the internal defect distribution on these samples. Procedures have been developed for the quantitative characterization of structural defects such as dislocation pits, precipitates, twin & grain boundaries using a QTM 720 Quantitative Image Analyzing System interfaced with a PDP 11/03 mini-computer. These procedures were routinely applied to all the samples. Characterization of the grain boundary length per unit area for poly crystalline samples was done by using the intercept method on an Olympus HBM Microscope. This report describes the steps involved in the characterization of structural defects in the various types of solar cell materials analyzed. A summary of results as well as discussions of the data are also presented.

TITLE: Final Report. October 1980 to April 1982. Continuous Cz Growth. Development of Advanced Cz Growth Process to Produce Low Cost 150 kg Si Ingots From A Single Crucible for Technology Readiness
AUTHOR: R.L. Lane
CORPORATE AUTH: Kayex Corp.
DATE: April 1982
REPORT NO: DOE-JPL 955733/6

ABSTRACT: The goals of this contract were: to design and construct a crystal grower capable of producing 150 kg of Si crystal from one crucible (5 x 30 kg ingots); to accelerate recharge and growth rate; microprocessor controls with improved sensors; after growth yields of 90%, and throughput of 2.5 kg/h. Subsequently, a Technical Direction Memorandum was issued which placed emphasis on: (1) the improvement of growth rates using radiation shielding, and (2) investigation of the crucible-melt interaction for improved yields. Growth runs were performed from both 15 and 16-in. dia crucibles, producing 30 and 37 kg ingots, respectively. Efforts to increase the growth rate of 150 mm dia ingots were limited by temperature instabilities believed to be caused by undesirable thermal convections in the larger melts. The radiation shield improved the growth rate somewhat, but the thermal instability was still evident, leading to non-round ingots and loss of dislocation-free structure. A 38 kg crystal was grown to demonstrate the feasibility of producing 150 kg with four growth cycles. After the grower construction phase, the Hamco microprocessor control system was interfaced to the JPL growth facility. This included the sensor for automatic control of seeding temperature, and the sensor for automatic shouldering. Efforts focused upon optimization of the seeding, necking, and shoulder growth automation programs. Demonstration of these three crystal growth areas was accomplished with 150 mm dia ingots and melts up to 40 kg. A laser beam reflection system for melt level sensing was installed on the grower and shown to function acceptably, although it was not interfaced with the microprocessor. A gas analysis system was designed, built, and operated as a part of the analytical program of this contract. Analyses of the crystal grower exhaust gas for CO, H_2O, and H_2 gas were performed on several crystal growth runs. Very high levels of CO accompany overheating of the crucible/melt, suggesting melt-down procedures should be controlled more closely to prevent excessive dissolution of the crucible. Graphite bakeout procedures have been improved by measuring CO and H_2 during the bakeout process to determine when graphite parts are sufficiently out gassed.

TITLE: Final Report. Large Area Si Sheet by EFG, October 29, 1975 to December 31, 1981
AUTHOR: J.P. Kalejs
CORPORATE AUTH: Mobil Solar Energy Corp. (Mobil Tyco Solar Energy Corp.)
DATE: September 15, 1982
REPORT NO: DOE/JPL 954355-81/21
AVAILABILITY: NTIS, PC A05/MF A01; 1

ABSTRACT: The objective of this contract was to develop a method for Si ribbon production by EFG for use as low-cost substrate material in terrestrial solar cell manufacture. The program has culminated in the construction of a multiple ribbon furnace unit that is designed to operate on a continuous basis for periods of at least one week, with melt replenishment and automatic ribbon width control, and to produce Si sheet at a rate of one square meter per hour. Program milestones set for single ribbon furnace operation to demonstrate basic EFG system capabilities with respect to growth speed, thickness and cell performance were achieved for 10 cm wide ribbon. At the program's conclusion, however, the integration of these individual performance levels into multiple ribbon furnace operation was not accomplished. Shortfalls in performance have occurred mainly in an inability to consistently and reproducibly achieve acceptable growth conditions that result in homogeneous ribbon of required quality. This has contributed to depressing average cell performance to the range of 9 to 10% efficiency at the best in the multiple furnace operational mode. A lack of flexibility in optimizing growth conditions may be a central element in contributing to deficiencies in both of these areas. Generation of high defect densities by stress relief is a second possible contributing factor in limiting cell performance. Even though residual stress has been reduced to a level where processing of large area cells is feasible, growth system configurations for which the defect density is reduced are not yet available.

TITLE: Final Report. Analysis of Defect Structure in Si Characterization of Semix Material
AUTHOR: R. Natesh, G. Stringfellow, et al.
CORPORATE AUTH: Materials Research, Inc.
DATE: February 1983
REPORT NO: DOE-JPL 955676-4
AVAILABILITY: NTIS, PC A07/MF A01; 1

ABSTRACT: Statistically significant quantitative structural imperfection measurements were made on samples from UCP Ingot 5848-13C. Important correlation was obtained between defect densities, cell efficiency, and diffusion length. Grain boundary substructure displayed a strong influence on the conversion efficiency of solar cells from Semix material. Quantitative microscopy measurements gave statistically significant information compared to other microanalytical techniques. A surface preparation technique to obtain proper contrast of structural defects suitable for QTM analysis was perfected and is now being used routinely. A study was made to determine the relationships between hole mobility and grain boundary density. Mobility was measured using the Van der Pauw technique, and grain boundary density was measured using a quantitative microscopy technique. Mobility was found to decrease with increasing grain boundary density.

TITLE: Final Report. Si Ingot Casting - Heat Exchanged Method Multi-Wire Slicing-Fixed Abrasive Slicing Technique: December 15, 1978 to June 30, 1981
AUTHOR: F. Schmid and C.P. Khattak

CORPORATE AUTH: Crystal Systems, Inc.
DATE: February 18, 1983
REPORT NO: DOE-JPL 954373-81/19
AVAILABILITY: NTIS, PC A12/MF A01; 1

ABSTRACT: Directional solidification by HEM is a viable approach for directional solidification of Si ingots to be used for terrestrial solar cell applications has been demonstrated. Some of the significant advances made during this phase of the program have been: Ingot size - 34 cm x 34 cm x 17 cm - 45 kg; Usable material yield - 90%; Solar cell efficiency averaged over the whole ingot - 85% of control Cz (35 kg ingot); Very uniform resistivity over the boule; and cycle time for 36 kg ingots - 56 h. A decrease of growth rate with increased ingot height, Si carbide precipitates, and high dislocation density in HEM material have been encountered. The Si carbide is attributed to backstreaming of oil vapors from the vacuum pump; the high dislocation density is associated with the thermal history of the boule. Using solar metallurgical meltstock a nearly single crystal structure has been achieved with one HEM directional solidification. Solar cells fabricated using this meltstock have shown up to 12.33% conversion efficiency. The projected add-on cost of HEM processing using the best simultaneous achievements is $17.39/m^2, well within the allocation of $18.15/m^2 for 1986 goals.

TITLE: Final Report. Development of a Polysilicon Process Based on CVD (Phases 1 & 2), October 11, 1982 to May 21, 1983
AUTHOR: J.R. McCormick, et al.
CORPORATE AUTH: Hemlock Semiconductor Corp.
DATE: July 14, 1983
REPORT NO: DOE-JPL 955533-83/8
AVAILABILITY: NTIS, PC A03/MF A01; 1.

ABSTRACT: DCS was used as the feedstock for an advanced decomposition reactor for Si production. The advanced reactor had a cool bell jar wall temperature, 300^{o}C, when compared to Siemen's reactors, approximately 750^{o}C, previously used for DCS decomposition. The cooler wall temperature allows higher DCS flow rates and concentrations. A Si deposition rate of 2.28 gm/h-cm was achieved with power consumption of 59 kWh/kg. Interpretation of data suggests that a 2.8 gm/h cm deposition rate is possible. The 2.8 gm/h cm deposition rate surpasses the goal of 2.0 gm/h cm. Power consumption and conversion should approach the program goals of 60 kWh/kg and 40%. Screening of lower cost materials of construction was done as a separate program segment. Stainless Steel (304 and 316), Hastalloy B, Monel 400 and 1010 1020 Carbon Steel were placed individually in an experimental scale reactor. Si was deposited from trichlorosilane feedstock. The resultant Si was analyzed for electrically active and metallic impurities as well as carbon. No material contributed significant amounts of electrically active metallic impurities, but all contributed carbon. Single crystal growth could not be maintained in most zone refining evaluations. No material need be excluded from consideration for use in construction of decomposition reactor components for production of PV grade Si; however, further evaluation and the use of the low carbon alloys is considered essential.

TITLE: Progress Report. September 1, 1981 to December 31, 1983. Surface Property Modification of Si
AUTHOR: S. Danyluk
CORPORATE AUTH: The Board of Trustees of the University of Illinois for Chicago Circle Campus
DATE: January 1984
REPORT NO: DOE-JPL 956053-84/05

ABSTRACT: The main emphasis of this work has been to determine the wear rate of Si in fluid environments and the parameters that influence wear. Three tests were carried out on single crystal Cz Si wafers: circular and linear multiple scratch tests in fluids by a pyramidal diamond simulated fixed particle abrasion; microhardness and three point bend tests were used to determine the hardness and fracture toughness of abraded Si and the extent of damage induced by abrasion. The mechanism by which the fluids influence wear is still not completely understood. Fluids apparently influence crack initiation and propagation, and dislocation formation and mobility.

TITLE: Quarterly Report, October 23, 1983 to December 31, 1983. Advanced Dendritic Web Growth Development
AUTHOR: C.S. Duncan, R.G. Seidensticker, and J.P. McHugh
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: March 6, 1984
REPORT NO: DOE-JPL 955843-84/13
AVAILABILITY: NTIS, PC A03/MF A01; 1

ABSTRACT: Two types of design concepts were evaluated with the thermal models: (1) a vertical thermal element which modifies both the temperature profile in the web, as well as the convective gas flow near the web, and (2) a thinner lid configuration in which the second lid is replaced by a hot cavity. Each involves trade-offs which need experimental evaluation. Residual stress measurements using the serial split-width technique indicated that the real residual stress was comparable to (or less than) the equivalent "residual stress." The latter has been used as a measure of structural perfection in web crystals in previous reports. New dynamic and new static configurations were given preliminary evaluation in the laboratory, with results generally in agreement with predictions. Improved system temperature measurements were made leading to growth in closer agreement with the model predictions. Improved methods for controlling convective gas flow and oxide deposition were developed.

TITLE: Quarterly Report No. 1. Si Film Solar Cell Process
AUTHOR: R.B. Hall, et al.
CORPORATE AUTH: Astrosystems, Inc.
DATE: May 15, 1984
REPORT NO: DOE-JPL 956769-84/01

ABSTRACT: The most promising way to reduce the cost of Si in solar cells while still maintaining performance is to utilize thin films (10-20 microns thick) of crystalline Si. The method of solution growth is being employed to grow thin polycrystalline films of Si on dissimilar substrates. The initial results indicate that, using tin as the solvent, this growth process only requires operating temperatures in the range of 800^{o}C to 1000^{o}C. Growth rates in the range of 0.4 to 2.0 microns/min and grain sizes in the range of 20 to 100 microns have been achieved on both quartz and coated-steel substrates. Typically, an aspect ratio of two to three between the width and the Si grain thickness is seen. Uniform coverage of Si growth on quartz over a 2.5 x 2.5 cm area has been observed.

TITLE: Final Technical Report. March 1 to May 1, 1984. Demonstration of the Feasibility of Microwave Heating in a Non-Reactive Fluidized Bed Reactor
CORPORATE AUTH: Superwave Technology, Inc.
DATE: July 13, 1984
REPORT NO: DOE-JPL 956801-84/1

ABSTRACT: Microwaves have the property to couple directly to Si with very high efficiencies. This enables rapid, and controlled heating with very low power requirements. Heating can be achieved in a Si bed contained in a quartz crucible. Quartz is transparent to microwave frequencies, and hence can be used as a clean and cost-effective crucible material. In an experimental situation, a multimode cavity was designed and built for a 3 in. high, 6 in. dia bed of Si with particle size of 100 500 micrometers. The quartz chamber was placed in a tuned cavity made of stainless steel, and microwave power was fed from a 6 kW generator. Maintainability and uniformity of heating at various power levels and gas flows was studied by placing thermocouples at various heights and measuring radial distribution. Results indicate that 1.5 kW of microwave power was required to maintain the (3" high) bed at 800^{o} $\pm$ 5^{o}C

at a gas flow exceeding 20 liters/min. Extending to a taller bed (>12" height) is feasible by utilizing multiple microwave inputs with modular power supply design. Utilizing direct coupled microwaves, therefore, provides an efficient and cost-effective means of Si bed heating in a fluidized-bed reactor.

TITLE: Final Technical Report. Quantitative Analysis of Defects in Si
AUTHOR: R. Natesh, R.M. Cohen, J. Dunn, et al.
CORPORATE AUTH: Materials Research, Inc.
DATE: January 1985
REPORT NO: DOE-JPL 956406-85/1
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: Defect density in Hamco Cz Si was measured. A sufficiently high precipitate density was found to cause a reduction in the minority carrier lifetime, and, thus, cell efficiency. Mobility studies in Semix UCP Si were conducted under both dark and illuminated conditions. Results from these measurements indicate that the grain boundaries act primarily as potential barriers to reduce the mobility. A secondary scattering mechanism, from an unknown defect associated with the grain boundaries, leads to a less dramatic reduction in mobility. Neutron activation analysis was used on selected samples provided by JPL for testing of trace elemental analysis. These analyses yielded generally good results. Thin layers of microcrystalline Si on c-Si substrates were analyzed to determine hydrogen content, the ratio of amorphous/microcrystalline material, and microcrystal size. Solar cells made with this structure were found to have higher efficiencies when containing higher concentrations of hydrogen. The ratio of amorphous/microcrystalline material was found to be about 10%, and the microcrystal sizes ranged from 50-150 Å.

TITLE: Final Report. Solid/Melt Interface Studies of High-Speed Si Sheet Growth
AUTHOR: T.F. Ciscek
CORPORATE AUTH: Solar Energy Research Institute
DATE: February 1985
REPORT NO: DOE-JPL WO8746-85/02

ABSTRACT: Radial growth-rate anisotropies and limiting growth forms of point-nucleated, dislocation-free Si sheets spreading horizontally on the free surface of a Si melt have been measured for (100), (110), (111), and (112) sheet planes. Sixteen-millimeter movie photography was used to record the growth process. Analysis of the sheet edges has lead to predicted geometries for the tip shape of unidirectional, dislocation-free, horizontally growing sheets propagating in various directions within the above-mentioned planes. Analysis also provides a crystallographic description of the radial leading edges of solid/liquid interface during flat-top transition growth in Cz pulling. Similar techniques were used to study polycrystalline sheets and dendrite propagation. For dendrites, growth rates on the order of 2.5 m/min and growth rate anisotropies on the order of 25 were measured. Feasibility was demonstrated for a CFH ribbon growth method. X-ray topography analysis of dendritic web silicon sheets was conducted and the resultant topographs are presented.

TITLE: Technical Report. Stress Strain Analysis of Si Ribbon
AUTHOR: O.W. Dillon, Jr.
CORPORATE AUTH: University of Kentucky Research Foundation
DATE: February 1, 1985
REPORT NO: DOE-JPL 956571-85/1

ABSTRACT: At the mini workshop on stresses and strains held at Mobil Solar on January 23-24, 1985, numerical results for the in-plane stresses and the dislocation fields in Si ribbon were reported. A number of convergent solutions which would be relied upon to provide insight into the physical phenomena involved has been obtained. It was emphasized at the meeting that the approach to the calculation for the dislocation density was unique and is the first such calculation ever done for any problem. In our model, the internal structure (here the dislocation density) of the material itself changed both due to the temperature field that is imposed and to the related stress field. The dislocation density changes from point to point and the result is a prediction of the dislocation density in the final ribbon. This appears to us to be a valuable aid to the improvement of quality of the ribbon and its ability to function as a solar cell. There has been no major difficulty with convergence when the dislocation density is kept fixed.

TITLE: Final Report. September 6, 1983 to December 1, 1984. Cryogenic Laser Calorimetry for Impurity Analysis
AUTHOR: R.T. Swimm
CORPORATE AUTH: University of Southern California
DATE: May 1985
REPORT NO: DOE-JPL 956613-85/01

ABSTRACT: This report presents the results of a one-year effort to determine the applicability of laser-calorimetric spectroscopy to the study of deep-level impurities in Si. Critical considerations for impurity analysis by laser-calorimetric spectroscopy are discussed, the design and performance of a cryogenic laser calorimeter is described, and measurements of background absorption in high-purity Si are presented.

TITLE: Final Report. Advanced Dendritic Web Growth Development and Development of Single Crystal Si Dendritic Ribbon and High-Efficiency Solar Cell Program
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: December 30, 1985
REPORT NO: DOE-JPL 956999-85/1

ABSTRACT: Work performed under this contract was a direct extension of work performed under JPL Contract 955843. This effort has continued into 1985 under JPL contract 957207. The long-range objectives of all these contracts are the same: to conduct development efforts to achieve initial deliverables of a JPL program aided at demonstrating that the Si dendritic web technology is ready for commercial use by the end of 1986. A commercial readiness goal involves improvements to crystal growth furnace throughput to demonstrate an area growth rate of greater then 15 cm^2/min while simultaneously growing 10 meters or more of ribbon under continuous melt replenishment. Specific tasks include computer thermal modeling required to define high speed, low stress, continuous growth configurations; a study of convective effects in the molten Si growth furnace cover gas; furnace component modifications; web quality assessments; and experimental growth activities to demonstrate progress. A specific milestone identified in this contract involved demonstration by the end of 1984 of an area-growth rate greater than 10 cm^2/min while simultaneously growing 10 meters or more of ribbon under conditions of continuous melt replenishment. The 1984 web growth goals of crystal length and time are presented. A comparison will show that stability improvements to increased uninterrupted growth times have exceeded the goals. Crystal pull speeds, however, have not increased as was hoped, resulting in shorter crystals than projected.

TITLE: Annual Report. September 1, 1984 to August 31, 1985. Electrical, Structural, and Chemical Characterization of Si Sheet Material
AUTHOR: D.G. Ast
CORPORATE AUTH: Cornell University
DATE: February 18, 1986
REPORT NO: DOE-JPL 956046-86/1

ABSTRACT: Study of web dendritic Si ribbons under four-point bending stress was undertaken to lead to an understanding of how web Si deforms under a well-defined

applied stress. Since the mechanical properties of Si are known to depend on the O content of the material, O measurements using Fourier Transform Infrared Spectroscopy were done to determine a proper control sample of nondefected c-Si. Four-point bending revealed a unique two-step bending behavior for the web Si ribbons. An initial theory for this behavior involves the interaction of the dislocations generated by the deformation with the central twin planes of the ribbons. Oxygen measurements showed a uniformly high O content for the Web Si ribbons, approximately 10^{18} atoms/cm^3 for all the samples measured. All the web samples had a much broader absorption peak at 9 μm than is usually seen for well annealed c-Si. This broadening is thought to be related to stress in the web Si ribbons. Two samples containing a known amount of residual stress support this hypothesis. Also, a shoulder on the infrared absorption peak associated with interstitial O in Si appears in the transmission vs. wavenumber plots for some of the web samples. In the literature, this shoulder has been associated with O-vacancy complexes or with O at dislocations. The O content and configuration do not seem to correlate with the growth configuration of the Web Si ribbon.

TITLE: High-Purity Si Crystal Growth Investigations
AUTHOR: T.F. Ciszek
CORPORATE AUTH: Solar Energy Research Institute
DATE: July 1986
REPORT NO: DOE-JPL WO8762-86/1

ABSTRACT: Si crystal growth parameter effects on minority-carrier lifetime using high purity FZ techniques were investigated. The goals of the work were to optimize dopants and minority-carrier lifetime in FZ material for high efficiency solar cell applications, to improve the understanding of lifetime degradation mechanisms (point defects, impurities, thermal history, etc.), and to characterize lifetime-related crystallographic defects in Si crystals via x-ray topography. Float zoning of high purity, dislocation-free Si was conducted both as a tool to study the dependence of minority-carrier lifetime on various growth parameters and also as a means of growing long-lifetime, heavily doped p-type Si for use in solar cells. The effect of crystal cooling rate on lifetime was determined for a range from 50°C to 600°C/min. Calculation techniques and pertinent property data were developed for a comparison of vacuum and gas ambients as they affect impurity concentration profiles in float-zoned and cold-crucible-grown crystals. X-ray topography was used to examine dislocations and lattice-plane curvature in Si ribbons grown by various methods as well as microdefects in dislocation-free Si crystals. Improvements in the lifetime measurement of heavily doped Si were also made.

TITLE: Final Report. July 9, 1982 to July 15, 1986. Stress and Efficiency Studies in EFG
AUTHOR: J.P. Kalejs
CORPORATE AUTH: Mobil Solar Energy Corp.
DATE: July 15, 1986
REPORT NO: DOE-JPL 956312-86/3

ABSTRACT: The goals of this program have been: (1) to define minimum stress configurations for Si sheet growth at high ($\geq$ 3 cm/min) speeds; (2) to quantify dislocation electrical activity and their limits on minority carrier diffusion length in deformed Si; and (3) to study reasons for degradation of lifetime with increases in doping level in EFG material. Among the main accomplishments have been: (1) Development of a finite element model for calculating residual stress with plastic deformation (with J. Hutchinson at Harvard University); (2) Verification of a finite element model for EFG control variable relationships to temperature field of the sheet to permit prediction of profiles and stresses encountered in EFG systems (with R.A. Brown, Massachusetts Institute of Technology); (3) Development of residual stress measurement technique for finite size EFG material blanks using shadow Moire interferometry (with S. Danyluk, University of Illinois at Chicago); (4) Investigation of transient creep response of Si in the temperature range between 800 and 1400°C in strain (10^{-3}) and strain rate (10^{-4} s^{-1}) regimes of interest in the stress analysis of sheet growth (at Mobil Solar); (5) Establishment of quantitative relationships between minority carrier diffusion length and dislocation densities using EBIC in FZ Si deformed in four-point bending in the temperature region between 800 and 1400°C (at Mobil Solar); and (6) Quantitative characterization of the effect of boron and gallium dopants on bulk lifetime and on recombination around dislocations for EFG material. The modeling work was supported by experiments carried out on EFG ribbon systems at Mobil Solar, which have studied the effects of post-growth temperature profile changes on ribbon stress and dislocation levels. Residual stress and dislocation densities were reduced by lowering growth speed to the order of 1 cm/min. At 2 cm/min and above, interface region temperature gradients had to be maintained at high values to maintain viable (stable) growth, and this has precluded obtaining such reductions. Stress analysis has shown that reduction of residual stress can be achieved by manipulation of transverse isotherms away from the growth interface, viz., cooling the sheet edge with respect to the center at distances of 1 to 5 cm from the interface. This is not effective in reducing high stresses very near (1 to 5 mm) the interface. The implication is that all vertical Si sheet bucke-free growth may be creep limited at speeds in the range of 3 cm/min.

TITLE: Final Report. The Role of Oxygen and Carbon in Process Induced Defects in Silicon
AUTHOR: J.W. Corbett
CORPORATE AUTH: The Research Foundation of State University of New York
DATE: August 13, 1986
REPORT NO: DOE-JPL 956989-86-2

ABSTRACT: Defects unintentionally introduced into solar cells during processing reduce the minority-carrier lifetime of the solar cells, and consequently, reduce the efficiency of the solar cells. These defects can arise in two ways: (1) Processing can cause the device material to change creating new defects, and (2) Processing can permit the introduction of defects from outside the sample. The bulk of the results of our contract relate to the oxygen related proglems; these results are summarized but are treated in depth in the Appendix.

TITLE: Final Report. Advanced Dendritic Web Growth Development
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: October 1980 to May 1985
REPORT NO: DOE-JPL 955843-85/19

ABSTRACT: Without shaping dies, the web process produces thin single crystal Si ribbons directly from a melt. Long-term DOE goals for low-cost PV power require advances in web-area growth rate, continuous replenishment technology, and process automation. Because thermally generated stresses limit the width to which web can be grown, computerized models were developed to calculate the temperature, stress and deformation behavior of the thin ribbons. These models were used for parametric analyses of stress generation for different growth geometries, coil elevation, melt levels and other factors. This led to the concept of a vertical thermal element (VTE) with substantial stress reduction benefit. Modeling also identified ways to minimize convection instabilities by control of the applied thermal gradient in the susceptor or by addition of baffles as flow controlling elements. A third modeling activity led to estimation of the temperature of various thermal elements (lids, shields) from the power input of the induction coil. A major focus of experimental work was to relate model predictions to actual growth conditions and, in turn, to structure of the crystals produced. The crystals produced were characterized by etch pit density measurements, residual stress determinations, and x ray topographic evaluation. Width controlled, continuous-replenishment

studies were carried out with a more sensitive melt-level control system and an adjustable integration time. Implementation was completed of an automated data acquisition system to monitor and store data from all eleven furnaces used for web growth. Experimental data collected from this facility formed the basis for a closed-loop growth-control system. Development of a completely automated closed-loop web growth control was initiated.

HIGH-EFFICIENCY SOLAR CELLS
JPL - IN-HOUSE ABSTRACTS

HIGH-EFFICIENCY SOLAR CELLS IN-HOUSE ABSTRACTS

TITLE: Structure of Deformed Si and Implications for Low Cost Solar Cells
AUTHOR: N. Mardesich, M.H. Leipold, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1978
REPORT NO: DOE-JPL 1012-78/3, JPL Pub. 78-13, 5101-56

ABSTRACT: The microstructure and minority carrier lifetime of Si were investigated in uniaxially compressed Si samples. The objective of the investigation was to determine if it is feasible to produce Si solar cells from sheet formed by high temperature rolling. The initial structure of the Si samples ranged from single crystal to fine-grained polycrystals. The samples had been deformed at strain rates of 0.1 to 8.5 sec^{-1} and temperatures of 1270-1380°C with subsequent annealing at 1270-1380°C.

TITLE: Determination of Bulk Diffusion Lengths for Angle-lapped Semiconductor Material via the Scanning Electron Microscope: A Theoretical Analysis
AUTHOR: O. von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 1978
REPORT NO: DOE-JPL 1012-78/8, and 5101-73

ABSTRACT: A standard procedure for the determination of the minority carrier diffusion length by means of a SEM consists of scanning across an angle lapped surface of a p-n junction and measuring the resultant short circuit current I_{sc} as a function of beam position. A detailed analysis of the I_{sc} originating from this configuration is presented.

TITLE: Effect of Copper Impurity on Polycrystalline Si Solar Cells
AUTHOR: T. Daud and K.M. Koliwad
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1978
REPORT NO: DOE-JPL 02890
AVAILABILITY: NTIS-02890

ABSTRACT: The presence of copper impurity, up to 10^{15} atoms/cc, in single crystal Si has been shown to have no deleterious effect on the p-n junction solar cell performance. In polycrystalline Si copper atoms tend to migrate to the defect sites because of the structural sensitive properties of copper. This study was undertaken to investigate the influence of this behavior of copper impurity on the performance of p-n junction solar cells fabricated from structurally imperfect silicon. Two sets of polycrystalline silicon substrates containing copper were examined. In one set of samples, copper was incorporated during growth, whereas in the other, copper was diffused. Solar cells were fabricated on both sets of substrates by a standard process. Dark and light I-V and spectral response characteristics of the cells were measured and compared with copper-free polycrystalline Si solar cells. The results and the model are discussed.

TITLE: Effect of Grain Boundary in Si Sheet on Minority Carrier Diffusion Length and Solar Cell Efficiency
AUTHOR: T. Daud and K.M. Koliwad
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1978
REPORT NO: 5101-69

ABSTRACT: The diffusion length of minority charge carriers in Si sheet containing grain boundaries has been measured by the EBIC technique using a scanning electron microscope. Quantitative variation of diffusion length as a function of the distance from the grain boundary has been determined.

TITLE: Determination of Silicon Solar Cell Parameters by use of a SEM: Eight Papers
AUTHOR: O. von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 15, 1979
REPORT NO: 5101-111

ABSTRACT: Some of the eight technical papers presented in this compilation have appeared, or will appear, in international technical journals. Others have previously been published internally to JPL. They all center around a common topic: the usefulness or lack of usefulness of the electron microscope in determining significant electrical characteristics of single-crystal Si solar cells. The work described here was performed during the larger part of 1978. For economy and timeliness, the original manuscripts of the papers have been reproduced here in essentially unmodified form.

TITLE: Measurement of Surface Recombination Velocity for Si Solar Cells Using a SEM with Pulsed Beam
AUTHOR: T. Daud and L-J Cheng
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1981
REPORT NO: DOE-JPL 1012-56, and 5101-176

ABSTRACT: In the design and fabrication of Si solar cells approaching theoretically ultimate conversion efficiencies, surface recombination velocity plays a crucial role. A technique using a SEM with pulsed electron beam has been developed for the measurement of this important parameter of Si surfaces. It is shown that the surface recombination velocity, s, increases by an order of magnitude when an etched surface degrades, probably as a result of environmental reaction. A textured front-surface-field cell with a high-low junction near the surface shows the effect of minority carrier reflection and an apparent reduction of s, whereas a tandem-junction cell with n^+-p junction near the surface shows an increasing s value. Electric fields at junction interfaces in front-surface-field and tandem-junction cells acting as minority carrier reflectors or sinks tend to alter the value of effective surface recombination velocity for different beam-penetration depths. A range of values of s from about 10^3 to 10^7 cm/sec has been found for different surfaces.

TITLE: Mathematical Analysis of the PVD Method for Minority Carrier Lifetime Measurements
AUTHOR: O.H. von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1982
REPORT NO: DOE-JPL 1012-65, JPL Pub. 82-3, 5101-203

ABSTRACT: When the diffusion length of minority carriers becomes comparable with or larger than the thickness of a p-n junction solar cell, the characteristic decay of the photon-generated voltage results from a mixture of contributions with different time constants. The minority carrier recombination lifetime τ and the time constant ℓ where τ is essentially the thickness of the cell and D the minority carrier diffusion length, determine the signal as a function of time. It is shown that for ordinary solar cells (n^+-p junctions), particularly when the diffusion length L of the minority carriers is larger than the cell thickness ℓ, the excess carrier density decays according to $\exp(-t/\tau - \pi^2 Dt/4\ell^2)$, τ being the lifetime. Therefore, τ can be readily determined by the PVD method once D and ℓ are known. An analysis of this matter was published recently in the Journal of Applied Physics. This report offers details of its mathematical development.

TITLE: A System for Measuring Thermal Activation Energy Levels in Si by Thermally Stimulated Capacitance
AUTHOR: R.H. Cockrum
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 15, 1982
REPORT NO: DOE-JPL 1012-78; JPL Pub. 82-82, 5101-217
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: The CTS method, used to determine energy level(s) and electrical activity of impurities in Si, is described. It can be classified into three basic categories: the TSCAP, the VSCAP, and the LSCAP. Only the first two categories are discussed. From the total change in capacitance and the time constant of the capacitance response emission rates, both energy levels, and trap concentrations can be determined. Major advantages of CTS are its abilities to detect both the presence of electrically active impurities that are invisible to other techniques, such as Zeeman-effect atomic absorption, and to detect more than one electrically active impurity in a sample. To illustrate the method and its sensitivity, examples of the detection of majority and minority carrier traps from gold donor and acceptor centers in Si are given. These examples illustrate the trap parameters that can be determined from capacitance transients. The experimental test procedure and equipment used are described.

TITLE: Characterization of Grain Boundaries in Si
AUTHOR: L.J. Cheng, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 15, 1983
REPORT NO: DOE-JPL 1012-90, JPL Pub, 83-87, 5101-233
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Results are reported from several research activities dealing with properties of grain boundaries in Si materials. Zero-bias conductance and capacitance measurements at various temperatures were used to study trapped charges and potential barrier height at the boundaries. DLTS was applied to measure the density of states at the boundary. The result is consistent with the model in which the density of states increases as the states become deeper. Anomalous phenomena have been observed by DLTS and other methods, which only can be explained by a new model in which the spatial distribution of the localized states is not uniform along the boundary in the microscopic scale. A study of photoconductivity of grain boundaries in p-type Si demonstrated the applicability of the technique in the measurement of minority-carrier recombination velocity at the grain boundary. The data are consistent with the concept of recombination velocity increasing with boundary state density and light intensity. Enchanced diffusion of phosphorus at grain boundaries in three cast polycrystalline PV materials was studied. Enhancements for the three were the same, indicating that the properties of boundaries are similar, although the materials were grown by different techniques. Grain boundaries capable of enhancing the diffusion were found always to have strong recombination activities; the phenomena could be related to dangling bonds at the boundaries. The present study gives the first evidence that incoherent second-order twins of {111}/{115} type are diffusion-active.

TITLE: Proceedings of the FSA Research Forum on High-Efficiency Crystalline Si Solar Cells
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 15, 1985
REPORT NO: DOE-JPL 1012-103, JPL Pub. 85-38, 5101-258
AVAILABILITY: NTIS, PC A21/MF A01; 1

ABSTRACT: The High-Efficiency Crystalline Si Solar Cells Research Forum was held on July 9-11, 1984, in Phoenix, Arizona. The Research Forum addressed high-efficiency concepts, surface-interface effects, bulk effects, modeling and device processing. These topics were arranged into six interactive sessions, which focused on the state-of-the-art of device structures, identification of barriers to achieve high efficiency cells, and potential ways to overcome these barriers. The Forum arrangement was intended to enable and encourage interaction and discussion among participants. Promising areas of future research are presented in these Proceedings.

TITLE: Proceedings of the FSA Workshop on Crystal Growth for High-Efficiency Si Solar Cells
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 15, 1985
REPORT NO: DOE-JPL 1012-109, JPL Pub. 85-59, 5101-272

ABSTRACT: A Workshop on Crystal Growth for High-Efficiency Si Solar Cells was held December 3 and 4, 1984, in San Diego, California. The Workshop offered a day and a half of technical presentations and discussions and an afternoon session that involved a panel discussion and general discussions of areas of research that are necessary to the development of materials for high-efficiency solar cells. Topics included the theoretical and experimental aspects of growing high-quality Si crystals, the effects of growth process-related defects on PV devices, and the suitability of various growth technologies as cost-effective processes. Fifteen invited papers were presented, with a discussion period following each presentation. The meeting was organized by JPL-FSA. These Proceedings are a record of the presentations and discussions, edited for clarity and continuity.

TITLE: High-Efficiency Si Solar-Cell Design Evaluation and Sensitivity Analysis
AUTHOR: A.R. Mokashi, T. Daud, and R.H. Kachare
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 15, 1985
REPORT NO: DOE JPL 1012-107, JPL Pub. 85-46, 5101-267
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: A copy of SCAP1D from Purdue University and a copy of SUPREM II from Stanford University were obtained and made functional at JPL. They are used as basic analytical tools for high-efficiency Si solar cell design, evaluation, and sensitivity analysis. A brief description of the mathematical model used in the SCAP1D program, including heavy doping effects, is presented. Results are compared with experimental data on representative high-efficiency cells. Sensitivity analysis of an 18.7% efficient cell reported in the literature is made with respect to key device parameters. The analysis indicates that a maximum efficiency of 20% is achievable.

TITLE: Sensitivity Analysis of a Passivated Thin Si Solar Cell
AUTHOR: A.R. Mokashi, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1, 1985
REPORT NO: DOE-JPL 1012-108, JPL Pub. 85-48, 5101-269
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: A new high-efficiency Si solar-cell design is analyzed. Innovative design features are incorporated to reduce losses. Bulk recombination losses are reduced by making the cell thin (100 μm). A back-surface reflector compensates for the optical absorption losses due to cell thinness. Both surfaces (front and back) are considered to be passivated by a Si dioxide layer to reduce the surface recombination velocities. Recombination losses under the contacts are reduced by providing a heavily doped polysilicon layer between the metal and the Si surface. This design is evaluated by using the SCAP1D, developed at Purdue Research Foundation. Sensitivity analysis is performed with respect to key parameters such as cell thickness, back surface recombination velocity and minority carrier lifetime. Practically achievable values for the surface recombination velocities at the front and at the back of 100 cm/s, and the minority carrier lifetime (τ) of 20 μs have been considered. The new cell design is evaluated and shown to be capable of achieving 20% efficiency. Considerable reduction of S_F and S_B and substantial improvement in τ would be necessary to achieve cell efficiency greater than 20%.

TITLE: High-Efficiency Si Solar-Cell Design and Practical Barriers
AUTHOR: A.R. Mokashi, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 15, 1985
REPORT NO: DOE-JPL 1012-112, JPL Pub. 85-75, 5101-281

ABSTRACT: A numerical evaluation technique is used to study the impact of practical barriers, such as heavy doping effects (Auger recombination, bandgap narrowing), surface recombination, shadowing losses and minority-carrier lifetime (τ), on the performance of a high-efficiency Si solar cell. A hypothetical case, considering only radiative recombination losses and ignoring technology-limited and fundamental losses, is evaluated to estimate highest efficiency. Considering a high τ of 1 ms, efficiency of a Si solar cell of the hypothetical case is estimated to be around 29%. This is comparable with (detailed balance limit) maximum efficiency of a p-n junction solar cell of 30%, estimated by Shockley and Queisser. Value of τ is varied from 1 sec to 20 μs. Heavy doping effects, and realizable values of surface recombination velocities and shadowing, are then considered in succession and their influence on cell efficiency is evaluated and quantified. It is shown that these practical barriers cause the cell efficiency to fall from the minimum value of 29% to the experimentally achieved value of about 19%. Improvement in V_{oc} is required to achieve cell efficiency greater than 20%. Increased value of τ reduces reverse saturation current and, hence, improved V_{oc}. Control of surface recombination losses becomes critical at higher V_{oc}. Substantial improvement in τ and considerable reduction in surface recombination velocities is essential to achieve cell efficiencies greater than 20%. Lack of available data for minority-carrier mobility, heavy doping effect, τ in thin emitters, surface recombination velocities, etc., are discussed. Limitations are pointed out for the use of one-dimensional numerical analysis in the consideration of two and three dimensional cell designs, such as floating emitter and dot-junction cells.

HIGH-EFFICIENCY SOLAR CELLS
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TITLE: Final Report. November 1982 through January 1984. Microcrystalline Si Growth for Heterojunction Solar Cells
AUTHOR: P.A. Iles, D.C. Leung, and P.H. Fang
CORPORATE AUTH: Applied Solar Energy Corp.
DATE: February 1984
REPORT NO: DOE-JPL 956369-84/3
AVAILABILITY: NTIS, PC A03/MF A01; 1

ABSTRACT: m-Si films with a 1.7 eV energy band gap and crystal size of several hundred Å were e-beam-evaporated on c-Si to form a heterojunction with the substrate, or a window layer to a c-Si p-n junction (heteroface structure). The goal was to enhance V_{OC} by such uses of the larger band gap m-Si, with the intriguing prospect of forming heterostructures with exact lattice match on each layer. It was found that the heterojunction structure was affected by interface and shunting problems and the best V_{OC} achieved was only 482 mV, well below that of c-Si homojunctions. The heteroface structure showed promise for some of the samples with p m-Si/p-n structure (the complementary structure did not show any improvement). Although several runs with different deposition conditions were run, the results were inconsistent. Any V_{OC} enhancement obtained was too small to compensate for the current loss due to the extra absorption and poor carrier transport properties of the m Si film. A study of the m-Si/c-Si interface using a p-p or n-n heterojunction showed that m-Si did not always serve as a minority carrier barrier as expected. The V_{OC} in many samples was of opposite polarity from that predicted, which indicated some degree of carrier collection. This raised problems concerning the nature of the m-Si/c-Si interface. For this approach to succeed, these interface problems need to be solved along with improvement of the m-Si layer quality.

TITLE: Final Technical Report. Si Sheet With Molecular Beam Epitaxy for High Efficiency Solar Cells
AUTHOR: F.G. Allen and P.D. Sparks
CORPORATE AUTH: The Regents of the University of California, Los Angeles
DATE: August 2, 1984
REPORT NO: DOE-JPL 956233-83/2
AVAILABILITY: NTIS, PC A06/MF A01; 1

ABSTRACT: A 2-year program has been carried out for JPL in which the UCLA Si MBE facility has been used to attempt to grow Si solar cells of high efficiency. MBE offers the potential of growing complex and arbitrary doping profiles with 10 Å depth resolution. It is the only technique that can readily grow built-in front and back surface fields of any desired depth and value in Si solar cells, or the more complicated profiles needed for a double junction cascade cell, all in Si, connected in series by a tunnel junction. Although the dopant control required for such structures has been demonstrated in Si by UCLA, crystal quality at the p-n junctions is still too poor to allow the other advantages to be exploited. Results from other laboratories indicate that this problem will soon be overcome. A computer analysis of the double cascade all in Si shows that efficiencies can be raised over that of any single Si cell by 1 or 2%, and that open circuit voltage of almost twice that of a single cell should be possible.

TITLE: Annual Report. September 1, 1983 to August 31, 1984. Investigation of Si Surface Passivation by Si Nitride Film Deposition
AUTHOR: L.C. Olsen
CORPORATE AUTH: University of Washington
DATE: September 1984
REPORT NO: DOE-JPL 956614-84/01

ABSTRACT: Studies of SiN_x-Si interface properties have been conducted for SiN_x films grown on Si for a range of film growth conditions. Films were grown on Si wafers having a (100) orientation, and resistivity of 2 ohm-cm. Two basic cleaning procedures were used: RCA cleaning procedure and a more abbreviated process which omits the RCA-peroxide steps. Substrates either had a native oxide or a thin oxide film (20 Å) formed by heat treating the wafer at 500°C for 20 min in oxygen. In addition, surfaces were either nitrided or not nitrided. Nitridation involves exposing a surface to a RF plasma and ammonia using 15 W RF power, 70 sccm NH_3 flow, and 270°C platen temperature. Thus, six initial surface conditions are defined by the various combinations of two chemical cleaning steps (RCA or abbreviated), two oxide films (native or 20 Å), and either nitrided or not. After surface preparation, SiN_x films were deposited with an RF power of either 13 W or 75 W, and with the platen temperature at 150°C or 270°C. After deposition of the films, aluminum gates were deposited on a region of the substrate and the surface state density obtained using high frequency C-V measurements. Effects of heat treatment were studied by annealing the films and depositing additional gates on another region of the substrate, and then conducting C-V measurements. Solar cells without AR coatings were provided by JPL for investigation of the passivation properties of SiN_x. Two groups of cells were provided: a set of terrestrial standard cells characterized by a base p-type resistivity of 2 ohm-cm and a junction depth of 0.4 μm, and a group of cells based on 2 ohm-cm p-type material and a 0.2 μm junction. All cells had Ti/Pd/Ag collector grids. These devices were characterized by photoresponse and I-V analyses before and after SiN_x deposition. Preliminary results were obtained for studies involving gated diode device structures. In one case, a decrease in short wavelength photoresponse was observed when a negative potential was applied to the gate of a gated n^+/p cell.

TITLE: Final Report (Phase V). January 1, 1983 through December 31, 1984. Si Solar Cell Process Development, Fabrication, and Analysis
AUTHOR: D.C. Leung and P.A. Iles
CORPORATE AUTH: Applied Solar Energy Corp.
DATE: 1985
REPORT NO: DOE-JPL 955089-85/1
AVAILABILITY: NTIS, PC A03/MF A01.

ABSTRACT: In this phase, the emphasis has been on more detailed study of the sheet materials. Two approaches were adapted. The small diodes (2.5 mm^2) study, which began in the last phase was continued. Also a fine light spot (approx. 015 mm^2) scan method with the response calibrated to measure the localized diffusion length of solar cells was established. The materials under study by both of these methods were cast polycrystalline Si including UCP, SILSO and HEM. Using these methods, the effects of grain boundaries, and of intragrain material quality, were correlated with cell performance. Except for the fine grain portion of SILSO, grain boundaries only played a secondary role in determining cell performance. The major factor was intragrain material quality and it varied with position in ingots and was probably related to the solidification procedure. There was also work in support of other FSA efforts including solar cells fabricated from Si grown in fluidized-bed reactors. Solar cells were fabricated with microcrystalline layers grown on Si substrates by Brookhaven National Laboratory for JPL, and solar cells were made in support of the surface study of University of Washington.

TITLE: Quarterly Technical Report. October 1, 1985 to December 31, 1985. Ink Jet Printing of Silver Metallization for PV
AUTHOR: R.W. Vest
CORPORATE AUTH: Purdue Research Foundation
DATE: January 21, 1985
REPORT NO: DOE-JPL 957031-85/5

ABSTRACT: A new base for the x-y table/print head assembly was constructed, in conjunction with the improvements made to the ink pressure control system by the addition of the MKS Instruments, Inc. equipment This unit, a consolidation of several subsections of the ink jet printing system, serves as a base for the table/print head assembly, houses all of the pressure control system, contains the drive electronics for the print head, and includes several other controls associated with the printing process. The completion of this base unit has simplified system operation and greatly improved pressure regulation accuracy. Initial setup and configuration tasks were completed on the IBM AT computer system and the Star Micronics printer and general system operational tests conducted on both the AT and dot matrix printer. A special communications software package was ordered to simplify communications between the IBM and Purdue's ECN. Progress was made with the completion of a printing and firing study. The contact resistance and the sheet resistance of the top metallization printing on the cell with the ink jet both contribute to the series resistance of the solar cells. This study was conducted to separate the different effects of the contact resistance and the sheet resistance on the overall series resistance of the cells. It was determined that contact resistance was the major problem limiting performance of the solar cells. The stability of a silver/bismuth ink was evaluated and it was determined how often fresh ink needed to be made. In conjunction with this test, an attempt was made to see whether some type of titanium compound could extend ink stability and improve adhesion. The compound, titanium tetramethoxide, was tried, but results were less than promising. Further work will be done in this area. Theoretical studies of ink jet printing were initiated. The purpose of these studies is to develop a model which will relate the amount of ink deposited per unit time to the physical properties of the ink and the machine parameters.

TITLE: Quarterly Progress Report No. 3. July 5, 1984 to December 4, 1984. Comprehensive Si Solar Cell Computer Modeling
AUTHOR: M.F. Lamorte
CORPORATE AUTH: Research Triangle Institute
DATE: March 1985
REPORT NO: DOE-JPL 956741-85/03
AVAILABILITY: NTIS, PC A02/MF A01; 1

ABSTRACT: In Quarterly Reports Nos. 1 and 2, the phenomena submodels and the method of solving the transport equations used in the simulation program were presented. In this Quarterly Report No. 3, the remaining phenomena submodels are presented and discussed. The behavior of the absorption coefficient is most important, along with band gap and diffusion length, in designing high-efficiency solar cells. Small changes in the absorption coefficient typically produce significant changes in the cell terminal characteristics. Experimental data for undoped Si in the energy range of 1.1 to 4.0 eV at 77 and 300 K are well documented. Data, also for undoped material, have been reported in the range of 1.0 to 1.5 eV in the temperature range of 4.2 to 415 K. Other data have been published for selected radiation wavelengths of 1.7 μm and 1.5 μm for undoped material over the temperature range of 300 to 1075 K and for a sample doped with 2×10^{18} cm^{-3} concentration over the same temperature range. Still other data have been published for the impurity concentration range of 10^{19} cm^{-3} to 10^{21} cm^{-3}, in the energy range of 1.5 to 4.0 eV at 300 K. Data at the band-edge and below are also available. Analytical functions representing absorption data as a function of photon energy in the energy range of 1.175 to 3.0 eV, using the Bardeen-Blatt-Hall relationship, have not been useful because of disagreements with experimental data. A more recent publication proposes an analytical relationship for undoped Si which gives good agreement with experimental data at 77 and 300 K over the energy range of 1.1 to 3.1 eV, and for selected energy values at 20 and 415 K. Moreover, a relationship has also been proposed to correct for the absorption coefficient in degenerately doped Si at 300 K.

TITLE: Annual Report. Minority Carrier Transport in Heavily Doped n-Type Si
AUTHOR: J.A. del Alamo
CORPORATE AUTH: The Board of Trustees of the Leland Stanford Jr. University
DATE: November 1985
REPORT NO: DOE-JPL 957159-85/1

ABSTRACT: From first principles it is demonstrated that there are three hole transport and recombination parameters in heavily doped n-type Si: the hole equilibrium concentration, the lifetime, and the diffusion coefficient. In steady-state, however, only two combinations of these three fundamental parameters are relevant: the hole equilibrium concentration-diffusion coefficient product, and the diffusion length. These two parameters have been measured in heavily phosphorus doped Si fabricated by epitaxy. Good quality epitaxial layers were grown with doping levels up to 1.6×10^{20} cm^{-3}. In the process of their characterization, accurate measurements of electron mobility and Hall scattering factor were carried out. For the measurement of the steady-state hole transport and recombination parameters, test structures with bipolar transistors have been fabricated. Based on recent measurement of hole lifetime, values for the hole mobility and equilibrium hole concentrations are obtained from the measured parameters. Fits to the doping level dependence of the three fundamental hole transport and recombination parameters are computed that are suitable for device modeling.

TITLE: Third Quarterly Technical Progress Report. Optimization Methods and Si Solar Cell Numerical Models
AUTHOR: K. Girardini
CORPORATE AUTH: The Regents of the University of California, Los Angeles
DATE: January 1986
REPORT NO: DOE-JPL 957170-85/3

ABSTRACT: The SCAP1D program has been successfully coupled with optimization methods. Several optimization runs have been made to test these methods and the results of these runs are included in Section 2 of this report. Section 1 discusses the final development of the optimization procedure, the cell parameters included as optimization variables, and two other optimization problems. In addition, Section 1 discusses the maximization of efficiency, which the final code will be capable of solving.

TITLE: Quarterly Report. February to April 1986. Rapid Thermal Processing of Ion Implanted Si as a Viable Solar Cell Technology
AUTHOR: G.A. Rozgonyi
CORPORATE AUTH: North Carolina State University
DATE: April 30, 1986
REPORT NO: DOE-JPL 957175-86/2

ABSTRACT: In order to understand the effect of a high temperature defect-dissolution process on the minority carrier lifetime, samples of y and z groups were pretreated with different thermal processes. RTP at 1200°C for 2 min in Ar, as well as conventional furnace annealing at 1200°C and 1250°C, respectively, for 30 min in different ambients, were used. These preheat-treated samples, along with reference virgin wafers, were furnace annealed in the lo, hi and lo-hi thermal processes. It was noted that a hi lo hi heat treatment sequence produces a deep denuded zone in Cz Si wafers and large amounts of precipitates and stacking faults in the bulk phase, as desired for intrinsic gettering.

TITLE: Quarterly Report. January 1, 1986 to March 31, 1986. Heavy Doping Effects in High-Efficiency Si Solar Cells
AUTHOR: F.A. Lindholm and A. Neugroschel
CORPORATE AUTH: University of Florida
DATE: June 6, 1986
REPORT NO: DOE-JPL 956525-86/1

ABSTRACT: The temperature dependence of the emitter saturation current for bipolar devices upon the surface recombination velocity at the emitter surface was studied. From this dependence a value is derived for the bandgap narrowing that is in better agreement with previous determinations obtained from the temperature dependence measured on devices with ohmic contacts. Results are reported of a first direct measurement of the minority-carrier transit time in a transparent heavily doped emitter layer. The value was obtained by a high-frequency conductance method recently developed and used for low-doped Si. Experimental evidence is presented for significantly greater charge storage in highly excited Si near room temperature than conventional theory would predict.

TITLE: Final Report. Use of Low-Energy Hydrogen Ion Implants in High-Efficiency Crystalline Si Solar Cells
CORPORATE AUTH: Pennsylvania State University
DATE: June 12, 1986
REPORT NO: DOE-JPL 957126-86/1

ABSTRACT: The program explored the use of low-energy hydrogen ion implants in the fabrication of high-efficiency crystalline Si solar cells. The work established that low-energy hydrogen ion implants can result in hydrogen-caused effects in all three regions of a solar cell; viz, emitter, space-charge region, and base. In web, Cz, and FZ material low energy hydrogen ion implantation can reduce surface recombination velocity. In web, Cz, and FZ material hydrogen implants were found to passivate space charge region recombination centers. In web cells, hydrogen implants were found also to passivate the base region. However, similar improvement was not seen for the base region of Cz or FZ cells. In the case of web material, hydrogen is believed to be able to diffuse into the base region where it can passivate structural defects present in the web base. In exploring the fundamental interaction of hydrogen with impurities in Si it was found using DLTS that H^+ implants can passivate the deep levels resulting from fast diffusing metal impurities (Au, Cr) but not those resulting from slow-diffusing metal impurities (Tl). This suggests that gettering, not some chemical interaction, is the dominant "passivation" effect in hydrogen's rendering deep levels inactive. Other fundamental work substantiated the recent result of other groups that hydrogen (in this case, implanted hydrogen) can neutralize boron acceptors in Si. Heating during H^+ implantation above $\approx 180^{\circ}C$ removes this neutralization phenomenon. Further, it was established that hydrogen implants can alter the diffusion properties of ion implanted boron in Si; however, this was not found to be the case for ion-implanted As.

TITLE: Final Technical Report. High-Efficiency Crystalline Si Solar Cells
AUTHOR: C.T. Sah
CORPORATE AUTH: C.T. Sah Associates
DATE: June 15, 1986
REPORT NO: DOE-JPL 956289-86/1

ABSTRACT: A review is given in this Final Report of the entire research program since its inception ten years ago. The initial effort focused on the effects of impurities on the efficiency of Si solar cells to provide figures of maximum allowable impurity density for efficiencies of up to about 16 to 17% (AM1). Highly accurate experimental techniques (capacitance transient spectroscopy) were extended to characterize the recombination properties of the residual impurities in Si solar cells. A novel numerical simulator of solar cells was also developed. It uses the circuit technique for semiconductor analysis, which has provided exact theoretical design criteria on the maximum allowable impurity density. Recent effort, until the end of this program, has focused both on the delineation of the material and device parameters which limited the Si AM1 efficiency to below 20% and on an investigation of cell designs to break the 20% barrier. It is shown that if all known and newly proposed high-efficiency design criteria were implemented successfully in one cell, they could give AM1 efficiencies of 20% or higher. These include implementing a thin grade-base back-surface-field by epitaxy, minimizing emitter contact and surface or interface recombination losses using high/low emitter junctions, removing junction perimeter recombination losses, and maintaining a high-base lifetime. Fabrication of such a cell has not been reported although an earlier cell design of Green came closest without using a graded base or special perimeter loss reduction. Novel designs of the cell device structure and geometry can further reduce recombination losses as well as the sensitivity and criticalness of the fabrication technology required to exceed 20%. These include texturized-grooved emitter and reflecting back surface for higher absorption, floating emitter transistor cell to eliminate emitter bulk and surface recombination, and polysilicon emitter and base contact barriers to further reduce emitter contact recombination. These innovative cell designs are essential to reach the fundamental or intrinsic limit of 25% efficiency. It is concluded that the practical limitation in Si cells with efficiency substantially higher than 20% comes from recombination of the photogenerated carriers at the residual impurity and defect recombination centers in the base. This calls for further research on the fundamental characterization of the carrier recombination properties at the chemical impurity and physical defect centers. It is further shown that only c-Si cell technology can be successful in attaining efficiencies greater than 20%. Other forms, such as polycrystalline Si and a-Si, are unlikely to exceed 20% efficiency due to the physical defects in these materials. Grain boundaries in the former and dangling bonds in the latter are efficient recombination sites that cannot be completely passivated by hydrogen or other neutralizing impurities and cannotreduce the residual active recombination center densities to less than 10^{10} cm^{-3}

PROCESS DEVELOPMENT
JPL - IN-HOUSE ABSTRACTS

PROCESS DEVELOPMENT IN-HOUSE ABSTRACTS

TITLE: Technology Development Update
AUTHOR: J.V. Goldsmith and D.B. Bickler
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 1978
REPORT NO: DOE/JPL-1012-78 and 5101-104
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: This document presents copies of the viewgraphs and a condensation of the comments by J.V. Goldsmith and D.B. Bickler of the LSA Project at its 10th PIM, August 16 and 17, 1978, at Caltech University, Pasadena, California. Their presentations focus on the state of the technology aimed at achieving the $500/kW goal by 1986.

TITLE: The Zero Depth Concentrator Phenomenon
AUTHOR: J.G. Mark and C.H. Volk
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 6, 1979
REPORT NO: 5101-136

ABSTRACT: The zero depth concentrator phenomenon, discovered by the General Electric Co., refers to the enhancement of the solar cell electrical output due to internally reflected light from the white background of a glass covered solar cell array. We have undertaken to describe this enhancement effect in terms of a series of basic models which yield an intuitive understanding of the mechanisms and allow tradeoff considerations of some design parameters.

TITLE: LSA Project Basic Sample Preparation Procedures and Evaluation of Si Sheet
AUTHOR: C. Radics
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1979
REPORT NO: 5101-128

ABSTRACT: Study of Si material for solar cell fabrication involves various sample preparation and examination techniques. The procedures for evaluation and characterization of Si are outlined, with special emphasis on the techniques for evaluating low cost Si sheets. Standard techniques of metallography for evaluation on the basic structure of Si material are extensively described. Surface etching, lapping and polishing operations are described in detail. Cross-sectional characterization and junction evaluation procedures through angle lapping and staining techniques are covered. Definitions of terms, scope and important safety precautions are given. These are followed by descriptions of procedures, materials and equipment to facilitate their effective use in the characterization laboratory. Spreading resistance measurement, a strong tool in the evaluation of low-cost Si sheet, is described with details of the equipment used and of operating procedures. Its use is emphasized as a high-resolution technique for checking of surface and depth homogeneity, multilayer characterization and effects associated with precipitates, grain boundaries, interfaces, etc.

TITLE: Near-Term Implementation of Flat-Plate PV Cost-Reduction Task
AUTHOR: D.W. Boyd
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1981
REPORT NO: 5101-180

ABSTRACT: In early 1978, the DOE committed $4.5 million to the LSA Project for use from 1979 through 1981 to investigate techniques for reducing the cost of producing flat-plate PV modules. In response, JPL designated the near-term cost reduction of modules to be a distinct Project task. JPL invited proposals and evaluated them on the basis of maximum potential for producing techniques that would lead to near-term cost reduction. Based on this evaluation, which included SAMICS computer simulation, JPL awarded 14 contracts to industry and various universities for the development and description of cost reduction processes for solar cell and solar-cell module manufacturing. Predictions of manufacturing cost reductions achievable from the implementation of these process developments, on an individual basis, range from $0.09 to $1.76/$W_p$. Manufacturing cost reductions, greater than $2.00/$W_p$, seem possible by simultaneous implementation of several compatible process developments. Several of the processes developed within this program are now being used in commercial production lines. In some cases, the process development itself is commercially available in the form of hardware or technology documentation. Project task objectives, contract awards, technology development, and cost-reduction results are summarized. Complete module manufacturing sequences including near-term cost-reduction process steps are also presented. The term "cost," as used in this report, usually means cost to consumer. Cost reduction is measured at JPL by using the SAMICS method, which includes a reasonable rate of return on equity, income taxes, and all other normal costs of doing business.

TITLE: Vacuum Lamination of PV Modules
AUTHOR: D.R. Burger
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1982
REPORT NO: DOE-JPL 1012-63, and 5101-188
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: Vacuum lamination of terrestrial PV modules is a new high-volume process requiring new equipment and newly developed materials. Equipment development, materials research, and some research in related fields and testing methods are discussed.

TITLE: Development of a Large, Low-Cost, Double-Chamber Vacuum Laminator
AUTHOR: D.R. Burger
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 15, 1983
REPORT NO: DOE-JPL 1012-83, JPL Pub. 83-22, 5101-226
AVAILABILITY: NTIS, PC A03/MF A01.

ABSTRACT: A double-chamber vacuum laminator was required to investigate the processing and control of the fabrication of large terrestrial PV modules, and the economic problems arising therefrom. Major design considerations were low cost, process flexibility and the exploration of novel equipment approaches. Spherical end caps for industrial tanks were used for the vacuum chambers. A stepping programmer and adjustable timers were used for process flexibility. New processing options were obtained by use of vacuum sensors. The upper vacuum chamber was provided with a diaphragm support to reduce diaphragm stress. A counterweight was used for handling ease and safety. Heat was supplied by a large electrical strip heater. Thermal isolation and mechanical support were provided inexpensively by a bed of industrial marbles. Operational testing disclosed the need for a differential vacuum gauge and proportional valve. Reprogramming of the process control system was simple and quick.

TITLE: Proceedings of the FSA Research Forum on PV Metallization Systems
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 15, 1983
REPORT NO: DOE-JPL 1012-92, JPL Pub. 83-93, 5101-239
AVAILABILITY: NTIS, PC A18/MF A01; 1

ABSTRACT: A PV Metallization Research Forum, under the sponsorship of FSA and DOE, was held March 16-18, 1983 at Pine Mountain, Georgia. The Forum consisted of five

sessions, covering: (1) the current status of metallization systems, (2) system design, (3) thick-film metallization, (4) advanced techniques, and (5) future metallization challenges. Twenty-three papers were presented.

TITLE: Summary Report on PV Thick-Film Metallization Systems
AUTHOR: B.D. Gallagher and J. Parker
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 1984
REPORT NO: JPL D-1786, and 5101-255

ABSTRACT: JPL's Automated Array Assembly Task (currently known as the Process Development Area) was assigned the objective of developing the technology for volume low-cost processes to produce Si solar cells and modules suitable for terrestrial applications. The existing state-of-the-art technology was assessed to identify the most cost-effective conceptual approaches. Rather early in both the Assessment and Process Development Phases, the economics of the required metallization system were noted to be a basic cost driver. This document is a summary of the development studies on the use of thick-film metallization systems as the conductive member of the cell structure.

TITLE: Environmental Tests of Metallization Systems for Terrestrial PV Cells
AUTHOR: P. Alexander, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 31, 1985
REPORT NO: DOE-JPL 1012-113, JPL Pub. 85-86, 5101-280

ABSTRACT: Seven different solar cell metallization systems were subjected to temperature cycling tests and humidity tests. Temperature cycling excursions were -50°C to 150°C per cycle. Humidity conditions were 98% relative humidity at 70°C . The seven metallization systems were: Ti/Ag; Ti/Pd/Ag; Ti/Pd/Cu; Ni/Cu; Pd/Ni/Solder; Cr/Pd/Ag; and Thick Film Ag. Graphs of the environmental exposures versus cell efficiencies are presented for each of the metallization systems, as well as environmental exposures versus fill factors or series resistance.

PROCESS DEVELOPMENT
CONTRACTOR ABSTRACTS

TITLE: Final Report. Failure and Degradation Analyses. MITRE Solar Energy Test System Evaluation
CORPORATE AUTH: Solarex Corp.
DATE: April 1976
REPORT NO: ERDA-JPL 954341

ABSTRACT: The objective of the contract was to perform Failure and Degradation Analyses on not more than three of the 136 Solarex Unipanels ™ in Mitre's 859 W_p solar array. This report details the observations and experiments performed on the two such Unipanels already in Solarex's possession. Individual Unipanels are the basic "building blocks" in the assembly of the 50 W_p modules that comprise the Mitre array. These panels were rated by Solarex to deliver a minimum of 6 W_p and were so arranged in groups of eight to deliver 50 W_p/ module. The two Unipanels that are the subject of this report were received from the Mitre Corp. in August 1975. These two panels subsequently labeled "Mitre A_1" and Mitre A_2", were described by Mitre officials at that time as "operational" (A_1) and "open" (A_2).

TITLE: Final Report. Solar Cell Testing Vol. 2, Appendix IV
AUTHOR: A.S. Cherdak and G.M. Haas
CORPORATE AUTH: The Mitre Corp.
DATE: May 1976
REPORT NO: ERDA-JPL 954342

ABSTRACT: In 1974, the MITRE Corporation purchased and installed on the roof of its building in McLean, Virginia, a 1 kilowatt peak PV arry consisting of 20, 50 W panels. These solar panels represented the state-of-the-art in terrestrial PV at the time. The primary purpose for establishing the MITRE Photovoltaic Array was to build a tool with which problems of designing, integrating, and operating terrestrial PV power systems could be studied. Little attention was paid initially to monitoring the array itself due to preoccupation with the overall system design and installation. During and after the first year of exposure to the environment, a variety of changes were noticed in many of the panels: a reduction in short circuit currents and reduced power output from the array. MITRE, funded by ERDA through JPL, undertook to investigate more thoroughly these apparently degraded panels. MITRE proceeded to fabricate and install a data acquisi tion system, discussed in detail in this report, to pro vide more accurate and consistent measurements, in situ, of all of the panels and modules in the array. The I V curves measured in this program show that the Solarex panels have a much lower output power than the other panels in the array. In fact, they measure significantly lower than their original power rating. The poor fill-factors obtained from these panels suggest a high series resistance. Visual observation of the physical condition of these panels after two years of exposure to the terrestrial environment shows significant deterioration of the packaging materials.

TITLE: Final Technical Report. Development of Methods and Procedures for High Rate Low Energy Expenditure Fabrication of Solar Cells
AUTHOR: A.R. Kirkpatrick, J.A. Minnucci, A.C. Greenwald
CORPORATE AUTH: Spire Corp. (Simulation Physics, Inc.)
DATE: November 15, 1976
REPORT NO: DOE-JPL 954289 76/4

ABSTRACT: A one year program to develop a new concept for Si solar cell production based upon the use of pulsed electron beam processes combined with ion implantation has been completed. Feasibility of producing solar cells at high speed by a simplified vacuum-room temperature processing sequence has been demonstrated. The method has many advantages, particularly for large scale production at lowest possible cost.

TITLE: Final Report. Terrestrial Solar Cell Module
CORPORATE AUTH: ARCO Solar, Inc.
DATE: January 1977
REPORT NO: DOE-JPL 954751-78/1
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: ASI's objective on this program was to establish a cost effective design and manufacturing process that would produce solar cell modules capable of meeting the JPL qualification test criteria. Emphasis was placed on the development of an aluminum paste back contact process. The use of aluminum paste as a Si solar cell back contact has the potential advantage of low resistance at low temperature firing and a highly doped p^+ region contributing to improved cell putput. The aluminum has a substantial cost advantage when compared to silver paste.

TITLE: Final Report. Transparent Superstrate Terrestrial Solar Cell Module
CORPORATE AUTH: Lockheed Missiles & Space Co., Inc.
DATE: October 1977
REPORT NO: DOE-JPL 954653-77/1

ABSTRACT: The mechanical features of the module design incorporate high transmission glass superstrate, custom extruded aluminum side and end rails, a backside center stiffening web which also served as a mounting for two electrical output connectors, and three compliant grommets for mounting the unit into subarray frames. The electrical portion of the design incorporates 3-in. dia circular cells from two vendors. The modules fabricated during the program are representative of the general design and of terrestrial cells currently available. To assess the value of primed versus unprimed glass, selected modules used no primer and other used two types of silicone primer. Also to gain additional comparative data in this developmental program, two types of encapsulants were used. Two methods of frame mechanical fastening were assessed, self-drilling tapping screws and blind or pop rivets. Riveting was found to be far superior.

TITLE: Final Report. Automated Array Assembly Task Phase I
AUTHOR: B.G. Carbajal
CORPORATE AUTH: Texas Instruments, Inc.
DATE: October 1977
REPORT NO: DOE-JPL 954405-77/7
AVAILABILITY: NTIS, PC A10/MF A01

ABSTRACT: This contract consists of an assessment of the state-of-the-art technologies that are applicable to Si solar cell and solar cell module fabrication. The assessment consists of a technical feasibility evaluation and a cost projection for high-volume production of Si solar cell modules. A novel approach to metal pattern design based on minimum power loss was developed. The quantitative nature of the design equations provided a solid technical basis for the choice of a metallization technology. A hermetic module was proposed that has a high probability of meeting the 20 yr life goal. Solar cell processing and module fabrication cost projections exceed the 1985 cost goal by only a factor of 3.

TITLE: Final Technical Report. Automated Array Assembly
AUTHOR: R.V. D'Aiello
CORPORATE AUTH: RCA Corp.
DATE: December 1977
REPORT NO: DOE-JPL 954352-77/4
AVAILABILITY: NTIS, PC A08/MF A01

ABSTRACT: This report contains three main sections which describe technology assessment and manufacturing cost analysis; a near-term (1982) factory design; and the results of an experimental production study for the large-scale production of flat-panel Si solar-cell arrays. We have found a minimum manufacturing cost in a highly automated line of $0.30/W assuming the Si is free. The panels

are of a double-glass construction and are based on round wafers. Screen-printed silver has been used as the metallization with a spray-coated AR layer. The least expensive junction-formation technology appears to be ion implantation. Based on the required investment, a profit of $0.05/W appears reasonable. If Si wafers are available at a price of $20 to 40/M^2, a selling price for these array modules of $0.50 to 0.66/W is projected. An analysis of the impact of factory size in the 1986 time frame has been made. A factory processing 50MW/yr using the same technology would sell modules for $0.54/W to 0.70/W.

TITLE: Final Report. Energy Requirement for the Production of Si Solar Arrays
AUTHOR: Joseph Lindmayer
CORPORATE AUTH: Solarex Corp.
DATE: December 1977
REPORT NO: DOE-JPL 954606-77/4
AVAILABILITY: NTIS, PC A07/MF A01

ABSTRACT: This report investigates the feasibility of manufacturing PV solar array modules by the use of energy obtained from similar or identical PV sources. The primary objective was the characterization of the energy requirements of current and developing technologies which comprise the PV field. These energy requirements were subsequently compared to the energy production potential of a future solar power plant and, as a result, the concept of the SOLAR BREEDER was refined and manifested in a computer program. The breeder model allows to take the energy requirements for any PV technology into account and calculate its energy economics. The report documents the energy assessment of the prevailing technologies and many alternative technologies currently under development. For cross-checking the energies of prevailing technologies Solarex data were also used and the wide-range assessment of alternative technologies included different refinement methods, various ways of producing light sheets, semi-crystalline cells, etc. These energy data are utilized to model the behavior of a future SOLAR BREEDER plant under various operational conditions.

TITLE: Final Report. Phase I of the Automated Array Assembly Task
AUTHOR: R.A. Pryor, L.A. Grenon, and M.G. Coleman
CORPORATE AUTH: Motorola, Inc.
DATE: January 1978
REPORT NO: DOE-JPL 954363-78/8

ABSTRACT: The first portion of the report presents the results of a study of process variables and solar cell variables. Emphasis in this portion is on identifying interactions between variables and their effects upon control ranges of the variables. The second portion of this report presents the results of a detailed cost analysis for manufacturing solar cells. This cost analysis includes a sensitivity analysis of a number of key cost factors.

TITLE: Final Report. Assessment of Present State-of-the-Art Sawing Technology of Large Diameter Ingots for Solar Sheet Material
AUTHOR: H.I. Yoo
CORPORATE AUTH: Applied Solar Energy Corp. (Optical Coating Laboratory, Inc.)
DATE: February 1978
REPORT NO: DOE-JPL 954830-78/2
AVAILABILITY: NTIS, PC A07/MF A01

ABSTRACT: The objective of this program is to assess the present state-of-the-art sawing technology of large diameter Si ingots (3" and 4" dia) for solar sheet materials. During this program, work has progressed in: (1) Slicing of the ingots with MBS saw, the MWS saw and the ID saw, (2) Characterization of the sliced wafers, and (3) Analysis of add-on slicing cost based on SAMICS. MWS slicing resulted in mechanical wafer yields of 95% for the 3" dia ingot and 84% for the 4" dia ingot (using a 230 blade package to cut 6" ingot in length). A slicing test with the I.D. saw was performed to obtain mechanical yield versus both wafer thickness and cut rate, and the result showed a good yield (above 95%) down to 7-8 mils of wafer thickness of the 3" wafers and 11-12 mils for the 4" wafers if the cut rates were reduced to one (1) inch/min. An ingot of 3" in dia and 3" in length was sliced with a multiwire slurry saw to obtain wafer yield of about 97%; 163 wires were used, and wafer thickness and kerf width were 10-1 mils and 8 mils respectively. Thickness, taper, bow, and roughness were measured to characterize the sliced wafers. Add-on slicing cost was evaluated based on SAMICS for three slicing types.

TITLE: Final Report. Spraylon Fluorocarbon Encapsulation for Si Solar Cell Arrays
AUTHOR: L.G. Naes
CORPORATE AUTH: Lockheed Missiles & Space Co., Inc.
DATE: April 1978
REPORT NO: DOE-JPL 954410-78/1

ABSTRACT: This program was a R&D program to evaluate the Lockheed-formulated liquid transparent film-forming, fluorocarbon, SPRAYLON, protective coating for terrestrial solar cell modules. Two modules were completed and field-tested for periods of up to two weeks. Problems developed early in the field testing which led to the shortened test period, specifically, lifting of the AR coating, followed in some areas by complete film delamination.

TITLE: Final Report. Development of Low Cost, High Energy Per-Unit Area Solar Cell Modules
AUTHOR: S.S. Rhee
CORPORATE AUTH: Photowatt International, Inc. (Sensor Technology, Inc.)
DATE: April 1978
REPORT NO: DOE-JPL 954605-78/5
AVAILABILITY: NTIS, PC A08/MF A01

ABSTRACT: Development of low-cost, high energy-per-unit-area solar cell modules was conducted in this program. This final report covers the development of two hexagonal solar cell process sequences, a laser-scribing process technique for scribing hexagonal and modified hexagonal solar cells, a large through-put diffusion process, and two surface macrostructure processes suitable for large scale production. Experimental analysis was made on automated spin-on AR coating equipment and high pressure wafer cleaning equipment. Six hexagonal solar cell modules were fabricated. Also covered in this report is a detailed theoretical analysis on the optimum Si utilization by modified hexagonal solar cells for low-cost, high energy per-unit-area solar cell modules.

TITLE: Final Report. Design and Fabrication of Solar Cell Modules
AUTHOR: T.P. Shaughnessy
CORPORATE AUTH: Spire Corp.
DATE: April 1978
REPORT NO: 954655-78/1

ABSTRACT: This program achieved its objective of producing 12 solar cell modules utilizing ion implanted solar cells and an all-glass encapsulation system. These modules have exhibited only cosmetic degradation after environmental testing. The principal problem encountered was the formation of bubbles in the Si gel due to gasket air leakage during thermal cycling. Developmental effort, after delivery of the modules to JPL, indicates that this can be rectified by the use of polysulfide gasket. Significant improvements in the module design that can be recognized are the use of tempered, low iron content glass for increased module output, and the substitution of a custom aluminum extrusion for reduced weight and increased rigidity.

TITLE: Final Report. High Efficiency, Long Life Terrestrial Solar Panel
AUTHOR: S. Khemthong
CORPORATE AUTH: Applied Solar Energy Corp. (Optical Coating Laboratory, Inc.)
DATE: April 1978
REPORT NO: DOE-JPL 954831-78/3

ABSTRACT: Six high efficiency, long life terrestrial modules were designed, fabricated and delivered to JPL. The module utilized 256 large area, rectangular, high efficiency solar cells. A flexible, overlapping design to connect cells in series was used to maximize the packing density. The efficiency of the six modules delivered, based on the overall dimensions at 100 mW/cm^2 and 28°C is tabulated in Table 2, and the contract goal of 13% array efficiency was achieved.

TITLE: Final Report. Center Punched Solar Cell Module Development Effort
AUTHOR: R.E. Ross and W.E. Mortensen
CORPORATE AUTH: Xerox Corp.
DATE: June 1978
REPORT NO: DOE-JPL 954693-78/1
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: This report describes the results of an advanced module development program with the objective of providing a low cost solar cell mechanical interconnect design. The design approach, which avoids soldering or welding operations, lends itself to automated assembly techniques thus supporting the LSA Project goals. A total of 12 modules were delivered to JPL for qualification testing. The first group of six modules contained aluminum palladium contact cells. This final report discusses the module design, manufacturing procedure, test program, significant problem areas and solutions, and conclusions and recommendations as formulated and conducted by XEOS.

TITLE: Final Report. EFG Solar Modules
CORPORATE AUTH: Mobil Solar Energy Corp. (Mobil Tyco Solar Energy Corp.)
DATE: September 1978
REPORT NO: DOE-JPL 954999-78/1
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Six PV modules using solar cells fabricated from Si ribbons were assembled. Each module was comprised of 4 separate submodules which were parallel connected. The submodules contained 45 EFG cells which were series interconnected by a "shingle" or overlapping design. The inherent rectangular shape of the cells allowed a high packing factor to be achieved. The average efficiency of the 6 modules, corrected to AM1 at 28°C was 8.7%, which indicates that the average encapsulated cell efficiency was 10.0%.

TITLE: Final Report. Phase 2, Automated Array Assembly, Task IV
CORPORATE AUTH: Lockheed Missiles and Space Co., Inc.
DATE: October 1978
REPORT NO: DOE-JPL 954898-78/4
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: This contract was a process development effort to verify the technological readiness of a selected process sequence from that as-sawn Cz grown Si wafers to the module assembly. The process investigated consisted of the following sequence: Starting Material: 3-in. as-sawn Cz Si wafers; texture etching of Si wafers using sodium hydroxide; junction formation by ion implantation of phosphorus; laser annealing of ion implanted wafers; screen printing of AG, AG-AL for ohmic contact; spraying of tantalum oxide AR coating; and assembly of modules using the LMSC module design as baseline. This selected process sequence was evaluated for its technical potential of achieving the economic goals of the Project of $.50/W for 500 megawatt/yr production by 1986. Evaluation procedures and results are reported.

TITLE: Final Report. Development and Testing of Shingle-Type Solar Cell Modules
CORPORATE AUTH: General Electric Co.
DATE: February 28, 1979
REPORT NO: DOE-JPL 954607-79/4
AVAILABILITY: NTIS, PC A07/MF A01

ABSTRACT: The design, development, fabrication and testing of a shingle-type terrestrial solar cell module which produces 98 W/m^2 of exposed module area at 1 kW/m^2 insolation and 61°C are reported. These modules make it possible to easily incorporate PV power generation into the sloping roofs of residential or commercial buildings by simply nailing the modules to the plywood roof sheathing. This design consists of nineteen series-connected 53mm dia solar cells arranged in a closely packed hexagon configuration. These cells are individually bonded to the embossed surface of a 3mm thick thermally tempered hexagon-shaped piece of ASG SUNADEX glass. Monsanto SAFLEX PVB is used as the laminating adhesive. RTVII functions as the encapsulant between the underside of the glass superstrate and a rear protective sheet of 0.8mm thick TEXTOLITE. The semi-flexible portion of each single module is a composite laminate construction consisting of outer layers of F.G. Goodrich FLEXSEAL and an epichlorohydrin closed cell foam core. The module design has satisfactorily survived the JPL-defined qualification testing program which includes 50 thermal cycles between -40 and +90°C, a seven day temperature humidity exposure test and a mechanical integrity test consisting of a bidirectional cyclic loading at 2390 Pa (50 lb/ft^2) which is intended to simulate loads due to a 45 m/s (100 mph) wind.

TITLE: Final Report. High Efficiency, High Density Terrestrial Panel
AUTHOR: J. Wohlgemuth
CORPORATE AUTH: Solarex Corp.
DATE: February 1979
REPORT NO: DOE-JPL 954822-78/1
AVAILABILITY: NTIS, PC A08/MF A01

ABSTRACT: Most commercially available PV modules employ the standard round cells. Because of the geometry limitations the packing density in these panels is typically 60 to 70%. The low packing density results in total area panel efficiencies of 6 to 7%. With these low efficiencies, excess encapsulation, framing and mounting materials are required per watt of power delivered, thereby significantly increasing the cost per watt to the consumer. In addition, because of the low panel efficiency many potential applications, with limited area available for array deployment, are not feasible. Solarex has developed the technology for producing large area square and rectangular cells with high (14 to 15%) conversion efficiencies at AM1 ($1kW/m^2$) at 28°C. In this program terrestrial panels have been fabricated using these rectangular cells resulting in the achievement of packing densities in excess of 90% with panel conversion efficiencies greater than 13% being obtained. Most importantly, higher density panels can be produced today on a cost competitive basis with the standard salami panels, with bright prospects of significant cost reductions in the near future.

TITLE: Final Report. High Efficiency Cell Development
AUTHOR: B.G. Carbajal
CORPORATE AUTH: Texas Instruments, Inc.
DATE: February 1979
REPORT NO: DOE-JPL 954881-79/5
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: The goal of this specific activity was to improve the Texas Instruments developed TJC as a high efficiency solar cell. The TJC development must be consistent with module assembly and should contribute to the

overall goals of the LSA Project. During 1978, TJC excess of 42 mA/cm^2 were observed at AM0. Open circuit voltages as high as 0.615 V were measured at AM0. Fill factor was only 0.68 - 0.75 due to a non-optimum metal contact design. A device model was conceived in which the solar cell is modelled as a transistor. This model will be very useful in directing future development activities. The planar back contact system of the TJC coupled with the high cell efficiency makes the TJC an excellent candidate solar cell for the fabrication of high efficiency modules, since there are virtually no interconnect or packing factor losses. The TJC is compatible with all conventional module fabrication systems. The back contact system lends itself readily to series, parallel or series-parallel interconnect schemes. A modification of the TJC, the FSF cell was also explored. The FSF cell using a floating p^+ layer on the front of the cell in place of the n^+ layer of the TJC. The FSF cell also features the planar back contact system. Photoresponse of FSF cells, while good, was not quite as good as the TJC.

TITLE: Final Report. Metallization of Large Si Wafers
AUTHOR: R.A. Pryor
CORPORATE AUTH: Motorola, Inc.
DATE: March 1979
REPORT NO: DOE-JPL 954689-78/4
AVAILABILITY: NTIS, PC A07/MF A01

ABSTRACT: A metallization scheme has been developed which allows selective plating of Si solar cell surfaces. The system is comprised of three layers. Palladium, through the formation of palladium silicide at 300°C in nitrogen, makes ohmic contact to the Si surface. Nickel, plated on top of the palladium silicide layer, forms a solderable interface. Lead-tin solder on the nickel provides conductivity and allows a convenient means for interconnection of cells. To apply this metallization, three chemical plating baths are employed. Palladium is deposited with an immersion palladium solution and an electroless palladium solution, and nickel is deposited with an elecroless nickel solution. Solder is applied with a molten solder dip. Extensive development work has been performed to achieve an effective immersion palladium silicide contact layer. This metallization system has been repeatedly demonstrated to be extremely effective. Current-voltage characteristic curve fill factors of 78% are easily achieved. This has been done while maintaining metal contact adhesion at such a strength as to fail by fracturing Si upon perpendicular pull testing rather than by delaminating the metal system. Demonstrations have been performed on a laboratory scale using beakers, hot plates, and lots of 24 three in. dia solar cells. On this basis, process specifications and procedure have been prepared. The laboratory process could be easily scaled to full production volume. Although this metallization system has been shown to be cost effective in its present state of readiness, specific areas have been identified which would profit from additional development, leading to appreciable further cost reductions which would make the metallization cost a minor factor in 50¢/W solar cell economics. A document, "Material, Supply, and Process Specifications and Procedures for Metallization of Large Silicon Wafers with the Palladium-Nickel-Solder Metallization System," has been prepared and will be available from JPL upon request.

TITLE: Final Report. Development of Economical Improved Thick Film Solar Cell Contact
CORPORATE AUTH: Bernd Ross Associates
DATE: April 1979
REPORT NO: DOE-JPL 955164-77/2
AVAILABILITY: NTIS

ABSTRACT: Materials were surveyed to provide candidates for an all metal electrode paste system. These consisted of a major constituent metal powder, a low melting metal powder material suitable as an etchant for Si dioxide at sintering temperatures. By means of thermal gravimetric analysis, a suitable binder was identified for low temperature fired inks. The all metal ink concept was first demonstrated with the silver system to avoid the problems of limited process windows encountered with base metal systems. A number of solid materials capable of selectively etching Si dioxide at modest temperatures were identified. The results of the study suggest further experimentation with eutectic additives to enable formation of a thin highly doped regrowth layer.

TITLE: Final Report. Development of Pulsed Processes for the Manufacture of Solar Cells
CORPORATE AUTH: Spire Corp.
DATE: April 1979
REPORT NO: DOE-JPL 954786-79/7
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: This report describes the results of a one and a half year program to develop the processes required for low-energy ion implantation for the automated production of Si solar cells. The program included (1) demonstrating state-of-the-art ion implantation equipment and designing an automated ion implanter, (2) making efforts to improve the performance of ion-implanted solar cells to 16.5% AM1, (3) developing a model of the pulse annealing process used in solar cell production, and (4) preparing an economic analysis of the process costs of ion implantation and furnace annealing. During the program, phosphorus ions at an energy of 10 keV and dose of 2 x 10^{15}cm^{-2} were implanted in Si solar cells to produce junctions, while boron ions at 25 keV and 5 x 10^{15}cm^{-2} were implanted in the cells to produce effective back surface fields. An ion implantation facility with a beam current up to 4 mA and a production throughput of 300 wafers per hour was designed and installed. A design was prepared for a 100-mA, automated implanter with a production capacity of 100 MW$_e$ per year. Two process sequences were developed which employ ion implantation and furnace or pulse annealing. The JPL SAMIS computer program was used to determine costs for junction formation by ion implantation and various furnace annealing cycles to demonstrate cost effectiveness of these methods.

TITLE: Final Report. Solar Cell Modules with Parallel Oriented Interconnections
CORPORATE AUTHOR: Motorola, Inc.
DATE: June 1979
REPORT NO: DOE-JPL 954716-79/1
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: This contract provided for delivery of 24 solar modules, half of which were to be 48 cells in an all-series electrical configuration and half of a 6 paralleled cells by 8 series cells. Upon delivery of environmentally tested modules to JPL, low power outputs were discovered. These low power modules were determined to have cracked cells which were thought to cause the low output power. The cracks tended to be circular or linear, which were caused by different stressing mechanisms. A subsequent contract amendment to the original contract was made to fully explore these stressing mechanisms. The contract amendment also provided for delivery of 36 cells with selected interconnect configurations and two additional modules. The series-parallel configuration modules were also changed to 4PX12S. Efforts were undertaken to determine the causes of cell fracture. This resulted in module design and process modifications, foremost among which was the decision to utilize a multiple back contact interconnect design. The design and process changes were subsequently implemented in production.

TITLE: Final Report. Evaluation of the Technical Feasibility and Effective Cost of Various Thickness for the Manufacture of Solar Cells
CORPORATE AUTH: Solarex Corp.
DATE: July 1979
REPORT NO: DOE-JPL 955077-79/5
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: The principal activities in the performance of this contract effort include practical evaluation of the Yasunaga YQ-100 saw in a production environment. The wafering system is a free-abrasive multiple-loop single wire machine where the number of wafers/cm is determined by the wire pitch. In addition, the effects of wire diameter and abrasive size were studied. Solar cells were manufactured from each saw run to analyze surface damage and effects of varying thickness on efficiency.

TITLE: Final Report. Automated Array Assembly Task In-Depth Study of Si Wafer Surface Texturizing
AUTHOR: G.T. Jones
CORPORATE AUTH: Photowatt International, Inc. (Sensor Technology, Inc.)
DATE: July 1979
REPORT NO: DOE-JPL 955266-79/2

ABSTRACT: An in-depth study of Si wafer surface texturizing was conducted in this program. The work discussed in this final report covers four tasks. Task (1) investigated a low-cost cleaning method that utilized recycled Freon in an ultrasonic vapor degreaser to remove organic and inorganic contaminants from the surface of Si wafers as received from Si suppliers. Task (2) demonstrated the use of clean dry air and high throughput wafer batch drying techniques to lower the cost of wafer drying. Task (3) examined the two stage texturizing process for suitability in large scale production. Task (4) performed an in-depth gettering study with the two stage texturizing process for the enhancement of solar cell efficiency, minimization of I-V curve dispersion, and improvement in process reproducibility.

TITLE: Final Report. A New Method of Metallization for Si Solar Cells
AUTHOR: M. Machs
CORPORATE AUTH: SOL/LOS Inc.
DATE: September 1979
REPORT NO: DOE-JPL 955318-79/3
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The new metallization process based on Mo-Sn system is the subject of this nine months program. MoO_3 is used as the source of Mo, since its relatively low melting point and ease of reduction to metallic molybdenum. The first part of the contract, the reaction mechanism study of MoO_3 and its mixture with Sn, was conducted in an experimental station consisting of a graphite strip-heater and a Pyrex belljar, under close control of temperature-atmosphere time, while allowing visual observations of the reactions. The metallization of the cells was done in a diffusion tube furnace. In order to obtain a low ohmic contact to the cell, the basic ink composition was modified with a small addition of titanium in the form of titanium resinate. The electrical characteristics of the cells were comparable with the existing metallization processes. The firing cycle still has to be optimized for the process used in the continuous conveyor belt furnace, especially in the cooling cycle around 450°C, which indicated a significant effect on the electrical characteristics. The cost analysis of the process was based on projected production output of 1 MW/yr, using 2" dia. Si crystal wafers and the current material cost. Therefore the calculated cost deviates from the projected price goal set up for the year 1986. In comparison with the standard processes using silver as the contacting metal, the saving obtained by the use of this new process is a direct result of the price difference between silver and molybdenum oxide with tin.

TITLE: Final Report. Phase 2 of the AAA Task
AUTHOR: R.B. Campbell
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: October 1979
REPORT NO: DOE-JPL 954873-79/8
AVAILABILITY: NTIS, PC A07/MF A01

ABSTRACT: The process sequence for the fabrication of dendritic web Si into solar panels has been modified to include aluminum back surface field formation. Sputtering is the preferred method for depositing the aluminum. Plasma etching has been shown to be a feasible technique for pre-diffusion cleaning of the web. This would replace wet chemical cleaning. Several contacting systems have been studied. The total plated Pd-Ni system (Motorola Process) is not compatible with our process sequence; however, the evaporated TiPd-electroplated Cu system has been shown stable under life testing. Ultrasonic bonding parameters have been determined for various interconnect and contact metals but the yield of the process is not sufficiently high to use for module fabrication at this time. Over 400 solar cells, about 11 cm^2 in area have been fabricated according to the modified sequence. No sub-process incompatibility was seen. These cells have been used to fabricate four demonstration modules. A cost analysis (SAMICS) of the modified process sequence resulted in a selling price of $\$0.75/W_p$ (1980$ in 1986).

TITLE: Final Report. Development of Economical Improved Thick Film Solar Cell Contact
CORPORATE AUTH: Bernd Ross Associates
DATE: December 1979
REPORT NO: DOE-JPL 955164-79/4

ABSTRACT: In the second half of the investigation of all metal screened electrodes, the focus was on base metal pastes in addition to further work with the silver systems. Contact resistance measurements were refined. A facility allowing firing in hydrogen and other atmospheres was acquired. Several experiments were made applying screenable pastes to solar cells. Doping investigations emphasized eutectic alloys reduced to powders. Metal systems were reviewed. A previously published vapor pressure curve for silver flouride was corrected. Base metal experiments were done with nickel and copper using lead and tin as the frit metals. No electrical experiments were done with the nickel ink.

TITLE: Final Report. Production Management Handbook
CORPORATE AUTH: Theodore Barry and Associates
DATE: January 1980
REPORT NO: DOE-JPL 955519-80/1

ABSTRACT: This handbook, which supplements the SAMIS model, will assist LSA production managers in reducing the cost of solar arrays. While the handbook includes mathematical models, it provides more than a set of analytical techniques. It discusses general principles for production economics, aggregate planning, facility design, production control, inventory management, quality control, maintenance management, materials handling, market strategy and risk management. The handbook emphasizes cost control and resource utilization. The general principles involve information measurement and evaluation. The objectives of the Production Management Handbook are to: Outline decision-making processes for cost-effective production; Develop industrial engineering tools applicable to the PV industry. Specifically, the handbook provides analytical models and algorithms to address: Production scheduling strategies; Inventory levels and storage requirements; Production process design and flow rates; Quality control criteria and implementation; Maintenance and outage strategies; Material handling methods; Market strategy, risk management, and contingency planning.

TITLE: Final Report. Evaluation of Ion Implanted Si
AUTHOR: P. A. Iles
CORPORATE AUTH: Applied Solar Energy Corp. (Optical Coating Laboratory, Inc.)
DATE: February 1980
REPORT NO: DOE-JPL 955118-80/2

ABSTRACT: This contract is a three-way joint effort, between California Institute of Technology, JPL and OCLI.

The goal is to investigate the potential for reduced cost ion-implantation to fabricate low cost solar cells. The team obtains overall guidance and some support related to low cost ion sources from JPL, Caltech performs all ion-implants (including variations in energy, fluence and ion species) and OCLI provides suitable Si slices, and processes and evaluates the implanted wafers as solar cells using a "baseline" process. To date about 280 slices have been prepared, implanted, and processed as cells. The detailed summary of the cell performance as a function of the various ion implantation parameters is contained in the Caltech final report on this phase of the work.

TITLE: Final Report. Phase 2 of the AAA Task
AUTHOR: M.G. Coleman, et al.
CORPORATE AUTH: Motorola, Inc.
DATE: March 1980
REPORT NO: DOE-JPL 954847-80/8
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: Several specific processing steps, as part of a total process sequence for manufacturing Si solar cells, were studied during this contract. Ion implantation has been identified as the Motorola preferred process step for impurity doping. Unanalyzed beam ion implantation has been shown to have major cost advantages over analyzed beam implantation. Further, high quality cells have been fabricated using a high current unanalyzed beam. Mechanically masked plasma patterning of Si nitride has been shown to be capable of forming fine lines on Si surfaces with spacings between mask and substrate as great as 250 μm (10 mils). Extensive work was performed on advances in plated metallization. The need for the thick electroless palladium layer has been eliminated. Further, copper has been successfully utilized as a conductor layer, utilizing nickel as a barrier to copper diffusion into the Si. Plasma etching of Si for texturing and saw damage removal has been shown technically feasible, but not cost-effective compared to wet chemical etching techniques.

TITLE: Final Report. Development of Low Cost Contacts to Si Solar Cells
AUTHOR: D.P. Tanner and P.A. Iles
CORPORATE AUTH: Applied Solar Energy Corp.
(Optical Coating Laboratory, Inc.)
DATE: April 1980
REPORT NO: DOE-JPL 955244-80/5
AVAILABILITY: NTIS, PC A07/MF A01

ABSTRACT: This report is a summary of work done on the development of a copper based contact system for Si solar cells. The work has proceeded in three phases: PHASE I: Development of a copper based contact system using plated Pd-Cr-Cu. PHASE II: The degradation in Phase I was identified as copper migration into the cells junction region. A paper study was conducted to find a proper barrier to the copper migration problem. PHASE III: An electroless nickel solution was substituted for the electroless chromium solution in the original process. Efforts were made to replace the palladium bath with an appropriate nickel layer, but these were unsuccessful. 150 cells using the Pd-Ni-Cu contact system were delivered to JPL. Also a cost study was made on the plating process to assess the chance of reaching 5¢/W.

TITLE: Final Report. Investigation of Proposed Process Sequence for the AAA Task Phase II
AUTHOR: Nick Mardesich
CORPORATE AUTH: Spectrolab, Inc.
DATE: June 1980
REPORT NO: DOE-JPL 954853-80/10
AVAILABILITY: NTIS, PC A21/MF A01

ABSTRACT: A selected process sequence for the low cost fabrication of PV modules was defined during this contract. Each part of the process sequence was looked at regarding its contribution to the overall dollars per watt cost. During the course of the research done, some of the initially included processes were dropped due to technological deficiencies. The printed dielectric diffusion mask, co-diffusion of the n^+ and p^+ regions, wrap-around front contacts and retention of the diffusion oxide for use as an AR coating were all the processes that were removed for this reason. Other process steps were retained to achieve the desired overall cost and efficiency. Square wafers, a polymeric spin on PX-10 diffusion source, a p^+ BSF and silver front contacts are all processes that have been recommended for use in this program. The printed silver solderable pad for making contact to the aluminum back was replaced by an ultrasonically applied tin-zinc pad. Also, the texturized front surface was dropped as inappropriate for the sheet sequence for module fabrication. A shift from bonding with a conformal coating to laminating with EVA and a glass superstrate is recommended for further module fabrication. The processes that were retained for the selected process sequence, spin-on diffusion, print and fire aluminum p^+ back, clean, print and fire silver front contact and apply tin pad to aluminum back, were evaluated for their cost contribution. The finalized process sequence is shown schematically on page 1A and in Table 3.21-1, page 295. The process specifications for the finalized process sequence are shown in Appendix F. The format A's for SAMICS calculations of the finalized process are shown in Appendix G.

TITLE: Final Report. Process Development for Automated Solar Cell and Module Production. Task 4: Automated Array Assembly
CORPORATE AUTH: Tracor MBAssociates (MBAssociates)
DATE: June 1980
REPORT NO: DOE-JPL 954882-80/21
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The scope of work under this contract involves specifying a process sequence which can be used in conjunction with automated equipment for the mass production of solar cell modules for terrestrial use. This process sequence is then critically analyzed from a technical and economic standpoint to determine the technological readiness of each process step for implementation. The process steps are ranked according to the degree of development effort required and according to their significance to the overall process. Under this contract the steps receiving analysis were: back contact metallization, automated cell array layup/interconnect, and module edge sealing. For automated layup/interconnect both hard automation and programmable automation (using an industrial robot) were studied. The programmable automation system was then selected for actual hardware development. This work has been done to improve the performance of solar modules and to lower the cost through process development and large scale automation. The guidelines used in this effort has been to work toward a process sequence which will provide a 500 MW/yr production capacity in the industry by the year 1986.

TITLE: Final Report. Development of High Efficiency (14%) Solar Cell Array Module
AUTHOR: P.A. Iles, et al.
CORPORATE AUTH: Applied Solar Energy Corp.
DATE: June 1980
REPORT NO: DOE-JPL 955217-80/5
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: Most effort was concentrated on development of procedures to provide large area (3" dia) high efficiency (16.5%, AM1, 28°C) p^+nn^+ solar cells. Intensive tests with 3" slices gave consistently lower efficiency (13.5%). The problems were identified as incomplete formation of an optimum BSF, and interaction of the BSF process and the shallow p^+ junction. Towards the end of the contract, a promising process sequence was identified, to meet the original goals and tests of this sequence are continuing outside of this program.

TITLE: Final Report. Automated Solar Module Assembly Line
AUTHOR: Max Bycer
CORPORATE AUTH: Kulicke & Soffa Industries, Inc.
DATE: August 1980
REPORT NO: DOE-JPL 955287-80/6
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: The solar module assembly machine which Kulicke and Soffa delivered under this contract is a cell tabbing and stringing machine, flexible in design, and capable of handling a variety of cells and assembling strings up to 4 feet in a series or parallel arrangement, and in a straight or interdigitated array format. The machine cycle is 5 s/solar cell. This machine is primarily adapted to 3 in. dia round cells with two tabs between cells. Pulsed heat is used as the bond technique for solar cell interconnects. The solar module assembly machine unloads solar cells from a cassette, automatically orients them, applies flux and solders interconnect ribbons onto the cells. It then inverts the tabbed cells, connects them into cell strings, and delivers them into a module array format using a track mounted vacuum lance, from which they are taken to test and cleaning benches prior to final encapsulation into finished solar modules. Throughout the machine the solar cell is handled very carefully, and any contact with the collector side of the cell is avoided or minimized. A lamp simulator has been used to test bonded solar cells to determine if the bonding operation had any degrading effect on the cell. I-V profile curves taken of these sample cells, before and after the bonding operation indicate no apparent effect on the electrical characteristics of the solar cell by the bonding operation.

TITLE: Final Report. Automated Array Assembly, Phase II
AUTHOR: R. V. D'Aiello
CORPORATE AUTH: RCA Corp.
DATE: October 1980
REPORT NO: DOE-JPL 954868-80/9
AVAILABILITY: NTIS, PC A10/MF A01

ABSTRACT: Figure 1 is a schematic representation of the work of the first year. The philosophy of this plan was to establish an experimental process line starting with 3-in.-dia Si wafers and consisting of junction formation using $POCl_3$ gaseous diffusion, screen-printed thick-film metallization, reflow solder interconnect, and double-glass lamination panel assembly. This experimental production line produced a sufficient number of solar cells to demonstrate the technological readiness of each of those process steps. Variations (of each process) were made to set limits on the usable range of each process step and to determine the interraction with adjoining steps. Inspection measurements, and tests were included to determine the output requirement characteristics of each step, obtain statistical variations, and evaluate the performance of the solar cells and panels. A description of this work, which was conducted from October 1977 through December 1978, is given in Sections III and IV. This was followed by an 18-month study in which three manufacturing sequences synthesized from the above work and from studies conducted by other participants in the LSA program were exercised. The objectives were to assess the compatibility between process steps for each sequence, to generate sufficient data for comparative SAMICS cost analysis, and to make recommendations of the suitability of one or more of these sequences for the large-scale automated production of solar cells within the cost goal of $\$0.70/W_p$. The detailed experimental results of this study are described in Section V, followed by SAMICS cost analysis, recommendations, and conclusions given in Sections VI and VII.

TITLE: Final Report. The Establishment of a Production-Ready Manufacturing Process Utilizing Thin Si Substrates for Solar Cells
AUTHOR: R. A. Pryor
CORPORATE AUTH: Motorola, Inc.
DATE: October 1980
REPORT NO: DOE-JPL 955328-80/4
AVAILABILITY: NTIS, PC A10/MF A01

ABSTRACT: Three inch diameter Cz Si substrates sliced directly to 5 mil, 8 mil, and 27 mil thicknesses with wire saw techniques were procured. Processing sequences incorporating either diffusion or ion implantation technologies were employed to produce n^+p or n^+pp^+ solar cell structures. These cells were evaluated for performance, ease of fabrication, and cost effectiveness. It was determined that the use of 7 mil or even 4 mil wafers would provide near term cost reductions for solar cell manufacturers.

TITLE: Final Report. Phase 2 of the AAA Task
AUTHOR: R.C. Petersen
CORPORATE AUTH: Solarex Corp.
DATE: November 1980
REPORT NO: DOE-JPL 954854-80/8
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: Studies were conducted on several fundamental aspects of electroless nickel/solder metallization for Si solar cells. A process proposed by Motorola, which precedes the electroless nickel plating with several steps of palladium plating and heat treatment, was compared directly with single step electroless nickel plating. Work was directed toward answering specific questions concerning the effect of Si surface oxide on nickel plating, effects of thermal stresses on the metallization, sintering of nickel plated on Si, and effects of exposure to the plating solution on solar cell characteristics. The Motorola process was compared with simple electroless nickel plating in a series of parallel experiments.

TITLE: Final Report. Automated Array Assembly Task Development of Low-Cost PV Solar Cells
CORPORATE AUTH: Photowatt International, Inc. (Sensor Technology, Inc.)
DATE: November 1980
REPORT NO: DOE-JPL 955265-80/3

ABSTRACT: Development of low-cost, large area polysilicon solar cells was conducted in this program. Three types of polysilicon material were investigated. Included in the study was the Wacker cast polysilicon, Crystal Systems HEM material, and Exotic Materials FAST-Cz polysilicon. The influence of crystal grains on solar cell efficiency was studied. A theoretical and experimental comparison between single crystal Si and polysilicon solar cell efficiency was performed. The feasibility of applying an anisotropic sodium hydroxide etching process to polysilicon wafers was investigated. The texture etching rate, time and solution concentration were evaluated. Several optional low-cost solar cell processes were investigated. They included $POCl_3$ gettering, spray-on n^+ polymer dopants, and printed aluminum. It was demonstrated that 10% efficient polysilicon solar cells can be produced with spray-on n^+ dopants. This result fulfills an important goal of this project, which is the production of batch quantity of 10% efficient polysilicon solar cells.

TITLE: Final Report. The Development of a Method of Producing Etch Resistant Wax Patterns of Solar Cells
AUTHOR: E. Pastirik
CORPORATE AUTH: Motorola, Inc.
DATE: November 1980
REPORT NO: DOE-JPL 955324-80/4

ABSTRACT: A potentially attractive technique for wax masking of solar cells prior to etching processes was studied. This technique made use of a reuseable wax composition which was applied to the solar cell in patterned form by means of a letterpress printing method. After standard wet etching was performed, wax removal by means of hot water was investigated. Application of the letterpress wax printing process to Si was met with a number of difficulties. The most serious shortcoming of the process was its inability to produce consistently well-defined printed patterns on the hard Si cell surface.

TITLE: Final Report. Phase II AAA Task
AUTHOR: C. Olson
CORPORATE AUTH: Photowatt International, Inc. (Sensor Technology, Inc.)
DATE: December 1980
REPORT NO: DOE-JPL 954865-80/9

ABSTRACT: The information presented provides a summary of the work performed from September 20, 1977 through June 20, 1980 by Sensor Technology, Inc., in Chatsworth, California and Photowatt International, Inc. in Tempe, Arizona. The initial contract was a Phase II Process Development for a process sequence, but with concentration on two particular process steps: laserscribing and spray-on junction formation. The balance of the process, although important, was to be a subordinate level of effort to support these two major tasks. The add-on portion of the contract was to further develop these tasks, to incorporate spray-on of AR coating and aluminum and to study the application of microwave energy to solar cell fabrication. The overall process cost projection is 97.918¢/W_p. The major contributor to this excess cost is the module encapsulation materials cost. The frame and encapsulation materials alone total 25.634¢/Wp. Since this was not an area of major effort on the contract, the approach was to automate what was available, not to develop new technologies and, as a result, less effort was devoted to this task. During the span of this contract the study of microwave application to solar cell fabrication produced the ability to apply this technique to any requirement of 600°C or less. Above this temperature, non-uniformity caused the processing to be unreliable. It became evident that fundamental development efforts were required and these are being pursued through another contract.

TITLE: Final Report. Development of Simplified Process for Environmentally Resistant Cells
AUTHOR: W.J. King
CORPORATE AUTH: Kinetic Coatings, Inc.
DATE: December 1980
REPORT NO: DOE-JPL 955079-80/1
AVAILABILITY: NTIS, PC A08/MF A01

ABSTRACT: This report describes a program to develop a simple, foolproof, all-vacuum solar cell manufacturing process which can be completely automated and which results in medium efficiency cells which are inherently environmentally resistant. All components of the completed cells are integrated into a monolithic structure with no material interfaces. The exposed materials (Si, Al_2O_3, Al, Ni) are all resistant to atmospheric attack and the junction, per se, is passivated to prevent long term degradation. Such cells are intended to be incorporated into a simple module consisting basically of a press-formed metallic superstructure with a separated glass cover for missile, etc., protection. A 5 cm x 5 cm test cell configuration was designed in which the various efficiency loss factors were adjusted to yield a 10% AM1 cell. Each of the cell elements was individually optimized for combination with the others. The basic cell consists of alloyed front (Al) and back (Ag plus Ni) contacts, a multi-purpose (AR, hermetic seal, implantation oxide) front surface coating of Al_2O_3, and an implanted front junction. Implantation damage annealing and contact alloying are carried out in a simple one step thermal treatment at 870°C using a resistance heated furnace in vacuum. Times at temperature as short as 15-20 s for complete cell activation were demonstrated in a related proprietary program. The use of non analyzed and semi-analyzed beams for fabricating these cells was developed by KCI for use on this contract. A final lot of 50 cells made using the semi-analyzed beam method had an average efficiency of 10.4% at AM1 (28 $\pm$ 1°C). An economic analysis predicts a manufacturing cost of \$.45/W_p for these cells using a one machine automatic method.

TITLE: Final Report. High Resolution, Low Cost Solar Cell Contact Development
AUTHOR: N. Mardesich
CORPORATE AUTH: Spectrolab, Inc.
DATE: December 1980
REPORT NO: DOE-JPL 955298-80/2
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Experimental work demonstrating the feasibility of the MIDFILM process as a low-cost means of applying solar cell collector metallization was completed during this contract. Cell efficiencies of above 14% (AM1, 28°C) were achieved with fritted silver metallization. Environmental tests suggest that the metallization is slightly humidity sensitive and degradation is observed on cells with high series resistance. The major yield loss in the fabrication of cells was due to discontinuous grid lines, resulting in high series resistance. Standard lead-tin solder plated interconnections do not appear compatible with the MIDFILM contact. Copper, nickel and molybdenum base powder were investigated as low-cost metallization systems. The copper based powder degraded the cell response. The nickel and molybdenum base powders oxidized then sintered in the oxidizing atmosphere necessary to ash the photoresin.

TITLE: Final Report. Cost Effective Flat Plate PV Modules Using Light Trapping
AUTHOR: C.N. Bain, B.A. Gordon, et al.
CORPORATE AUTH: Science Applications, Inc.
DATE: April 1981
REPORT NO: DOE JPL 955787-81/1
AVAILABILITY: NTIS, PC A11/MF A01

ABSTRACT: This report and Appendix A give the results of the study. The Final Report details the analyses and calculations performed to arrive at the design guidelines, and Appendix A is an Optical Design Guide which contains rules and guidelines for the practicing PV design engineer. Science Applications is extending prior in-house work in optical trapping in "thick films" to form a design guide for PV engineering. The Design Guide shows the reader how to construct PV modules to use and even to exploit this concept. By SAI calculations up to 20% improvements in standard module performance can be expected. Even larger improvements can be received in special modules constructed to exploit these thick film effects as discussed in the Final Report.

TITLE: Final Report. Processing Experiments on Non-Cz Si Sheet (MEPSDU Support Contract)
AUTHOR: R.A. Pryor, L.A. Grenon, et al.
CORPORATE AUTH: Motorola, Inc.
DATE: April 1981
REPORT NO: DOE-JPL 955844-81/2

ABSTRACT: A program of six months duration was performed to support and promote the further development of processing techniques which may be successfully and cost-effectively applied to low-cost non-Cz Si sheet for solar cell fabrication. Results are reported in the areas of process technology, cell design, cell metallization, and production cost simulation.

TITLE: Final Report. Automated Solar Panel Assembly Line
AUTHOR: Howard Somberg
CORPORATE AUTH: ARCO Solar, Inc.
DATE: May 1981
REPORT NO: DOE-JPL 955278-81/5

ABSTRACT: This report contains the results of a two-year effort to design, develop and operate automated equipment for the interconnection of solar cells and lamination of cell circuits into modules. The overall objective was to effect near-term reduction of Si solar cell array costs so as to achieve the 1985 goal of \$0.70/W*. The program consisted of four sections: (1) design of a module that lends

itself to automated assembly, (2) design and development of prototype equipment for the interconnection and lamination of solar cells into a completed module, (3) the operation of a pilot production line using the equipment developed in this program, and (4) perform a cost analysis of the production run. This program was originally proposed as a 12 month effort. However, because of the complexity of the soldering equipment task the program was extended to 27 months. In late 1979, a prototype element of the soldering machine was implemented into the module production operation. This section of the machine consisted of a roller transport mechanism integrated with an electromagnetic induction coil** for soldering continuous ribbon interconnects to the front of solar cells. In a fashion, it was the first step in the mechanization of soldering or "tabbing" solar cells, and this simple mechanism has reliably tabbed about 1.8 million solar cells to date.

* All costs in this report are given in 1980 $
** The automated soldering machine was subsequently redesigned to use an infrared heat source.

TITLE Final Report. Laser Annealing of Ion Implanted Si for Solar Cell Junction Formation
CORPORATE AUTH: Lockheed Missiles & Space Company, Inc.
DATE: June 1981
REPORT NO: DOE-JPL 955696-81/4
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: An investigation was conducted which evaluated the merits of large spot size pulsed laser annealing of phosphorus implanted, Cz grown Si for junction formation of solar cells. The feasibility and requirements were also determined to scale-up a laser system to anneal 7.62 cm dia wafers at a rate of 1 wafer/s. Laser parameters were developed for optimized performance. These parameters were substantiated by surface analysis, including SIMS, TEM and RBS techniques, followed by fabrication of 2 x 2 cm, 2 x 4 cm and 7.62 cm dia. functional cells to verify acceptability.

TITLE: Final Report. High Resolution, Low Cost Solar Cell Contact Development
AUTHOR: N. Mardesich
CORPORATE AUTH: Spectrolab, Inc.
DATE: November 1981
REPORT NO: DOE-JPL 955725-81/1

ABSTRACT: MIDFILM cell fabrication and encapsulation have been demonstrated as a means of applying low-cost solar cell collector metallization. The average cell efficiency of 12.0% (AM1, 28°C) was achieved with fritted silver metallization with a demonstration run of 500 starting wafers. A 98% mechanical yield and 80% electrical yield were achieved through the MIDFILM process. High series resistance was responsible for over 90% of the electrical failures and was the major factor causing the low average cell efficiency. Environmental evaluations suggest that the MIDFILM cells do not degrade. A slight degradation in power was experienced in the MIDFILM minimodules when the AMP Solarlok connector delaminated during environmental testing.

TITLE: Final Program Summary Report. Evaluation and Verification of Epitaxial Process Sequence for Si Solar-Cell Production
AUTHOR: D. Redfield
CORPORATE AUTH: RCA Corp.
DATE: November 1981
REPORT NO: DOE-JPL 955825-81/3
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: To achieve the program goals, 28 minimodules were to have been fabricated and tested, using 600 cells made from three in.-dia wafers processed by the sequence chosen for this purpose. Of these 600 cells, half were to be made from epitaxially grown layers on potentially low-cost substrates. The other half were to be made from commercial SG, single-crystal Si wafers that served as controls. Cell processing was normally performed on mixed lots containing significant numbers of each of these two types of wafers. After evaluation of the performance of all cells, they were separated by types for incorporation into modules that were to be tested for electrical performance and response to environmental stress. A simplified flow chart displaying this scheme, for quantities representing half of the planned total to be processed, is presented. Documentation of the specifications and procedures of all process steps chosen for this program, and detailed SAMICS cost analyses have been provided in separate reports bearing those titles. As with all R&D projects, however, there are unavoidable differences between some of the laboratory processes used to fabricate cells and modules for the present evaluations and the analogous processes as they would take place in a factory at high production rates. In all cases where uncertainties may exist in specific process steps, the materials or procedures used were consistent with developments occurring under either the LSA Program or the ED contract that RCA was conducting for SERI. In this report, some information is provided on relevant work under the ED Program.

TITLE: Final Report. Equipment Development for Automated Assembly of Solar Modules
CORPORATE AUTH: Tracor MBAssociates (MBAssociates)
DATE: January 1982
REPORT NO: DOE-JPL 955699-81/05
AVAILABILITY: NTIS, PC A08/MF A01

ABSTRACT: Prototype equipment was developed which allows for totally automated assembly in the three major areas of module manufacture: cell stringing, encapsulant layup and cure and edge sealing. The equipment is designed to be used in conjunction with a standard Unimate 2000B industrial robot although the design is adaptable to other transport systems.

TITLE: Final Report. Si Dendritic Web Material Process Development
AUTHOR: D.L. Meier, R.B. Campbell, et al.
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: March 1982
REPORT NO: DOE-JPL 955624-82/3
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: The purpose of this program was to develop a low-cost contact system for solar cells and to integrate techniques for fabricating, interconnecting, and encapsulating solar cells in order to produce several demonstration modules. Two experimental contact systems were examined and compared to a baseline contact system consisting of evaporated layers of titanium, palladium, and silver and an electroplated layer of copper. The first experimental contact system consisted of evaporated layers of titanium, nickel, and copper and an electroplated layer of copper. The second experimental contact system consisted of evaporated layers of nickel and copper and an electroplated layer of copper.

TITLE: Analysis and Evaluation of Processes and Equipment
AUTHOR: M. Wolf and H Goldman
CORPORATE AUTH: The Trustees of the University of Pennsylvania
DATE: April 1981
REPORT NO: DOE-JPL 954796 81-13
AVAILABILITY: NTIS, PC A15/MF A01

ABSTRACT: The metallization pattern design, or grid line design, is examined so as to define the design which combines minimum series resistance losses and area coverage. Power output losses due both to the voltage drop from series resistance and to the shadowing by the front metallization can be held to 5% of the maximum power output for

a 10 cm x 10 cm cell. Tapered grid lines are found to have less of an effective voltage drop than grid lines of constant width, and grid lines normal to the bus lines give better performance than obliquely arranged grid lines. On the basis of the findings of the grid line design analysis, a set of design rules for solar cells is presented. Process options for applying the metal to the Si surface are discussed. Options considered include immersion plating, electroless plating, electrolytic plating, vacuum deposition (including sputtering) and thick film screen printing. By comparative evaluation, electroless and electrolytic plating are found to be the most cost-effective options, with vacuum deposition being competitive. Due to problems connected with masking, the use of the antireflection coating as the metallization mask is expected to be less attractive.

TITLE: Final Report. Analysis and Evaluation in the Production Process and Equipment Area
AUTHOR: M. Wolf
CORPORATE AUTH: The Trustees of the University of Pennsylvania
DATE: April 30, 1982
REPORT NO: DOE-JPL 956034/1
AVAILABILITY: NTIS, PC A 04/MF A01

ABSTRACT: The project began with techno economic evaluations of MEPSDU processes, and then proceeded to a study of requirements for the longer range, potentially substantial improvement of the efficiency of Si solar cells. Of the MEPSDU processes investigated, it was found that the Solarex metallization design and process selection should be modified to yield substantially higher output of the 10 cm x 10 cm cells, while the Westinghouse design is extremely close to the optimum. In addition, further attention to the Solarex p-n junction and base high/low junction formation processes could be beneficial. For future efficiency improvement, it was found that refinement of the various minority carrier lifetime measurement methods is needed, as well as considerably increased sophistication in the interpretation of the results of these methods. In addition, it was determined that further experimental investigation of the Auger lifetime is needed, to conclusively determine the Auger coefficients for the direct Auger recombination at high majority carrier concentrations. This will determine the ultimately achievable efficiency of Si solar cells. If the Auger coefficients should be substantially lower than presently thought, more attention may have to be given to bandgap narrowing. Finally, more needs to be known about the effects of various device processes on the minority carrier lifetime ultimately existing in the diverse layers of the device.

TITLE: Final Report. Development of Technique for AR Coating and Nickel and Copper Metallization of Solar Cells
CORPORATE AUTH: Photowatt International, Inc.
DATE: February 2, 1983
REPORT NO: DOE-JPL 955986/4
AVAILABILITY: NTIS, PC A03/MF A01.

ABSTRACT: Solar cells were made with a variety of base-metal screen printing inks applied over a Si nitride AR coating and copper electroplated. Fritted and fritless nickel and fritless tin-base printing inks were evaluated. Conversion efficiencies as high as 9% were observed with fritted nickel ink contacts. Curve shapes, however, were generally poor, reflecting high series resistance. Problems encountered in addition to high series resistance included loss of adhesion of the nickel contacts during plating, poor adhesion, oxidation, and inferior curve shapes with the tin-base contacts.

TITLE: Final Report. Hermetic Edge Sealing of PV Modules
CORPORATE AUTH: Spire Corp.
DATE: July 1983
REPORT NO: DOE-JPL 956352/2
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: The program objective was to investigate the feasibility of using an ESB and ultrasonic welding process to produce hermetic edge seals on terrestrial solar cell modules. The fabrication sequence is to attach an aluminum foil "gasket" to the perimeter of a glass sheet. A cell circuit is next encapsulated inside the gasket, and its aluminum foil back cover is seam welded ultrasonically to the gasket. An ESB process for sealing aluminum to glass was developed in an ambient air atmosphere, which eliminates the requirement for a vacuum or pressure vessel. An ultrasonic seamwelding process was also developed which did not degrade the quality of the ESB seal. Good quality welds with minimal deformation were produced. This program has been successful in demonstrating the technical feasibility of producing hermetically sealed edges on PV modules using a combination of ESB and ultrasonic welding.

TITLE: Final Report. Investigation of Nickel-Si Metallization Process
AUTHOR: M. Macha
CORPORATE AUTH: SOL/LOS, Inc.
DATE: July 22, 1983
REPORT NO: DOE-JPL 956276-83/1

ABSTRACT: The metallization of Si solar cells passivated with Si nitride coating was investigated by using commercial Ni pastes No. 5517 from Thick Film Systems, No. 7028-5 from Cermalloy, experimental formulation No. X-A by SOL/LOS, Inc. and evaporated Ti-Ni film. Comparative and reference tests were done with the Dupont Ag paste No. 7095 and with a mixture of Ni paste No. 5517 with Ag paste No. 7095 in the respective ratio of 9 to 1 by weight. The evaluation criteria for the metallization were the mechanical bond strength of the contact, solderability, copper plating ability and electrical characteristics in terms of V_{oc}, I_{sc} values and shape of the I-V curve.

TITLE: Final Report for Period November 26, 1980 to September 30, 1983. Process Research on Non-Cz Si Material
AUTHOR: C.M. Rose
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: September 30, 1983
REPORT NO: DOE JPL 955909-83/11
AVAILABILITY: NTIS, PC A14/MF A01; 1

ABSTRACT: The primary objective of this contract was to investigate high-risk, high-payoff research areas associated with the Westinghouse process for producing PV modules using non-Cz sheet material. All investigations were performed using dendritic web Si, but all process steps studied are directly applicable to other ribbon forms of sheet material. These tasks were addressed: (1) Liquid junction technical feasibility study (the objective of this task was to determine the technical feasibility of forming front and back junctions in non-Cz Si using liquid dopant techniques. Numerous commercially available liquid phosphorus and boron dopant solutions were investigated. Optimal diffusion parameters required for this process step using liquid dopants were determined); (2) Liquid diffusion mask feasibility study (the objective of this task was to determine the technical feasibility of forming a liquid applied diffusion mask to replace the more costly chemical vapor deposited SiO_2 diffusion mask) (3) Application studies of AR material using a meniscus coater (the objective of this task was to determine the technical feasibility of applying liquid AR solutions using meniscus coating equipment. Film thickness relationships with AR capabilities were investigated. The AR films formed were shown to have uniform thickness along the web and possess the required AR properties).

TITLE: Final Report. May 1980 to January 1983. Development of an All-Metal Thick-Film, Cost-Effective Metallization System for Solar Cells
AUTHOR: B. Ross and J. Parker

CORPORATE AUTH: Bernd Ross Associates
DATE: December 1983
REPORT NO: DOE-JPL 955688-82/10
AVAILABILITY: NTIS, PC A07/MF A01

ABSTRACT: Properties of copper pastes did not reproduce earlier results in rheology and metallurgy. Electrodes made with pastes were analyzed and raw material characteristics were compared. A needle-like structure was observed on electroded solar cells, and was identified as eutectic copper-Si by electron probe x-ray spectroscopy. To improve performance characteristics, experiments were conducted with variations in paste parameters, firing conditions, including gas ambients, furnace furniture, Si surface, etc. A liquid medium, intended to provide transport during the carbon-fluoride decomposition, was incorporated in the paste. It resulted in better adhesion and survival of the preliminary environmental test. Solar cells (2 x 2 cm) were made with fluorocarbon-activated copper electrodes and gave 7% AM1 efficiency (without AR coating). A cooperative experiment was initiated with State University of New York, Albany, New York, on the effect of heat-treatments in various atmospheres on the hydrogen profile of Si surfaces. Contact theory was explored to determine the role of various parameters on tunneling and contact resistance. In a further experiment, copper pastes with different AgF additions were utilized as front contacts at two temperatures. An experiment was run with carbon monoxide gas used as the reducing ambient during firing.

TITLE: Final Report. December 15, 1982 to December 1, 1983. Evaluation of the Ion Implantation Process for Production of Solar Cells From Si Sheet Materials
CORPORATE AUTH: Spire Corp.
DATE: December 1983
REPORT NO: DOE-JPL 956381-84/1

ABSTRACT: This report describes research on the evaluation of the ion implantation process for junction formation in present-day sheet materials, including Cz, edge defined film-fed growth, heat exchanger method, Semix, SILSO and dendritic web. Both furnace annealing and low temperature PEBA are examined and the presence of temperature effects is identified. It is shown that efficiency can be increased by optimization of the thermal processing. A comparison of ion implantation to alternative processes is made. The manner in which high efficiency may be achieved with each of these materials is discussed.

TITLE: Final Report. Development and Fabrication of a Solar Cell Junction Processing System
CORPORATE AUTH: Spire Corp.
DATE: June 1984
REPORT NO: DOE-JPL 955640-84/10
AVAILABILITY: NTIS, PC A07/MF A01; 1.

ABSTRACT: A program was undertaken to develop, construct and deliver to JPL a processing system capable of producing solar cell junctions by ion implantation followed by PEBA. The machine was to be capable of processing 4-inch diameter single-crystal wafers at a rate of 10^7 wafers per year. A microcomputer-controlled PEBA annealer with a vacuum interlocked wafer transport system was designed, built and demonstrated to produce solar cell junctions on 4-in. wafers with an AM1 efficiency of 12%. Experiments showed that a NMA ion beam could implant 10 keV phosphorus dopant to form solar cell junctions which were equivalent to mass analyzed implants. A NMA ion implanter, compatible with the PEBA and wafer transport system was designed in detail but was not built because of program termination.

TITLE: Final Report. Process Research on Polycrystalline Si Material
AUTHOR: J.S. Culik
CORPORATE AUTH: Solarex Corp.
DATE: June 20, 1984
REPORT NO: DOE-JPL 955902-83/11
AVAILABILITY: NTIS, PC A03/MF A01; 1.

ABSTRACT: The performance-limiting mechanisms in large-grain (greater than 1 to 2 mm in diameter) polycrystalline Si solar cells were investigated by fabricating a matrix of $4cm^2$ solar cells of various thicknesses from 10 cm x 10 cm polycrystalline Si wafers of several bulk resistivities. Further investigation of the performance-limiting mechanisms consisted of fabricating a set of "mini-cell" wafers from a selection of 10 cm x 10 cm polycrystalline Si wafers. Measurement of the dark I-V characteristics of mini-cells from several wafers with few inclusions indicates that spatial variations in quasi-neutral recombination current are the dominant cause of open-circuit voltage variations. A damage gettering heat-treatment was investigated and was found to improve the minority-carrier diffusion length in low-lifetime polycrystalline Si.

TITLE: Final Technical Report. Process Research of Polycrystalline Si Material
AUTHOR: J.S. Culik and C.Y. Wrigley
CORPORATE AUTH: Solarex Corp.
DATE: February 7, 1985
REPORT NO: DOE-JPL 956698-84/4

ABSTRACT: Recent reported results of hydrogen-passivated polycrystalline Si solar cells are summarized. Most of the studies have been performed on very small grain or short minority-carrier diffusion length Si. Hydrogenated solar cells fabricated from this material appear to have effective minority-carrier diffusion lengths that are still not very long, as shown by the open-circuit voltages of passivated cells. The open-circuit voltages are still significantly less than those of single crystal solar cells. The goal of this program was to minimize variations in open-circuit voltage and fill factor caused by defects by passivating these defects using a hydrogenation process.

TITLE: Final Report. Development of Metallization Process
AUTHOR: A. Garcia, III
CORPORATE AUTH: Spectrolab, Inc.
DATE: April 1985
REPORT NO: DOE-JPL 956205-85/9
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: The object of this contract was the optimization, evaluation, and demonstration of a novel metallization applied by a screen printing process. Based on previous results of JPL contract No. 955725 "High Resolution, Low Cost Solar Cell Contact Development," a paste consisting of molybdenum, tin, and titanium hydride was selected as the promising composition. No satisfactory cells were made using any of the molybdenum/tin pastes used as a complete replacement for conventional silver pastes. The major problem is the inability to form a bond between the pastes and Si that withstands soldering. This problem can be overcome using a two-step process where any interconnection to the cell is done at small pads of conventional screen-printed silver. The most promising use of the molybdenum/tin metallization system would be this two-step process with a silver paste serving as the soldering pad. The Mo/Sn system would compete with silver economically if silver prices rose and could serve as a backup process. Toward the end of this contract the use of a heated stage SEM with reactive gases was a great help in elucidating problems and suggesting solutions.

TITLE: Final Technical Report. January 1 to March 31, 1986. MOD Silver Metallization for PV
AUTHOR: R.W. Vest
CORPORATE AUTH: Purdue Research Foundation
DATE: April 23, 1985
REPORT NO: DOE-JPL 956679-86/1

ABSTRACT: After completing the printing studies of the last quarter, it was determined that high contact resistance was the major limiting factor in producing high efficiency solar cells. Further tests were conducted which confirmed this conclusion, and also demonstrated

that high quality cells can be produced using silver MOD inks printed with this ink jet system if the contact resistance can be reduced to acceptable levels. Other experiments were conducted: (1) to study the effects of the thermal processes (belt furnace firing and box furnace spiking) and furnace atmospheres on the solar cells; (2) to find a material that could improve the contact resistance between the silver conductor layer and the solar cell substrate; and (3) to determine if the previous multiple printing and firing method of making solar cells gave consistent results.

TITLE: Final Report. Demonstration of Feasibility of Depositing Semiconductor Layers Using Microwave Enhanced Plasma Techniques
CORPORATE AUTH: Superwave Technology, Inc.
DATE: May 21, 1985
REPORT NO: DOE-JPL 956828/3

ABSTRACT: Manufacturing of low-cost, more-efficient PV cells depends partly on the development of new process technologies, one of which is the deposition of thin films at relatively low substrate temperatures. Superwave Technology, in an effort to demonstrate the feasibility of microwave-enhanced plasma as a means of producing better quality films, has successfully developed a simple but versatile system with features including: (1) Separation of plasma region from the reaction region; (2) Substrate temperature < 250°C; (3) Deposition rates >500Å/min;
(4) Sputter (gas/solid phase) and plasma (gas/gas phase) reaction; (5) Efficient use of constituent gases; and (6) Efficient conversions of microwave energy to gas plasma. The microwave-enhanced plasma system developed under the present contract has the capability of depositing various films of different compositions. This effect was directed towards deposition of Si nitride film through a gas-phase plasma reaction.

TITLE: Final Report. Excimer Laser Annealing to Fabricate Low Cost Solar Cells
AUTHOR: A.C. Greenwald
CORPORATE AUTH: Spire Corp.
DATE: August 1985
REPORT NO: DOE-JPL 956797-85/01

ABSTRACT: The objective of this program is to show the feasibility of using excimer lasers for cost-effective annealing of ion-implanted emitters in the fabrication of Si solar cells. The maximum AM1 efficiency achieved by the PELA process for n^+pp^+ cells was 15.6% for a 2 cm x 2 cm cell with photolithographically-patterned contacts. The maximum AM1 efficiency achieved by this PELA process for 100 mm diameter cells with screen-printed contacts was 12%. These results are comparable with both diffused junction cells, and cells fabricated by ion-implantation and conventional furnace annealing. The costs of furnace and laser annealing are comparable. For the production levels considered in this work, however, the cost of the ion implantation and laser anneal process is greater than the cost of diffusion.

TITLE: Annual Report. December 13, 1974 through September 30, 1985. Laser-Assisted Solar Cell Metallization Processing
AUTHOR: A. Rohatgi, P. McMullin, T. O'Keefe
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: January 6, 1986
REPORT NO: DOE-JPL 956615-86/2
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: In this contract, laser-assisted processing techniques for producing high quality solar cell metallization patterns are being investigated, developed, and characterized. The tasks comprising these investigations are outlined. Four new batches of solar cells were processed, in addition to several test runs on wafers, using the laser decomposition of spun-on silver neodecanoate to metallize cells. Decomposition of silver neodecanoate was carried out at different laser powers on different cells on a given wafer to determine whether this would have any effect on cell performance. A 1 W laser power gave an electroplated linewidth of 50 µm, while at 8 W the line width was 90 µm.

TITLE: Eighth Quarterly Progress Report. January 1 to March 31, 1986. Development of High-Efficiency Solar Cells on Si Web
AUTHOR: D.L. Meier, et al.
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: May 12, 1986
REPORT NO: DOE-JPL 956786-86/2

ABSTRACT: The major objective of this contract is to improve web base material with a goal of obtaining solar cell efficiencies in excess of 18% (AM1). Efforts in this program are directed toward identifying carrier loss mechanisms in web Si, eliminating or reducing these mechanisms, designing a high-efficiency cell structure with the aid of numerical models, and fabricating high-efficiency web solar cells. Fabrication techniques must preserve or enhance carrier lifetime in the bulk of the cell and minimize recombination of carriers at the external surfaces. During this reporting period, three completed cells were viewed by cross-sectional TEM in order to investigate further relation between structural defects and electrical performance of web cells. Consistent with past TEM examinations, the cell with the highest efficiency (15.0%) had no dislocations but did have 11 twin planes. Of the remaining two cells, one was made from a section near the beginning of a crystal and the other was made from a section near the end of the same crystal. The most prominent feature of this pair of cells is the location of the twin planes relative to the external surface. For the cell near the beginning of the crystal, the heavily twinned region is located approximately midway through the thickness of the web. For the cell near the end of the crystal, the heavily twinned region has moved to within a few microns of the external surface. This suggests that the termination of the crystal may have been a result of the twin planes exiting the web ribbon. In order to passivate the dislocation/precipitate structural defect that has been observed by TEM in completed web cells, hydrogen ions have been implanted into web strips. The implantation was done after boron and phosphorus diffusions, but before metallization. This is the first time that hydrogen has been implanted at this point in the processing sequence. Implanting hydrogen at this point is compatible with the overall Westinghouse process.

TITLE: Final Report. Process Research of Non-Cz Si Material
CORPORATE AUTH: Westinghouse Electric Corp.
DATE: June 1986
REPORT NO: DOE-JPL 956616-86/1

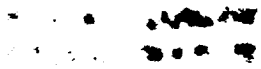
ABSTRACT: The major objectives of this program were to develop a process for simultaneously diffusing the front and back junctions into dendritic web Si to form a solar cell structure, to determine process control parameters and the sensitivity of cell parameters to variations in these control parameters, and to perform a cost analysis on the simultaneous junction formation method and compare this result to a sequential diffusion process. All of the studies mentioned above were carried out on dendritic web Si grown in the Westinghouse Pre-Pilot facility. Dendritic web is a ribbon form of single-crystal sheet material produced (grown) from a molten Si charge using a dendritic seed. The web can be grown as either n type or p type conductivity with a wide range of resistivity levels. Conductivity and resistivity levels are controlled by the dopants added to the molten Si during the growth cycle. Dendritic web is a high quality, pure, crystalline material and cells have been fabricated from web with efficiencies in excess of 15% using a standard process sequence developed by Westinghouse. The standard sequence uses a

sequential diffusion process for front and back junction formation. Thus cell data obtained in the simultaneous diffusion experiments conducted in this contract can be correlated with cells produced using the baseline sequence. The three basic techniques used to study simultaneous junction formation in dendritic web Si were: to diffuse where phosphorus- and boron-containing liquid metallo-organic precursors were applied to the appropriate sides of a strip of dendritic web Si, dried and diffused at standard temperature/time cycles in a tube-type diffusion furnace or a belt furnace; to drive the liquid dopants into the web surface using an excimer laser; and to investigate for simultaneous junction formation using rapid thermal processing equipment. A cost analysis was performed on this third method for simultaneous junction formation and the results indicate greater than a 60% saving (for this step) in a large-scale automated production line.

TITLE: Final Report. Pulsed Excimer Laser Processing for Cost-Effective Solar Cells
AUTHOR: D. Wong
CORPORATE AUTH: ARCO Solar, Inc.
DATE: July 1, 1986
REPORT NO: DOE-JPL 956831-85/2

ABSTRACT: The application of excimer lasers in the fabrication of PV devices has been investigated extensively. Processes included junction formation, laser-assisted CVD metallization, and laser-assisted CVD surface passivation. Results demonstrated that implementation of junction formation by laser annealing in production is feasible because of excellent control in junction depth and quality. Both metallization and surface passivation, however, were found impractical to be considered for manufacturing at this stage.

RELIABILITY AND ENGINEERING SCIENCES
JPL - IN-HOUSE ABSTRACTS



TITLE: Solar Cell Module Performance, Environmental Test, Handling, Storage and Inspection Procedure
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 27, 1976
REPORT NO: 5101-6

ABSTRACTS: This document covers the procedures for performance evaluation, environmental testing, handling, storage and inspection of sample solar cell modules form the 40 kW procurement. The tests to be conducted are shown on Fig. 1. There are four sets of tests to be performed, each on a different set of modules, designated Sets A, B, C, and D. Set A modules will be subjected to the same environments that the contractor will perform--thermal cycling and humidity. Electrical performance measurements will be made before and after each environmental exposure. Set B will subject a different set of modules to other terrestrial environments--humidity/freezing, rain/heat, and salt fog. Set C modules will be subjected to an environment favorable to fungus growth to determine suitability for use in certain moist, tropical areas. Set D modules will undergo a field test at a local site for various time periods interrupted by performance evaluations. Set A tests, thermal cycling and humidity, will be performed in Building 144. Test flow and test durations for Set A modules are shown in Fig. 6. This document contains test procedures for only set A tests at this time. Procedures for Set B, Set C, and Set D tests will be generated in the near future.

TITLE: Solar Cell Array Design Handbook. Volume I
EDITOR: H.S. Rauschenbach
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1976
REPORT NO: JPL-SP-43-38 (VOL. 1)
AVAILABILITY: NTIS

ABSTRACT: The Solar Cell Array Design Handbook is written at a practicing engineering level and provides a comprehensive compilation of explanatory notes, design practices, analytical models, solar cell characteristics, and material properties data of interest to personnel engaged in Solar Cell Array Performance Specification, Hardware Design, Analysis, Fabrication and Test. Twelve handbook chapters discuss the following: Historical developments, the environment and its effects, solar cells, solar cell filters and covers, solar cell and other electrical interconnections, blocking and shunt diodes, substrates and deployment mechanisms, material properties, design synthesis and optimization, design analysis, procurement, production and cost aspects, evaluation and test, orbital performance, and illustrative design examples. A comprehensive index permits rapid locating of desired topics.

TITLE: Solar Cell Array Design Handbook. Volume II
EDITOR: H.S. Rauschenbach
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1976
REPORT NO: JPL-SP-43-38 (VOL. 2)
AVAILABILITY: NTIS

ABSTRACT: This volume contains detailed design data in appendix-like fashion and includes solar cell performance data, applicable unit conversion factors and physical constants, and mechanical, electrical, thermal, optical, magnetic, and outgassing material properties. Extensive references are provided.

TITLE: Cyclic-Pressure Load Developmental Testing of Solar Panels
AUTHOR: D. Moore
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1976
REPORT NO: 5101-19
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Nine solar panels of 5 different designs were subjected to a 50 lb/ft^2 uniform load which was alternately applied to the front and back sides of the panel. The loading was intended to simulate periodic recurrence of wind loading over the lifetime of a solar panel. Each of the 5 designs was subjected to at least 10,000 pressure cycles. No gross structural failures occurred. One of the designs failed regularly at the cell interconnects. Another design shorted out one or more cells upon panel flexure. Both problems are readily explained in terms of design deficiencies in the cell interconnects, and therefore appear to be easily remedied in future designs. The cyclic pressure loading apparatus developed as part of this effort performed more than 130,000 cycles to the various panels tested.

TITLE: Availability of UV Radiation Data (For Encapsulation System Design)
AUTHOR: C. Gonzalez
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1977
REPORT NO: 5101-13

ABSTRACT: The purpose of this report is to review the literature in order to determine the availability and adequacy of UV data which is required to predict the effects of solar UV radiation (less than 4000 A^{o} magnitude and spectral distribution) on terrestrial solar cell encapsulants. In addition, the characteristics of UV radiation which affect the amount reaching the Earth's surface will be considered. The parameters and relationships reviewed include: the ratio of the UV (selected bands) intensity to the total surface incident horizontal solar radiation; seasonal and diurnal UV variation; atmospheric conditions-haze, turbidity, smog, ozone; UV variation with solar altitude; UV variation with receiving plane orientation; ground reflectance; ratio of direct-to-diffuse radiation; and anisotropy of sky UV.

TITLE: Test Program on Low-Cost Connector For Solar-Array Modules
AUTHOR: A.H. Cantu
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1977
REPORT NO: 5101-20

ABSTRACT: A recently-developed low-cost electrical connector (the ITT Cannon Sure-Seal) was selected for and subjected to a qualification test series related to terrestrial solar-array applications. Ninety-four mated pairs were subjected to an environmental test program to determine whether this connector could be used in this application. The solar panel interconnect requirement for voltages in the 220-250 Vdc range appears to be adequately met by this connector. The connector was originally designed for automotive use at a 12 Vdc working voltage level. The simplicity of its design and its low cost made it an attractive candidate for this test. The connector body is made by injecting a Nitrile rubber and PVC compound into separate male and female molds. The contacts are a stamped copper-alloy tin-lead plate. The cost of a 4-contact mated-pair connector is approximately $1.25 in quantities. The results indicate that the present production configuration while performing better than expected under environmental exposure still has some problems. The Nitrile rubber, PVC compound connectors were attacked harshly by the ozone and UV environments. The EPDM connectors are not in production; however, a few samples were available for test. In general, they performed better than the Nitrile rubber PVC. The ozone and UV did not significantly affect them. The contact resistance seemed to increase more than the Nitrile rubber PVC connectors when exposed to moisture. A new configuration with a longer wire entry barrel will provide added protection. The insulation resistance of the EPDM was outstanding. EPDM connectors are not as resilient as the other connectors, as evidenced by some elongation of the wire entry holes, but this condition can be alleviated by prudent wire routing.

TITLE: Summary Results of Block I (46 kW) Module Testing
AUTHOR: J.S. Griffith and S.G. Sollock
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 1977
REPORT NO: 5101-27

ABSTRACTS: This report documents the test procedure and the results of testing the modules procured by JPL under Block I. Included are tabulations of module features and performance data, descriptions of the variety of exploratory tests, a summary of the analysis of problems and failures and a summary of conclusions and recommendations.

TITLE: Thermal Performance Testing and Analysis of PV Modules in Natural Sunlight
AUTHOR: J.W. Stultz and L.C. Wen
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 1977
REPORT NO: 5101-31

ABSTRACT: The electrical power output of PV solar cell modules is dependent upon the operating temperature of the cells, and decreases at a rate of approximately 0.5%^{o}C with increasing cell temperature. Because of this temperature sensitivity, it is important to understand the thermal characteristics of modules so that modules and their supporting structures can be designed to reduce cell temperature to the extent that it is cost-effective. An understanding of module operating temperature characteristics is also necessary to allow accurate prediction of module power output under field operating conditions, and to allow accurate comparison of the field electrical performance of alternate module designs. The activity described in this report was conducted throughout 1976 as a part of the Engineering Area of the JPL LSSA Project. At the start of the investigation, available data was limited on several key parameters necessary to design, predict, and compare the thermal-electrical performance of terrestrial flat-plate solar cell modules. In particular, the thermal performance of current commercially available modules was unknown and the thermal significance of the key environmental and module thermal parameters was not well understood. As a result, a combined study was undertaken to characterize types and, simultaneously, to develop a basic understanding of the important thermal properties (environmental and module related) that could guide future module developments.

TITLE: LSSA Field Test Activity System Description
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 1977
REPORT NO: 5101-39

ABSTRACT: The purpose of this memorandum is to provide details of the current status and plans of the Field Testing Activity. An attempt has been made to incorporate into these plans the capability of being responsive to the changing needs of the Project. This has, hopefully, been accomplished by not only recognizing near-term requirements but also by providing embedded flexibility in the structure of the activity. The objectives of the Activity are to (1) obtain high quality continuous performance field data on a limited quantity of modules; (2) track module degradation to provide a base for the development of endurance projection techniques; (3) develop improved in-situ diagnostic testing tools and analytical techniques; (4) provide confirmation data for qualification testing, and (5) provide real-time/real-weather facilities for general Project use.

TITLE: Humidity and Temperature Cycling Tests of Spectrolab Solar Cells
AUTHOR: J.S. Griffith
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1977
REPORT NO: 5101-42

ABSTRACTS: Seventy-two new Spectrolab evaporated contact solar cells and eight older Process A printed contact cells were tested at JPL to determine if the former would be a suitable replacement for the older type in production solar modules. Cells were divided into three lots: one lot received humidity exposure, the second lot humidity and temperature cycling, and the third lot was held out for control. Results indicate that the newer evaporated contact cells are much superior to the older cells based on electrical tests and mechanical tab pull tests. Pull tests of soldered tabs on the contacts were inconclusive. This can be attributed in the case of the evaporated contacts to difficulties in soldering tabs to the cells.

TITLE: User Handbook for Block II Si Solar Cell Modules
AUTHOR: M.I. Smokler
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1977
REPORT NO: 5101-36

ABSTRACT: The program of the LSSA Project includes a series of competitive procurements of production quantities of solar cell modules. The objectives of this procurement effort are to stimulate reduction in manufacturing cost and to provide modules for test of solar cell arrays in practical applications. The first in this series of procurements, designated Block I, included the purchase from five contractors of a quantity of modules having a total nominal power output of about 58 kW. These Modules were procured to the contractor's specifications as a means of ascertaining the state of the art of terrestrial solar cell modules and of providing modules for early test and applications programs. Block II, the second in the series of procurements, involved purchase of 123 kW of total power capacity from four contractors. Block II introduced a degree of standardization by defining the module design specifications and by providing for a design qualification test program. The purpose of this User Handbook is to supply engineering data necessary for planning or investigating application programs utilizing the Block II modules.

TITLE: Module Efficiency Definitions, Characteristics and Examples
AUTHOR: R. Grippi
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1977
REPORT NO: 5101-43

ABSTRACT: With the current trend toward lower module dollar-per-watt cost, present system studies are placing greater emphasis on module efficiency since area-related costs become a greater portion of the system costs. The increased emphasis on module efficiency provides the need for establishing a standard method for specifying, comparing and discussing module efficiency. This report presents the definition of module efficiency and discusses the factors that comprise module efficiency. In addition, numerous examples of module efficiency factors are presented and discussed based on existing JPL large scale procurements and research and development modules. Conclusions are drawn as to the maximum module efficiency possible with current technology.

TITLE: Environmental Hail Model For Assessing Risk to Solar Collectors
EDITOR: C. Gonzalez
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 1977
REPORT NO: N-78-26541, and 5101-45
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The probability of solar arrays being struck by hailstones of various sizes as a function of geographic location and service life was assessed. The study complements parallel studies of solar array sensitivity to hail damage, the final objective being an estimate of the most cost effective level for solar array hail protection.

TITLE: Interface Management Plan for Block III Solar Cell Modules in Field Test and Applications
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 2, 1977
REPORT NO: 5101-48

ABSTRACTS: This plan is intended to provide clarification for the user regarding responsibilities and interfaces of JPL and Block III module users. The provisions herein apply to modules procured by JPL for DOE during 1978 in the following quantities, hereafter referred to as Block III. The Block III procurement supports the project objective to increase manufacturing capacity and reduce the price of solar cell modules and to provide modules for test and application projects sponsored by DOE.

TITLE: Measurement of Solar and Simulator UV Spectral Irradiance
AUTHOR: R.S. Estey
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1978
REPORT NO: 5101-58

ABSTRACT: This report presents in summary form the intensity and spectral characteristics of the sun and various engineering sources of radiation relevant to the operation and testing of PV cell arrays and presents a description of the characteristics and operation of a spectroradiometer system developed to measure and document the radiation from the source of interest. Sun and other source measurements support durability studies of external surfaces exposed to sun and weather. These studies are a part of the LSSA program to develop low cost and long life solar cells. This report discusses the characteristics of sun and sky radiation, the UV from the solar simulators, the details of the UV spectroradiometer system and field measurements.

TITLE: PV Module Design, Qualification, and Testing Specification
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1978
REPORT NO: DOE-JPL 1012-78/7A, and 5101-65
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: This specification establishes minimum design, qualification and acceptance requirements for terrestrial solar cell modules suitable for incorporation in PV array applications in the 20 kW to 500 kW range, such as defined by DOE PRDA EM-D-04-0038. Both mandatory and recommended requirement levels for selected performance criteria have been specified for modules within these arrays. As applicable, the manufacturer/contractor shall be responsible for generation and selection of appropriate design or test levels within the scope of these criteria. Specification of any additional requirements as necessary to satisfy the particular array or system application shall be the responsibility of the manufacturer/contractor. Environmental requirements imposed by this specification are considered to be the minimum level acceptable to DOE. Test procedures are detailed.

TITLE: Thermal and Other Tests of PV Modules Performed in Natural Sunlight
AUTHOR: J.W. Stultz
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 1978
REPORT NO: DOE-JPL 1012-78/9, and 5101-76
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The electrical power output of PV solar cell modules is dependent upon the operating temperature of the cells, and decreases at a rate of approximately 0.5% per ^{o}C with increasing cell temperature. Because of this temperature sensitivity, it is important to understand the thermal characteristics of modules so that modules and their supporting structures can be designed to reduce cell temperature to the extent that it is cost-effective. An understanding of module operating temperature characteristics is also necessary to allow accurate prediction of module power output under field operating conditions, and to allow accurate comparison of the field electrical performance of different module designs. The activity described in this report was conducted throughout 1977 and during the first half of 1978, as a part of the Engineering Area of the JPL LSA Project. This report is a follow-up of the first thermal report (5101-31) and covers all the thermal activity in this interim period. The bulk of the testing has been the characterization of twenty-nine modules according to their NOCT and the effect on NOCT of changes in module design, various residential roof mounting configurations, and dirt accumulation. Other tests, often performed parallel with the NOCT measurements, evaluated the improvement in electrical performance by cooling the modules with water and by channeling the waste heat into a phase change material (wax). Electrical degradation resulting from the natural marriage of PV and solar water heating modules was also demonstrated. Cost effectiveness of each of these techniques are evaluated in light of the LSA cost goal of $0.50 per watt.

TITLE: Field Test Annual Report, August 1977-August 1978
EDITOR: P. Jaffe
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 15 September 1978
REPORT NO: DOE-JPL 1012-78/12, and 5101-85
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: The JPL life testing program for solar cell arrays is described. The testing sites include one at JPL, one at Table Mountain in the San Bernardino Mountains, one in the desert at Goldstone near Barstow, California, and one at the Coast Guard facility at Point Vincente on the Palos Verdes Peninsula. The test stands and data acquisition systems are described, and test results are presented and discussed.

TITLE: PV Solar Panel Resistance to Simulated Hail
EDITOR: D. Moore and A. Wilson
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1978
REPORT NO: DOE-JPL 1012-78/6, and 5101-62
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: As part of the JPL's LSA Project, test methods have been evaluated and procedures developed for testing PV flat-plate solar cell modules for resistance to impact by hailstones. Testing has included the use of simulated hailstones (frozen ice spheres projected at terminal velocity), steel balls, and other projectile types applied with three loading methods: Pneumatic gun, gravity drop, and static loading. Results are presented that compare the advantages and disadvantages of the three test methods. The critical failure mechanism of each module type is explored and means for improving the hail resistance of future modules are described.

TITLE: Bias-Humidity Testing of Solar Cell Modules
AUTHOR: A.R. Hoffman and E.L. Miller
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1978
REPORT NO: DOE-JPL 1012-78/11, and 5101-84
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Humidity-related degradation of solar cells and modules is well known from both space and terrestrial experience. Current humidity cycling tests being applied to flat plate modules (References 1, 2) are "survival" tests, i.e., the modules are not operating -- no illumination, no voltage, terminals short-circuited. A standard environmental test in the semiconductor industry is to subject devices to 85^{o}C, 85% relative humidity while imposing a voltage bias across the device (Reference 3). A TV manufacturer in Japan found a positive correlation between MTBF from an accelerated life test (TV set operat-

ing) at high temperature and high humidity and MTBF from field conditions (Reference 4). The results indicated that for each hour of operation at 35°C and 95% relative humidity, the manufacturer expected about 16.8 hours of operation under field conditions. Also, experienced people at JPL noted that with an applied voltage-humidity combination using a ground plane the resulting electrolysis would accelerate the deterioration of the insulating material. Furthermore, if a voltage gradient from cell to cell were applied, metal migration may be accelerated. For these reasons, the feasibility and value for solar cell modules of a humidity test combined with a voltage bias was an appropriate subject for research and development. The objectives of the bias-humidity efforts were: to develop testing procedures combining voltage biasing with a humidity cycle for the purpose of accelerating failure mechanisms which may occur in long term field use, to define the bias-humidity tolerance of current PV module designs, to define design changes associated with improving bias-humidity tolerance, and to determine value of bias-humidity testing as a mandatory qualification test. This report describes the results associated with these efforts.

TITLE: Quality System Requirements for Flat-Plage Solar PV Systems: General Specification
AUTHOR: G. Inskeep, and K. Anhalt
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 23, 1978
REPORT NO: 5101-97

ABSTRACT: This specification covers the quality system requirements for flat-plage solar PV systems. It includes a definitive outline of quality-oriented activities to be pursued by the contractor to assure the physical and operational quality of delivered hardware. To the greatest extent possible, the contractor's existing quality and inspection programs shall be used to minimize changes to an acceptable operating quality systems.

TITLE: Block IV Solar Cell Module Design and Test Specification for Intermediate Load Center Applications
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1978
REPORT NO: DOE-JPL 1012-78/10, and 5101-16, Rev. A
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: This document establishes requirements for performance of terrestrial solar cell modules intended for use in various test applications typically characterized as intermediate load centers. During the 1979-80 time period, such applications are expected to be in the 20 kW to 500 kW size range. In general, modules satisfying these requirements will have the following design features and characteristics: (1) 15.0 Vdc nominal operating voltage; (2) ability to be series connected to operating voltages of 500 Vdc, (3) Nominal length of 1.2 m; (4) Width from 0.2 m to 1.2 m in 20 mm increments; (5) output power rated at the Standard Operating Conditions; (6) Flat plate configuration (non-concentrating). In addition to module design and performance requirements, a series of characterization and qualification tests necessary to certify the module design for production, and the necessary performance tests for acceptance of modules are also specified.

Applicable Documents

The following documentation is applicable to the extent specified:

1. Military: MIL-STD-810 C, Environmental Test Methods, March 10, 1975
2. Energy Research and Development Administration: TM 73702, ERDA/NASA/1022-77/16 "Terrestrial PV Measurement Procedures," June 1977, Lewis Research Center, Cleveland, Ohio, 44135.

TITLE: Block IV Solar Cell Module Design and Test Specification for Residential Applications
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1978
REPORT NO: DOE-JPL 1012-78/14, and 5101-83
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: This specification provides near-term design, qualification and acceptance requirements for terrestrial solar cell modules suitable for incorporation in PV power sources (2 kW to 10 kW) applied to single family residential installations. Requirement levels and recommended design limits for selected performance criteria have been specified for modules intended principally for rooftop installations. Modules satisfying the requirements of this specification fall into one of two categories, residential panel or residential shingle, both meeting general performance requirements plus additional category peculiar constraints.

TITLE: Acceptance/Rejection Criteria for JPL/LSA Modules
AUTHOR: W.E. Bishop and K.J. Anhalt
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 3, 1978
REPORT NO: 5101-21, Rev B.

ABSTRACT: The objective of this document is to establish the basis for the workmanship inspection criteria which are to be written and made a part of the Inspection System Plan used in the production of solar cell modules procured for the JPL LSA Project. The criteria, terminology, and illustrations are derived from the details of specific module designs. It is understood that the criteria presented herein may not be applicable to certain module designs, and that other module designs will contain features which require criteria not presented in this document, but which must be included in the operational Inspection System Plan.

TITLE: Solar Cell Module Problem/Failure Reporting Procedure
AUTHOR: Operations Area
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1979
REPORT NO: 5101-26, Rev. A

ABSTRACTS: The problem/failure reporting system is described, and detailed instructions are provided for the initiation, review and closeout of Problem/Failure Reports (P/FRs).

TITLE: Environmental Testing of Block II Solar Cell Modules
EDITOR: J.S. Griffith
CORPORATE AUTHOR: Jet Propulsion Laboratory
DATE: January 1, 1979
REPORT NO: DOE-JPL 1012-79/1, and 5101-98
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: The results of environmental tests of Block II solar modules are described. Block II was the second large scale procurement of Si solar cell modules made by the JPL LSA Project with deliveries in 1977 and early 1978. The results of testing showed that the Block II modules were greatly improved over Block I modules. In several cases it was shown that design improvements were needed to reduce environmental test degradation. These improvements were incorporated during this production run.

TITLE: User Handbook for Block III Si Solar Cell Modules
AUTHOR: M.I. Smokler
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1979
REPORT NO: DOE/JPL-1012-79/6, and 5101-82

ABSTRACT: The LSA Project has included a series of competitive procurements of production quantities of solar cell modules. The objectives of this procurement effort were to stimulate reduction in manufacturing cost and to provide modules for test of solar cell arrays in practical applications. The first in this series of procurements, designated Block I, included the purchase from five contractors of a quantity of modules having a total nominal power output of approximately 58 kW. These modules were procured to the contractors' specifications as a means of ascertaining the state-or-the-art of terrestrial solar cell modules and of providing modules for early test and applications programs. Block II, the second in the series of procurements, involved purchase of 123 kW of total power capacity from four contractors. Block II introduced a degree of standardization by defining the module design specifications and by providing for a design qualification test program. The Block II modules are described in JPL document 5101-36, "User Handbook for Block II Silicon Solar Cell Modules." Block III, the third in the series, consisted of procurement of a nominal 205 kW of total power capacity from five contractors. The design specifications were essentially the same as for Block II. As no design or development was permitted under the contracts, only designs which previously had been qualified by JPL were eligible for Block III contracts.

TITLE: Module Performance Assessment: Laboratory and Field Environment
AUTHOR: P. Tsou and D. Schwartz
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1979
REPORT NO: DOE-JPL 1012-23, and 5101-96

ABSTRACT: This report examines several methods that can be used to assess the performance of solar modules in a terrestrial environment. The report presents results that are derived from extensive laboratory and field measurements on four Solarex Energizer modules. The major thrusts of this study are 1) an analysis of the I-V curve translation model that is currently being used to correct field and laboratory measurements for temperature and solar insolation variations, and 2) a characterization of module performance parameters as functions of solar insolation and temperature. Applications of the above techniques to the assessment of performance degradation due to dust in the field environment are reported.

TITLE: The Zero Depth Concentrator Phenomenon
AUTHOR: J.G. Mark and C.H. Volk
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 6, 1979
REPORT NO: 5101-136

ABSTRACT: The zero depth concentrator phenomenon, discovered by the General Electric Co., refers to the enhancement of the solar cell electrical output due to internally reflected light from the white background of a glass covered solar cell array. We have undertaken to describe this enhancement effect in terms of a series of basic models which yield an intuitive understanding of the mechanisms and allow trade-off considerations of some design parameters.

TITLE: Environmental Testing of Block III Solar Cell Modules. Part I: Qualification Testing of Standard Production Modules
AUTHOR: J.S. Griffith
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1979
REPORT NO: DOE-JPL 1012-30, JPL Pub. 79-96, 5101-134
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: This report describes the results of qualification tests of Block III solar modules. Block III was the third large-scale procurement of Si solar cell modules made by the JPL LSA Project; the qualification modules were delivered in 1978. Block III modules continue to show improvements over Block I and Block II modules. Cell cracking and delamination are less prevalent, and interconnect problems and electrical degradation from environmental testing are now rare.

TITLE: Field Test Annual Report August 1978-August 1979
AUTHOR: P. Jaffe
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 1979
REPORT NO: DOE-JPL 1012-38, JPL Pub. 80-5, 5101-141
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: In the course of three years of testing no evidence has resulted to suggest that the twenty-year-life goal for PV modules will not be met. Results of studies of more than 600 modules under test show that they are generally enduring well both electrically and physically, particularly those from more recent procurements. Degradation tests performed at JPL indicate that electrical degradation is not a slow monotonically increasing phenomenon as originally thought but occurs abruptly as the result of some traumatic event. This finding has led to a change in the test philosophy. The report includes a discussion of this change, a summary of degradation and failure data from all the sites, results from a variety of special tests, and a description of new instrumentation for in field measurements. The field testing activity was expanded by the addition of twelve remote sites located as for away as Alaska and the Canal Zone. A description of the new sites is also included.

TITLE: 1982 Technical Readiness Module Design and Test Specification - Intermediate Load Applications
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1980
REPORT NO: DOE-JPL 1012-36, and 5101-138
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: This document establishes the requirements for the design and test of terrestrial solar cell modules for one phase of DOE's LSA Project. Modules designed to meet this specification are intended to show that technology needed to meet the overall project goals for 1986 can be demonstrated in 1982 for intermediate load applications.

TITLE: Proposed Method for Determining the Thickness of Glass in Solar Collector Panels
AUTHOR: D.M. Moore
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1980
REPORT NO: DOE-JPL 1012-41, JPL Pub. 80-34, 5101-148
AVAILABILITY: NTIS, HC A04/MF A01

ABSTRACT: As part of the JPL's LSA Project, an analytical method has been developed for determining the minimum thickness for simply supported, rectangular glass plates subjected to uniform normal pressure environmental loads such as wind, earthquake, snow, and deadweight. The method consists of comparing an analytical prediction of the stress in the glass panel to a glass breakage stress determined from fracture mechanics considerations. Based on extensive analysis using the nonlinear finite element structural analysis program ARGUS, design curves for the structural analysis of simply supported rectangular plates have been developed. These curves yield the center deflection, center stress and corner stress as a function of a dimensionless parameter describing the load intensity. Results are included for plates having length-to-width ratios of 1, 1.5, 2, 3 and 4. The load range considered extends to 1000 times the load at which the behavior of the plate becomes significantly nonlinear. Over the load range analyzed, the analysis shows that the ratio of center deflection to plate thickness for a plate of length-to-width ratio of 4 is less than 70 to 1, whereas linear theory would predict a center deflection about 1200 times the plate thickness. The stress is also markedly lower

than would be predicted by linear theory. These analytical results show good agreement with the analytical and experimental work of others. A method of estimating the glass breakage stress as a function of a specified failure rate, degree of glass temper, design life, load duration time, and panel size is presented. Development of this method consisted largely of collecting and/or adapting, in convenient form, the best available information from the literature. To establish the glass breakage stress versus probability of failure, the experimental data of other investigators has been reanalyzed to obtain a "best-fit" Weibull statistical distribution. This state-of-the-art analysis yields the glass breakage strength as a function of failure probability.

TITLE: Insolation at Goldstone - 1976
AUTHOR: R.S. Estey
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 1980
REPORT NO: 5101-153

ABSTRACT: Radiometer data for 1976 have been extracted from ongoing measurements made at the Goldstone Tracking Station and are presented in Tables and Graphs displaying values of direct and global solar energy.

TITLE: Flat-Plate PV Module and Array Circuit Design Optimization Workshop Proceedings
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 1980
REPORT NO: 5101-170

ABSTRACT: This document contains the proceedings of the Flat-Plate PV Module and Array Circuit design Optimization Workshop held at JPL during May of 1980. The workshop was held to discuss the problem of optimizing terrestrial PV array cell and circuit reliability and the methods of resolving this problem. The objective of the workshop was to investigate the effectiveness of certain circuit-design strategies in ameliorating the effects of faults on module and array-system performance. A set of guidelines was presented for use in developing module and array-system circuit design strategies that maximize reliability through use of fault-tolerant circuiting. For simplicity, the open-circuit cell interconnect failure mode was emphasized in the workshop. Cost and efficiency values presented in the proceedings are values accepted at the time of the workshop. All costs are in 1975 dollars.

TITLE: PV Module Soiling Studies May 1978 to October 1980
AUTHOR: A.R. Hoffman, and C.R. Maag
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1980
REPORT NO: DOE-JPL 1012-49, JPL Pub. 80-87, 5101-131
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The retention of particulate contamination on the surface of flat-plate PV devices is adversely affecting electrical performance of outdoor-exposed modules. This report describes the results of an experimental study being performed by the JPL's LSA Project to characterize and understand the effects of outdoor contaminants on sensitive optical surfaces of flat-plate PV modules and cover materials. Comparative electrical and optical performance data from PV modules and materials subjected to outdoor exposure at field test sites throughout the United States have been collected and examined. The results show significant time- and site-dependence. During periods when natural removal processes do not dominate, the rate of particulate contamination accumulation appears to be largely material-dependent. Glass and acrylic top-cover materials retain fewer particles than silicone rubber does. Side-by-side outdoor exposure testing for long duration is presently the most effective means of evaluating soiling differences between materials. Changes in spectral transmission as a function of time and location and limited scattering data are presented.

TITLE: Determining Terrestrial Solar Cell Reliability. Proceeding of Workshop
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1980
REPORT NO: 5101-163

ABSTRACTS: This document is an outgrowth of a workshop on "Determining Terrestrial Solar Cell Reliability," which was held May 1-2, 1980, at Clemson University, Clemson, South Carolina. The workshop was organized jointly by JPL and Clemson University, and was sponsored by the LSA Project. The purpose of the workshop was the critical review of Si solar cell test results from a reliability testing program being carried out by Clemson University. Since 1977 Clemson has conducted experimental reliability investigations on more than 1000 unencapsulated solar cells procured from seven PV industry manufacturers. A total of 33 persons attended the workshop, representing fourteen organizations including private industry, national laboratories, and universities. This group of basic scientists, design engineers, and personnel involved in quality assurance and module/array field reliability participated actively in two days of workshop activities which included technical sessions, a tour of the test facilities, review of reliability test methods for solar cells, critique of test results, and moderated discussion sessions. The workshop provided a forum for productive discussion of various aspects of solar cell reliability by a broad spectrum of PV industry personnel. Much valuable information was exchanged, and recommendations were made regarding the validity of reliability data obtained to date and the direction in which future work should be channeled. Included are reproductions of graphic presentation materials and highlights of discussions related to solar cell reliability test methods.

TITLE: Field Test Annual Report August 1979 August 1980
AUTHOR: P. Jaffe
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 1980
REPORT NO: DOE-JPL 1012-52, JPL Pub. 81-21, 5101-166
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: After almost four years of endurance testing of PV modules, no fundamental life-limiting mechanisms have been identified that could prevent the twenty-year life goal from being met. The endurance data show a continual decline in the failure rate with each new large-scale procurement. Cracked cells and broken interconnects continue to be the principal causes of failure. Although the modules are more adversely affected physically by hot, humid environments than by cool or dry environments, there are insufficient data to correlate failures with environment. There is little connection between the outward physical condition of a module and changes in its electrical performance. Electrical degradation is a transient condition that is generally intermittent and is present before a module destined to fail finally fails. Analysis of year-long electrical performance data indicates that the fill factor is insensitive to most measurement problems and remains the best diagnostic tool for determining module degradation. Investigations at the JPL site reveal that shadowing the indirect component of irradiance can reduce the electrical output of modules and result in anomalous performance data. Extrapolating this result to arrays suggests that a loss of power can result if indirect shadowing is not considered in the array layout. The introduction of the Portable I-V Data Logger was a success. About 1200 high quality I-V curves were obtained during a tour of the 15 remote sites. Next year a major reorganization in the inventory of test modules is planned. A significant portion of the older modules will be removed and replaced with modules from the upcoming Block IV large scale procurement.

TITLE: The Correction for Spectral Mismatch Effects on the Calibration of a Solar Cell When Using a Solar Simulator
AUTHOR: C.H. Seaman
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1981
REPORT NO: DOE-JPL 1012-50, and 5101-169

ABSTRACT: A general expression has been derived to enable calculation of the calibration error resulting from simulator-solar AMX spectral mismatch and from reference cell-test cell spectral mismatch. The information required includes the relative spectral response of the reference cell, the relative spectral response of the cell under test, and the relative spectral irradiance of the simulator (over the spectral range defined by cell response). The spectral irradiance of the solar AMX is assumed to be known.

TITLE: Block V Solar Cell Module Design and Test Specification for Intermediate Load Applications 1981
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 20, 1981
REPORT NO: 5101-161
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACTS: This document establishes the requirements for the design and test of terrestrial solar cell modules for one phase of DOE's LSA Project. Intermediate-load modules designed to meet this specification will generally have the following design features and characteristics: (1) V_{no} between 5 Vdc and 20 Vdc; (2) ability to be series-connected to worst-case open-circuit voltages of 1000 Vdc; (3) Dimensions not exceeding 1.22 m x 2.44 m (4 ft x 8 ft), (4) flat-plate configuration (non-concentrating); and (5) output power referenced to NOC and V_{no}. In addition to module design and performance requirements, a series of characterization and qualification test are also specified.

TITLE: Block V Solar Cell Module Design and Test Specification for Residential Applications - 1981.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1981
REPORT NO: 5101-162

ABSTRACT: This specification provides near-term design, qualification and acceptance requirements for terrestrial solar cell modules suitable for incorporation in PV power sources (2 kW to 10kW) applied to single-family residential installations. Requirement levels and recommended design limits for selected performance criteria have been specified for modules intended principally for rooftop installations. Modules satisfying the requirements of this specification fall into one of two categories, residential panel or residential shingle, both meeting general performance requirements plus additional category peculiar constraints. Residential modules designed to meet this specification will generally have the following design features and characteristics: (1) V_{no} between 5 Vdc and 20 Vdc; (2) Ability to be series-connected to worst-case open-circuit voltages of 300 Vdc; (3) Mounting arrangement compatible with new or existing residences; (4) flat-plate configuration (non-concentrating); and (5) output power referenced to NOC and V_{no}. In addition to module design and performance requirements, a series of characterization and qualification tests are also specified.

TITLE: Interim Standard for Safety: Flat-Plate PV Modules and Panels. Volume I: Construction Requirements
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 20, 1981
REPORT NO: 5101-164, Vol. I

ABSTRACTS: Underwriters Laboratories, Inc., has conducted a study of present PV module array designs and configurations likely to be used in residential, commercial, and industrial applications. That investigation of engineering safety requirements has resulted in the development of this Interim Standard for Safety. This document, primarily written by UL, is published in two volumes. Volume I, Construction Requirements, contains safety requirements for flat-plate PV modules and panels. Volume II, Performance Requirements, contains test procedures and methods to verify compliance with the safety requirements set forth in Volume I. The purpose of this documents is to offer to the flat-plate PV community, for trial use, this Interim Standard for Safety. Volume I is intended to be used on a trial basis with the latest Block V Module Procurement Specifications for Intermediate Load and Residential Applications, 5101-161 and 5101-162, respectively. Volume II contains test methods currently defined within the above module specifications together with additional tests under consideration by UL. Volume II is not intended for immediate use, but is designed to serve as a focus for review and iteration of future tests. The results of feedback on these volumes will be submitted to UL for further refinement and ultimately for publication as a standard containing basic requirements for products covered by UL under its Follow-Up Service.

TITLE: Low-Cost Solar Array Structure Development
AUTHOR: A.H. Wilson
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1981
REPORT NO: DOE-JPL 1012-53, and 5101-165
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Early studies of flat-plate arrays have project costs on the order of $\$50/m^2$ for installed array support structures. This report describes an optimized low-cost frame-truss structure that is estimated to cost below $\$25/m^2$, including all markups, shipping and installation. The structure utilizes a planar frame made of members formed from light-gauge galvanized steel sheet and is supported in the field by treated-wood trusses that are partially buried in trenches. The buried trusses use the overburden soil to carry uplift wind loads and thus to obviate reinforced-concrete foundations. Details of the concept, including design rationale, fabrication and assembly experience, structural testing and fabrication drawings are included.

TITLE: Field Test Annual Report - August 1980-August 1981
AUTHOR: P. Jaffe, R.W. Weaver and R.H. Lee
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 1981
REPORT NO: DOE-JPL 1012-59, and 5101-197
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: A complete restructuring of FSA Project field-test activity was done during the past year; its major element was redirecting emphasis away from collecting endurance data and toward the early identification and analysis of fundamental module problems. To support this shift and to accommodate an expected reduction in resources: (1) the 12 Continental Remote Sites have been decommissioned; (2) testing has been consolidated into a five-site network consisting of the four Southern California sites and a new Florida site; (3) 16 kW of new state-of-the-art modules are being deployed at the five sites; (4) testing of the old modules is continuing at the Goldstone site but as a low-priority item; (5) the major thrust of the new emphasis- early problem detection- will be accomplished by array testing of modules at the JPL site; (6) additional new testing capabilities are being added to the JPL site, which will elevate its operations to those of a field test laboratory for the simulation and investigation of real-use problems and the development of improved testing techniques; (7) a new key instrument is being fabricated, a versatile battery-powered array data logger, which will permit in-field diagnoses of arrays as large as 40 amperes and 400 V. Restructuring is progressing on schedule. A final set of failure and

degradation data was obtained from the modules at the Southern California sites before they were relocated at Goldstone. The mean composite failure rate for all the modules (Blocks I, II and III) over the past five years is 2.0 %/yr. Considering the final two years only, the rate is 4.4 %, suggesting a significant upward trend with age.

TITLE: Interconnect Fatigue Design for Terrestrial PV Modules
AUTHOR: G.R. Mon, D.M. Moore, and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1, 1982
REPORT NO: DOE-JPL 1012-61, and 5101-173
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACTS: Fatigue of solar cell electrical interconnects due to thermal cycling has historically been a major failure mechanism in PV arrays; the results of a comprehensive investigation of interconnect fatigue that has led to the definition of useful reliability-design and life-prediction algorithms are presented. Experimental data gathered in this study indicate that the classical strain-cycle (fatigue) curve for the interconnect material is a good model of mean interconnect fatigue performance, but it fails to account for the broad statistical scatter, which is critical to reliability prediction. To fill this shortcoming the classical fatigue curve is combined with experimental cumulative interconnect failure rate data to yield statistical fatigue curves (having failure probability as a parameter) which enable (1) the prediction of cumulative interconnect failures during the design life of an array field, and (2) the unambiguous, i.e., quantitative, interpretation of data from field service qualification (accelerated thermal cycling) tests. Optimal interconnect cost-reliability design algorithms are derived based on minimizing the cost of energy over the design life of the array field. This procedure yields not only the minimum break-even cost of delivered energy, but also the required degree of interconnect redundancy and an estimate of array power degradation during the design life of the array field. The usefulness of the design algorithms is demonstrated with realistic examples of design optimization, prediction, and service qualification testing.

TITLE: An Investigation of the Effect of Wind Cooling on PV Arrays
AUTHOR: L. Wen
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1982
REPORT NO: DOE-JPL 1012-69, JPL Pub. 82-28, 5101-201
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Convective cooling of PV modules is investigated for different wind conditions, including steady-state controlled testing in a solar simulator and natural test environments in a field. Analytical thermal models of different module designs were used to correlate experimental data. The results obtained in the controlled environment confirm the applicability of existing heat-transfer correlations. The result of long-term field testing at the JPL test site is not conclusive because wind conditions were measured at different heights than of the modules. Nevertheless, reasonable agreement can be obtained by applying a power law wind profile.

TITLE: Experimental Evaluation of the Battelle Accelerated Test Design for the Solar Array at Mead, Nebraska
AUTHOR: P.O. Frickland, and J. Repar
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 6, 1982
REPORT NO: DOE-JPL 1012-73, JPL Pub. 82-52, 5101-211
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: A previously developed test design for accelerated aging of PV modules was experimentally evaluated. The studies included a review of relevant field experience, environmental chamber cycling of full-size modules, and electrical and physical evaluation of the effects of accelerated aging during and after the test. The test results indicated that thermally induced fatigue of the interconnects was the primary mode of module failure as measured by normalized power output. No chemical change in the silicone encapsulant was detectable after 360 test cycles.

TITLE: User Handbook for Block IV Si Solar Cell Modules
AUTHOR: M.I. Smokler
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1, 1982
REPORT NO: DOE-JPL 1012-75, JPL Pub. 82-73, 5101-214
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The essential electrical and mechanical characteristics of Block IV PV solar-cell modules that have been tested by JPL are described. Such module characteristics as power output, nominal operating voltage, current-voltage characteristics, nominal operating cell temperature, and dimensions are tabulated. The limits of the environmental and other stress tests to which the modules are subjected are briefly described. Potential users of modules will find this listing helpful in selecting modules for use either by themselves or in arrays.

TITLE: PV Array Power Conditioner Interface Characteristics
AUTHOR: C.C. Gonzalez, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 15, 1982
REPORT NO: DOE-JPL 1012-79, JPL Pub. 82-109, 5101-202
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The electrical output (power, current, and voltage) of flat-plate solar arrays changes constantly, due primarily to changes in cell temperature and irradiance level. As a result, array loads such as dc-to-ac power conditioners must be capable of accommodating widely varying input levels while maintaining operation at or near the maximum power point of the array. This report presents the results of an extensive computer simulation study used to define array operating characteristics and extreme output limits necessary for the systematic design of array-load interfaces under a wide variety of climatic conditions in the United States. A number of interface parameters are examined, including optimum operating voltage, voltage tracking width necessary to capture various fractions of the available energy, maximum power and current limits, and maximum open-circuit voltage. The effect of array degradation and I-V curve fill factor on the array-power conditioner interface also is discussed. Results are presented as normalized ratios of power-conditioner parameters to array parameters, making the results universally applicable to a wide variety of system sizes, sites, and operating modes.

TITLE: FSA Field Test Report 1980-1982
AUTHOR: H.G. Maxwell, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 15, 1983
REPORT NO: DOE-JPL 1012-85, JPL Pub. 83-29, 5101-215
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: PV modules made of new and developing materials were tested in a continuing study of weatherability, compatibility, and corrosion protection. Over a 2-yr period, 365 two-cell submodules have been exposed for various intervals at three outdoor sites in Southern California or subjected to laboratory acceptance tests. Results to date show little loss of maximum power output, except in two types of modules. In the first of these, failure is due to cell fracture from stresses that arise as water is regained from the surrounding air by a hardboard substrate. The latter had shrunk as it dried during its encapsulation in plastic film at 150°C *in vacuo*. In the

second type of module, the glass superstrate is sensitive to cracking, which also damages the cells electrostatically bonded to it. Inadequate bonding of interconnects to the cells is also a problem in these modules. In a third type of module, a polyurethane pottant has begun to yellow, although this discoloration is without significant effect, as yet, on maximum power output.

TITLE: Proceedings of the FSA Research Forum on The Design of Flat-Plate PV Arrays for Central Stations (December 5-8, 1983, at Sacramento, California)
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 15, 1983
REPORT NO: DOE-JPL 1012-98, JPL Pub. 84-44, 5101-247
AVAILABILITY: NTIS, PC A14/MF, A01

ABSTRACT: The FSA, managed by JPL for the DOE, has focused on advancing technologies relevant to the design and construction of megawatt-level central-station systems. PV modules and arrays for flat-plate central-station or other large-scale electric power production facilities require the establishment of a technical base that resolves design issues and results in practical and cost-effective configurations. The Central Station Research Forum addressed design, qualification and maintenance issues related to central-station arrays derived from the engineering and operating experiences of early applications and parallel laboratory research activities. Technical issues were examined from the viewpoint of the utility engineer, architect-engineer, and laboratory researcher. The forum included presentations on optimum source circuit designs, module insulation design for high system voltages, array safety, structural interface design, measurements and array operation and maintenance. The Research Forum focused on current capabilities as well as design difficulties requiring additional technological thrusts and/or continued research emphasis. Session topic summaries highlighting major points during group discussions, identifying promising technical approaches or areas of future research, are presented.

TITLE: FSA Field Test Annual Report August 1981 to January 1984
AUTHOR: R.W. Weaver, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 15, 1984
REPORT NO: DOE JPL 1012-100, JPL Pub. 84-52, 5101-254
AVAILABILITY: NTIS, PC A03/MF A01; 1

ABSTRACT: During this reporting period the restructuring plan presented in the previous annual report was modified in response to budgetary pressures. The latter part of the period was marked by further budget reductions, which required a further curtailment of the FSA's field-testing activities. The modified plan was implemented with the following accomplishments: (1) six arrays containing Block IV modules were completed at the JPL site, (2) the portable array data-logger was completed and used at both the JPL site and at several non-JPL installations, and (3) representative samples of Block I, II, and III modules were redeployed to the Goldstone site for continued endurance testing. Those portions of the plan that were modified were: (1) a reduction in the number of Block IV modules deployed, (2) a reduced data-acquisition schedule, (3) abandonment of the Table Mountain and Point Vincente sites, and (4) the carrying out of the final test procedures for only a sample of the modules from the 12 continental remote sites. The most recent endurance data are presented for the remaining Block I, II and III modules. These data indicate that more of these modules have failed or decreased in power output during this period. None of the Block IV modules under test during this period have failed, but 11 of the 155 deployed modules show reduced power output.

TITLE: User Handbook for Block V Si Solar Cell Modules
AUTHOR: M.I. Smokler
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 15, 1985
REPORT NO: DOE-JPL 1012-106, JPL Pub. 85-34, 5101-262
AVAILABILITY: NTIS, PC A03/MF A01; 1

ABSTRACT: The program of the JPL-FSA has included a series of competitive procurements, designated Block I through Block V, of various quantities of solar modules. The objectives of these procurement efforts were to stimulate reduction in the cost of PV energy by encouraging technology advances and to make modules of advanced design available for field testing and for commercial applications. The essential electrical and mechanical characteristics of Block V PV solar-cell modules are described. Such module characteristics as power output, current-voltage characteristics, nominal operating cell temperature, and dimensions are tabulated. The limits of the environmental and other stress tests to which the modules are subjected are briefly described. Potential users of modules will find this listing helpful in selecting modules and in planning module array systems.

TITLE: Reliability and Engineering of Thin-Film PV Modules: Research Forum Proceedings
AUTHOR: R.G. Ross and E.L. Royal
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1, 1985
REPORT NO: DOE-JPL 1012-111, JPL Pub. 85-73, 5101-264

ABSTRACT: A Research Forum on Reliability and Engineering of Thin-Film PV Modules, under sponsorship of JPL-FSA and DOE, was held in Washington, D.C., on March 20, 1985. Reliability-attribute investigations of a-Si cells, submodules, and modules were the subjects addressed by most of the Forum presentations. Included among the reliability research investigations reported were: Arrhenius-modeled accelerated stress tests on Si-cells, electrochemical corrosion, light-induced effects and their potential effects on stability and reliability measurement methods, laser-scribing considerations, and determination of degradation rates and mechanisms from both laboratory and outdoor exposure tests.

RELIABILITY AND ENGINEERING SCIENCES
CONTRACTOR ABSTRACTS

TITLE: Final Report. Fabrication, Test, and Delivery of 8 kW of Solar Power Modules
AUTHOR: P.A. Dennis
CORPORATE AUTH: Photowatt International, Inc. (Sensor Technology, Inc.)
DATE: October 15, 1976
REPORT NO: ERDA-JPL 954387-76/1

ABSTRACT: Through this contract, and the cooperative program resulting from the JPL-ERDA-NASA LSSA Project, Sensor Technology has produced modules at the rate of 3.5 kW/month with a power output of 83.2 W per 4' x 4' array. These modules were produced at a cost of $19.07/W. The production techniques of this program make it easily possible to expand this to the 10 to 15 kW per month range and methods were developed by which future costs may be reduced by 15 to 30%. Two inch diameter cells were used on this project, however, facilities now exist to process 3 in., 3.56 in. and 4 in. dia wafers. The module design, performance, cost factors, problem areas, efficiency, encapsulation, and humidity and temperature test results are reported.

TITLE: Final Report. Large Scale Production Task
CORPORATE AUTH: Spectrolab, Inc.
DATE: December 1976
REPORT NO: ERDA-JPL BQ649005-76/1
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: Two thousand solar power modules capable of producing over 10 kW of peak power were delivered. These modules have good structural and thermal dissipation characteristics, but difficulties were encountered with respect to delamination of the encapsulant material, low electrical breakdown resistance and humidity sensitivity. Design modifications that have been recommended to improve reliability and reduce cost, include the elimination of metal substrate, replacement of silicone with a more suitable encapsulant, larger module size and use of series-parallel circuit configurations.

TITLE: Final Technical Report. Large Scale Production Task
CORPORATE AUTH: Solarex Corp.
DATE: December 1976
REPORT NO: DOE/JPL BQ649006-76/1

ABSTRACT: Twenty production modules, representing the state of-the-art, were produced for qualification testing and for installation of the thermal cycling and temperature humidity chambers. The first 10 modules completed the required thermal cycling and program without electrical, mechanical, structural or optical degradation. After temperature humidity testing significant electrical degradation was observed. Early indications were that production error was the cause in that the silicone rubber used in those panels was not properly dehydrated. It was also learned that the freshly cured silicone rubber is quite permeable to water. To correct the problem palladium was added to the contact metallization. This completely eliminated any electrical degradation problems for the remainder of the delivery.

TITLE: Final Report. Si Solar Cells With Total Power Capacity of 30 kW
CORPORATE AUTH: Solarex Corp.
DATE: October 1977
REPORT NO: DOE-JPL 954577-77/1

ABSTRACT: There are two phases of the contract effort to design, develop, manufacture, test and deliver a quantity of solar cell modules capable of providing 30 kW of power. The first phase consists of module design, preproduction module fabrication, inspection and test. Phase two consists of production, test and delivery.

TITLE: Final Technical Report. 40 kW of Solar Cell Modules for the Large Scale Production Task
AUTHOR: G.T. Jones
CORPORATE AUTH: Photowatt International, Inc. (Sensor Technology, Inc.)
DATE: December 1977
REPORT NO: DOE-JPL 954565-77/1
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Forty kW of solar cell modules was produced in this program. This is equivalent to 4123 modules. The average power output per module was 9.7 W at 16.5 V, 60°C and 100 MW/CM^2. The peak production rate was 200 modules/wk which is equal to 1.9 kW/wk. This rate was sustained for over four and one-half months and is equivalent to 100 kW/yr. The solar cell module design, electrical and power performance, module preproduction environmental test results, production and shipping schedule, program summary, are dpresemted. A cost analysis section is written. Particular emphasis on the percentage of labor and material utilized in constructing a solar cell module is presented. Also included are cost reduction recommendations. It was concluded from this program that volume production on the order of hundreds of kW/yr/company as a minimum is required to significantly reduce the price/W for solar cell modules. Sensor Technology more than doubled its solar cell module manufacturing facilities since the completion of the JPL Block II procurement. Plans are being made for large scale expansion of our facilities to meet growing procurements.

TITLE: Final Technical Report. Terrestrial Central Station Array Life-Cycle Analysis Support Study
CORPORATE AUTH: Bechtel National, Inc.
DATE: August 1978
REPORT NO: DOE-JPL 954848-78/1
AVAILABILITY: NTIS, PC A09/MF A01

ABSTRACT: The purpose of the study was to provide input cost data in support of array-life-cycle cost analysis being conducted by JPL for utility central station PV power plant application. Primary emphasis was on the solar cell modules and arrays, with balance of-plant concepts developed only as far as necessary to determine their impact on module and array design and vice versa. Assessments were made of five alternate array configurations and the impact of parameters such as site weather, onside energy storage, system voltage, energy losses within the plant, maintenance requirements and module design. The plant design used as the baseline for this study is a 200 MW (nominal) central station PV power plant using 8 by 16 ft flat-plate Si solar panels comprised of 4' by 8' glass superstrate modules. The five alternate array design configurations evaluated were rack, tandem, horizontal, seasonally adjusted and tracking-tape arrays.

TITLE: Final Report. Module/Array Interface Study
CORPORATE AUTH: Bechtel National, Inc.
DATE: August 1978
REPORT NO: DOE-JPL 954698-78/1A
AVAILABILITY: NTIS, PC A11/MF A01

ABSTRACT: A study of alternate module, panel, and array designs for use in large scale applications such as central station PV power plants has been conducted. The objective of the study is to identify design features that will lead to minimum plant costs. Several aspects of module design are evaluated, including glass superstrate and metal substrate module configurations, the potential for hail damage, light absorption in glass superstrates, the economics of glass selection, and electrical design. Three alternate glass superstrate module configurations are evaluated by means of finite element computer analyses. Two panel sizes, 1.2 x 2.4 m and 2.4 x 4.8 m, are used to support 3 module sizes, 0.6 x 1.2 m, 1.2 x 1.2 m, and 1.2 x 2.4 m, for design loadings of about 1.7 kPa (35 psf), 2.4 kPa (50 psf), and 3.6 kPa (75 psf). Designs and cost estimates are presented for 20 panel types and 9 array configurations at each of the 3 design loadings. Structural cost sensitivities of combined array configurations and panel cases are presented.

TITLE: Final Technical Report. Large Scale Production Task
CORPORATE AUTHOR: Spectrolab, Inc.
DATE: September 1978
REPORT NO: DOE-JPL 954587-1
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Several design concepts were evaluated and compared with respect to potential for low cost and automation, protection against weathering, potential for array efficiency as a function of weight and area, potential for design flexibility and exposure to electrical breakdown or leakage to ground. This evaluation program narrowed attention to design concepts involving glass as the primary structural and weather resistant component of the module. The leading specific design structure consisted of the solar cell circuit embedded in polyvinyl butyrate by lamination between a glass front surface and a polyester film rear surface. Preliminary evaluation of this structure in high humidity and thermal cycle was promising, and extensive field experience with similar structures in architectural and automotive applications was favorable. The specific design proposed was comprised of 120 two-in. dia cells in a series-parallel configuration. The laminate was mounted in an aluminum frame with a neoprene gasket providing the requisite mechanical strength with flexibility. The resulting module size of 15 by 46 in. permits three modules to be neatly fitted into the 46 in. square subarray specified by JPL. The design as modified to accommodate subsequent experience is shown. Performance and environmental test results are presented and discussed.

TITLE: Final Report. Phase I: Feasibility Study of Solar Dome Encapsulation of PV Arrays
AUTHOR: D.K. Zimmerman
CORPORATE AUTH: The Boeing Co.
DATE: December 1978
REPORT NO: DOE-JPL 954833-78/1

ABSTRACT: This report describes a study which investigated the potential technical and economic advantages of using air-supported plastic enclosures to protect flat plate PV arrays. Conceptual designs for a fixed, latitude-tilt array and a fully tracking array were defined. Another program provided much of the design and supporting analyses for the tracking array. Detailed wind loads and strength analyses were performed for the fixed array. Detailed thermal and power output analyses provided array performance for typical seasonal and extreme temperature conditions. Costs of each design as used in a 200 MWE central power station were defined from manufacturing and material cost estimates. The capital cost and cost of energy for the enclosed fixed tilt array were lower than for the enclosed tracking array. The enclosed fixed-tilt array capital investment was 38% less, and the levelized bus bar energy cost was 26% less than costs for a conventional, glass-encapsulated array design. The predicted energy cost for the enclosed fixed array was 79 mils/kW H for direct current delivered to the power conditioning units.

TITLE: Final Report. Residential PV Module and Array Requirements Study
CORPORATE AUTH: Burt Hill Kosar Rittelmann Associates
DATE: June 1979
REPORT NO: DOE-JPL 955149-79/1
AVAILABILITY: NTIS, PC A04/MF A01
955149-1 (Appendices) NTIS, PC 24/MF A01

ABSTRACT: A study has been conducted to identify design requirements for PV modules and arrays used in residential applications. Building codes and referenced standards were reviewed for their applicability to residential PV array installations. Four installation types were identified: integral (replaces roofing), direct (mounted on top of roofing), stand off (mounted away from roofing), and rack (for flat or low slope roofs, or ground mounted). Installation costs were developed for these mounting types as a function of panel/module size. Cost drivers were identified. Studies were performed to identify optimum module shapes and sizes and operating voltage cost drivers. The general conclusion is that there are no perceived major obstacles to the use of PV modules in residential arrays. However, there is no applicable building code category for residential PV modules and arrays and early additional work is needed with standards writing organizations to develop residential module and array requirements.

TITLE: Final Report. Wind Loads on Flat Plate PV Array Fields
AUTHOR: R. Miller
CORPORATE AUTH: The Boeing Co.
DATE: September 1979
REPORT NO: DOE-JPL 954833-79/2
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: This report describes a theoretical study of the aerodynamic forces resulting from winds acting on flat plate PV arrays. Local pressure distributions and total aerodynamic forces on the arrays are shown. Design loads are presented to cover the conditions of array angles relative to the ground from 20^{o} to 60^{o}, variable array spacings, a ground clearance gap up to 1.1 m (4 ft) and array slant heights of 2.4 m (8 ft) and 4.8 m (16 ft). Several means of alleviating the wind loads on the arrays are detailed. The expected reduction of the steady state wind velocity with the use of fences as a load alleviation device are indicated to be in excess of a factor of three for some conditions. This yields steady state wind load reductions as much as a factor of ten compared to the load incurred if no fence is used to protect the arrays. This steady state wind load reduction is offset by the increase in turbulence due to the fence but still an overall load reduction of 2.5 can be realized. Other load alleviation devices suggested are the installation of air gaps in the arrays, blocking the flow under the arrays and rounding the edges of the array. Included is an outline of a wind tunnel test plan to supplement the theoretical study and to evaluate the load alleviation devices.

TITLE: Final Report. Design, Fabrication, Test, Qualification and Price Analysis of "Third Generation" Design Solar Cell Modules
AUTHOR: N F. Shepard
CORPORATE AUTH: General Electric Co.
DATE: March 1980
REPORT NO: DOE JPL 955401-80/1

ABSTRACT: This design, development, fabrication and qualification testing of a "third-generation" solar cell module for residential applications is reported. This Block IV shingle type module makes it possible to apply a PV array to the sloping roof of a residential building by simply nailing the overlapping hexagon-shaped shingles to the plywood roof sheathing. This "third generation" shingle module design consists of nineteen series connected 100 mm dia solar cells which are arranged in a closely packed hexagon configuration. The solar cells are individually bonded to the embossed underside of a 4.4 mm thick thermally tempered piece of ASG Sunadex glass. An experimental GE silicone pottant, which is identified by the number 534-044, was used as the transparent bonding adhesive between the cells and glass. The encapsulant between the underside of the glass superstrate and a rear protective sheet of Mead Pan-L board is GE Silglaze SCS 2402. The semi flexible portion of each shingle module is a composite laminate construction consisting of an outer layer of B.F. Goodrich FLEXSEAL bonded to an inner core of closed cell polyethylene foam. Uniroyal Silaprene M6338 is used as the substrate lamination adhesive. The module design has satisfactorily survived the JPL-defined qualification testing program which includes 50 thermal cycles between -40 and +90°C, a seven day temperature humidity exposure test and a wind resistance test per UL997.

TITLE: Final Report. Study of Curved Glass PV Module and Module Electrical Isolation Design Requirements
CORPORATE AUTH: Bechtel National, Inc.
DATE: June 1980
REPORT NO: DOE-JPL 954698 80/2

ABSTRACT: A study was conducted to evaluate the technical feasibility and cost effectiveness of curved glass superstrate PV modules for use in large scale applications such as central station power plants. The study also evaluated electrical insulation and isolation design considerations with regard to module encapsulation systems. The design of a 1.2 by 2.4 m (4 by 8 ft) curved glass superstrate and support clip assembly is presented, along with the results of finite element computer analyses and a glass industry survey conducted to assess the technical and economic feasibility of the concept. Installed costs for four curved glass module array configurations are estimated and compared with costs previously reported for comparable flat glass module configurations. Electrical properties of candidate module encapsulation systems are evaluated along with present industry practice for the design and testing of electrical insulation systems. Electrical design requirements for module encapsulation systems are also discussed.

TITLE: Final Report. PV Module Electrical Termination Design Requirement Study
AUTHOR: F.J. Mosna, Jr. and J. Donlinger
CORPORATE AUTH: Motorola, Inc.
DATE: July 1980
REPORT NO: DOE-JPL 955367-80/1
AVAILABILITY: NTIS, PC 07/MF A01

ABSTRACT: The purpose of this document is to provide additional details and information to supplement the data provided in the Executive Summary. The document consists of Appendices 2.0, 3.0, and 4.0 which address the major tasks of the project (criteria development; ranking; and results/conclusions, respectively) and Appendix 5.0, a series of mini-appendices addressing specific topics complementing the major task areas.

TITLE: Final Report. Operation and Maintenance Cost Data for Residential PV Modules/Panels
CORPORATE AUTH: Burt Hill Kosar Rittelmann Associates
DATE: July 1980
REPORT NO: DOE-JPL 955614-80/1
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: A study has been conducted to identify and estimate costs associated with the operation and maintenance of residential PV modules and arrays. Six basic topics related to operation and maintenance to PV arrays were investigated - General (Normal) Maintenance, Cleaning, Panel Replacement, Gasket Repair/Replacement, Wiring Repair/Replacement, and Termination Repair/Replacement. The effects of the mounting types - Rack Mount, Stand-Off Mount, Direct Mount, and Integral Mount - and the installation/replacement type - Sequential, Partial Interruption, and Independent - have been identified and described. Recommendation on methods of reducing maintenance costs have been made.

TITLE: Final Report. Third Generation Design Solar Cell Module LSA Task V, Large Scale Production
AUTHOR: K.S. Ling
CORPORATE AUTH: Applied Solar Energy Corp.
DATE: August 1980
REPORT NO: DOE-JPL 955409-80/1

ABSTRACT: During this contract solar cell modules were designed and built in accordance with the JPL Document No. 5101-16 Revision A, entitled "Block IV Solar Cell Module Design and Test Specification for Intermediate Load Center Applications." A total of twelve (12) preproduction modules were constructed, tested and delivered. A new concept to the frame assembly was designed and proven to be quite reliable. This frame design, as well as the rest of the assembly, was designed with future high volume production and the use of automated equipment in mind.

TITLE: Final Report. Analysis of the Effects of Impurities in Si
CORPORATE AUTH: Solar Power Corp.
DATE: September 1980
REPORT NO: DOE-JPL 955403-80/1

ABSTRACT: This final design report for the Low Cost Solar Array Block IV Program has been prepared in response to the CDRL Item #6 DRD No. SE-2. The report includes an updated program plan showing the task descriptions depicting the work, progress, achievements and the cause of any deviations from the original plan (SC-1), and how this impacted on the original schedule of the program. In addition there is an update documenting all design alterations made during the preproduction phase and a complete up to date set of Engineering and Manufacturing Documentation (CM-1). The purpose of this report is to document the work performed through the final design and the test results of the modules developed under this contract, and to use this documentation to further the understanding and evolution of solar cell module design.

TITLE: Final Report. Design, Fabrication, Test, Qualification and Price Analysis of Third Generation Design Solar Cell Modules
CORPORATE AUTH: Spire Corp.
DATE: October 1980
REPORT NO: DOE-JPL 955405-80/1

ABSTRACT: This report describes a one year program to design, develop and produce a high-efficiency Block IV Solar Module according to JPL requirements defined in document 5101-16 Revision A, "Block IV Solar Cell Module Design and Test Specifications for Intermediate Load Center Applications." The module design is described along with the rationale for each major component choice. Experiments performed during the development phase of the program are described. The Quality Assurance Plan is outlined. Both cell and module fabrication are described. Performance and yield data on modules are given. Testing, both to determine module characteristics and to establish qualifications are discussed. Finally, the results of the SAMIS cost analysis are presented. The results of this program are that a JPL qualified module with a power density of 125 W/m^2 at 28°C has been developed and manufactured.

TITLE: Quarterly Report. A Program to Develop Elements of a Reliability Design Guidebook for Flat Plate PV Modules/Arrays
CORPORATE AUTH: IIT Research Institute
DATE: October 1980
REPORT NO: DOE-JPL 955720-80/1

ABSTRACT: The objective of this support study is to provide and/or develop engineering-oriented reliability data, guidelines, procedures and techniques to serve as elements of a reliability design guidebook on terrestrial, low-cost, PV modules/arrays. The approach being used in this support study is to first initiate an on-going reliability engineering data base and then develop and validate design guidelines that can be used by the PV industry to build reliability into their products most cost effectively.

TITLE: Final Report. Design, Fabrication, Test, Qualification And Price Analysis of "Third Generation" Design Solar Cell Modules
AUTHOR: E. Pastirik
CORPORATE AUTH: Motorola, Inc.
DATE: January 1981
REPORT NO: DOE-JPL 955406-81/1

ABSTRACT: Motorola entered into a contract with JPL on May 16, 1979, to design, fabricate, test, qualify, and deliver preproduction Block IV modules satisfying the requirements of JPL Document 5101-16, Revision A. The following report reviews the schedule of this effort as well as the basic module design and test results. Modifications to the design which occurred as a result of problems are also considered. Module qualification was achieved in December, 1980, and all documentation submissions were completed in January, 1981.

TITLE: Final Report. Safety and Liability Considerations for PV Modules/Panels
AUTHOR: D.G. Meeker and A.S. Weinstein
CORPORATE AUTH: Carnegie-Mellon University
DATE: January 1981
REPORT NO: DOE-JPL 955846-81/1
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The concept of product liability implies that a manufacturer is responsible to the consumer for products that are not reasonably safe. Recently, consumers have become more aware that manufacturers could be liable for harm incurred by a consumer while using their products. Evidence of this awareness can be seen by the increase in product liability suits and sizes of awards in recent years. Clearly this presents a problem for the manufacturer. Not only must the product be reliable and safe for its intended purpose, but it must also be safe for foreseeable misuse. This preliminary report explores product safety and product liability considerations for PV module/array devices. The purpose of this study is twofold--first to give an overview of legal issues as they apply to design, manufacture and use; second, to suggest a methodology to be used during design of a PV module/array to minimize or eliminate perceived hazards. This study does not attempt to answer any of these questions in detail, but only to pose them so as to stimulate consideration of this area. The questions raised in this study can only be answered through future efforts in concert with the manufacturers.

TITLE: Final Report. Wind Loads on Flat Plate PV Array Fields
AUTHOR: R. Miller
CORPORATE AUTH: The Boeing Co.
DATE: April 1981
REPORT NO: DOE-JPL 954833-81/3
AVAILABILITY: NTIS, PC A17/MF A01

ABSTRACT: This report presents the results of an experimental analysis (boundary layer wind tunnel test) of the aerodynamic forces resulting from winds acting on flat plate PV arrays. Local pressure coefficient distributions and normal force coefficients on the arrays are shown and compared to theoretical results. Parameters that were varied when determining the aerodynamic forces included tilt angle, array separation, ground clearance, protective wind barriers, and the effect of the wind velocity profile. Recommended design wind forces and pressures are presented, which envelop the test results for winds perpendicular to the array's longitudinal axis.

TITLE: Quarterly Report No. 1. Integrated Residential PV Array Development
CORPORATE AUTH: AIA Research Corp.
DATE: April 1981
REPORT NO: DOE-JPL 955893-81/1
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: This first quarterly report on a contract to develop an optimal integrated residential PV array describes sixteen conceptual designs produced by eight teams. Each design concept was evaluated by an industry advisory panel using a comprehensive set of technical, economic and institutional criteria. Key electrical and mechanical concerns that affect further array sub-system development are also discussed.

TITLE: Final Report. Phase IV. Wind Loads on Flat Plate PV Array Fields (Nonsteady Winds)
AUTHOR: R.D. Miller and D.K. Zimmerman
CORPORATE AUTH: The Boeing Co.
DATE: August 1981
REPORT NO: DOE-JPL 954833-81/4
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: This report presents the results of a combined experimental (wind tunnel test results) and theoretical analysis utilizing random harmonic analysis techniques to predict the dynamic response and the structural dynamic loads of flat plate PV arrays due to wind turbulence. Guidelines for use in predicting the turbulent portion of the wind loading on future similar arrays using the results of this study are presented.

TITLE: Final Report. Design, Fabrication, Test, Qualification and Price Analysis of "Third Generation" Design Solar Cell Modules. Part 1: Intermediate Load Module
CORPORATE AUTH: ARCO Solar, Inc.
DATE: September 1981
REPORT NO: DOE-JPL 955402-81/1
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: This final design report presents an updated program plan for the design, fabrication, test and qualification of the "third generation" design intermediate load solar cell module. This updated program plan and narrative reflects the design and development work done and progress made in establishing a viable design for these modules. Design alterations from the preproduction plan are discussed on experience gained during the preproduction phase of the program.

TITLE: Final Report. Design, Fabrication, Test, Qualification, and Price Analysis of "Third Generation" Design Solar Cell Modules
CORPORATE AUTH: Solarex Corp.
DATE: October 1981
REPORT NO: DOE-JPL 955404-81/1

ABSTRACT: Description of Program: The Solarex Block IV contract calls for the design, manufacture, and delivery of eighteen residential load modules and eighteen intermediate load modules. Common features of both modules include:
- 72 9.5 cm X 9.5 cm Semicrystalline Cells
- Cells - Ti-Pd-Ag front Metallization with n/p p+ junction
- Geometrically arranged in 6 X 12 matrix
- 3/16" Sunadex tempered glass superstrate
- Ethylene vinyl acetate as encapsulant with Craneglas spacer
- White Tedlar moisture barrier
- Redundant Cell-Interconnect Design which has six pads per cell
- Wraparound Interconnect
- Circuit-board style interconnect with in-plane stress relief feature.
- Two pigtail connections per positive or negative outlet.

Features which are different are shown in Table I.

TITLE: Final Report. Commercial/Industrial PV Module and Array Requirement Study
CORPORATE AUTH: Burt Hill Kosar Rittelmann Associates
DATE: December 1981
REPORT NO: DOE JPL 955698-81/1
AVAILABILITY: NTIS, PC A15/MF A01

ABSTRACT: A study has been conducted to identify design requirements for PV modules and arrays used in commercial and industrial applications. Building codes and referenced standards were reviewed for their applicability to commercial and industrial PV array installation. Four general installation types were identified - integral (replaces roofing), direct (mounted on top of roofing), stand-off

(mounted away from roofing), and rack (for flat or low slope roofs, or ground mounted). Each of the generic mounting types can be used in vertical wall mounting systems. Installation costs were developed for these mounting types as a function of panel/module size. Cost drivers were identified. Studies were performed to identify optimum module shapes and sizes and operating voltage cost drivers. As some obstacles could make PV extremely costly, this report makes recommendations to the PV industry which will facilitate a more successful product entrance into the building industry.

TITLE: Final Report. Integrated Residential PV Array Development
CORPORATE AUTH: General Electric Co.
DATE: December 1981
REPORT NO: DOE-JPL 955894-4
AVAILABILITY: NTIS, PC A08/MF A01

ABSTRACT: An advanced, universally-mountable, integrated residential PV array concept has been defined based upon an in-depth formulation and evaluation of three candidate approaches which were synthesized from existing or proposed residential array concepts. Past residential PV array concepts emphasized the module as given. This study addresses the next level of detail by considering the impact of module circuitry and process sequence, and by identifying technology gaps and performance drivers associated with residential PV array concepts. The actual learning experience gained from the comparison of the problem areas of the hexagonal shingle design with the rectangular module design has led to what is considered an advanced array concept. Building the laboratory mockup provided actual experience and the opportunity to uncover additional technology gaps.

TITLE: Final Report. Bypass Diode Integration
CORPORATE AUTH: General Electric Co.
DATE: December 1981
REPORT NO: DOE-JPL 955894-5

ABSTRACT: This report summarizes the results of a bypass diode integration study which was conducted as part of the "Integrated Residential PV Array Development" effort. The study involved research into protective bypass diodes and mounting configurations which are applicable for use with PV modules having power dissipation requirements in the 5 to 50 watt range. Using PN Si and Schottky diode characterization data on packaged diodes and diode chips, typical diodes were selected as representative for each range of current carrying capacity, an appropriate heat dissipating mounting concept along with its environmental enclosure was defined, and a thermal analysis relating junction temperature as a function of power dissipation was performed. In addition the heat dissipating mounting device dimensions were varied to determine the effect on junction temperature. The results of the analysis are presented as a set of curves indicating junction tempera ture as a function of power dissipation for each diode package.

TITLE: Final Report. Design, Fabrication and Testing of Block IV Design Solar Cell Modules, Part II: Residential Module
CORPORATE AUTH: ARCO Solar, Inc.
DATE: April 1982
REPORT NO: DOE-JPL 955402-82/2

ABSTRACT: This final design report concludes work performed on the design, fabrication and test of the Block IV Residential Load Module by ARCO Solar, Inc. This report outlines design changes from the proposed module design through three iterations to the discontinuance of testing agreed upon by both JPL and ARCO Solar, Inc.

TITLE: Final Report. Diodes in PV Modules and Arrays
CORPORATE AUTH: General Electric Co.
DATE: March 15, 1984
REPORT NO: DOE-JPL 956254-84/2
AVAILABILITY: NTIS, PC A02/MF A01; 1

ABSTRACT: The use of diodes to enhance the energy generation capability and improve the reliability of PV modules and arrays is the subject of this final report. Beginning with a discussion of the array-level considerations influencing the application of such diodes in a bypass mode, the report continues further to describe several methods for the mechanical and electrical integration of these devices as an integral part of the module electrical termination means. Particular emphasis is placed on the description of innovative approaches for the external mounting of bypass diodes. These descriptions were used as the basis for a detailed cost analysis and comparison among the candidate concepts. The PV source circuit blocking or isolation function can be implemented using the same basic diode enclosure designs with provisions for the inclusion of a fuse for overcurrent protection.

TITLE: Final Design Report. Intermediate Load Modules for Test and Evaluation
AUTHOR: M.J. Bower
CORPORATE AUTH: Applied Solar Energy Corp.
DATE: March 30, 1984
REPORT NO: DOE-JPL 956350-84/1

ABSTRACT: Two versions of a 36-cell stainless-steel solar module was built. The first version was built as a commercial module for marine applications and was purchased for evaluation by JPL. Design deficiencies were identified as a result of the evaluation. This report describes the second version that was built and the improvements that resulted from design changes. Assembly problems, electrical performance, and qualification test results are provided.

TITLE: Final Report. Block V Documentation and Solar Modules
CORPORATE AUTH: Spire Corp.
DATE: May 1984
REPORT NO: DOE-JPL 956334 85/1
AVAILABILITY: NTIS, PC A03/MF A01; 1

ABSTRACT: Design and fabrication of Spire Corp.'s Block V PV flat-plate module is reviewed. These modules exhibited power of about 70 watts under standard test conditions. Results of performance and environmental testing are provided.

TITLE: Final Report. Safety-Related Requirements for PV Modules and Arrays
CORPORATE AUTH: Underwriters Laboratories, Inc.
DATE: September 1984
REPORT NO: DOE-JPL 955392-84/3
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: Safety requirements for wiring systems and connections, and for separable connectors for use in roof-mounted PV arrays, are identified. These requirements were established by considering the environmental use-conditions applicable to PV arrays and the differences between integral-, direct-, standoff- and rack-mounted modules. The articles in the NEC covering wiring systems are discussed: (1) to define the wiring systems, (2) to identify the permitted uses and use restrictions, (3) to outline the advantages and disadvantages and (4) to address the concerns regarding support, protection against mechanical damage, and wet-versus-dry locations. An overall assessment is made of the advantages and disadvantages of each wiring system to arrive at candidate wiring systems that are best suited for use in PV arrays. For candidate wiring systems having use restrictions that may prohibit their use, considerations are given that need to be addressed by any proposed revision to the NEC to permit accept-

ance by the inspection authorities. The various wiring termination methods that are permitted by the NEC are discussed and those that have features desirable for PV applications are identified. Performance and construction requirements for PV cable and for PV connectors are presented in separate outlines of proposed investigations of these products.

TITLE: Final Design Report. Intermediate Load Modules for Test and Evaluation
CORPORATE AUTH: Solavolt International
DATE: September 7, 1984
REPORT NO: DOE-JPL 956349-84/01

ABSTRACT: The purpose of this contract was to provide PV modules for test and qualification against the JPL Block V qualification tests as outlined in JPL 5101-161, dated February 20, 1981. Tasks involved the following activities: (1) Delivery of 20 solar cells for use as reference cells; (2) Module documentation and inspection plans specifying the 10 Group I modules delivered to JPL prior to this contract; (3) A design review with JPL to review module documentation and test results from Group I modules; (4) Revise module documentation and inspection plans incorporating changes to overcome any problems or deficiencies associated with the Group I modules; (5) Delivery of 10 Group II modules built to revised specifications; and (6) Testing of Group II modules to the criteria as outlined in JPL 5101-161 Block V qualification specification.

TITLE: Final Report. Block V Documentation and Solar Cell Modules
AUTHOR: E. Tornstrom
CORPORATE AUTH: Mobil Solar Energy Corp.
DATE: November 21, 1984
REPORT NO: DOE-JPL 956335-84/1

ABSTRACT: A redesign of the initial (Group I) Block V module was done and documented. Manufacturing experience and accelerated test data from Group I formed the basis for the redesign. Ten Block V Group II modules were submitted for evaluation and the results are presented.

TITLE: Final Report. Electrical Research on Solar Cells and PV Materials
AUTHOR: J. Orehotsky
CORPORATE AUTH: Wilkes College
DATE: March 5, 1985
REPORT NO: DOE-JPL 956766-85/1

ABSTRACT: The objective of this contract is a systematic study of the properties of various polymer pottant materials and of the electrochemical corrosion mechanisms in solar cell materials required for advancing the technology of terrestrial PV modules. The items of specific concern in the sponsored research activity at Wilkes College involve: (1) Kinetics of plasticizer loss in PVB, (2) Kinetics of water absorption and desorption in PVB, (3) Kinetics of water absorption and desorption in EVA, (4) The electrical properties of PVB as a function of temperature and humidity, (5) The electrical properties of EVA as a function of temperature and humidity, (6) Solar cell corrosion characteristics, (7) Water absorption effects in PVB and EVA, and (8) Ion implantation and radiation effects in PVB and EVA.

TITLE: Final Report. Documentation and Solar Cell Modules: Block V
CORPORATE AUTH: Solarex Corp.
DATE: March 19, 1985
REPORT NO: DOE-JPL 956333-85/1

ABSTRACT: The Solarex Block V Group II module is a large frameless module intended for installation in a larger panel framework for use in intermediate to large size power system arrays. The module is a large one, based on a 0.125-in. thick tempered glass superstrate, containing 117 sq. cells, each one 10 cm on a side, arranged in a 13 series, 9-parallel matrix. The design peak power at 25°C is in the 135-140 W range. The module has a novel back sheet comprising a laminate of Tedlar, Mylar and a modified polyethylene. The Solarex Block V Group II module, designated Model C-120-10A, passed the JPL Block V qualification tests. A number of cracks were observed in cells in the two modules which underwent 200 thermal cycles, but the peak power change was less than 2% in each case. The frames supplied to simulate a proposed mounting support structure were not satisfactory. They damaged the edges of the module laminate during thermal cycling. The module design was adequate, however, to avoid any electrical problems from this edge damage.

TITLE: Final Report. Intermediate Load Modules for Test and Evaluation
CORPORATE AUTH: Solenergy Corp.
DATE: March 22, 1985
REPORT NO: DOE-JPL 956347-85/1

ABSTRACT: The objective of the contract was to furnish solar modules for evaporation per JPL Document 5101-161, Design and Test Specification for Intermediate Load Modules 1981, dated February 20, 1981. JPL has performed qualification tests in accordance with JPL Document 5101-161 on Group 1 and Group II modules and has reported the resulting data to the Contractor. The purpose of this contract is to provide modules that are designed to be consistent with the Block V Electrical and Mechanical Design Requirements, Section IIB and IIC of JPL Doc. 5101-161 or 5101-162. Also these modules must meet the design requirements of Block V Environmental Design Requirements, Section IID or JPL Doc. 5101-161 or 5101-162. We generally feel the modules performed satisfactorily although some workmanship problems were noted helping us correct our own production. It also appears that further work on EVA lamination by interested parties is required to address some problems associated with this method of production.

TITLE: Final Report. Fabrication, Documentation and Qualification Testing of Block V Intermediate Load PV Modules
AUTHOR: J.C. Arnett and E.I. Prokopovych
CORPORATE AUTH: ARCO Solar, Inc.
DATE: November 25, 1985
REPORT NO: DOE-JPL 956336-85/1

ABSTRACT: ARCO Solar, Inc. has completed a contract to document, evaluate, and perform qualification testing of the design of a new series of PV modules, developed in response to the JPL Block V module specification, 5101-161. The M56, an 84 watt, 5 V dc nominal output, 2 x 4" configuration power module, representative of the ARCO Solar M-Series module designs, was demonstrated to have successfully passed the qualification requirements for Block V. This design produced the highest module efficiency (11.3%) evaluated by JPL during the Block V procurement program. This report documents the design features of the module and its encapsulation system, and describes the testing programs conducted at JPL and at ARCO.

TITLE: High Efficiency Flat-Plate Modules
CORPORATE AUTH: Spire Corp.
DATE: July 1986
REPORT NO: DOE JPL 956641-86/1

ABSTRACT: The objective of this work was the design and fabrication of improved highly efficient silicon flat-plate modules. The successful development of a module with an efficiency of 15.2% is reported. A photograph of the module is shown in Figure 1-1. At the outset of this work, the intention was to form solar cells with reduced solar absorptance, thereby reducing the NOCT. The reduction of NOCT yields not only a grain in efficiency, but also an increase in module lifetime. The successful

development of a BSR solar cell that rejects approximately 80% of the sub-bandgap radiation is reported. An actual decrease in NOCT of 5°C in modules fabricated with such cells has been measured. In the course of this development program, other research on laboratory-scale (4 cm^2) Si cells indicated that very high efficiency (18%) could be achieved with certain design enhancements. Investigation applying these design features to large-area cells was done. This work was highly successful, and led to the fabrication of large-area (53 cm^2) cells with AM1.5 efficiency of 18%. This report will summarize all research and development in the contract. The work has included the entire range of technology that spans from cell design to module testing.

TITLE: Final Report. Effect of Row-to-Row Shading on the Output of Flat-Plate South Facing Solar Arrays
AUTHOR: D.Y. Goswami
CORPORATE AUTH: North Carolina Agricultural & Technical State University
DATE: July 1986
REPORT NO: DOE-JPL 957021-86/1

ABSTRACT: When solar arrays (PV, thermal, etc.) are arranged in multiple rows of modules, all but the first row suffer a reduction in (power) output, even when sufficient spacing between rows is provided. The reduction in output power occurs because the first row prevents some of the diffuse and reflected radiation from reaching the row directly behind it. This work presents the results of a study undertaken to estimate the effect of shading on the amounts of solar radiation received by consecutive rows of flat-plate arrays. By using a derived set of equations representing the beam, diffuse and reflected components of radiation received by two south facing rows placed one directly behind the other, a computer program has been developed in order to determine the effect of location (latitude), array-tilt angle, spacing between rows, ground offset, ground reflectivity and weather conditions (percent sunshine, clearness number) on the amount of total radiation received by each of the two rows.

TITLE: Final Report. Amorphous Silicon Solar Cell Reliability Research
AUTHOR: J.W. Lathrop
CORPORATE AUTH: Clemson University
DATE: September 1986
REPORT NO: DOE-JPL 954929-86/13

ABSTRACT: This is the final report of a reliability research program to study the response of a-Si solar cells to accelerated temperature testing. The goal of the research was to utilize accelerated testing to identify failure/degradation modes and to relate them to basic physical, chemical, and metallurgical phenomena. Four types of single junction commercial modules were subjected to 140°C testing, both in the dark and under illuminated conditions. The before and after electrical characteristics of individual cells were measured and compared and correlated with physical evidence. A fifth module type could not be tested because of poor adherence of the films to the glass superstrate. A short term effect of stressing was noted which dramatically improved cells with low V_{oc} on one type of construction. All cells eventually showed long term irreversible degradation, but the time to 50% Pm reduction varied by as much as two orders of magnitude depending on construction. No basic difference could be detected between degradation under illuminated or non-illuminated conditions, when cells were either open or short circuited. Comparison with one type of tandem cell and with published results of Japanese cell testing indicated the marked superiority of the tandem cell to all other types. Cells were examined physically by optical, IR, and SEM, and by Auger spectroscopy, secondary ion-mass spectroscopy, and energy dispersive x-ray analysis. The long-term degradation was felt to be due to localized penetration of aluminum through amorphous film.

MODULE ENCAPSULATION
JPL - IN-HOUSE ABSTRACTS

MODULE ENCAPSULATION IN-HOUSE ABSTRACTS

TITLE: Materials Consideration for Encapsulation of Terrestrial PV
AUTHOR: W.F. Carroll and E. Cuddihy
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 1976
REPORT NO: DOE-JPL 00654
AVAILABILITY: NTIS-00654

ABSTRACT: This paper deals with several key considerations regarding development of reliable, low-cost encapsulation systems for terrestrial PV. Critical materials's properties and their relationship to encapsulation requirements and options for encapsulation implementation are described. The obvious requirements for transparency (of the cover), structural support and electrical conduction/insulation are treated only in relation to other properties. Available data on moisture diffusion through polymers (measured with finite driving force) tend to indicate that no polymeric system will preclude penetration of moisture to junctions and metallization. Only glass ceramics and metals have diffusion rates sufficiently low to predict adequate protection. Recent work indicates interface (polymer/device) adhesion plays a critical role in limiting diffusion. Terrestrial PV devices will be subject to nearly 10^4 diurnal (plus numerous shorter and longer) thermal cycles during a 20-year lifetime. Differential thermal expansion must be minimized and/or accommodated in module design. Mechanical stress is known to accelerate environmental degradation (oxidation, photochemical, etc.) of some polymer systems. The "true elastic limit" of polymers is critical to reliable encapsulation system design. The derivation of true elastic limit and its significance to "fatigue" will be described.

TITLE: Development and Validation of a Life Prediction Methodology for LSSA Encapsulated Modules
AUTHOR: C. Coulbert
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1977
REPORT NO: 5101-40
AVAILABILITY: NTIS, PC 346-223-CC

ABSTRACT: This report outlines an approach to the development of a life prediction methodology for polymer encapsulated PV cell solar array hardware. The characteristics and output of an ideal life prediction model are described. Such a model depends on the development of quantitative intermediate relationships between the environmental exposure parameters and the basic chemical mechanisms of material aging. These are described conceptually along with suggested relationships which might be developed for two potential solar array failure modes, optical transmission loss and delaminations. The use of accelerated/abbreviated testing in the development of a life prediction methodology is reviewed. The distinction between testing to reveal failure modes and testing to define rates of degradation is presented. The point is also made that acceptance tests and performance tests which involve some degree of stress acceleration have very limited application to predicting module lifetimes.

TITLE: Material and Design Considerations of Encapsulants for PV Arrays in Terrestrial Applications
AUTHOR: W. Carroll, E. Cuddihy, and M. Salama
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1978
REPORT NO: DOE-JPL 00844-1
AVAILABILITY: NTIS-00844-1

ABSTRACT: Encapsulated PV arrays for terrestrial application are constructed from widely varying combinations of materials having dissimilar coefficients of thermal expansion. Cyclic mechanical stresses will develop throughout the array as a result of daily temperature excursions, and to avoid mechanical failures and interfacial delaminations, it is necessary in the array design to minimize the stress levels generated throughout the system. The concept of "Thermal Stiffness," the product of Young's modulus, is presented and its applicability to minimizing mechanical stresses in system designs is demonstrated in the analysis of various models of encapsulated arrays. Also presented is the concept of the "Proportional-Limit" which should be taken as the upper limit of design stress for plastics, and a discussion of the permeability to gases of polymeric materials.

TITLE: Encapsulation Material Trends Relative to 1986 Cost Goals
EDITOR: E. Cuddihy
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 1978
REPORT NO: 5101-61
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: The status and an assessment of solar PV module encapsulation systems applicable to the LSA Project 1986 cost and performance goals are presented. The 1986 LSA cost goal for a 20-yr life solar cell module is \$.50/W or $\$5/ft^2$. Out of this cost goal, $\$.25/ft^2$ is currently allocated for the encapsulation construction materials, including the mechanical support for the cells. Six basic construction elements were identified and their functions defined. These elements are outer covers, pottants, substrates, superstrates, adhesives, and back covers. For each construction element, a uniform costing basis was established for comparative analysis and an extensive survey of existing commercial materials which could be used was carried out. This survey generated an appreciation of the minimum costs which must be paid for the materials of each construction element and a better awareness of the likelihood of fabricating a $\$.25/ft^2$ encapsulation system. The survey permitted identifiction of the lowest-costing material classes which could be used to meet the 1986 cost goals. Material deficiencies identified in this survey also permitted recognition of material developmental activities needed in the future. The resultant output from cost and materials analysis derived from these ongoing surveys, suggests that a $\$.25/ft^2$ encapsulation cost goal is attainable, but not without some specifically directed material developmental activities. These activities will focus on modifications to existing materials and evolvement of new and specific product lines from existing and well-established material families.

TITLE: A Life Prediction Methodology for Encapsulated Solar Cells
AUTHOR: C. Coulbert
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 1978
REPORT NO: DOE-JPL 02582
AVAILABILITY: NTIS-02582

ABSTRACT: This paper presents an approach to the development of a life prediction methodology for encapsulated solar cells which are intended to operate for 20 yr or more in terrestrial environment. The use of accelerated/abbreviated testing to develop these intermediate relationships and in revealing failure modes is discussed. An approach to enhancing the value of such field tests to provide data for life prediction is described.

TITLE: Encapsulant Candidate Materials for 1982 Cost Goals
AUTHOR: H. Maxwell
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1978
REPORT NO: 5101-72

ABSTRACT: A cost of \$2.00/W by 1982 has been established by the LSA Project as an intermediate goal to the primary Project goal of \$0.50/strawman designs for \$2.00/W arrays, including various options, tradeoffs, and cost. To sup-

port this primary output, information is presented on encapsulation experience, encapsulation system design criteria, and basic preparation and costs of candidate materials. The encapsulation system can be subdivided into six basic elements: top covers, superstrates, pottants, adhesives, substrates, and bottom covers. The roles of these elements in the encapsulation system are described in this document. Candidate materials are examined in relationship to their usage as one or more of the six basic encapsulation elements. Their properties, cost considerations, availability, and processing characteristics are discussed.

TITLE: Photodegradation of Polymeric Encapsulants of Solar Cell Modules
AUTHOR: A. Gupta
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 1978
REPORT NO: 5101-77

ABSTRACT: This report deals with the mechanisms of photodegradation of encapsulant materials in solar cell modules. Data have been presented on irradiation sources, their applications in simulative or accelerated testing or mechanistic studies, and their calibration. In discussing mechanisms, the emphasis has been on the possible application of these mechanisms in creating models which correlate a change in molecular structure to changes in physical properties, which, in turn, control performance in the field. For example, photooxidation of silicones has been shown to yield hydroxyl groups pendant on the siloxane chain which increases the polar character of the silicone surface, as indicated by surface energy analysis. A change in the surface polarity of silicones directly affects their interfacial bond strength to module substrates and causes weakening of bond strength to hydrophobic surfaces. Experiments prove that such a UV weakened bond may undergo delaminatlong on exposure to moisture. A major section of the report is devoted to acrylic photochemistry and the role of UV stabilizers and screening agents, because they are viewed as potential low-cost encapsulants capable of outdoor performance for 20 yr or more. In addition to reviewing some of the rich literature in these areas, we have described some inhouse work of preliminary nature. It is hoped that the addition of these recent results will add a topical flavor to the report. Among the acrylics we have studied are the methacrylates, the acrylates, and their copolymers which often possess unique photochemical properties not ascribable to either of the two copolymers by themselves.

TITLE: Effect of Photodegradation on Chemical Structure and Surface Characteristics of Silicone Pottants Used in Solar Cell Modules
AUTHOR: A. Gupta
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 1978
REPORT NO: 5101-79

ABSTRACT: Solar cell modules of Block I and Block II purchase delaminated in the field after passing JPL acceptance tests. Attempts to simulate field failure using conventional thermal and humidity cycling tests were unsuccessful. It was surmised that delamination might be caused by degradation of the adhesive bond caused by solar UV. A failure analysis was carried out in terms of generic phys iochemical mechanisms which included a careful assessment of time acceleration of UV radiation. The proposed model included rate of change of silicone material properties, including properties of the surface as a function of aging under well characterized UV irradiation and rate of change in bond strength. Failure observed in the field was then simulated in test specimens, and the failure rate was compared to that observed in the field. The inherent varia bility of the silicone surface from point to point often exceeds changes in properties caused by aging, and it is therefore difficult to obtain unambiguous results from the failure analysis described above. This ambiguity may be resolved by monitoring more than one surface property whose degradation correlates with the failure mechanism under study. For delamination of silicones (RTV-615 and Sylgard-184) from certain hydrophobic substrates we have identified material properties of the polymer which correlate with bonding properties of its surface and therefore predict environmental aging conditions under which debonding would occur from a specific substrate. This type of analysis of the failure mechanism probes into the molecular basis of the failure and is of use in designing accelerated tests which would allow predicting lifetimes under given (or known) environments. Figure 1 summarizes this mechanistic approach to failure analysis and lifetime prediction.

TITLE: Encapsulation Materials for PV Arrays
AUTHOR: C. Coulbert
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 1978
REPORT NO: DOE-JPL 00128
AVAILABILITY: NTIS-00128

ABSTRACT: Materials currently in use for encapsulating PV arrays of Si solar cells are too costly if the DOE goal of reducing the price of PV arrays to 50¢/W from $10.00 to $20.00/W is to be achieved. Current encapsulation materials include silicone rubbers, glass, and PVB as transparent covers with stainless steel, aluminum, and fiberglass composites as the structural substrates. As a part of the LSA Project, an Encapsulation Task has been established to identify, develop, and evaluate new low-cost, long-life encapsulation systems capable of meeting the project cost and performance goals. Low-cost materials system candidates have been identified and are being characterized in laboratory and field tests with detailed evaluation of their environmental stability when subjected to temperature cycling, humidity, UV radiation, dirt, and various other environmental hazards. Experimental data and analyses to date provide confidence that the cost and performance goals can be met.

TITLE: Low-Cost Encapsulation Materials for Terrestrial Solar Cell Modules
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 1978
REPORT NO: 5101-78

ABSTRACT: Solar cell modules must undergo dramatic reductions in cost in order to become economically attactive as practical devices for the production of electricity. A federal goal seeks to have, by 1986, and industrial capability of producing solar cell modules at a cost of 50¢/W (in 1975 dollars) and a service lifetime of 20 yr. Today's modules cost more than $11.00/W, and they have an undefined lifetime. Part of the cost reductions must be realized by the encapsulation materials which are used to package, protect, and support the solar cells, electrical interconnects, and other ancillary components. It is estimated that to meet a cost goal of 50¢/W, encapsulation materials, including the structural substrate or superstrate, should cost between $2.70 and $5.00/$m^2$ of module area (in 1975 dollars). This document presents the findings of material surveys intended to identify low cost materials which could be functional as encapsulants. This document further assesses the prognosis for achieving an encapsulation system at the lower cost goal of $2.70/$m^2$, and identifies the technologies which must be advanced or developed to achieve 20 yr life with the lowest costing materials.

TITLE: Experience with Silicones in PV Modules
AUTHOR: J. Repar
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1979
REPORT NO: DOE-JPL 1012-79/8A, and 5101-103

ABSTRACT: PV cells which are employed in terrestrial environments require extensive protection for various

reasons. The cells are fragile, and metal components are subject to corrosion as the result of chemical reaction with various constituents in the atmosphere. Electrical insulation is required where metal substrates or frames are used. In addition, the deposition of atmospheric dust on surfaces requires that the surfaces be capable of withstanding repeated cleaning operations. Materials covering the cells on the sunlit side must be transparent with low light absorption, particularly in the range of 400 to 1100 nanometers where Si solar cells are most responsive. Although various types of glass and plastics have been employed as encapsulation materials, several room temperature curing silicones have processing characteristics which are readily applicable to encapsulation of Si solar cells and also have excellent light transmission properties coupled with high dielectric strengths. This report will be confined to a discussion of experience with room temperature curing silicones. Experience in both field and laboratory tests has indicated that delamination and other bond failures occur where silicones are used. The three which have been most widely used are General Electric's RTW-615 and two from Dow Corning, namely, Sylgard 184 and Q3-6527. A thin silicone film, Q1-2577, which is also a Dow Corning product, has been used as a hard cover over either RTV-615 or Sylgard 184. These studies were undertaken in an effort to determine the causes of delamination and other bond failures associated with the use of these silicones. The effects of deviation from recommended processing procedures during manufacture, and of various environmental factors during field exposure were examined.

TITLE: Chemical Bonding Technology for Terrestrial Solar Cell Modules
AUTHOR: E.P. Plueddemann
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1, 1979
REPORT NO: 5101-132

ABSTRACT: This report on chemical bonding technology for terrestrial solar cell modules includes an introduction to the state-of-the-art, general principles for module application, as well as test results and evolving recommendations of chemical bonding agents for EVA.

TITLE: Reactor for Simulation and Acceleration of Solar UV Damage
AUTHOR: E. Laue and A. Gupta
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1979
REPORT NO: DOE-JPL 1012-31, JPL Pub. 79-92, 5101-135
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: An environmental test chamber providing acceleration of UV radiation and precise temperature control ($\pm$ 1°C) has been designed, constructed and tested. This chamber allows acceleration of solar UV up to 30 suns while maintaining temperature of the absorbing surface at 30°C - 60°C). This test chamber utilizes a filtered medium pressure mercury arc as the source of radiation, and a combination of selenium radiometer and Si radiometer to monitor solar UV (295 - 34 nm) and total radiant power output, respectively. Details of design and construction and operational procedures are presented along with typical test data.

TITLE: Encapsulation Materials Status to December 1979
AUTHOR: E.F. Cuddihy
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1980
REPORT NO: 5101-144

ABSTRACT: Two task objectives have been defined in achieving 1986 technology readiness of encapsulation systems: (1) Materials and Processes. Define, develop, demonstrate and qualify encapsulation systems, materials, and processes that meet the Project life, cost and performance goals. (2) Life Prediction Method. Develop and validate a module life prediction method based on modeling life-limiting failure modes and on conducting and analyzing accelerated aging tests of candidate encapsulation systems. This is a status report on the first task objective, to date. The Project goal is to sponsor and stimulate activities that will reduce solar array prices to \$0.14/W_{pk} or \$14/m^2 of completed module including an edge seal and gasket. Surveys of encapsulation materials capable of meeting the Project goal have been carried out (References 2, 3) and were reported in April 1978 in the Project report "Encapsulation Material Trends Relative to 1986 Cost Goals" (Reference 3). This was followed by a shortened version entitled "Low-Cost Encapsulation Materials for Terrestrial Solar Cell Modules" (Reference 4). The 1978 articles reported on a broad class of candidate materials by generic description, such as EVA, recognizing that many of the reported materials were not immediately useful for encapsulation. Since April 1978 no new generic classes of materials have been identified, and the emphasis in the intervening period has been on the identification, development and evaluation of specific materials within the generic classes, and the evolution of encapsulation processes and of module designs with the low-cost materials. In April 1978, encapsulation materials industrially used consisted essentially of two castable silicone elastomers (Sylgard 184 and RTV 615), a silicone gel, PVB laminating film, a hard silicone soil-resistant top coat, Tedlar and Mylar films, glass superstrate, and several substrate panels such as aluminum, NEMA G10 epoxy board, and glass-reinforced polyester. Many of these materials are still being used and evaluated by module manufacturers; therefore the LSA program has chosen not to duplicate evaluation of them.

TITLE: Glass for Low-Cost PV Solar Arrays
AUTHOR: F.L. Bouquet
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1980
REPORT NO: DOE-JPL 1012-40, JPL Pub. 80-12, 5101-147
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: In PV systems, the encapsulant material that protects the solar cells should be highly transparent and very durable. Glass satisfies these two criteria and is considered a primary candidate for low-cost, PV encapsulation systems. In this report, various aspects of glass encapsulation are treated that are important for the designer of PV systems. Candidate glasses and available information defining the state of the art of glass encapsulation materials and processes for automated, high volume production of terrestrial PV devices and related applications are presented. The criteria for consideration of the glass encapsulation systems were based on the Project goals for arrays: (a) a low degradation rate, (b) high reliability, (c) an efficiency greater than 10 percent, (d) a total array price less than \$500/kW, and (e) a production capacity of 5 x 10^5 kW/yr. The glass design areas treated herein include the types of glass, sources and costs, physical properties and glass modifications, such as AR coatings.

TITLE: PV Module Soiling Studies May 1978 to October 1980
AUTHOR: A.R. Hoffman, and C.R. Maag
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1, 1980
REPORT NO: DOE/JPL 1012-49, JPL Pub. No. 80-87, 5101-131

ABSTRACT: The retention of particulate contamination on the
surface of flat-plate PV devices is adversely affecting electrical performance of outdoor-exposed modules. This report describes the results of an experimental study being performed to characterize and understand the effects of outdoor contaminants on sensitive optical surfaces of flat-plate PV modules and cover materials. Comparative electrical and optical performance data from PV modules and materials subjected to outdoor exposure at field-test sites throughout the United States have been collected and examined. The results show significant time- and site depend-

ence. During periods when natural removal processes do not dominate, the rate of particulate contamination accumulation appears to be largely material-independent. The effectiveness of natural removal processes, especially rain, is strongly material-dependent. Glass and acrylic top-cover materials retain fewer particles than silicone rubber does. Side-by-side outdoor exposure testing for long duration is presently the most effective means of evaluating soiling differences between materials. Changes in spectral transmission as a function of time and location and limited scattering data are presented.

TITLE: Development of Reduced Variable Master Curves for Estimating Tensile Stresses of Encapsulated Solar Cells Caused by Module Deflection or Thermal Expansion
AUTHOR: E.F. Cuddihy
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 1, 1981
REPORT NO: 5101-182

ABSTRACT: Complex computer programs are being used by Spectrolab, Inc., to achieve encapsulation engineering optimization of PV modules. Optimization involves structural adequacy, electrical isolation (safety), maximum optical transmission, and minimum module temperature, at the lowest life-cycle energy cost. A goal of this activity is the generation, where possible, of encapsulation engineering generalities, principles, and design aids (tables or graphs) that would permit a ready, desktop capability to an engineering evaluation of encapsulation options involving materials or designs. This article reports the first efforts to generate reduced variable master curves to serve as structural-analysis design aids.

TITLE: PV Module Encapsulation Design and Materials Selection: Volume I
AUTHOR: E. Cuddihy, W. Carroll, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1982
REPORT NO: DOE-JPL 1012-60, JPL Pub. 81-102, 5101-177
AVAILABILITY: NTIS, PC A08/MF A01

ABSTRACT: Encapsulation-material system requirements, material-selection criteria, and the status and properties of encapsulation materials and processes available to the module manufacturer are presented in detail. Technical and economic goals established for PV modules and encapsulation systems and their status are described for material suppliers to assist them is assessing the suitability of materials in their product lines and the potential of new-material products. A comprehensive discussion of available encapsulation technology and data is presented to facilitate design and material selection for Si flat-plate PV modules, using the best materials available and processes optimized for specific power applications and geographic sites. Section II provides a basis for specifying the operational and environmental loads that encapsulation material systems must resist. Potential deployment sites for which cost effectiveness may be achieved at a module price much greater than $\$0.70/W_p$, are also considered; data on higher-cost encapsulant materials and processes that may be in use and other material candidates that may be justified for special application are discussed. Section III describes encapsulation-system functional requirements and candidate design concepts and materials that have been identified and analyzed as having the best potential to meet the cost and performance goals for the FSA Project. Sections IV, V, and VI present the available data on encapsulant material properties, fabrication processing, and module life and durability characteristics.

TITLE: PV Characterization of Encapsulant Materials for PV Modules
AUTHOR: R. Liang, A. Gupta, and S.D. Stefano
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1982
REPORT NO: DOE-JPL 1012-72, JPL Pub. 82-42, 5101-210

ABSTRACT: A PV test matrix and a low-cost testing apparatus for encapsulant materials of PV modules have been defined and illustrated. Photothermal studies were conducted in order to screen and rank existing as well as future encapsulant candidate materials and/or material formulations in terms of their long-term physiochemical stability under accelerated photothermal aging conditions. Photothermal characterization of six candidate pottant materials and six candidate outer cover materials have been carried out. Principal products of photothermal degradation were identified. Certain critical properties were also monitored as a function of photothermal aging.

TITLE: PV Module Encapsulation Design and Materials Selection, Volume I (Abridged)
AUTHOR: E. Cuddihy
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1, 1982
REPORT NO: DOE-JPL 1012-77, JPL Pub. 82-81, 5101-216
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: The functional requirements and the status of candidate material systems and processes for PV modules is described in detail in PV Module Encapsulation Design and Materials Selection, Volume I, JPL Document No. 5101-177, JPL Publication 81-101, DOE/JPL-1012-60, JPL, Pasadena, California, June 1, 1982 (Reference 1). This document, a summary of Volume I, presents the basic encapsulation systems, their purposes and requirements, and the characteristics for the most promising candidate systems and materials, as identified and evaluated by FSA. This summary necessarily omits considerable detail and much supporting and experimental information. A reader interested in references, literature citations, and in more detailed information on specific topics, should consult Reference 1.

TITLE: The Application of Encapsulation Material Stability Data to PV Module Life Assessment
AUTHOR: C.D. Coulbert
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 1, 1983
REPORT NO: DOE-JPL 1012-84, JPL Pub. 83-27, 5101-224
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: For any piece of hardware that degrades when subjected to environmental and application stresses, the route or sequence that describes the degradation process may be summarized in terms of six key words: LOADS, RESPONSE, CHANGE, DAMAGE, FAILURE, AND PENALTY. Applied to PV modules, these six factors form the core outline of an expanded failure analysis matrix for unifying and integrating relevant material-degradation data and analyses. An important feature of this approach is the deliberate differentiation between factors such as CHANGE, DAMAGE, and FAILURE. The application of this outline to materials-degradation research facilitates the distinction between quantifying material property changes and quantifying module damage or power loss with their economic consequences. The approach recommended for relating material stability data to PV module life is to use the degree of DAMAGE to: (1) optical coupling, (2) encapsulant package integrity, (3) PV circuit integrity, or (4) electrical isolation as the quantitative criterion for assessing module potential service life rather than simply using module power loss. The failure analysis matrix and its application to module life assessment, with specific examples and data, are described.

TITLE: Applications of Ethylene Vinyl Acetate as an Encapsulation Material for Terrestrial PV Modules
AUTHOR: E. Cuddihy, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 15, 1983
REPORT NO: DOE JPL 1012-87, JPL Pub. 83-35, 5101-220
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: Terrestrial PV modules must undergo substantial reductions in cost to become economically attractive as practical devices for large-scale production of electricity. Part of the cost reductions must be realized by the encapsulation materials that are used to package, protect, and support the solar cells, electrical interconnects, and other ancillary components. Because many of the encapsulation materials are polymeric, cost reductions necessitate the use of low-cost polymers. The performance and current status of ethylene vinyl acetate, a low-cost polymer being investigated as an encapsulation material for terrestrial PV modules, are described.

TITLE: Handbook of Photothermal Test Data on Encapsulant Materials
AUTHOR: R.H. Liang, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 1, 1983
REPORT NO: DOE-JPL 1012-86, JPL Pub. 83-32, 5101-230
AVAILABILITY: NTIS, PC A08/MF A01

ABSTRACT: This report describes laboratory tests performed to characterize candidate encapsulation materials with respect to changes in their physical and chemical properties caused by photothermal aging. Several key material properties relating directly to material degradation and deterioration of performance have been identified and have been monitored as functions of aging conditions and time. This handbook provides a status report on accelerated testing activities and presents experimental data collected before and during December 1982. It will be updated periodically as more data become available.

TITLE: Proceedings of the FSA Project Research Forum on Quantifying Degradation
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1, 1983
REPORT NO: DOE-JPL 1012-89, JPL Pub. 83-52, 5101-231
AVAILABILITY: NTIS, PC A22/MF A01; 1

ABSTRACT: For PV modules to become practical for large-scale electrical power production, they must undergo cost reductions and they must become sufficiently durable to perform reliably for many years. FSA, managed by JPL for DOE, has established cost and life goals of $\$14.00/m^2$ and 20 years. FSA research has identified and advanced technologies with potential for achieving the cost goal, and seeks to identify and advance relevant technologies for meeting the durability goal. The Quantifying Degradation Research Forum addressed identification and quantification of module degradation rates and mechanisms. Acquisition and analysis of degradation data and formulation of analytical models may facilitate assessment of the life potential of hardware designs, provide design criteria for improved hardware, and help develop tests and standards to assure the durability and quality of future modules. To assess long-term durability from short-term field or accelerated testing, it is essential to identify, understand and quantify potential life-limiting damage mechanisms. Approaches to identifying and characterizing degradation mechanisms such as corrosion, cyclic fatigue, photothermal aging, soiling, debonding, and electrical stress effects are addressed. Experience and approaches of other industries in achieving and assuring hardware durability are reviewed and discussed.

TITLE: Chemical Bonding Technology for Terrestrial PV Modules Status to February, 1983
AUTHOR: D.R. Coulter, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 15, 1983
REPORT NO: DOE-JPL 1012-91, JPL Pub. 83-86, 5101-232
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: Encapsulated PV modules must hold together for 20 years, reliably resisting delamination and separation of any of the component materials. Delamination of encapsulation materials from each other, or from solar cells and interconnects, can create voids for accumulation of water, promoting corrosive failure. Delamination of silicone elastomers from unprimed surfaces was a common occurrence with early modules, but the incidences of silicone delamination with later modules decreased when adhesion promoters recommended by silicone manufacturers were used. An investigation of silicone delamination from unprimed surfaces successfully identified the mechanism, which was related to atmospheric oxygen and moisture. This early finding indicated that reliance on physical bonding of encapsulation interfaces for long life in an outdoor environment would be risky. For long outdoor life, the materials components of a module must therefore be held together by weather-stable adhesion promotors that desirably form strong, interfacial chemical bonds. The Environmental Isolation Task of FSA, managed by JPL for the DOE, conducted a program to identify, develop, and validate weather-stable chemical bonding adhesion promotors for terrestrial PV. This program is a joint effort currently involving Dow Corning Corp., Case Western Reserve University, Rockwell International, Springborn Laboratories, Inc., and JPL. This report is intended to accomplish three purposes: to provide a status report on chemically bonding adhesion promotors, with data on bond strength performance; to describe and discuss the theories of the chemically bonded interface; and to identify processing considerations relevant to achieving long-term interfacial chemical bonding.

TITLE: A Concept for the Intrinsic Dielectric Strength of Electrical Insulation Materials
AUTHOR: Edward Cuddihy
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 15, 1984
REPORT NO: DOE-JPL 1012-105, JPL Pub. 85-30, 5101-252
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: A concept is described for a possible definition of the intrinsic dielectric strength of insulating materials. This can be considered as a fundamental material property similar to other material properties, such as Young's modulus, index of refraction, and expansion coefficient. The events leading to the recognition of this property are reported, and the property is defined. This intrinsic dielectric strength concept should facilitate interpretation of results from accelerated and/or natural aging programs intended to predict electrical insulation service-life of encapsulants in PV modules. As a practical application, this new concept permitted a possible explanation of the cause of failures in buried high-voltage cables with polyethlene insulation, as well as a possible explanation of the causes of electrical trees in polyethylene.

TITLE: PV Module Encapsulation Design and Materials Selection: Volume II
AUTHOR: E. Cuddihy
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1, 1984
REPORT NO: DOE-JPL 1012-97, JPL Pub. 84-34, 5101-237
AVAILABILITY: NTIS, PC A06/MF A01; 1

ABSTRACT: Volume I (Reference 1), published June 1, 1982, described encapsulation material system requirements, material-selection criteria, and the status and properties of encapsulation materials and processes available to module manufacturers. To assist material suppliers in assessing the suitability of materials in their product lines and the potential of new material products, technical and economic goals established for PV modules and encapsulation systems and their status were described. A comprehensive discussion of available encapsulation technology and data was presented to facilitate design and material selection for Si flat-plate PV modules, using the best materials available and processes optimized for specific power applications and geographic sites. Volume II extends and supplements Volume I by describing FSA encapsulation technology developed between June 1, 1982, and January 1, 1984.

Emphasis during this period shifted from materials development to demonstration of reliability and durability in an outdoor environment. The updated information in this volume reflects the developing technology base related to both reliability and encapsulation process improvements.

TITLE: Antisoiling Technology: Theories of Surface Soiling and Performance of Antisoiling Surface Coatings
AUTHOR: E.F. Cuddihy and P.B. Willis
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 15, 1984
REPORT NO: DOE-JPL 1012-102, JPL Pub. 84-72, 5101-251
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Physical examination of surfaces undergoing natural outdoor soiling suggests that soil matter accumulates in as many as three distinct layers. The first layer involves strong chemical attachment or strong chemisorption of soil matter on the primary surface. The second layer is physical. It consists of a highly organized arrangement of soil creating a gradation in surface energy from a high associated with the energetic first layer to the lowest possible state as dictated by the chemical and physical nature of the regional atmospheric soiling materials. These first two layers are resistant to removal by rain. The third layer constitutes a settling of loose soil matter, accumulating in dry periods and being removed during rainy periods. Theories and evidence suggest that surfaces that should be naturally resistant to the formation of the first two rain-resistant layers should be hard, smooth, hydrophobic, free of first-period elements, and have the lowest possible surface energy. These characteristics, evolving as requirements for low soiling surfaces, suggest that surfaces or surface coatings should be of fluorocarbon chemistry. Evidence is presented for the three soil layer concept, as well as data on the positive performance of candidate fluorocarbon coatings on glass and transparent plastic films after 28 months of outdoor exposure.

TITLE: A Concept for the Intrinsic Dielectric Strength of Electrical Insulation Materials
AUTHOR: E.F. Cuddihy
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 15, 1985
REPORT NO: DOE/JPL 1012-105, and 5101-252

ABSTRACT: A concept is described for a possible definition of the intrinsic dielectric strength of insulating materials, which can be considered as a fundamental material property similar to other material properties, such as Young's modulus, index of refraction, and expansion coefficients. The events leading to the recognition of this property are reported, and the property is defined. This intrinsic dielectric strength concept should facilitate interpretation of results from accelerated and/or natural aging programs intended to predict electrical insulation service life of encapsulants in PV modules. As a practical application, this new concept enabled a possible explanation of the cause of failures in buried high voltage cables with polyethylene insulation, and a possible explanation of the causes of electrical trees in polyethylene; these also are described.

TITLE: Chemical Bonding Technology: Direct Investigation of Interfacial Bonds
AUTHOR: J.L. Koenig, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1986
REPORT NO: DOE-JPL 1012-120, JPL Pub. 86-6, 5101-284

ABSTRACT: This is the third FSA document reporting on chemical bonding technology for terrestrial PV modules. The impetus for this work originated in the late 1970s when PV modules employing silicone encapsulation materials were undergoing delamination during outdoor exposure. At that time, manufacturers were not employing adhesion promoters and, hence, module interfaces in common with the silicone materials were only in physical contact and therefore easily prone to separation if, for example, water were to penetrate to the interfaces. Delamination with silicone materials virtually vanished when adhesion promoters, recommended by silicone manufacturers, were used. With the decrease in use of silicone encapsulants, and the increase in use of hydrocarbon encapsulants such as EVA, the need developed for adhesion promoters specifically developed for these new materials. The adhesion promoters being developed for EVA-type materials are based on organo-silanes, which generate primary chemical bonds at the interface, that is, chemical bonding. These adhesion promoters are commonly referred to as "primers". The first report on this subject (Chemical Bonding Technology for Terrestrial Solar Cell Modules, by E.P. Plueddeman, JPL 5101-132, dated September 1, 1979) described the chemistry of primers based on organosilane chemistry, and the second report (Chemical Bonding Technology for Terrestrial PV Modules, by D.R. Coulter, E.F. Cuddihy and E.P. Plueddeman, JPL Pub. 83-86, dated November 15, 1983) described chemical bonding theories, and also included a listing of candidate primer and adhesive systems being investigated for all of the various module interfaces. This report describes the activities related to the direct investigation of chemically bonded interfaces.

TITLE: The Aging Correlation (RH + t): Relative Humidity (%) + Temperature (^{o}C)
AUTHOR: E.F. Cuddihy
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 15, 1986
REPORT NO: DOE JPL 1012-121, JPL Pub. 86-7, 5101-283

ABSTRACT: An aging correlation between corrosion lifetime, and relative humidity RH(%) and temperature t(^{o}C) has been reported in the literature. This aging correlation is a semi-log plot of corrosion lifetime on the log scale versus the interesting summation term {RH(%) + t(^{o}C)} on the linear scale. This empirical correlation was derived from observation of experimental data trends and has been referred to as an experimental law. Using electrical resistivity data of PVB measured as a function of relative humidity and temperature, it was found that the electrical resistivity could be expressed as a function of the term {RH(%) + t(^{o})}. Thus, if corrosion is related to leakage current through an organic insulator, which, in turn, is a function of RH and t, then some partial theoretical validity for the correlation is indicated. This article describes the derivation of the term {(RH(%) + t(^{o}C)} from PVB electrical resistivity data.

MODULE ENCAPSULATION
CONTRACTOR ABSTRACTS

MODULE ENCAPSULATION CONTRACTOR ABSTRACTS:

TITLE: Final Report. Terrestrial Service Environments for Selected Geographic Locations.
AUTHOR: D.C. Carmichael and R.E. Thomas
CORPORATE AUTH: Battelle Memorial Institute, Columbus Laboratories
DATE: June 1976
REPORT NO: ERDA-JPL 954328-76/5

ABSTRACT: This report contains results obtained from analyses of climatic, precipitation, air pollution and other environmental data for the years 1965-1974 at nine widely different geographic locations in the United States. In addition to descriptive and diurnal statistics for 24 individual climatic variables, "environmental cell" statistics were computed to obtain the frequencies, durations, and transitions for the simultaneous occurrence of various combinations of environmental variables. Results are presented for the simultaneous occurrence of specific levels of air temperature, relative humidity, wind speed, and insolation, in addition to representative results obtained for other combinations of variables. The results characterize the environmental conditions to which terrestrial solar arrays would be exposed over a 20-yr lifetime, and serve to identify environmental factors and levels that can be used in testing candidate encapsulation materials and systems for such terrestrial exposures. An innovative methodology was applied to obtain these results for combinations of environmental variables. Because of its generality and demonstrated feasibility, it is concluded that the methodology also has broad applications to other testing programs.

TITLE: Final Technical Report. Review of World Experience and Properties of Materials for Encapsulation of Terrestrial PV Arrays
AUTHOR: D.C. Carmichael
CORPORATE AUTH: Battelle Memorial Institute, Columbus Laboratories
DATE: July 21, 1976
REPORT NO: ERDA-JPL 954328-76/4

ABSTRACT: Available information defining the state of the art of encapsulation materials and processes for terrestrial PV devices and related applications were collected and analyzed. The criteria for consideration of the encapsulation systems were based on the LSA goals for arrays with a lifetime of over 20 yrs high reliability, and efficiency greater than 10%, a total array price less than \$500/kW, and a production capacity of 5 x 10^5kW/yr. Published and unpublished information relating to encapsulation systems and materials properties was collected by searching the literature. None of the encapsulation materials used meets all of the LSA criteria (particularly cost), but some have performed well. Since the design of the ultimate LSA device is yet to be established, selection of candidate materials was based upon both LSA criteria and specific materials properties (e.g., light transmission) requisite to the functions of various components (e.g., covers pottants, etc.) in potential encapsulation systems, as well as upon temperature and processing constraints associated with the cell structure. The recommended materials (all commercially available) include, depending upon the device design, various borosilicate and soda-lime glasses and numerous polymerics suitable for specific encapsulation-system functions.

TITLE: Final Report. Methodology for Designing Accelerated Aging Tests for Predicting Life of PV Arrays
AUTHOR: G.B. Gaines
CORPORATE AUTH: Battelle Memorial Institute, Columbus Laboratories
DATE: February 1, 1977
REPORT NO: DOE-JPL 954328-77/1

ABSTRACT: This study undertook to develop a methodology for designing aging tests in which life prediction was paramount. Part II presents the improved methodology developed in this study. The developed methodology emphasizes the importance of incorporating substantial contributions at the time of initiation of the test design from statisticians, material scientists, and test engineers in order to achieve a test design that is both statistically satisfactory and is practical in terms of the number of tests to be run. The first 6 steps of the developed methodology focus on the explicit identification of necessary engineering input information, identification of possible failure modes and environmental variables (stresses) that may affect the time rates of degradation for each failure mode without changing the failure mode, estimation of expected overall severity of each combination of environmental stresses, and analysis of severity ratings as a hierarchical tree. An examination of the tree makes it possible to identify those test conditions (combinations of environmental stress levels) that are expected to produce the largest changes in degradation rates. Because the remaining tests may not form a suitable experimental design, the methodology provides for the inclusion of selected additional tests to remove as may statistical deficiencies as possible within the allowable time/cost constraints. Considerations of precision, accuracy, and test sensitivity are also included in the report.

TITLE: Final Report. Accelerated/Abbreviated Test Methods for Predicting Life of Solar Cell Encapsulants. October 25, 1977 to April 30, 1978
AUTHOR: J.M. Kolyer, N.R. Mann and J. Farrar
CORPORATE AUTH: Rockwell International Corp.
DATE: April 30, 1978
REPORT NO: DOE-JPL 954458-78/10
AVAILABILITY: NTIS, PC A13/MF A01

ABSTRACT: Accelerated and abbreviated test methods were developed for predicting the outdoor lifetime of solar cell encapsulants. Encapsulants are clear materials applied as covers to protect the cells from environmental hazards. An important principle is that encapsulants should be tested in a total array system allowing realistic interaction of components. Therefore, micromodule test specimens were fabricated with a variety of encapsulants, substrates, and types of circuitry. Interactions, some times favorable, were observed between these components. One common failure mode was corrosion of circuitry and solar cell metallization due to moisture penetration. Another was darkening and/or opacification of encapsulant. However, the power output remained high despite drastic visual changes. A test program plan was proposed. It included multicondition accelerated exposure, which was demonstrated to give successful predictions for property changes. Another method was hyperaccelerated photochemical exposure using a solar concentrator. It simulates 20 yrs of sunlight exposure in a short time period of one to two weeks. The study was beneficial in identifying some cost-effective encapsulants and array designs. It was shown that Si junctions are remarkably resistant to moisture and contaminants. With corrosion-resistant circuitry, the encapsulant could be a low cost plastic which protects cells from dust, abrasion, and mechanical shock.

TITLE: Final Report. Studies and Testing of AR Coatings for Soda-Lime Glass
AUTHOR: E.M. Pastirik, T.G. Sparks, and M.G. Coleman
CORPORATE AUTH: Motorola, Inc.
DATE: May 1978
REPORT NO: DOE-JPL 954773-78/1
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: Experimental results on this feasibility study to establish processes for producing AR films on glass are very encouraging. Efforts have been concentrated in three areas: acid etching of glass, plasma etching of glass, and acid development of sodium silicate films on glass. The best transmission to date has been achieved through the

acid etching technique, while the most durable films have been produced from development of sodium silicate films. Control of the acid etching technique is presently inadequate for production implementation, and large scale application methods for sodium silicate films need further definition. While films having excellent AR properties have been fabricated by plasma etching techniques, all have been water soluble, disqualifying the films from a weatherability standpoint.

TITLE: Final Report. Evaluation of Available Encapsulation Materials for Low-Cost Long-Life Si PV Arrays
AUTHOR: D.C. Carmichael, G.B. Gaines, et al.
CORPORATE AUTH: Battelle Memorial Institute, Columbus Laboratories
DATE: June 1978
REPORT NO: DOE-JPL 954328-78/2
AVAILABILITY: NTIS, PC A06/MF A01

ABSTRACT: The 1986 objectives of the LSA Project are to develop the technology and manufacturing capability to produce 500,000 kW/yr of PV arrays at a cost of less than $500/kW, with an efficiency of greater than 10% and a service life of 20 yrs. One of the tasks (Encapsulation Task) of this project is concerned with the development and evaluation of the protective encapsulation-material systems which will be required to meet these cost and service life objectives, as well as the production and performance objectives for terrestrial PV arrays. To help evaluate the requirements and potential of encapsulation systems for arrays, an extensive review and analysis was made, in a previous study, of prior world experience with PV arrays in the field and the service behavior of encapsulation materials for PV and related applications. In addition to an appraisal of field experience and problems, candidate materials for various functions in the array encapsulation system were recommended for investigation and pertinent properties of these materials were collected and reported in that study. The study that is reported here consists of the experimental evaluation of selected encapsulation designs and materials based on the earlier study which have potential for use in low-cost, long-life PV arrays.

TITLE: Final Report. Ion Plating of Solar Cell Arrays
CORPORATE AUTH: Endurex Corp.
DATE: December 1978
REPORT NO: DOE-JPL 954728-78/2
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: Endurex has been engaged in a feasibility study to determine practicality of utilizing Endurex ion plated films to serve as anti-reflective and/or protective encapsulants for solar cell arrays. It has been demonstrated that thin films of oxide materials between 1000 and 2000 A thick will protect a PV device from degradation in salt spray. Additionally, transmissivity data accumulated on Endurex coatings show that the AR properties of this film are equal to any achieved by more widely used processes. The Endurex ion plating process is capable of being scaled up to meet 1986 throughput goals at a cost which is in line with 1986 cost goals. An additional benefit that may be realized by the utilization of ion plating is that it is an effluent free process utilizing no wet chemistry.

TITLE: Final Report. Measurement Techniques and Instruments Suitable for Life-Prediction Testing of PV Arrays
AUTHOR: G.T. Noel, V.E. Wood, et al.
CORPORATE AUTH: Battelle Memorial Institute, Columbus Laboratories
DATE: March 1979
REPORT NO: DOE-JPL 954328-79/12
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: The validation of a 20-yr service life for low-cost PV arrays is a critical requirement in the LSA Project. Of necessity, this validation must be accomplished through accelerated life-prediction tests. A methodology for such tests has been developed in a preceding study at Battelle for the LSA Project. Remaining needs before such tests are carried out are the identification, assessment, and experimental evaluation of diagnostic techniques and instruments that make it possible to measure failure related degradative property changes over a short time period with sufficient precision to allow the prediction of sevice life exceeding 20 yr. A two-phase study has been conducted addressing these needs. Phase I, the results of which were discussed in the interim report on this study, accomplished the initial identification and assessment of all known measurement techniques and instruments that might be used in these life-prediction tests and included recommendations on their use. The results and recommended techniques from the Phase I investigation are summarized in the Appendix of this report. Phase II of the study, covered in this report, consisted of experimental evaluations of three techniques selected from those recommended as a result of the Phase I findings. The three techniques evaluated were specular and nonspecular optical reflectometry, chemiluminescence measurements, and electrical current noise measurements.

TITLE: Final Report. Development of an Accelerated Test Design for Predicting the Service Life of the Solar Array at Mead, Nebraska
AUTHOR: G.B. Gaines, R.E. Thomas, et al.
CORPORATE AUTH: Battelle Memorial Institute, Columbus Laboratories
DATE: June 1979
REPORT NO: DOE JPL 954328-79/13
AVAILABILITY: NTIS, PC A03/MF A01

ABSTRACT: This report describes an accelerated test which is designed to predict the life of the 25-kW PV array installed near Mead, Nebraska. Emphasis is placed on the power output degradation at the module level and on long term degradation modes, as appropriate for life prediction of mature devices for which infant failures are few. A quantitative model for accelerating testing using multiple environmental stresses is used to develop the test design. The model accounts for the effects of thermal stress by a relation of the Arrhenius form. This relation is then corrected for the effects of nonthermal environmental stresses, such as relative humidity, atmospheric pollutants, and UV radiation. The correction factors for the nonthermal stresses include temperature-dependent exponents to account for the effects of interactions between thermal and nonthermal stresses on the rate of degradation of power output. Quantitative estimates, a priori, of the model parameters are then used to compute expected degradation rates under various test conditions associated with a complete factorial experimental design. The test conditions, measurements, and data analyses for the accelerated tests are presented for determining the predicted life of the modules in service at Mead. Constant-temperature, cyclic-temperature, and UV types of tests are specified, incorporating selected levels of relative humidity and chemical contamination and an imposed forward-bias current and static electric field. It is recommended that as a first step in test implementation, the model be selectively validated using identified portions of the accelerated test design.

TITLE: Final Report. Develop Silicone Encapsulation Systems for Terrestrial Si Solar Arrays
CORPORATE AUTH: Dow Corning Corp.
DATE: December 1979
REPORT NO: DOE-JPL 954995-80/6
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: This work resulted in two basic accomplishments. The first was the identification of DOW CORNING Q1-2577 as a suitable encapsulant material for use in cost effective

encapsulation systems. The second was the preparation of a silicone-acrylic cover material containing a durable UV screening agent for the protection of photo-oxidatively sensitive polymers. The most expeditious method of fabrication is one in which the encapsulant material performs the combined function of adhesive, pottant, and outer cover. The costs of the encapsulant can be minimized by using it as a thin conformal coating. Our evaluation of methods by which to process encapsulation systems and the screening of candidate materials took those factors into consideration. One encapsulation system using silicones was identified from this work which provided protection to PV cells and survived the JPL qualification tests. This encapsulation system uses DOW CORNING as the combined adhesive, pottant and cover material. The lowest cost encapsulation system using Q1-2577 had Super Dorlux as the substrate structural member. The overall material cost of this encapsulation system is 0.74¢/ft^2 (1980 dollars) based on current material prices, which could decrease with increased production of Q1-2577.

TITLE: Final Report. AR Coatings Applied by Acid Leaching Process
AUTHOR: E. Pastirik
CORPORATE AUTH: Motorola, Inc.
DATE: September 1980
REPORT NO: DOE-JPL 955387-80/3
AVAILABILITY: NTIS, PC A04/MF A01

ABSTRACT: The Magicote C process developed by S.M. Thompsen was evaluated for use in applying an AR coating to the cover plates of solar panels. The process uses a flourosilicic acid solution supersaturated with silica at elevated temperature to selectively attack the surface of soda-lime glass cover plates and alter the physical and chemical composition of a thin layer of glass. The altered glass layer constitutes an AR coating. The process produces coatings of excellent optical quality which possess outstanding resistance to soiling and staining. The coatings produced are not resistant to mechanical abrasion and are attacked to some extent by glass cleansers. Control of the filming process was found to be difficult.

TITLE: Final Report. Integral Glass Encapsulation for Solar Arrays
CORPORATE AUTH: Spire Corp.
DATE: July 1981
REPORT NO: DOE-JPL 954521-81/15
AVAILABILITY: NTIS, PC A05/MF A01

ABSTRACT: This program has developed the technology of electrostatic bonding as an encapsulation technique for terrestrial solar arrays. The process produces full integral, hermetic bonds with no adhesives or pottants. Demonstration panels of six solar cells on a single glass superstrate were produced. Electrostatic bonding was also developed as a means of making the cell front contact. A metal mesh is trapped into contact with the cell front during the bonding process. Demonstration six-cell panels using the bonded mesh as the only cell front contract were produced. Exploratory development was done on the possibility of using lower cost glass, with a higher thermal expansion mismatch to Si, by making lower temperature (250-300°C) bonds. This was shown to require a planar surface cell (no front contacts). Demonstration panels of twelve 3" round wafers on a 12 x 18" glass sheet were made.

TITLE: Final Report. Development of Synthetic Procedures for Polymer UV Stabilizers and Absorbers
CORPORATE AUTH: University of Massachusetts
DATE: December 20, 1982
REPORT NO: DOE-JPL 955531-82/2

ABSTRACT: The objective of this work was to devise polymeric materials that are stable enough to use outdoors, in excess of 20 yrs, without any changes taking place. Our particular objective was to synthesize new and effective UV stabilizers for plastic materials, to prepare polymerizable UV stabilizers, particularly of the 2(2-hydroxyphenyl) 2H-benzotriazole family, to demonstrate their polymerization, copolymerization and grafting onto other polymers, to devise new effective UV-stabilizing systems, and to assist JPL in its evaluation of these materials from the photophysical point of view. Unsaturated polyesters were copolymerized.

TITLE: Final Report. Ion Plating of Solar Cell Arrays Encapsulation Task
CORPORATE AUTH: Illinois Tool Works, Inc.
DATE: April 1983
REPORT NO: DOE-JPL 955506-83/3
AVAILABILITY: NTIS, PC A03/MF A01; 1

ABSTRACT: The objective of the contract was to initiate, investigate, develop and demonstrate the capability to produce operational solar cells having metallization and AR coatings deposited by gasless ion plating, which will separately and/or in combination with a low-cost encapsulation system, meet the LSA project life, cost and performance goals. The capability to produce operational solar cells, both n on p and p on n types, with ion-plated metallizations has been developed. Further, the ability to deposit AR coatings by ion plating has been demonstrated. The performance characteristics of solar cells thus produced has been equal to that of control cells finished with conventional metallization systems. Additionally, SAMICS analyses have shown that such processes can meet cost requirements. Although life tests have not been performed, corrosion tests, which have been performed, imply that solar cells with ion-plated metallization and AR coating will be much less susceptible to corrosion of the electrodes than will solar cells with conventional metallizations and AR coatings.

TITLE: Final Report. March 23, 1977 to January 31, 1984. Study Program for Encapsulation Materials Interface
AUTHOR: D.H. Kaelble and C.L. Leung
CORPORATE AUTH: Rockwell International Corp.
DATE: April 1984
REPORT NO: DOE-JPL 954739/06
AVAILABILITY: NTIS, PC A04/MF A01; 1

ABSTRACT: The first annual report (Science Center Report No. SC5106.22AR) outlines and implements a physical/chemical evaluation program for solar cell encapsulants. The results of computer-controlled ultrasonic and optical/ellipsometric mapping for interface defect characterization in solar modules are summarized in the second annual report (SC5106.49AR). The development and validation of an atmospheric corrosion model and a test plan for LSA outdoor service at the Mead, Nebraska, test site are presented in the third annual report (SC5106.86AR). Development of ac impedance as a method of evaluating solar cell and module properties and further development of corrosion models are summarized in the fourth annual report (SC5106.104AR). The fifth annual report (SC5106.123AR) summarized the development of materials selection criteria for encapsulant bond integrity, and additional validation of ac impedance methods for detecting early electrical malfunction in solar modules. The sixth and final phase of the program, as reported in this document, generates and validates the necessary design and process principles for achieving long-term IBS of PV encapsulated systems.

TITLE: Triannual Report. For Period Ending July 31, 1984. Design, Analysis and Test Verification of Advanced Encapsulation Systems
AUTHOR: N. Mardesich
CORPORATE AUTH: Spectrolab, Inc.
DATE: August 1984
REPORT NO: DOE-JPL 955567-84/15
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: This program will develop the analytical methodology for advanced encapsulation designs. From these methods, design sensitivities will be established for the development of PV module criteria and the definition of needed research tasks. The program consists of four phases. In Phase I, analytical models were developed to perform optical, thermal, electrical and structural analyses on candidate encapsulation systems. From these analyses, several candidate encapsulation systems were selected for qualification testing during Phase II. Additionally, during Phase II, test specimens of various types were constructed and tested to determine the validity of the analysis methodology developed in Phase I. During Phase III the following items will be covered: (1) Correction of identified deficiencies and/or discrepancies between analytical models developed during Phase I and relevant test data obtained during Phase II of the above contract, (2) Improvement and extension of prediction capability of present analytical models, and (3) Generation of encapsulation engineering generalities, principles, and design aids for PV module design. In Phase IV a final optimum design based on knowledge gained in Phases I, II and III will be developed and delivered to JPL.

TITLE: Annual Report, 1983. Modeling of Photodegradation in Solar Cell Modules of Substrate and Superstrate Design Made with Ethylene-Vinyl Acetate as Pottant Material
AUTHOR: A.C. Somersall and J.E. Guillet
CORPORATE AUTH: The Governing Council of the University of Toronto
DATE: January 2, 1985
REPORT NO: DOE-JPL 955591-84/11

ABSTRACT: A computer model has been developed that can generate realistic concentration-versus-time profiles of the chemical species formed during photooxidation of hydrocarbon polymers. The input data used is a set of elementary reactions with corresponding rate constants and initial conditions. The results of computer simulation have been shown to be consistent with the general experimental observations of the photooxidation of polyethylene exposed to sunlight at ambient temperatures. The useful lifetime (5% oxidation) of the unstabilized polyethylene is predicted to vary from a few months in hot weather (100°F) to almost two years in cool weather (45°F) with apparent net activation energy of 10 kcal/mol. Modelling studies of alternative mechanisms for stabilization of clear, amorphous, linear polyethylene suggest that the optimum stabilizer would be a molecularly dispersed additive in very low concentration which can trap peroxy radicals and also decompose hydroperoxides. In principle, the lifetimes could then be extended over 20 yrs. The diffusion of oxygen into the polymer is not rate limiting to the photooxidation process but edge seals and impervious covers could preclude any autocatalytic photooxidation and thereby extend lifetimes very considerably.

TITLE: Ninth Annual Report. Investigation of Test Methods, Material Properties, and Processes for Solar Cell Encapsulants
AUTHOR: P.B. Willis
CORPORATE AUTH: Springborn Laboratories, Inc.
DATE: June 18, 1985
REPORT NO: DOE-JPL 954527-85/28
AVAILABILITY: NTIS, PC A06/MF A01; 1

ABSTRACT: To ensure high reliability and long-term performance, the functional components of the solar cell must be adequately protected from the environment by some encapsulation technique. The potentially harmful elements to module functioning include moisture, UV radiation, heat build-up, thermal excursions, dust, hail, and atmospheric pollutants. Additionally, the encapsulation system must provide mechanical support for the cells and corrosion protection for the electrical components. The encapsulation system is defined as all the construction materials required in a module to provide this mechanical support and environmental isolation. In addition, the module must be based on construction materials and design considerations that meet the field operating requirements while also maximizing the cost performance. The goal of this program is to identify and develop encapsulation systems consistent with the PV-module operating requirements of 30 yr life and a target cost of $\$0.70/W_p$ ($\$70/m^2$) (1980 dollars). Assuming a module efficiency of 10%, which is equivalent to a power output of 100 W/m^2 in midday sunlight, the capital cost of the modules may be calculated to be $\$70.00/m^2$. Out of this cost goal, only 20% is available for encapsulation due to the high cost of the cells, interconnects, and other related components. The encapsulation cost allocation may then be stated as $\$14.00/m^2$ which includes all coatings, pottant and mechanical supports for the cells.

TITLE: Design, Analysis and Test Verification of Advanced Encapsulated Systems
AUTHOR: A. Garcia, III
CORPORATE AUTH: SPectrolab, Inc.
DATE: Oct. 31, 1985 (Received Oct. 1986)
REPORT NO: DOE JPL 955567-85/16

ABSTRACT: Methods have been developed to aid the PV manufacturer in the design of modules which will optimize the use of materials and method of manufacture for novel encapsulation schemes. Methods are described for using master curves to enable the design of modules which will with stand pressure loading from wind and/or precipitation as well as stress produced from diurnal and seasonal thermal cycling. Analysis methods using finite element modeling are presented to examine maximum electric field concentrations dependent on the geometry of cells and interconnects. Techniques for determining the operating temperature and optical efficiency of panels are presented. Several novel methods of manufacturing modules are described. Experimental results in the use of conductive polymers in PV cells as AR coatings, conductivity enhancers and passivation coatings are discussed.

PROJECT ANALYSIS AND INTEGRATION
JPL - IN-HOUSE ABSTRACTS

PROJECT ANALYSIS AND INTEGRATION IN-HOUSE ABSTRACTS:

TITLE: Preliminary Analysis of Industrial Growth and the Factors that Affect Industrial Growth Rates
AUTHOR: E. Edelson and T.K. Lee
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1976
REPORT NO: 5101-14

ABSTRACT: Research on the experience of growth in industries other than Si solar arrays has been undertaken to provide a perspective on the goals established for the U. S. Photovoltaic Conversion Program. Comparative information on the growth experienced by other industries will provide important research questions that must be addres sed if the goals are to be achieved. Presently, this work has been conducted at three levels. The first level is purely analytical, and applies mathematical equations describing exponential growth and linear growth to the goals stated for the LSSA Project. In the framework established by these equations, the growth rates implied by the LSSA goals may be computed. At the second level, some interpretation of these rates is provided by comparing them to growth rates experienced by other industries. Although a historical rate of growth is only a superficial indication of an industry's development, it does provide a first-order indicator of what levels of growth different industries have been able to achieve in the past. The use of growth rate comparisons does not detract from the importance of examining, in detail, those factors that determine the rate of growth. The factors presently under consideration are: (1) Level of Industry investment; (2) Gov ernment subsidization and incentives; (3) Government regu lation; (4) Competition within the industry and with other industries; (5) Market characteristics; and (6) Consumer behavior. Because information on these constraints and incentives is necessary to understand the observed growth rates, the third level of research is a case study on one relevant industry to examine what constrains and motivates an industry.

TITLE: The Cost of Energy from Utility-Owned Solar Electric Systems
AUTHOR: J.W. Doane, R.R. O'Toole, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1976
REPORT NO: ERDA-JPL 1012-76/3, and 5040 29

ABSTRACT: This methodology calculates the electric energy busbar cost from a utility-owned solar electric system. This approach is applicable to both publicly - and privately-owned utilities. Busbar cost represents the minimum price per unit of energy consistent with producing system-resultant revenues equal to the sum of system-resultant cost. This equality is expressed in present value terms, where the discount rate used reflects the rate of return required on invested capital. Major input variables describe the output capabilities and capital cost of the energy system, the cash flows required for system operation and maintenance, and the financial structure and tax environment of the utility.

TITLE: Interim Price Estimation Guidelines: A Precursor and an Adjunct to SAMIS III
AUTHOR: R.W. Aster and R.G. Chamberlain
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1977
REPORT NO: 5101-33

ABSTRACT: The problem of estimating the market price of a product that is obtainable from an unproven technological process is a very difficult one. Direct costs can be estimated much more easily. However, if one can then estimate the direct requirements for both the process and the organization employing the process, then a total cost estimate is possible. If this total cost includes estimates of all the production, administration, and financial costs, then the result is the minimum price that a firm requires to enter the market with that given process. This problem faces the LSSA Project, which is charged with the task of developing technological processes which meet certain price goals. Accordingly, there have been numerous cost models developed by various Project elements. A growing need has been recognized for a standard methodology which allows (1) relative comparisons of the potential prices attributable to competing processes, and (2) a best possible estimate of the actual price obtainable from a process. SAMIS will be a powerful tool for producing accurate comparable estimates of the prices implied by sequences of manufacturing processes. SAMIS will not, however, be available for several months, and price estimates are being made now by various Project elements. To provide a basis for consis tency among these estimates, this document establishes an interim standard method to be used throughout the Project (except in the Si Material Task, where the Lamar University procedure may be better suited than this interim standard method.)

TITLE: The Penetration of the International Market by Domestically Produced PV Power Systems: A Survey of Recent Estimates
AUTHOR: G.M. Ziman and J.L. Smith
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1978
REPORT NO: 5101-75

ABSTRACT: Increasing interest in the potential market for PV power systems in foreign countries, particularly the lesser developed countries, has prompted a review of seve ral studies that have attempted to quantify that market. The express purpose for this review is to see if any kind of consensus for foreign market size exists among those studies, and to judge whether such estimates can reasonably be done at all. Various approaches have been tried, each with differing degrees of credibility, and a wide range of estimates has been produced, thus failing to substantially reduce the uncertainty associated with that market. This report presents and compares those estimates for the period 1984-86 from the studies referred to above (References [1], [2], [8], and [13]), and a discussion of factors not easily quantifiable (both favorable and unfavorable) that will impact PV power systems sales in foreign markets is included in Section II. A summary of the report and conclusions drawn is presented as Part III, and the methods used to derive the estimates are discussed in the Appendix.

TITLE: Product Pricing in the Solar Array Manufacturing Industry: An Executive Summary of SAMICS
AUTHOR: R.G. Chamberlain
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: 1978
REPORT NO: DOE-JPL 311.2-486
AVAILABILITY: NTIS-311.2-486

ABSTRACT: The SAMICS methodology is quite general - application to production-line manufacturing outside the solar array industry is expected to require only relatively minor augmentation of the data base. This paper is intended to serve as an executive summary of SAMICS, and contains a discussion of capabilities and limitations, a non-technical overview of the methodology, and a description of the input data which must be collected. It also describes the activities that have been and are being taken to ensure validity of the results and contains an up todate bibliography of related documents.

TITLE: Solar Array Manufacturing Industry Costing Standards
AUTHOR: R.G. Chamberlain and R.W. Aster
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1978
REPORT NO: 5101-59

ABSTRACT: The Solar Array Manufacturing Industry Costing

Standards are prepared by the LSSA PA&I Area and are intended to provide a standard procedure and data base for estimating, from descriptions of the manufacturing processes, the price at which solar modules would have to be sold to realize a specified after-tax rate of return on equity. The first few weeks of use SAMICS, along with the exercise we performed prior to the Eighth LSSA PIM in December, have led to some very penetrating questions. The purpose of this document is to answer those questions and to clarify and/or establish how to handle the following topics: (1) Elimination of the 42-hour work week; (2) Clearer labels on Format A and on Process and Company Work Sheets; (3) Relief labor; (4) Partial inspection processes; (5) Format A Column A22 - amount required per batch; (6) Processes that draw power even when not in use; (7) Format A Line A6 and Column A26 - output rate and yield factor; (8) Rework loops; (9) Processes that use parts that require processing; (10) More general rework loops; (11) General technological loops; (12) Integerization of numbers of people and machines; and (13) When to burden and when not to burden materials and supplies.

TITLE: Historical Evidence of Importance to the Industrialization of Flat-Plate Si PV Systems
AUTHOR: J.L. Smith, W.R. Gates and T. Lee
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 1978
REPORT NO: DOE-JPL 1012-78/1, and 5101-54 Vol. I & Vol. II

AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: This study was prepared by the Project staff on two somewhat disjointed subjects: the diffusion of new industrial production technologies and the determinants of success of previous federally funded demonstration projects. The research was limited to secondary sources. In essence, a literature search on these two subjects was the primary aim of the study. That search led, however, to some fairly strong conclusions out of which specific recommendations for the future plans and conduct of the Project have been derived. It must be emphasized that these recommendations are made only on the basis of the evidence considered. That is, no attempt has been made here to incorporate the myriad other factors which bear significantly on the Project (e.g., funding levels or political imperatives). Thus, these recommendations are not intended as a comprehensive set of project management recommendations to the PV Program or DOE. They are to be viewed as an input into such a comprehensive set.

TITLE: The Penetration of the International Market by Domestically Produced PV Power Systems: A Survey of Recent Estimates
AUTHOR: G.M. Ziman, and J.L. Smith
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: May 30, 1978
REPORT NO: 5101-75

ABSTRACT: Increasing interest in the potential market for PV power systems in foreign countries, particularly the lesser developed countries, has prompted a review of several studies that have attempted to quantify that market. The express purpose for this review is to see if any king of consensus for foreign market size exists among those studies, and to judge whether such estimates can reasonably be done at all.

TITLE: Lifetime Cost and Performance Model for PV Power Systems
AUTHOR: C.S. Borden
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 1978
REPORT NO: DOE-JPL 311.5-305
AVAILABILITY: NTIS-311.5-305

ABSTRACT: This paper describes the approach and procedures of the LCP model for PV power systems. The LCP model is designed to evaluate the impact of alternative initial design and recurrent policy decisions on both cost and power output over the lifetime of a PV power plant. LCP is useful to system designers and operators for addressing questions relating to optimal system configuration, installation activities, level of effort and timing of operations/maintenance actions, allowable degradation and replacement options.

TITLE: Economic Analysis of a Candidate 50¢/W_p Flat-Plate PV Manufacturing Technology
AUTHOR: R.W. Aster
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 1978
REPORT NO: DOE JPL 1012-78/17, and 5101-94

ABSTRACT: The SAMICS methodology was used to analyze the first candidate manufacturing sequence that could meet the Project's 1986 price goal. That goal represents a reduction in PV prices by a factor of a hundred over a 10-yr period, from approximately 50$/Wpk in 1975 to 50¢/Wpk in 1986. The results of analysis which has occurred since the original presentation of the 5¢/Wpk candidate factory at the 10th Project Integration Meeting are described. Briefly, if a number of events occur, such as a high cell efficiency (14% for this technology), vertical industry integration, long periods of amortizing the initial capital investment, and full utilization of a large plant, then a price of 39.9¢/Wpk is possible. Non optimal circumstances will increase this required price, and several of these circumstances are addressed.

TITLE: A Normative Price for a Manufactured Product: The SAMICS Methodology. Volume I: Executive Summary, Volume II: Analysis
AUTHOR: R.G. Chamberlain
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1979
REPORT NO: DOE-JPL 1012-79/5, and 5101-93

ABSTRACT: SAMICS provides standard formats, data, assumptions, and procedures for determining the price a hypothetical solar array manufacturer would have to be able to obtain in the market to realize a specified after-tax rate of return on equity for a specified level of production. This document presents the methodology and its theoretical background. It is contended that the model is sufficiently general to be used in any production-line manufacturing environment. Implementation of this methodology by SAMIS III, Release 1 is discussed.

TITLE: ESEA Methodology and User's Guide
AUTHOR: M.L. Slonski
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 1979
REPORT NO: 5101-102

ABSTRACT: The ESEA capability is a flexible analytical tool which may be used for rank ordering (in terms of cost) alternative energy systems. The capability consists of a set of three computer programs, all developed around the same basic computational structure. The conceptual basis of the ESEA capability is described in The Cost of Energy from Utility-Owned Solar Electric Systems (JPL 5040-29, ERDA/JPL 1012-76/3), denoted hereafter as "USES." In particular, the ESEA capability utilizes the more flexible and generalized computational structure described in Appendix E of the USES document which incorporates a more explicit treatment of taxes and depreciation. The ESEA program set provides three related but separate capabilities: analysis of a single system, comparative analysis of two systems, and graphical representation of both parametric and continuous sensitivity analyses on a single system, comparative analysis of two systems, and graphical representation of both parametric and continuous sensitivity analyses on a single system. The single system analysis produces essentially the USES output with expanded

documentation. The program produces a printed summary that contains inputs, intermediate values, a capital expenditures table, life-cycle cost, net present value when applicable, and the busbar energy cost. The comparative analysis contrasts two system; for example, a system which utilizes conventional technology and a system which utilizes a new or alternative technology. For each system the program produces a printed summary in the same format as the single system analysis. In addition, the primary economic differences between the two systems are highlighted. The parametric representation provides a graphical presentation of continuous sensitivities on user-selected parameters over a selected range of values. In addition it optionally provides the single system analysis printed summary for the system in the "baseline" state before any sensitivities are performed. Collectively, the ESEA program package offers the analyst considerable flexibility, such as break-even system and subsystem capital costs, break-even fuel costs, evaluations of net present value and internal rate of return, and sensitivities of busbar energy costs to a large variety of factors.

TITLE: Technical Readiness 1982
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 31, 1979
REPORT NO: 5101-114

ABSTRACT: The need to find new methods to economically generate enough electrical power to meet future demand motivated the establishment of the PV Conversion Program in January 1975. The long range Program objectives developed are: (1) to develop the technology for low cost PV power and (2) to stimulate industry to produce, market, and distribute PV systems for widespread residential, commercial, and governmental use. The LSA Project was established at the JPL as part of the government's program. The Project goal is to greatly reduce the price of flat plate solar arrays by improving manufacturing technology, adapting mass production techniques, and promoting user acceptance. The Project's approach includes the development of improved solar array designs and manufacturing technologies, their transfer and deployment to commercial practice by industry, the evaluation of the economics involved, and the development of the necessary PV supply industry infra structure to ensure establishment of a viable source for solar electric energy systems. In October 1977, DOE was formed and the LSA Project become part of the solar energy activities of DOE. The breadth of the Project was expanded to include materials other than Si. The Project activities have been divided into four phases: technology process identification, process development (including quantity scale up), Technical Readiness, and commercial readiness. The first two phases have been completed and this document presents the plans for achieving Technical Readiness for Phase Three by the end of FY82.

TITLE: Price Allocation Guidelines
AUTHOR: R.W. Aster
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1980
REPORT NO: DOE-JPL 1012-47, and 5101-68 Rev. A

ABSTRACT: The PAGs are an integrated set of specific cost targets for several task areas within the LSA Project. PAG is a working tool of LSA Project management designed to provide consistent and meaningful guidelines for costs of polycrystalline Si material, sheet, cells, encapsulants, and module manufacturing. It is expected that advanced PV concepts derived from industry and the research community can be developed so that it will be possible by the end of 1982 to demonstrate production processes, all process steps, and prototype equipment required to manu facture flat-plate PV modules. This demonstration would incorporate production rates and product quality consistent with a specific market price determined by the program. This stage of development has been referred to as "Technical Readiness." A goal of $0.70/$W_p$ (1980 dollars) has been established for the cost of electricity generated by PV modules. The processes for producing modules demon strated to be technically ready must be amenable to scale up so that this price goal can eventually be achieved in the marketplace. The guidelines described in this docu ment allocate portions of that goal to each module compon ent. Sheet materials derived from the following five tech nologies are considered: Cz, HEM, EFG, dendritic web, and SOC. Each type of material provides a unique combination of projected Si yield, cell efficiency, and module packing efficiency. Also included are tables describing actual inflation rates form 1975 to 1979, and projected inflation rates to mid 1980. Project goals are now expressed in 1980 dollars rather than 1975 dollars, and these tables enable conversion of dollar amounts from prior years (1974-1980) to their 1980 or 1975 equivalents.

TITLE: Handbook of Solar Energy Data for South Facing Surfaces in the United States. Volume I: An Insolation, Array Shadowing, and Reflector Augmentation Model
AUTHOR: J.H. Smith
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1980
REPORT NO: DOE-JPL 1012-25 Vol. 1, and 5101-91 Vol. I

ABSTRACT: This handbook provides estimates of average available solar insolation to fixed, flat plate, south facing collector surfaces at various array tilt angles at numerous sites in the United States. This first volume contains average daily, total insolation estimates, by month, and annual totals for 235 locations. The second and third volumes contain the daily profiles by hour used to compute the daily totals for the 235 locations (at selected array tilt angles). A model that estimates the direct, diffuse, and reflected components of total insolation on an hourly, daily, and monthly basis is presented. A shadow loss model and a reflector augmentation model providing estimates of the losses and gains associated with various fixed array geometries are also described. These models can be used with the insolation model provided or with other recorded data. A FORTRAN computer program with users guide is presented. The program can be used to gen erate additional handbook values or to examine the effects of array shadowing and fixed reflector augmentation effects on a daily, monthly, or annual basis. Array shadowing de pends on location, array size, array tilt, array separa tion, and time. The program can be used to examine trade offs between array spacing and insolation losses due to shadowing. The reflector augmentation program can be used to examine trade offs among array size and tilt, separa tion, and reflector tilt to determine the combination of design values that optimize the economic objectives or technical criteria of the system.

TITLE: Handbook of Solar Energy Data for South Facing Surfaces in the United States. Volume II: Average Hourly and Total Daily Insolation Data for 235 Localities (Alaska Montana)
AUTHOR: J.H. Smith
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1980
REPORT NO: DOE-JPL 1012-25, and 5101-91

ABSTRACT: No Abstract

TITLE: Handbook of Solar Energy Data for South Facing Surfaces in the United States. Volume III: Average Hourly and Total Daily Insolation Data for 235 Localities (North Carolina-Wyoming)
AUTHOR: J.H. Smith
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 1980
REPORT NO: DOE-JPL-1012-25, and 5101-91

ABSTRACT: Appendix D of the three volume report A Handbook of Solar Energy Data for South-Facing Surfaces in the United States is presented in Volumes II and III. It gives

average hourly and daily total insolation estimates for 235 U.S. sites at a variety of array tilt angles. The reader should refer to Volume I for the insolation, array shadowing, reflector augmentation models, and the computer program used to generate this Appendix.

TITLE: SAMICS Input Data Preparation
AUTHOR: R.G. Chamberlain and R.W. Aster
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: April 21, 1980
REPORT NO: 5101-44, Rev. B

ABSTRACT: The SAMICS provides standard formats, data, assumptions, and procedures for estimating the price that a manufacturer would have to charge for the product of a specified manufacturing process sequence. This document gives a line by-line explanation of the standard formats that describe the economically important characteristics of the manufacturing processes and the technological structure of the companies and the industry. This revision provides an updated description of the data requirements of Release 3 of the SAMIS computer program. It also presents and describes the May 1980 versions of Format A - Process Description, Format B - Company Description, and Format C - Industry Description.

TITLE: Lifetime Cost and Performance Model for Distributed PV Systems
AUTHOR: C.S. Borden
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 1981
REPORT NO: 5220-12

ABSTRACT: This report summarizes a method that provides information on the performance, cost, and value of distributed PV systems over their useful lifetime. The LCP Model for Distributed PV Systems is a simulation model that has been developed to assist in the evaluation of utility grid connected PV power generators that range from small residential systems to intermediate and large size industrial/commercial applications. Dispersed PV systems that are utility grid interactive, but not utility owned, are evaluated because this configuration offers substantial benefits. In particular, non utility owners of qualifying energy generation facilities are able to sell electricity back to the interconnected utility at the utility's avoided cost for energy and capacity as recently allowed by Sections 201 and 210 of the Public Utility Regulatory Policies Act of 1978 Public Law 95 617. In order to evaluate PV technology development and applications, a sequence of models has been developed under the guidance of the Photovoltaics Technology Development and Applications Lead Center at JPL. LCP's function in this sequence of models is to: (1) simulate the energy output, and (2) derive the pre tax cash flows (expenditures and revenues) associated with dispersed PV systems over a specified lifetime. Results are then input into a financial model that translates this information, combined with additional investor and tax-related attributes, into various after tax financial figures of merit. When used in this manner, LCP is able to assist PV system designers, potential PV investors, and utility planners who determine cost effective PV designs and sizes, estimate energy output over time, investigate alternative operations/maintenance strategies, determine the effects of various utility pricing policies and interconnection requirements, and evaluate the effects of differing levels of customer demand for electricity. Further, these models provide the tools required by the Photovoltaics Program for an in depth understanding of system design and application alternatives and analysis of Program goals. The LCP model for distributed PV systems was created subsequent to the development of a model for the lifetime cost and performance of utility owned PV central power systems. A separate model for non utility owned systems has been formulated as dictated by the significant differences in required assumptions and analytical procedures for energy output and ownership factors. Most importantly, analysis of utility ownership of PV requires the direct evaluation (via utility production costing and capacity expansion simulation) of the economic value of PV system output. In contrast, the LCP model for distributed systems employs actual customer purchase and sell back rate schedules as set by each utility, which may be regarded as an indirect measure of PV system worth.

TITLE: A Normative Price for Energy from an Electricity Generation System: An Owner Dependent Methodology for Energy Generation (System) Assessment (OMEGA), Volume I: Summary
AUTHOR: R.G. Chamberlain (JPL), and K.M. McMaster (Loyola Marymount University, Los Angeles, California
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: October 15, 1981
REPORT NO: DOE ET 20356-5, JPL Pub. No. 81-86, 5220-7

ABSTRACT: This report presents a generalization and updating of the Utility-Owned Solar Electric System methodology, which is in widespread use throughout the energy generation systems analysis community. The major new contributions are these: (1) Relaxation of the ownership assumption (2) Removal of the constraint that all systems compared must have the same system lifetime. (3) Explicit treatment of residual system value at the end of system life. (4) Explicit treatment of variations in system performance with time. (5) Explicit treatment of tax incentives, including use of the investment as a tax shelter. Tax incentives incorporated include investment tax credits, solar tax credits, property tax rates, accelerated depreciation, and capital gains. (6) Incorporation of financial benefits of usable thermal energy, utility buy back (in parallel or simultaneous mode) of excess electricity generated, capacity displacement and fuel savings credits, and, where appropriate, roof credits. The new present value of the system, viewed as an investment, is determined by consideration of all financial benefits and costs (including a specified return on investment). Along the way, life cycle costs, life cycle revenues, and residual system values are obtained. Break even values of system parameters are estimated by setting the net present value to zero. While the model was designed for PV generators with a possible thermal energy byproduct, its applicability is not limited to such systems. The resulting Owner dependent Methodology for Energy Generation system Assessment (OMEGA) consists of a few equations that can be evaluted without the aid of a high speed computer. This report is published in two volumes. Volume I is a self contained summary, and can be thought of as a user's guide to the application of OMEGA. Volume II gives the complete derivation.

TITLE: SAMICS Short Course
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 1981
REPORT NO: 5101-196

ABSTRACT: This document contains viewgraphs used in the Short Course.

TITLE: Introduction to SIMRAND
AUTHOR: R.F. Miles, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: March 1982
REPORT NO: DOE JPL 1012-68, and 5101-204

ABSTRACT: SIMRAND is a methodology developed at JPL to aid the engineering and management decision process in the selection of the optimal set of systems of tasks to be funded on a R&D Project. A R&D project may have a set of systems or tasks under consideration for which the total cost exceeds the allocated budget. Other factors such as personnel and facilities may also enter as constraints. Thus the project's management must select, from among the complete set of systems or tasks under consideration, a partial set that satisfies all project constraints. The SIMRAND methodology uses analytical techniques of proba

bility theory, decision analysis of management science, and computer simulation, in the selection of this optimal partial set. The SIMRAND methodology is truly a management tool. It initially specifies the information that must be generated by the engineers--thus providing information for the management direction of the engineers--and it ranks the alternatives according to the preferences of the decision makers. The decision makers could be either the project's management, the funding agency, or the end users.

TITLE: The SIMRAND Methodology: SIMulation of Research ANd Development Projects
AUTHOR: R.F. Miles, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 1, 1982
REPORT NO: JPL 5101-213

ABSTRACT: SIMRAND is a methodology for aiding the management decision process in the selection of the optimal set of systems or tasks to be funded on a research and development project. The SIMRAND methodology models the decision process by means of alternative networks that represent the feasible subsets of systems or tasks that are to be considered. Each path through an alternative network represents one way of satisfying the project goals. Equations are developed that relate the system or task variables to the measure of preference. Uncertainty is incorporated by treating the variables of the equations probabilistically as random variables, with cumulative distribution functions assessed by technical experts. Analytical techniques of probability theory are used to reduce the complexity of the alternative networks. Cardinal utility functions over the measure of preference are assessed for the decision makers. A SIMRAND computer program is run, which combines in a Monte Carlo simulation model, the network structure, the equations, the cumulative distribution functions, and the utility functions. Repeated runs of the SIMRAND computer program are made for each of the alternative networks to determine the optimal subset of systems of tasks.

TITLE: Lifetime Cost and Performance Model
AUTHOR: M.C. Davisson, C.S. Borden, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 15, 1983
REPORT NO: 5220-20, JPL D 944

ABSTRACT: The LCP Model is a simulation program capable of modeling the lifetime performance of a PV array. The product of the LCP simulation is the electricity output, and cost and revenue streams from the systems operation. LCP calculation of system energy output is based on the systems electrical design, hourly weather conditions, and long-term variations in power output. Simulating the system's performance on an hourly basis makes it possible to calculate revenues under a time of day or a block rate schedule. This document is a practical guide to developing inputs for case studies and for program use. The general procedures for running the computer program, written in BASIC, are discussed. The document also includes a sample implementation of the program.

TITLE: Funding of Redundant R&D Tasks With Probabilistic Outcomes
AUTHOR: J.F. Bard
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: September 1, 1983
REPORT NO: JPL D 935, and 5101-240

ABSTRACT: A principal aspect of R&D management includes decisions of both task selection and resource allocation. Because individual task outcomes and cumulative project performance can never be predicted exactly, any attempt at a rigorous analysis must first confront the inherent uncertainties in the system. This paper specifically addresses the problem of funding redundant R&D tasks across several stages or parts of a project. Instead of simply defining a probability of success for each task and treating each stage separately, a stochastic network is proposed which takes into account the algebraic complexity of individual tasks as well as the interstage dependencies. Using the overall utility of the project outcome as the basic performance measure, the problem is first formulated as an integer program and then simplified to gain insight into possible solution techniques. Subsequently, an algorithm combining dynamic programming and simulation is developed to provide a near-optimal investment plan. Its computational implications and effectiveness are demonstrated by way of examples.

TITLE: A Probabilistic Analysis of Silicon Cost
AUTHOR: L.J. Reiter
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: November 15, 1983
REPORT NO: DOE/JPL 1012-93, JPL Pub. 84-94, 5101-246
AVAILABILITY: NTIS, PC A02/MF A01

ABSTRACT: Si materials costs represent both a cost driver and an area where improvement can be made in the manufacture of PV modules. This study analyzes the costs of three processes for the production of low-cost Si being developed under the DOE National PV Program. The approach is based on probabilistic inputs and makes use of two models developed at JPL: SIMRAND and IPEG. The approach, assumptions, and limitations are detailed in the study along with a verification of the cost analyses methodology. The results are presented in the form of cumulative probability distributions for Si cost. These results indicate that there is 55% chance of reaching the DOE target of $16/kg for Si material. This is a technically achievable cost based on expert forecasts of the results of ongoing research and development and do not imply any market prices for a given year.

TITLE: Summary of Photovoltaic System Performance Models
AUTHOR: J.H. Smith, and L.J. Reiter
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: January 15, 1984
REPORT NO: DOE/ET 20356-11, JPL Pub. No. 84-8, 5220-22

ABSTRACT: The purpose of this study is to provide a detailed overview of PV performance modeling capabilities that have been developed during recent years for analyzing PV system and component design and policy issues. A set of 10 performance models have been selected which span a representative range of capabilities from generalized first-order calculations to high specialized electrical network simulations. A set of performance modeling topics and characteristics is defined and used to examine some of the major issues associated with PV performance modeling. Next, each of the models is described in the context of these topics and characteristics to assess its purpose, approach, and level of detail. Then each of the issues is discussed in terms of the range of model capabilities available and summarized in tabular form for quick reference. Finally, the models are grouped into categories to illustrate their purposes and perspectives.

TITLE: Sensitivies of Projected 1990 Photovoltaic System Costs to Major System Cost Drivers
AUTHOR: L.W. Zimmerman, and J.L. Smith
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 15, 1984
REPORT NO: DOE/ET 20356-20, JPL Pub. No. 84-93, 5220-28

ABSTRACT: This report examines the sensitivity of projected 1990 PV system costs to major system cost drivers, including (1) module costs and module efficiencies, (2) area-related balance-of-system costs, (3) inverter costs and efficiencies, and (4) module marketing and distribution markups and system integration fees. The report reviews recent PV system cost experiences, illustrating the high costs of electricity from the systems. Based on a review of selected PV engineering literature, 1990

system costs are then projected for five classes of PV systems, including four ground-mounted 5-MW_p systems and one residential 5-kW_p system. System cost projections are derived by first projecting costs and efficiencies for all subsystems and components. Sensitivity analyses reveal that reductions in module cost (including marketing mark-ups) and engineering and system integration fees seem to have the greatest potential for contributing to system cost reduction. Although module cost is clearly the prime candidate for fruitful PV research and development activities, engineering and system integration fees seem to be more amenable to reduction through appropriate choice of system size and market strategy. Inverter costs are not as significant to total system costs as are other cost categories. But increases in inverter as well as module efficiency yield significant benefits, especially for systems with high area-related costs.

TITLE: Relative Potentials of Concentrating and Two-Axis Tracking Flat-Plate Photovoltaic Arrays for Central Station Applications. Issue Study
AUTHOR: C.S. Borden, and D.L. Schwartz
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 31, 1984
REPORT NO: DOE-ET 20356 22, JPL Pub. No. 85-16, 5230 15

ABSTRACT: The purpose of this study is to assess the relative economic potentials of concentrating and two axis tracking flat-plate PV arrays for central-station applications in the mid-1990's. Specific objectives of this study are to provide information on concentrator PV collector probabilistic price and efficiency levels to illustrate critical areas of R&D for concentrator cells and collectors, and to compare concentrator and flat plate PV price and efficiency alternatives for several locations, based on their implied costs of energy. To deal with the uncertainties surrounding research and development activities in general, a probabilistic assessment of commercially achievable concentrator PV collector efficiencies and prices (at the factory loading dock) is performed. The results of this projection of concentrator PV technology are then compared with a previous flat-plate module price analysis (performed early in 1983). To focus this analysis on specific collector alternatives and their implied energy costs for different locations, similar two axis tracking designs are assumed for both concentrator and flat-plate options. The results of this study provide the first comprehensive assessment of PV concentrator collector manufacturing costs in combination with those of flat-plate modules, both projected to their commercial potentials in the mid-1990's.

TITLE: CELLOPT: A Grid Optimization Design Program for PV Cells
AUTHOR: R.E. Daniel and T.S. Lee
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: June 15, 1985
REPORT NO: JPL D-2330, and 5101-266

ABSTRACT: CELLOPT is an interactive optimization program written in APL to run on the UNIVAC 1100/81 computer. It can assist a PV solar-cell engineer in the design of the current-collecting grid pattern used on solar cells. CELLOPT analyzes the parasitic resistance losses and shadow loss associated with the metallized grid pattern on both round and rectangular solar cells. It is assumed that the round cell has one or two bus bars; the rectangular cell can have any number. The fine grid lines are assumed to be perpendicular to the bus bars. CELLOPT calculates the dimensions of the chosen design variable to optimize the grid design. Thus, it will design a grid with minimum power loss. The designer has the option of choosing any two or all three of the following design variables to optimize his grid design: busbar width, grid line width and grid line spacing. The designer also has the option of having the bus bar of the same metal and thickness as the grid lines, or having the bus bar with a "strap"; i.e., with thicker metallization or a metallic ribbon. As with most optimization routines, a reasonable initial estimate of the solution is required. CELLOPT has a subroutine that allows the user to "bracket" the solution variables, and it calculates a best first guess, thus eliminating false starts.

TITLE: SAMICS: Cost Account Catalog, Version 5
AUTHOR: L.J. Reiter, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 15, 1985
REPORT NO: JPL D 2491, and 5101-273

ABSTRACT: This revision of the SAMICS Cost Account Catalog was done for release in conjunction with the SAMICS PC computer program. The main focus of this effort was to bring cost and inflation data up to date. Not every item in the catalog was adjusted. Priority first was given to those costs that have major impact on the final product cost, and second to those items that are most often used in SAMICS runs. The inflation rates, however, have been adjusted on all of the items in the catalog. A general baseline inflation rate of 5% has been used throughout the catalog, with certain specific items given different rates as appropriate. Certain commodities in the catalog are meant to be input directly as solar values (e.g., item E12568, Expendable Tools). It is crucial to the accuracy of the results that the user bear the base year in mind when making cost inputs. In the past the base year for all dollar inputs was 1975. This has been changed to 1982. Adjustments will be necessary if the user does not have data in 1982 dollars for these inputs.

TITLE: A Sensitivity Analysis of Central Station Flat Plate PV Systems and Implications for National PV Program Planning
AUTHOR: M.R. Crosetti, et al.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: August 30, 1985
REPORT NO: DOE JPL 1012 114, JPL Pub. 85-92, 5101-265

ABSTRACT: The purpose of this study is to explore the sensitivity of the National PV Research Program goals to changes in individual PV system parameters. Using the relationship between lifetime cost and system performance parameters, tests were made to see how overall PV system energy costs are affected by changes in the goals set for module cost and efficiency, system component costs and efficiencies, operation and maintenance costs, and indirect costs. The results are presented in tables and figures for easy reference. An analysis is made of the effects of regional differences in competing energy costs and solar insolation levels on the competitiveness of PV systems. The sensitivity of competing energy costs (coal, combustion turbine, and combined cycle oil-fired generators) to escalation rates for capital and fuel are explored. Alternative tracking configurations (fixed, one axis, and two-axis tracking) are also introduced into the sensitivity analysis. Goal values for PV systems parameters were reviewed on the basis of the most recent research findings. Sensitivity tests were made to see how research progress in areas such as power related balance of-system cost affected the combinations of module cost and module efficiency that meet program goals for system energy costs.

TITLE: Standard Assembly Line Manufacturing Industry Simulation (SAMIS) PC User's Guide, SAMIS Release 6.0
AUTHOR: S.C. Zendejas, R.G. Chamberlain, and R.E. Daniel
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: December 1985
REPORT NO: 5101-285, JPL D-2991

ABSTRACT: All versions of the SAMIS program contained in this package (SAMIS, SAMPEG, and IPEG) produce estimates of the price a manufacturer would have to receive for its product to recover all of the costs of production and make a specified profit. The SAMIS version provides the most

detailed analysis of production costs. A hypothetical factory, based on a detailed set of manufacturing process descriptions provided by the user, is "built." To simulate the facility's performance, an appropriate workforce is determined which consists of a complete staff, including administrators and managers. The cost of labor along with materials, building space and utilities are taken from a supporting cost account catalog which can be augmented by the user to support any particular study. A detailed financial model is applied to determine the annual costs of operation including depreciation, insurance, taxes, annual costs of operation, including depreciation, insurance, taxes, amortization of startup costs, and so on. Because the SAMIS model is so detailed, a run can be expected to take a few hours. After the computations have been completed, an extensive set of output reports, including year-by year financial reports for the hypothetical company, is available. SAMPEG is a simplified version of SAMIS which has become the usual way to run the program. It takes only a few minutes to run, but the reports available are significantly less detailed. They consist of a summary cost estimate for the hypothetical company and each of its manufacturing processes. IPEG, which can be accessed after choosing to START SAMIS, provides for rapid sensitivity studies of the effects of financial parameters. Price estimates calculated with either SAMPEG or IPEG will approximate a SAMIS estimate. SAMPEG combines the data manager (editor) and manufacturing process sequencing algorithm from SAMIS with the factory construction, staffing approximations and financial submodels of IPEG. IPEG uses overhead factors to convert direct input costs to total costs. It provides for rapid sensitivity studies of the effects of financial parameters on the cost estimates. The purpose of this document is to provide you with a stand alone description of everything you need to know to use SAMIS PC.

TITLE: The SIMRAND 1 Computer Program
AUTHOR: R.F. Miles, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 15, 1986
REPORT NO: DOE-JPL 1012-115, JPL Pub. 85-96, 5101-274

ABSTRACT: SIMRAND is a methodology for the selection of the optimal subset of systems or tasks to be implemented on a R&D project. The SIMRAND methodology models the alternative subsets of systems or tasks under consideration with alternative networks. Each path through an alterna tive network represents one way of satisfying the Project goals. Equations are developed that relate the system or task variables to the measure of preference. Uncertainty is incorporated by treating the variables of the equations probabilistically as random variables, with associated cumulative distribution functions. Cardinal utility func tions are assessed over the measure of preference. The SIMRAND I Computer Program is run for each alternative network, incorporating the network structure, the equa tions, the cumulative distribution functions, and the utility functions in a Monte Carlo simulation model. The alternative network yielding the most preferred value for the measure of preference, or the highest utility function value, is the optimal network. This Report documents the SIMRAND I Computer Program (Version 5.0 x 03) written in Microsoft FORTRAN for the IBM PC microcomputer and its com patibles. The SIMRAND I Computer Program comprises eleven modules a main routine and ten subroutines. Two addition al files are used at compile time, one inserts the system or task equations into the source code, while the other inserts the dimension statements and common blocks. The SIMRAND I Computer Program can be run on most microcom puters or mainframe computers with only minor modifications to the computer code.

TITLE: The RANDOM Computer Program
AUTHOR: R.F. Miles, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 15, 1986
REPORT NO: DOE-JPL 1012-116, JPL Pub. 85-97, 5101-275

ABSTRACT: The RANDOM Computer Program is a FORTRAN program for generating random number sequences and testing LCGs. This document discusses the linear congruential form of a random number generator, and describes how to select the parameters of an LCG for a microcomputer. This document describes the following: the RANDOM Computer Program; RANDOM.MOD, the computer code needed to implement an LCG in a FORTRAN program; and The RANCYCLE and the ARITH Com puter Programs that provide computational assistance in the selection of parameters for an LCG. The RANDOM, RANCYCLE, and ARITH Computer Programs are written in Microsoft FORTRAN for the IBM PC microcomputer and its compatibles. With only minor modifications, the RANDOM Computer Program and its LCG can be run on most micro computers or mainframe computers.

TITLE: The SIMRAND Methodology
AUTHOR: R.F. Miles, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: February 15, 1986
REPORT NO: DOE-JPL 1012-117, JPL Pub. 85-98, 5101-277

ABSTRACT: A R&D project often involves a number of deci sions that must be made concerning which subset of systems or tasks are to be undertaken to achieve the goal of the R&D Project. To help in this decision making, SIMRAND is a methodology for the selection of the optimal subset of systems or tasks to be undertaken on an R&D Project. Using alternative networks, the SIMRAND methodology models the alternative subsets of systems or tasks under considera tion. Each path through an alternative network represents one way of satisfying the project goals. Equations are developed that relate the system or task variables to the measure of preference. Uncertainty is incorporated by treating the variables of the equations probabilistically as random variables, with cumulative distribution functions assessed by technical experts. Analytical techniques of probability theory are used to reduce the complexity of the alternative networks. Cardinal utility functions over the measure of preference are assessed for the decision makers. A run of the SIMRAND Computer I Program combines, in the Monte Carlo simulation model, the network structure, the equations, the cumulative distribution functions, and the utility functions. Repeated runs of the SIMRAND I Computer Program are made for each of the alternative net works to determine the optimal subset of systems of tasks. The SIMRAND methodology has been used by JPL, SERI, and DOE for the evaluation of solar-energy R&D projects.

TITLE: SAMICS Abridged Cost Account Catalog, Rev. 1
AUTHOR: R.W. Aster, R.G. Chamberlain, and B.L. Jackson
CORPORATE AUTH: Jet Propulsion Laboratory
DATE: July 10, 1986
REPORT NO: DOE-JPL 5101-299, JPL D-3491

ABSTRACT: The Abridged Cost Account Catalog supports SAMICS users with a list of expense items that are commonly used as direct inputs by manufacturing processes. The direct inputs are used in the preparation of Format A manufacturing process descriptions. Format As are used to run the SAMIS computer program or the IPEG model when developing production cost estimates. Direct inputs for the abridged catalog were taken from Version 5 of the complete SAMICS Cost Account Catalog which was updated and revised on July 15, 1985. The catalog contains a complete, alphabetized list of facilities, personnel, utilities, byproducts, effluents, and commodities which has been developed over the years in support of SAMICS users. The abridged catalog is like the complete catalog except that items which serve only as indirect requirements for manufacturing processes are excluded from the abridged catalog. Nevertheless, users of the SAMIS computer program will find that tae indirect cost elements are automatically accounted for. Users of the SAMIS computer program have a complete cost account catalog available including indirect requirements.

PROJECT ANALYSIS AND INTEGRATION
CONTRACTOR ABSTRACTS

PROJECT ANALYSIS AND INTEGRATION CONTRACTOR ABSTRACTS

TITLE: A Critical Review of SAMICS
CORPORATE AUTH: Theodore Barry & Associates
DATE: July 1977
REPORT NO: DOE-JPL 954800-77/1

ABSTRACT: This report documents the findings, analysis, and recommendations of the SAMICS critique. The SAMICS model is designed to compare the cost of producing solar arrays using alternative manufacturing processes. The critique focuses on three main elements of the SAMICS procedure: 1) Workbook format and presentation, 2) Theoretical model validity, and 3) Standard financial parameters. The SAMICS model is an excellent mathematical formulation; however the workbook presentation is too theoretical for a practical application procedure.

TITLE: SAMICS Support Study: Cost Account Catalog
CORPORATE AUTH: Theodore Barry & Associates
DATE: September 1977
REPORT NO: DOE-JPL 954800-77/2.1

ABSTRACT: A standardized costing procedure has been developed to assist JPL in examining the feasibility of new industry to produce PV solar energy collectors similar to those used on spacecraft. The name of the costing procedure is SAMICS. Volume I contains a description of the cost account structure and the cost account catalog. Volume II presents several submodel analyses, including the indirect requirements relationships, facilities capital cost estimating one-time costs. Volume III contains conceptual plant designs and the corresponding manufacturing price estimates for three alternative levels of solar array production: .5, 15, 500 MW of peak capacity/yr.

TITLE: SAMICS Cost Account Catalog
CORPORATE AUTH: Theodore Barry & Associates
DATE: April 1978
REPORT NO: DOE-JPL 954909-78/1

ABSTRACT: The Cost Account Catalog contains a list of all items that may be required directly or indirectly, by a solar array manufacturing firm. The list includes a catalog number, a name, and a unit of measure for each item. Where appropriate, it also provides price information (price year, inflation rate, and either a price or a price versus quantity table). The catalog expense items are organized into 6 accounts: (1) facilities parameters, (2) personnel, (3) utilities and plant services, (4) by products, (5) commodities, and (6) resources.

TITLE: SAMICS Marketing & Distribution Model
CORPORATE AUTH: Theodore Barry & Associates
DATE: April 1978
REPORT NO: DOE-JPL 954909-78/2

ABSTRACT: This report presents a model for computing marketing and distribution costs. This marketing and distribution model is a simplification intended to recognize the added costs of marketing and transporting the solar arrays from the factory to the customer. The model covers selling, transportation, and storage costs in transit from the loading dock to the point of use.

TITLE: Lifetime Cost and Performance Model Support Study
CORPORATE AUTH: Theodore Barry & Associates
DATE: September 1978
REPORT NO: DOE-JPL 955161-78/01

ABSTRACT: This report represents the first definitive work that details PV central power plant installation, operation, and maintenance activities, thus avoiding the necessity to appeal to "rules of thumb" derived from experience with other types of power plants.

TITLE: Industrialization Study
CORPORATE AUTH: Gnostic Concepts, Inc.
DATE: September 1978
REPORT NO: DOE-JPL 954899-78/3

ABSTRACT: Information concerning the investment process within the US industry was collected. Emphasis was placed upon characterizing the critical elements in major high-risk investment decisions by industry. The relationship between these critical elements was interpreted as to how they influence the investment decision outcome. The results of this analysis found wide differences between companies in the manner in which evaluation criteria are applied. Even within similar industrial sectors, totally different behavior patterns were observed. Motivation was determined to be the greatest single force to induce a company to invest in a high-risk venture. The higher the motivation, both financial and personal, the greater the risk a company is prepared to accept in a new investment. The effect of government actions upon these motivations and the degree of risk acceptance by industry is discussed on a qualitative as well as a quantitative basis. The relative impact of alternative government programs and policies upon industry motivations, with its resulting impact upon PV industrialization, is assessed. This assessment is based upon field interviews with a cross-section of industry decision-makers to solicit their attitudes toward alternative government programs and policies. The government alternatives have been ranked on the basis of their ease of implementation and their probable impact. A commentary is included on the recommended sequence in which these government policies should be applied to maximize the industrialization of the PV venture.

TITLE: Industrialization Study
CORPORATE AUTH: Gnostic Concepts, Inc.
DATE: January 1979
REPORT NO: DOE-JPL 954899-78/6

ABSTRACT: Areas covered in this report include the technical assessments of selected advanced technologies. Information collected was in the area of manufacturing process steps and their implications on cell performance, along with present and future expected performance characteristic. A summary of the technical and manufacturing barriers and a summary of other influences is provided. A comparative assessment of the advanced technology bases was also constructed. It consists of comparing each of the advanced technologies to the present-day single crystal Si wafer technology that dominates commercial activities today and a comparison of the advanced technologies to each other. From this was extracted those technologies of industrialization efforts. A rank ordering of the advanced technologies is provided. The various ranking schemes were based upon present-day efficiency levels, their stability and long-term reliability prospects, material production level, and associated variable costs. A final selection was made of those advanced PV technologies that have a high potential for industrialization prospects and an estimate of the timing of the possible readiness of these advanced technologies for technology development programs and industrialization.

TITLE: Final Report. SAMICS Support Study, Phase III
CORPORATE AUTH: Theodore Barry & Associates
DATE: April 1979
REPORT NO: DOE-JPL 955123-79/1

ABSTRACT: This is a review and validation of the SAMICS model. The purposes for this review were the following: a) To test the computational validity of the computer model by comparison with preliminary TB&A hand calculations based on conventional cost estimating techniques; b) To review and improve the accuracy of the cost relationships being used by the model; and c) To provide an independent verification to users of the model's value in decision making for allocation of research and development funds and for investment in manufacturing capacity. This

report provides the basis for our conclusions. It also contains recommendations for increasing the usefulness of SAMICS. The purpose of SAMICS is to provide a consistent basis for estimating array costs and comparing production technology costs. The user of SAMICS provides detailed process information for calculating direct cost. To these are added indirect and overhead expenses. Although documentation of direct processes requires a significant initial effort, the process gives SAMICS its primary strength. A complete accounting of direct process resource requirements establishes an audit trail that will help to monitor the realism of assumptions before production and to later identify variations from forecasted operating parameters after production begins. SAMICS will be valuable to the LSA Project in monitoring program objectives. It integrates all the production processes involved in module manufacturing. Thus, technology transfer from task to task and to manufacturers under contract, followed by audits of operations, should help JPL's decision makers to allocate research funds more effectively to the lowest cost technologies. Some limitations of SAMICS should be noted. There are three components of profit that the model calculates. The first is the conventional profit after tax in the accounting sense. The other two are amortized one-time costs and return on equity. Output formats should indicate that all three of these are returns on the capital investment. The SAMICS model calculates annual operating expense based on a steady state condition following a number of years of operation. In addition to these steady state operating costs, initial start-up costs are computed and amortized over the economic life of the facilities. The user should be aware of the difference that the two lifetimes may have on product price.

PROCEEDINGS AND
PUBLISHED DOCUMENTS

TITLE: Evaluation of Silicon Ribbon Material for Solar Cell Fabrication
AUTHOR: M. Leipold, R. Stirn, J. Zoutendyk, and R. DeAngelis
CORPORATE AUTH: Jet Propulsion Laboratory; University of Kentucky, Lexington, Kentucky
MEETING LOCATION: 11th IEEE Photovoltaic Specialists Conference, Scottsdale, Arizona, May 6-8, 1975, Conference Record. (A76-14727 04-44) New York, 1975, p. 290-298

ABSTRACT: Optical microscopy, electron microscopy, and x-ray diffraction were utilized to characterize Si ribbon structure. Complex twin formation was observed in nearly all ribbons examined. Twins formed in the 110-plane 112-line ribbon orientation appear stable, and this orientation may be preferable when the ribbon is utilized for solar cells. In addition to twinning, grain boundaries and other structural defects were observed in the ribbon material. Hall effect, resistivity, spreading resistance, surface photovoltage, and solar cell electrical/optical measurements were performed on ribbon samples and correlated with structural and ribbon growth characteristics. Only those ribbon samples with either single crystal structure or with parallel twin formations were capable of solar-cell performance approaching that of Cz material.

TITLE: EFG Silicon Ribbon Solar Cells
AUTHOR: K.V. Ravi, H.B. Serreze, H.E. Bates, A.D. Morrison, D.N. Jewett, and J.C.T. Ho
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: 11th IEEE Photovoltaic Specialists Conference, Scottsdale, Arizona, May 6-8, 1975, Conference Record. (A76-14727 04-44) New York, 1975, p. 280-289

ABSTRACT: The growth and characteristics of EFG Si ribbons are discussed. Factors involved in the growth of continuous lengths of 1 in. wide ribbons are examined. The structural and electrical characteristics of the ribbons have been studied and the results are presented. Solar cells have been fabricated using the ribbon crystals and typical AMO efficiencies of 6 to 10% have been realized.

TITLE: Grain Boundary and Impurity Effects in Low Cost Silicon Solar Cells
AUTHOR: S.I. Soclof and P.A. Iles
CORPORATE AUTH: Optical Coating Laboratory, Inc., City of Industry, California
MEETING LOCATION: 11th IEEE Photovoltaic Specialists Conference, Scottsdale, Arizona, May 6-8, 1975, Conference Record. (A76-14727 04-44) New York, 1975, p. 56-61

ABSTRACT: Low-cost approaches to solar-cell manufacture probably require the use of Si with reduced crystalline perfection and higher concentrations of impurities. This paper describes experimental work to evaluate the separate effects of grain boundaries and high impurity concentrations on PV performance. Theoretical estimates are presented to indicate the conversion efficiency expected for Si solar cells if reasonable control of both the grain size and impurity levels can be achieved.

TITLE: Dendritic Web - A Viable Material for Silicon Solar Cells
AUTHOR: R.G. Seidensticker, L. Scudder, and H.W. Brandhorst, Jr.
CORPORATE AUTH: Westinghouse Research Laboratories, Pittsburgh, Pennsylvania; NASA Lewis Research Center, Cleveland, Ohio
MEETING LOCATION: 11th IEEE Photovoltaic Specialists Conference, Scottsdale, Arizona, May 6-8, 1975, Conference Record. (A76-14727 04-44) New York, 1975, p. 299-302

ABSTRACT: The dendritic web process is a technique for growing thin-silicon ribbon from liquid Si. The material is suitable for solar cell fabrication and, in fact, cells fabrication on web material are equivalent in performance to cells fabricated on Cz-grown material. A recently concluded study has delineated the thermal requirements for Si web crucibles, and a detailed conceptual design has been developed for a laboratory growth apparatus.

TITLE: Electron and Proton Damage Coefficients in Low-Resistivity Silicon
AUTHOR: J.R. Srour, S. Othmer, and K.Y. Chiu
CORPORATE AUTH: Northrop Research and Technology Center, Hawthorne, California
PUBLICATION: (Institute of Electrical and Electronics Engineers, Annual Conference on Nuclear and Space Radiation Effects, 12th, Arcata, California, July 14-17, 1975.) IEEE Transactions on Nuclear Science, vol. NS-22, Dec. 1975, p. 2656-266

ABSTRACT: The electron and proton damage coefficients for low resistivity p-type boron-doped Si were determined from minority-carrier lifetime measurements on bulk material and diffusion length measurements on solar cells. The bulk samples were irradiated with electrons at three energy levels (0.5, 1.5, and 2.5 MeV) using a Dynamitron. Life time measurements were made with a steady-state photoconductivity apparatus, and comparison measurements of diffusion length were obtained using the steady-state surface photovoltage method (Goodman, 1961). The diffusion-length damage coefficients increased with decreasing resistivity for boron-doped Si; this dependence can be qualitatively accounted for using a two-level Hall-Shockley-Read model. The damage coefficients for solar cells were larger than for their bulk-material counterparts. The damage coefficient was apparently independent of the dislocation density in the 0.1 ohm-cm bulk samples and solar cells investigated.

TITLE: The Silicon Ribbon Solar Cell
AUTHOR: K.V. Ravi and A.I. Mlavsky
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: Heliotechnique and Development; Proceedings of the International Conference, Dhahran, Saudi Arabia, November 2-6, 1975. Volume 1. (A77-19043 06-44) Cambridge, Massachusetts, Development Analysis Associates, Inc., 1976, p. 563-587

ABSTRACT: The technique of growing ribbon shaped crystals of Si by the EFG process is discussed. A discussion of the growth process is followed by an analysis of the ribbon quality. A detailed economic analysis indicates that low cost PV systems can be realized through the use of this technology.

TITLE: Maximum Growth Rates for Melt-Grown Ribbon-Shaped Crystals
AUTHOR: T.F. Ciszek
CORPORATE AUTH: International Business Machines Corp., Hopewell Junction, New York
PUBLICATION: Journal of Applied Physics, vol. 47, Feb. 1976, p. 440-442.

ABSTRACT: From heat-balance considerations at the growing interface and an assumption of predominantly radiative heat loss from the surface, an expression for the maximum growth rate of melt-grown ribbon-shaped crystals has been derived.

For a given material and a large width-to thickness ratio, the maximum growth rate varies as the square root of the ribbon thickness and is independent of its width. A comparison of the maximum cylindrical and ribbon growth rates is made for the silicon system. Some representative values at 7.5 cm diameter or width are 45 cm/h or 2000 cu cm/h for a cylindrical Cz-grown crystal and 625 cm/h or 95 cu cm/h for a 0.02-cm-thick ribbon.

TITLE: Silicon Solar Cell Development
AUTHOR: M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
MEETING LOCATION: International Conference on Solar Electricity, Toulouse, France, March 1-5, 1976, Reports. (A77-21776 08-44) Toulouse, Centre National d'Etudes Spatiales, 1976, p. 113-140

ABSTRACT: The paper takes a look at some of the main fronts on which effort in Si solar cell development is being focused. These are the improvement of collection efficiency and of the current-voltage characteristic; increasing the production rate of solar arrays; and the search for large-scale low-cost production methods. At present there is a problem with the low open circuit voltage attainable on Si solar cells, and some of the possible causes under investigation are indicated. Several approaches to obtaining low cost silicon of adequate purity are outlined. Estimates of the required capital for plant and equipment to provide for given planned production rates are made.

TITLE: Multi-Crystal Silicon Solar Cells Fabrication by Czochralski Method
AUTHOR: J. Lin, J.W. Faust, Jr., and R.B. Hilborn
CORPORATE AUTH: University of South Carolina, Columbia, South Carolina
MEETING LOCATION: Engineering in a Changing Economy; Proceedings of the Southeast Region 3 Conference, Clemson, South Carolina, April 5-7, 1976. (A76-47201 24-99) New York, Institute of Electrical and Electronics Engineers, Inc., 1976

ABSTRACT: This paper reports results of an investigation into the growth and processing of polycrystalline Si for use in the fabrication of PV devices. A discussion is presented on the growth conditions to be established for obtaining large-grain polycrystalline Si from a Cz puller. Output characteristics are given for multicrystal solar cells fabricated from Cz-grown polycrystalline ingots. A comparison is made between these curves and simple theoretical relations to relate their features to the physical aspects of the solar cells.

TITLE: Purification of Metallurgical-Grade Silicon to Solar-Grade Quality
AUTHOR: L.P. Hunt, V.D. Dosaj, J.R. McCormick, and L.D. Crossman
CORPORATE AUTH: Dow Corning Corp., Hemlock, Michigan
MEETING LOCATION: International Symposium on Solar Energy, Washington, D.C., May 5-7, 1976, Proceedings. (A76-47051 24-44) Princeton, New Jersey, Electrochemical Society, Inc., 1976, p. 200-215

ABSTRACT: Selection of raw materials, improvements in the arc furnace process, acid leaching, and unidirectional solidification are examined as possible methods of removing impurities in metallurgical-grade Si (MG-Si) to obtain material suitable for production of solar cells. Use of purer raw materials is particularly important in regard to boron and phosphorus impurities, since it is the only means currently considered for reducing the concentrations of these elements. Replacement of as many of the reductants as possible by charcoal is also being investigated as an effective means of lowering the amount of impurities entering through the arc furnace process. Iron and aluminum can both be reduced by an order of magnitude by acid leaching MG-Si. Final purification to solar-grade Si occurs effectively during crystal growth because of the small segregation coefficients of aluminum and transition elements. It thus appears possible to attain the goal of $10/Kg for solar-grade Si by pulling single-crystal ingot from chemically upgraded MG-Si by the advanced Cz technique.

TITLE: Continuous Silicon Ribbon Growth for Possible Solar Cell Application
AUTHOR: A.D. Morrison, D.N. Jewett, B.H. Mackintosh, W.T. Little, V.E. White, and D.A. Yates
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: International Symposium on Solar Energy, Washington, D.C., May 5-7, 1976, Proceedings. (A76-47051 24-44) Princeton, New Jersey, Electrochemical Society, Inc., 1976, p. 216-226

ABSTRACT: Single crystal Si ribbon suitable for solar cell use has been grown continuously by the EFG method. Both induction and resistance heated growth systems were used. These continuous ribbon growth systems and specific EFG growth set-up components are described. The growth process is also described

TITLE: Electrical Effects of SiC Inclusions in EFG Silicon Ribbon Solar Cells
AUTHOR: C.V. Rao, H.E. Bates, and K.V. Ravi
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts)
PUBLICATION: Journal of Applied Physics, vol. 47, June 1976, p. 2614-2619

ABSTRACT: The electrical effects of included Si carbide (SiC) particles in edge defined film-fed grown Si ribbons have been examined. By employing a scanning electron microscope operated in the electron-beam-induced current mode, as well as observing the effects of SiC particles on solar-cell characteristics, the electrical activity of particles and particle-generated defects were studied. The influence of SiC particles largely appears to be a result of impurity accumulation around them rather than a direct effect of the inclusions.

TITLE: Thermal Emission Rates and Activation Energies of Electrons at Tantalum Centers in Silicon
AUTHOR: K. Miyata and C.T. Sah
CORPORATE AUTH: Hitachi, Ltd., Ibarki, Japan; University of Illinois, Urbana, Illinois
PUBLICATION: Solid-State Electronics, vol. 19, July 1976, p. 611-613

ABSTRACT: The thermal emission rates and activation energies of electrons trapped at the two Ta donor centers in n-type Si are determined from transient capacitance measurements on Schottky barrier diodes made on phosphorus and tantalum doubly doped Si crystals. The thermal activation energies are 232 and 472 MeV for the two donor levels below the conduction band edge and the pre exponential factors, A, are both 15 billion/sec in the Arrhenius equation for the emission rate.

TITLE: Outdoor Weathering Performance of Solar Electric Generators
AUTHOR: C.R. Maag, Jr.
CORPORATE AUTH: Mega Analytical Research Services, Inc., Silver Spring, Maryland
PUBLICATION: American Institute of Aeronautics and Astronautics, Thermophysics Conference, 11th, San Diego, California, July 14-16, 1976, 11 p.

ABSTRACT: An investigation was conducted to determine the effects of outdoor exposure on the performance of commercially available PV terrestrial power systems and encapsulant materials. The experimental program involved one year of continuous exposure (real time), preceded and followed by both spectral transmission and electrical output measurements on the cover materials and solar cell modules, respectively. Parameters considered were solar radiation at the test site, temperature effects, dirt, rain, snow and unwelcome migratory birds. Results indicate that the solar cell modules encapsulated in polycarbonate are considerably more protective to the environment than those covered with silicone rubber. Many of the exposed encapsulant materials showed large amounts of degradation in spectral transmission. FEP Teflon showed no damage after environmental exposure.

TITLE: Development of Low-Cost Silicon Crystal Growth Techniques for Terrestrial Photovoltaic Solar Energy Conversion
AUTHOR: J.A. Zoutendyk
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Sharing the Sun: Solar Technology in the Seventies; Proceedings of the Joint Conference, Winnipeg, Canada, Aug. 15-20, 1976. Volume 6. (A77-48910 23-44) Cape Canaveral, Florida, International Solar Energy Society, 1976, p. 34-47

ABSTRACT: Because of the growing need for new sources of electrical energy, PV solar energy conversion is being developed. PV devices are now being produced mainly from silicon wafers obtained from the slicing and polishing of cylindrically shaped single crystal ingots. Inherently high-cost processes now being used must either be eliminated or modified to provide low-cost crystalline Si. Basic to this pursuit is the development of new or modified methods of crystal growth and, if necessary, crystal cutting. If Si could be grown in a form requiring no cutting, a significant cost saving would potentially be realized. Therefore, several techniques for growth in the form of ribbons or sheets are being explored. In addition, novel techniques for low-cost ingot growth and cutting are under investigation.

TITLE: Design Considerations of Solar Arrays for Terrestrial Applications
AUTHOR: R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Sharing the Sun: Solar Technology in the Seventies; Proceedings of the Joint Conference, Winnipeg, Canada, Aug. 15-20, 1976. Volume 6. (A77-48910 23-44) Cape Canaveral, Florida, International Solar Energy Society, 1976, p. 48-56

ABSTRACT: The primary objective of the LSSA Project, which forms a major part of a national PV program, is the timely development of low-cost commercial-quality PV arrays through an active program of industrial and academic involvement. The definition of future array requirements is considered as a necessary step toward meeting this objective. An overview of array requirement trends which begin to evolve from the various ERDA activities is presented. For present terrestrial arrays the primary requirement is to generate power for small, often remote electric-power applications. To meet an objective of increased energy independence requires that PV become economically viable for the large energy consumption of the future. Various developments needed to achieve such an economic viability are discussed.

TITLE: EFG Growth of Silicon Ribbon for Solar Cells
AUTHOR: K.V. Ravi and A.I. Mlavsky
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: Sharing the Sun: Solar Technology in the Seventies; Proceedings of the Joint Conference, Winnipeg, Canada, Aug. 15-20, 1976. Volume 6. (A77-48910 23-44) Cape Canaveral, Florida, International Solar Energy Society, 1976, p. 23-33

ABSTRACT: The paper reviews the status of the EFG process for producing ribbon-shaped crystals of Si for solar cell applications. Attention is given to equipment, cost and ribbon-quality considerations along with crystal growth characteristics. Solar cells in two sizes have been fabricated from the Si ribbons: 1 cm x 2 cm and 1 in x 4 in. Cell efficiencies are in the 7-12% (AM1) range, with the larger area cells exhibiting the lower efficiencies.

TITLE: Consideration of Encapsulants for Photovoltaic Arrays in Terrestrial Applications
AUTHOR: E.F. Cuddihy and W.F. Carroll
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Optics in Solar Energy Utilization II; Proceedings of the Seminar, San Diego, California, August 24, 25, 1976. (A77-29576 12-44) Palos Verdes Estates, California, Society of Photo-Optical Instrumentation Engineers, 1977, p. 16-22

ABSTRACT: Long-term survivability of PV arrays and components in terrestrial environments will require development of adequate protective systems. Highly considered are polymeric encapsulants, a method which was successfully employed in space and aerospace applications to protect critical electrical circuitry. To be employable, however, the polymer encapsulants must themselves be chemically and mechanically resistant to failure in terrestrial service. Chemical resistance includes stability to the degrading actions of UV light, oxygen, moisture and elevated temperatures in sun rich areas. Programs are underway to identify and develop chemically stable encapsulant candidates. Chemical considerations aside, mechanical failures of the encapsulants must also be avoided in array designs. This paper discusses design considerations for avoiding mechanical failures of polymeric encapsulants, with emphasis on biaxial properties, thermal fatigue, and anisotropy and nonhomogeneity of material properties. The general principles to be presented evolved from actual failures of polymeric materials in engineering applications. Also included are brief remarks on the permeability of polymer materials to atmospheric gases.

TITLE: Orientation Dependence of Defect Structure in EFG Silicon Ribbons
AUTHOR: L.C. Garone, C.V.H. Rao, A.D. Morrison, T. Surek, and K.V. Ravi
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
PUBLICATION: Applied Physics Letters, vol. 29, Oct. 15, 1976, p. 511-513

ABSTRACT: Sustained growth of long lengths of Si ribbons by the EFG technique is shown to result in the attainment of an 'equilibrium' defect structure and orientation by the crystals. The structure consists of parallel defect boundaries parallel to the edges of the ribbon with a specific ribbon orientation. The influence of seed orientation on the attainment of this structure has been examined.

TITLE: Materials for Encapsulation Systems for Terrestrial Photovoltaic Arrays
AUTHOR: D.C. Carmichael, G.B. Gaines, F.A. Sliemers, and C.W. Kistler
CORPORATE AUTH: Battelle Columbus Labs., Ohio

MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 317-331

ABSTRACT: The paper is concerned with glass and polymeric candidate materials and processes for potential encapsulation systems that could be used in low-cost long-life terrestrial PV arrays. The characteristics of encapsulation systems in use are reviewed, and the properties of proposed materials are examined. These materials include acrylics, epoxies, fluorocarbons, polycarbonates, polyesters, polyimides, polyxylylenes, and silicones. Properties of glass types are also considered. The prospects for glass and polymeric systems are analyzed, and the knowledge gained from a study of existing systems is discussed with attention to weather/aging effects, failures, environments, hazards, costs, development efforts, and materials choices.

TITLE: Total Energy Use in the Production of Silicon Solar Cells from Raw Materials to Finished Product
AUTHOR: L.P. Hunt
CORPORATE AUTH: Dow Corning Corp., Hemlock, Michigan
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10901 01-44) New York, 1976, p. 347-352

ABSTRACT: The total energy required to produce Si solar cells from the raw material SiO_2 is estimated. Metallurgical-grade Si, semiconductor-grade trichlorosilane, polycrystalline semiconductor-grade Si, and Si solar cells are considered in terms of the process energy required to produce them and in relation to the total energy expended in their manufacture. The energy payback times using present technology is 24 years for space cells and 12 yrs for terrestrial cells. Improvements are described which could reduce the energy payback time to as little as four months for terrestrial cells.

TITLE: Production of Solar-Grade Silicon from Purified Metallurgical Silicon
AUTHOR: L.P. Hunt, V.D. Dosaj, J.R. McCormick, and L.D. Crossman
CORPORATE AUTH: Dow Corning Corp., Hemlock, Michigan
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 125-129

ABSTRACT: The long-term goal of this work is to produce Si of solar-grade quality at 3×10^6 Kg/y for less than $10/Kg by, or before 1986. The approach is to improve and expand upon the technology used today to commercially produce metallurgical-grade Si. This is currently being accomplished by using purer raw materials in the arc furnace process for producing MG-Si, by upgrading the furnace itself, and by unidirectionally solidifying the molten Si exiting the furnace. Solar cells fabricated from partially purified MG-Si have shown average AMO efficiencies in the range of 9-11%. Since further MG Si purification yet remains possible, fabrication of cells of considerably higher conversion efficiency is deemed feasible.

TITLE: The Conceptual Design and Analysis of a Photovoltaic Powered Experimental Residence
AUTHOR: N.F. Shepard, Jr. and R. Landes
CORPORATE AUTH: General Electric Co., Philadelphia, Pennsylvania
MEETING LOCATION: 12th IEEE Photovoltaics Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 705-714

ABSTRACT: The paper deals with the results of a six-month definition study conducted to analyze, the performance, plan the testing program, and specify the test equipment requirements for an experimental PV powered residence. In the residence of the type proposed, the solar cell modules are mounted above the south-facing roof in such a way that the natural convective cooling from the rear side can be used to reduce the cell operating temperature. Other functional elements are a PV system components room, and a room housing the data-acquisition and control systems required to monitor the experiment. A display panel is also provided as a visual aid to graphically represent the operation and performance of the system tested. Following a 12-month operational evaluation period, a lead-acid battery was added to the PV system. The results of a performance sensitivity analysis for four selected site locations are evaluated.

TITLE: Dip-Coated Sheet Silicon Solar Cells
AUTHOR: J.D. Heaps, R.B. Maciolek, J.D. Zook, and M.W. Scott
CORPORATE AUTH: Honeywell Corporate Research Center, Bloomington, Minnesota
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 147-150

ABSTRACT: A cost-effective method is being developed for producing solar cell quality sheet Si by dip coating inexpensive ceramic substrates with a thin layer of large grain silicon. Mullite (Aluminum Silicate) ceramic substrates coated with a thin layer of graphite have been dipped into molten Si to produce 20-150 micron thick layers having grain sizes as large as .4 cm x 4 cm. With these Si layers PV diodes have been fabricated with measured and inherent conversion efficiencies of 4% and 7%, respectively.

TITLE: Results of Accelerated Thermal Cycle Tests of Solar Cells Modules
AUTHOR: P. Berman, R. Mueller, M. Salama, and R. Yasui
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 379-387

ABSTRACT: Various candidate solar panel designs were evaluated, both theoretically and experimentally, with respect to their thermal cycling survival capability, and in particular with respect to an accelerated simulation of thermal cycles representative of Viking '75 mission requirements. The experimental results were obtained on mini-panels thermally cycled in a newly installed automated test facility herein described. The resulting damage was analyzed physically and theoretically, and on the basis of these analyses the panel design was suitably modified to significantly improve its ability to withstand the thermal environment. These successful modifications demonstrate the value of the complementary theoretical experimental approach adopted, and discussed in detail in this paper.

TITLE: Material and Design Considerations of Encapsulants for Photovoltaic Arrays in Terrestrial Applications
AUTHOR: W. Carroll, E. Cuddihy, and M. Salama
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 332-339

ABSTRACT: Procedures for analyzing cyclic mechanical stresses in encapsulated PV arrays designed for terrestrial application are discussed. The concept of thermal stiffness, the product of alpha and Young's modulus, is presented, and its usefulness for minimizing mechanical stresses is demonstrated. The concept of the 'proportional-limit' helps indicate the upper limit of design stress for plastics. System design is considered with attention to cell dimensions, cell to substrate adhesive, single encapsulant system, double layer encapsulant, and stresses in the interconnects. The permeability of polymeric materials to gases is examined.

TITLE: SAMIS - A Simulation of the Solar Array Manufacturing Industry
AUTHOR: R.G. Chamberlain
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78 10902 01-44) New York, 1976, p. 353-359

ABSTRACT: SAMIS is a continuing activity of the Project Analysis and Integration Task of the LSSA Project. It provides a standardized procedure for producing reliable estimates of the cost of manufacturing solar arrays or their components. These estimates are based on descriptions of the manufacturing processes which are being studied and developed by LSSA subcontractors and will be used to assess the commercial viability of those processes and to set research priorities.

TITLE: Some Observations on the Characteristics of Low-Cost Silicon Sheets
AUTHOR: T.G. Digges, Jr., M.H. Leipold, K.M. Koliwad, G. Turner, and G.D. Cumming
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 120-124

ABSTRACT: To meet the need for low cost Si sheet material in the ERDA/JPL PV program, JPL has initiated a wide ranging technology development effort in crystal growth that includes several different technology thrusts. They range in scope from innovative ingot growth and multislice wafering, to shaped growth techniques, substrate related processes and hot forming techniques. In this paper, some salient observations on materials resulting from these processes are reported. Included are multiblade wafering-induced damage studies, interface morphology studies on the heat exchanger cast Si, some diffusion length measurements in thin Si layers on ceramic substrates, and results on the equilibrium structure found in laser zone ribbon growth.

TITLE: Economic Analysis of Low-Cost Silicon Sheet Produced from Czochralski Grown Material
AUTHOR: K.M. Koliwad, M.H. Leipold, G.D. Cumming, and T.G. Digges, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 841-844

ABSTRACT: This study shows that the lower limits for manufacturing add-on costs to convert polysilicon to wafers is in the range of $22 to $26/sq m with the cost about equally divided between the crystal growth and wafering processes. However, the $22 to $26/sq m cost limit should be viewed as an asymptote since it is based on multicharge or continuous growth configurations, solidification rates in excess of 2 Kg/hr, multiblade wafering and a slice plus kerf of .045 cm. It should also be emphasized that the results of this study are based on as-sawn wafers, 100% yields (growth and slicing) and no profit. To the first approximation, the limiting cost factors are crucible material and furnace parts for growth and blade material and slurry for slicing.

TITLE: Interface Design Considerations for Terrestrial Solar Cell Modules
AUTHOR: R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 801-806

ABSTRACT: The need for increased solar array electrical efficiency and reliability in the achievement of future large-scale system cost goals is discussed. The relative performance of various array module designs currently on the market is evaluated, and further design improvements are suggested. The subjects of module efficiency, temperature control, and series/parallel reliability are analyzed. Applications for various combinations of array characteristics are considered.

TITLE: Ribbon-to-Ribbon Crystal Growth for Solar Cell Fabrication
AUTHOR: I.A. Lesk, A. Baghdadi, R.W. Gurtler, R.J. Ellis, J.A. Wise, and M.G. Coleman
CORPORATE AUTH: Motorola, Inc., Phoenix, Arizona
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 173-181

ABSTRACT: A new ribbon growth technique utilizes scanned laser beams to create a localized molten region in a preformed polycrystalline Si ribbon; translating the melt converts the starting material to single crystal (or large grain) ribbon. Solar cells with useful efficiency have been fabricated on grown ribbon. Theoretical analysis, coupled with experimental results, indicate that this technique should be capable of providing Si substrates for manufacture of solar cells to meet the long range ERDA objectives.

TITLE: An Analysis of Factors Influencing the Efficiency of EFG Silicon Ribbon Solar Cells
AUTHOR: K.V. Ravi, F.V. Wald, R. Gonsiorawski, H. Rao, L.C. Garone, J.C.T. Ho, and R.O. Bell
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 182-190

ABSTRACT: The performance characteristics of EFG Si ribbon solar cells have been analyzed with a view towards determining the material and process related parameters that influence cell conversion efficiencies. Solar cell conversion efficiencies in excess of 10% have been realized. The performance and yield limiting factors in these materials have been identified, with lifetime reducing impurities being implicated as the principal problem in current generation EFG ribbons.

TITLE: Processing Ramifications of Textured Surfaces of Silicon Wafers for Solar Cells
AUTHOR: M.G. Coleman, W.L. Bailey, and R.A. Pryor
CORPORATE AUTH: Motorola, Inc., Phoenix, Arizona

MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 313-316

ABSTRACT: The paper is concerned with the complications that result from the presence of textured surfaces on Si wafers. Direct process interactions are discussed with attention to handling, cleaning and wet chemistry, vacuum evaporation, photolithography, and ion implantation. Indirect process interactions can affect measurements and AR material selection. Textured surfaces are used to enhance light penetration into the surface of a solar cell.

TITLE: A Novel Solar Cell Interconnection Design
AUTHOR: R.A. Pryor, M.G. Coleman, and M.C. Keeling
CORPORATE AUTH: Motorola, Inc., Phoenix, Arizona
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 375-378

ABSTRACT: A novel interconnection design for solar cells within modules is developed. The design places thin buss plates beneath the solar cells. These buss plates can be designed for series, parallel-series, or parallel interconnection with equivalent ease. Such designs can incorporate multiple contacts to each solar cell and can reduce series resistance losses. Furthermore, this interconnection system is easily adapted to any size or shape of solar cell.

TITLE: Basic Corrections to Predictions of Solar Cell Performance Required by Nonlinearities
AUTHOR: F.A. Lindholm, J.G. Fossum, and E.L. Burgess
CORPORATE AUTH: University of Florida, Gainesville, Florida; Sandia National Labs., Albuquerque, New Mexico
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 33-39

ABSTRACT: The superposition principle is used to derive the approximation that the current-voltage characteristic of an illuminated solar cell is the dark current-voltage characteristic shifted by the short circuit photocurrent. The derivation requires the linearity of the boundary value problems that underlie the electrical characteristics. The shifting approximation is invalid if considerable photocurrent and considerable dark current both occur within the junction space-charge region; it is invalid also if sizable series resistance is present or if high-injection concentrations of holes and electrons exist within the quasi-neutral regions.

TITLE: Investigation of the Double Exponential in the Current-Voltage Characteristics of Silicon Solar Cells
AUTHOR: M. Wolf, G.T. Noel, and R.J. Stirn
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania; Jet Propulsion Laboratory
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 44-52

ABSTRACT: A theoretical analysis is presented of certain peculiarities of the current-voltage characteristics of Si solar cells, involving high values of the empirical constant A in the diode equation for a p-n junction. An attempt was made in a lab experiment to demonstrate that the saturation current which is associated with the exponential term qV/A2kT of the I-V characteristic, with A2 roughly equal to 2, originates in the space charge region and that it can be increased, as observed on ATS-1 cells, by the introduction of additional defects through low energy proton irradiation. It was shown that the proton irradiation introduces defects into the space charge region which give rise to a recombination current from this region, although the I-V characteristic is, in this case, dominated by an exponential term which has A = 1.

TITLE: Experiments to Evaluate High-Temperature Rolling as a Low-Cost Process for Silicon Solar Cells
AUTHOR: G.T. Noel, S. Kulkarni, M. Wolf, D.P. Pope, and C.D. Graham
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 168-172

ABSTRACT: Mechanical rolling (a process used in industry for producing large quantities of metallic sheet and strip) has been suggested for the rapid low-cost manufacture of Si sheet to be used for PV power generation equipment, such as solar arrays. The advantages of rolling include: high rates of production, wide sheets as products, good control of dimension, and (in the case of solar grade Si) minimal development of impurities. Experiments have been performed using high-temperature, high-speed compression of polycrystalline Si cylinders. Metallography and x-ray diffraction techniques have been used to examine the samples both before and after compression, and a model process has been designed to evaluate the technical practicality and economic feasibility of the method.

TITLE: Solar Cell Processing with Spin-On Diffusion Sources
AUTHOR: T.C. Chandler, Jr., R.B. Hilborn, Jr., and J.W. Faust, Jr.
CORPORATE AUTH: University of South Carolina, Columbia, South Carolina
MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 282-285

ABSTRACT: In the study described, the problem of the poor quality of solar cells prepared from spin on diffusion sources was attacked by studying the diffused layers by means of metallurgical techniques. It was found that device performance was degraded by nonuniform diffusion over the surface of the wafer and that nonuniform diffusion was caused by variations in the thickness of the spin on silica layer. Cells which were diffused, using a uniform film of spin-on doping source exhibited better current-voltage characteristics, lower series resistance, and higher values of fill factor. It is shown that this better performance can be ensured by taking steps to maintain the uniformity of the film coverage, to eliminate cracks and bubbles, and to maintain the proper temperature of both the spin on source and wafer during the spinning operation, and also to maintain the appropriate speed and duration of spin. The respective conditions are specified.

TITLE: Silicon Solar Cells from Transition Metal Doped Czochralski and Web Crystals
AUTHOR: J.R. Davis, P. Rai-Choudhury, P.D. Blais, R.H. Hopkins, and J.R. McCormick
CORPORATE AUTH: Westinghouse Research Labs., Pittsburgh, Pennsylvania; Dow Corning Corp., Hemlock, Michigan

MEETING LOCATION: 12th IEEE Photovoltaic Specialists Conference, Baton Rouge, Louisiana, Nov. 15-18, 1976, Conference Record. (A78-10902 01-44) New York, 1976, p. 106-111

ABSTRACT: The influence of metallic impurities on solar cell characteristics has been examined to establish the cost sensitive purity versus performance trade-offs. Solar cells were fabricated on 2 to 4 ohm-cm p-type substrates obtained by Cz and dendritic web growth processes. Controlled amounts of metallic impurities were introduced into the melt during growth and included Fe, Cr, Mn, Ni, Cu, Ti, V, Zr, Mg, Az, and Al. Impurity concentrations in the crystals were determined using emission and mass spectrographic techniques and in some cases by neutron activation analysis. The solar cells were characterized by means of a computer program to curve-fit measured voltage-current data. The principal effect of the added impurities is a degradation of lifetime and diffusion length.

TITLE: The Growth of EFG Silicon Ribbons
AUTHOR: K.V. Ravi
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
PUBLICATION: Materials and Energy; Selected topics. (A78-53487 24-44) Amsterdam, North-Holland Publishing Co., 1977, p. 1-16

ABSTRACT: The technology associated with the EFG process of producing ribbon-shaped crystals of Si is discussed. Aspects relating to the growth of crystals, equipment and theoretical considerations are presented. The crystallographic and electrical characteristics of these crystal are discussed in terms of their impact on the performance characteristics of solar cells. Solar cell data are presented demonstrating the capability of these crystals of furnishing cells with conversion efficiencies in excess of 10%.

TITLE: Dendritic Web Silicon for Solar Cell Application
AUTHOR: R.G. Seidensticker
CORPORATE AUTH: Westinghouse Research Laboratories, Pittsburgh, Pennsylvania
MEETING LOCATION: Materials and Energy; Selected Topics. (A78-53487 24-44) Amsterdam, North Holland Publishing Co., 1977, p. 17-22

ABSTRACT: The dendritic web process for growing long thin ribbon crystals of Si and other semiconductors is described. Growth is initiated from a thin wirelike dendrite seed which is brought into contact with the melt surface. Initially, the seed grows laterally to form a button at the melt surface; when the seed is withdrawn, needlelike dendrites propagate from each end of the button into the melt, and the web portion of the crystal is formed by the solidification of the liquid film supported by the button and the bounding dendrites. Apparatus used for dendritic web growth, material characteristics, and the two distinctly different mechanisms involved in the growth of a single crystal are examined. The performance of solar cells fabricated from dendritic web material is indistinguishable from the performance of cells fabricated from Cz grown material.

TITLE: The Near-Term Prospectives for Photovoltaic Solar Energy Conversion
AUTHOR: M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
PUBLICATION: (International Conference on Electronics +5, Paris, France, Mar. 28-Apr. 1, 1977.) Acta Electronica, vol. 20, no. 2, 1977, p. 205-215

ABSTRACT: Changes in the price/demand curve for PV energy conversion devices during the next five years, as well as technological advances affecting the cost of photocells, are discussed. Innovations such as the black or nonreflective Si solar cell, or cells employing thin (50 to 100-micron) Si layers and Ceria-doped glass covers are described; GaAs cells are also mentioned. A mathematical model for evaluating the economic viability of solar systems with varying cost per unit of array is given. In addition, a price/demand curve for solar arrays sold in the U.S., including historical data as well as predictions through 1982, is developed. The forecast involves annual doubling of production, with a 25% price reduction for each doubling, and an increase of cell efficiency to 12% by 1982.

TITLE: Investigation of the Double Exponential in the Current-Voltage characteristics of Silicon Solar Cells - Proton Irradiation Effects on ATS 1 cells
AUTHOR: M. Wolf, G.T. Noel, and R.J. Stirn
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania; Jet Propulsion Laboratory
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-24, Apr. 1977, p. 419-428

ABSTRACT: Difficulties in relating observed current-voltage characteristics of individual Si solar cells to their physical and material parameters were underscored by the unexpected large changes in the current-voltage characteristics telemetered back from solar cells on the ATS-1 spacecraft during their first year in synchronous orbit. Depletion region recombination was studied in cells exhibiting a clear double-exponential dark characteristic by subjecting the cells to proton irradiation. A significant change in the saturation current, an effect included in the Sah, Noyce, Shockley formulation of diode current resulting from recombination in the depletion region, was caused by the introduction of shallow levels in the depletion region by the proton irradiation. This saturation current is not attributable only to diffusion current from outside the depletion region and only its temperature dependence can clarify its origin. The current associated with the introduction of deep-lying levels did not change significantly in these experiments.

TITLE: Physical Operation of Back-Surface-Field Silicon Solar Cells
AUTHOR: J.G. Fossum
CORPORATE AUTH: Sandia National Laboratories, Albuquerque, New Mexico
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-24. Apr. 1977, p. 322-325

ABSTRACT: The performance of back-surface-field solar cells is simulated numerically by a semiconductor device analysis computer code. The physical operation of these Si solar cells is elucidated on the basis of exact one dimensional solutions of carrier transport. Carrier densities, backside built-in electric field, potential, and carrier recombination throughout the device are studied, in addition to predicted terminal performance, to shed light on the mechanisms at work in the n^+-p-p^+ BSF Si solar cell.

TITLE: The Dependence of Open-Circuit Voltage on Illumination Level in p-n Junction Solar Cells
AUTHOR: J.G. Fossum and F.A. Lindholm
CORPORATE AUTH: Sandia National Laboratories, Albuquerque, New Mexico; University of Florida, Gainesville, Florida
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-24. Apr. 1977, p. 325-329

ABSTRACT: Simple analytical dependencies of solar cell open-circuit voltage on illumination level, valid for high injection, are derived. The developments are guided and verified by exact computer-aided numerical simulations of Si cells. The results are related to an easily measured device parameter, the uncompensated photocurrent, through

the use of the principle of superposition. An advantage of p^+-n over n^+-p cells with respect to open-circuit voltage at high levels of illumination is predicted.

TITLE: An Optical Scanning Technique for Evaluating Silicon Solar Cells
AUTHOR: C.T. Chandler, Jr., R.B. Hilborn, Jr., and J.W. Faust, Jr.
CORPORATE AUTH: University of South Carolina, Columbia, South Carolina
MEETING LOCATION: Imaginative Engineering thru Education and Experience; Proceedings of the Southeast Region 3 Conference, Williamsburg, Virginia, Apr. 4-6, 1977. (A78-17526 05-31) New York, Institute of Electrical and Electronics Engineers, Inc., 1977, p. 281-284

ABSTRACT: The present paper deals with Si solar cells which operate by the PV effect common to p-n junctions. The theory is highly developed, but solar cell efficiencies, series resistance, and other parameters do not always agree with theoretical values, the discrepancies resulting from inhomogeneities in the diffused region of the cells. The relationship between the inhomogeneities and solar cell parameters is studied by evaluating the variations in surface concentration, making use of the bulk PV effect, and by using a specially adapted curve tracer to display the forward (illuminated) characteristic of the test cell. It is found that the bulk PV scanning technique has some disadvantages, including difficulties in interpreting the bulk EMF vs lateral distance curve and also the associated resistivity profile for an n-type crystal. However, variations in resistivity profile large enough to degrade cell performance can be easily detected.

TITLE: Characterization of Terrestrial Service Environments - The Simultaneous Occurrence of Combined Conditions of Solar Insolation and Climatic Variables
AUTHOR: R.E. Thomas, D.C. Carmichael, and W.F. Carroll
CORPORATE AUTH: Battelle Columbus Labs., Ohio; Jet Propulsion Laboratory
MEETING LOCATION: International Solar Energy Society, Annual Meeting, Orlando, Florida, June 6-10, 1977, Proceedings. Sections 14-25. (A78 11212 01-44) Cape Canaveral, Florida, International Solar Energy Society, 1977, p. 14-1 to 14-6

ABSTRACT: Computational methods for occurrences of combined environmental and pollution variables are compared. General statistical data and diurnal statistics on 24 environmental variables are treated. Combinations of variables dealt with include: air temperature, relative humidity, wind speed, total insolation; air temperature and weather event (rain, fog); air pollutant and weather event; wind speed, wind direction, and weather event; air temperature, total insolation, and weather event; air temperature, relative humidity, wind speed, computed direct insolation levels; air temperature, relative humidity, air pollution.

TITLE: Structure Development in Silicon Sheet by Shaped Crystallization
AUTHOR: M.H. Leipold and R.J. DeAngelis
CORPORATE AUTH: Jet Propulsion Laboratory; University of Kentucky, Lexington, Kentucky
MEETING LOCATION: Photovoltaic Solar Energy Conference, Luxembourg, Sept. 27-30, 1977, Proceedings. (A78 52776 24-44) Dordrecht, D. Reidel Publishing Co., 1978, p. 872-881

ABSTRACT: Models are presented for the development of a parallel twinned structure of the 110 plane type and the 112 line type in Si ribbons. The models are believed to be mutually compatible and operable. The first model relates the requirements for super-cooling during crystallization. The existence of reentrant angles associated with the twin structure is proposed to provide a rough interface to reduce super-cooling. The spacing of the twins is proposed to be limited by the geometrical relationship between the thermal gradient in the liquid and the dimensions of the twinned crystallization front. The second model relates the thermal stress configuration to detail dislocation reactions which would be expected to develop twins. While a specific dislocation mechanism cannot yet be defined, a number of alternatives are presented. All of these various dislocation mechanisms would result in the observed crystalline configuration and the choice among them is not critical.

TITLE: The Properties of Silica Diffusion Sources Under Oxidizing Ambient Conditions and their Application to Solar Cell Fabrication
AUTHOR: C.T. Chandler, Jr., R.B. Hilborn, Jr., and J.W. Faust, Jr.
CORPORATE AUTH: University of South Carolina, Columbia, South Carolina
PUBLICATION: Electrochemical Society, Journal, vol. 124, Sept. 1977, p. 1409-1413

ABSTRACT: In this paper a technique for the design and fabrication of Si solar cells using spin-on silica doping sources is discussed. This technique involves the use of an oxidizing ambient during diffusion which limits the diffusion flux and yields lower surface concentrations of impurities and shallow p-n junctions. It is shown that the uniformity of the film thickness is an important factor in maintaining a uniform surface concentration of impurities in a diffused substrate. Data are given to demonstrate the effects of such silica film thickness variations on solar cell performance.

TITLE: Electricity From Sunlight - Low-Cost Silicon for Solar Cells
AUTHOR: C.L. Yaws, J.W. Miller, R. Lutwack, and G. Hsu
CORPORATE AUTH: Lamar Univ., Beaumont, Texas; Jet Propulsion Laboratory
MEETING LOCATION: Energy and the environment; Proceedings of the Fifth National Conference, Cincinnati, Ohio, Nov. 1-3, 1977. (A79 14106 03-45) Dayton, Ohio, American Institute of Chemical Engineers, 1978, p. 329-334

ABSTRACT: The paper discusses a number of new unconventional processes proposed for the low cost production of Si for solar cells. Consideration is given to: (1) the Battelle process ($Zn/SiCl_4$), (2) the Battelle process (SiI_4), (3) the Silane process, (4) the Motorola process (SiF_4/SiF_2), (5) the Westinghouse process ($Na/SiCl_4$), (6) the Dow Corning process (C/SiO_2), (7) the AeroChem process ($SiCl_4$/H/atom), and the Stanford process (Na/SiF_4). Preliminary results indicate that the conventional process and the SiI_4 processes cannot meet the project goal of $10/kg by 1986. Preliminary cost evaluation results for the $Zn/SiCl_4$ process are favorable.

TITLE: Development of Low Cost Silicon Crystal Growth Techniques for Terrestrial Photovoltaic Solar Energy Conversion
AUTHOR: J.A. Zoutendyk
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Solar Energy, vol. 20, no. 3, 1978, p. 249-257

ABSTRACT: None

TITLE: Large Area Silicon Sheet by EFG
AUTHOR: C.V.H. Rao, T. Surek, B. Mackintosh, K.V. Ravi and F.V. Wald

CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: Sun: Mankind's Future Source of Energy; Proceedings of the International Solar Energy Congress, New Delhi, India, January 16-21, 1978. Vol. 2 (A79-17276 05-44) Elmsford, New York, Pergamon Press, Inc., 1978, p. 643-650

ABSTRACT: The EFG technique has been employed to grow Si ribbons for PV applications. Considerable progress has been made in recent years in developing the technique to the point that long lengths of Si ribbon can be routinely grown. In order to attain the full low-cost potential of the EFG technique, several further developments such as the growth of thinner and wider ribbons, increase in ribbon growth rate, and improvements in material quality are needed. The technological problems to be solved and the approaches employed to achieve these goals are discussed.

TITLE: Simulated Hail Impact Testing of Photovoltaic Solar Panels
AUTHOR: D. Moore, A. Wilson, and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Combined environments: Technology interrelations; Proceedings of the Twenty-fourth Annual Technical Meeting, Fort Worth, Texas, Apr. 18-20, 1978. (A79-16076 04-38) Mount Prospect, Illinois, Institute of Environmental Sciences, 1978, p. 419-430

ABSTRACT: Techniques used to simulate and study the effect of hail on PV solar panels are described. Simulated hail stones (frozen ice spheres projected at terminal velocity) or steel balls were applied by air guns, gravity drop, or static loading. Tests with simulated hail and steel balls yielded different results. The impact strength of 10 commercially available flat-plate PV modules was tested. It was found that none of the six panel designs incorporating clear potting silicone material as the outermost layer remained undamaged by 1-in. simulated hailstones, while a PV module equipped with a 0.188-in.-thick acrylic cover sheet would be able to withstand the impact of a 2-in.-diameter hailstone.

TITLE: Recent Developments in Low-Cost Silicon Solar Cells for Terrestrial Application Sheet Production Methods
AUTHOR: M.H. Leipold
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Selective Application of Materials for Products and Energy; Proceedings of the Twenty-Third National Symposium and Exhibition, Anaheim, California, May 2-4, 1978. (A79-2081 07-23) Azusa, California, Society for the Advancement of Material and Process Engineering, 1978, p. 354-365

ABSTRACT: A variety of techniques may be used for PV energy systems. Concentrated or not concentrated sunlight may be employed, and a number of materials can be used, including Si, gallium arsenide, cadmium sulfide, and cadmium telluride. Most of the experience, however, has been obtained with Si cells employed without sunlight concentration. An industrial base exists at present for producing solar cells at a price in the range from \$15 to \$30/W_p. A major federal program has the objective to reduce the price of power provided by Si solar system to approximately \$1/W_p in the early 1980's and \$0.50/W by 1986. The approaches considered for achieving this objective are discussed.

TITLE: Integral Assembly of Photovoltaic Arrays Using Glass
AUTHOR: P.R. Younger, A.R. Kirkpatrick, H.G. Maxwell, and R.F. Holtze
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts; Jet Propulsion Laboratory
PUBLICATION: Society for the Advancement of Material and Process Engineering, National Symposium and Exhibition, 23rd, Anaheim, California, May 2-4, 1978, Paper. 6 p.

ABSTRACT: For a number of reasons glass is an excellent material for encapsulation of solar cell arrays. Glass can be readily available at relatively low cost. It exhibits excellent stability against degradation by solar ultraviolet illumination and atmospheric pollutants. A superior approach results if glass is employed directly as an integral encapsulant without secondary organic materials. A description is presented of an electrostatic bonding process which is being developed for integral assembly of glass encapsulation arrays. Solar cells are placed in contact with the glass surface, temperature is raised until the glass becomes ionically conductive, and an electric field is applied to initiate the bonding action. Si solar cells up to 3 in. in dia. have been integrally bonded without degradation.

TITLE: Fracture Toughness of Silicon
AUTHOR: C.P. Chen and M.H. Leipold
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: (American Ceramic Society, Annual Meeting 80th, Detroit, Michigan, May 8, 1978) American Ceramic Society Bulletin, vol. 59, Apr. 1980, p. 469-472

ABSTRACT: The paper presents a study to determine the fracture toughness and to characterize fracture modes of Si as a function of the orientation of single crystal and polycrystalline material. It is shown that bar specimens cracked by Knoop microhardness indentation and tested to fracture under four-point bending at room temperature were used to determine the fracture toughness values. It is found that the lowest fracture toughness value of single crystal Si was 0.82 MN/m to the 3/2 in the 111 plane type orientation, although the difference in values in the 111, 110, and 100 planes was small.

TITLE: Measurement Requirements and Techniques for Degradation Studies and Lifetime Prediction Testing of Photovoltaic Modules
AUTHOR: G.T. Noel, F.A. Sliemers, G.C. Derriner, V.E. Wood, K.E. Wilkes, G.B. Gaines, and D.C. Carmichael
CORPORATE AUTH: Battelle Columbus Labs., Ohio
MEETING LOCATION: Seminar on Testing Solar Energy Materials and Systems, Gaithersburg, Maryland, May 22-24, 1978, Proceedings. (A79-35038 14-44) Mt. Prospect, Illinois, Institute of Environmental Sciences, 1978, p. 24-29

ABSTRACT: Tests of weathering and aging behavior are being developed to characterize the degradation and predict the lifetimes of low-cost PV arrays. Environmental factors which affect array performance include UV radiation, thermal energy, water, oxygen (generally involved in synergistic effects with UV radiation or high temperatures), physical stress, pollutants (oxides of nitrogen, sulfur dioxide and ozone), abrasives and dirt. A survey of PV array testing has shown the need to establish quantitative correlations between certain measurable properties (carbonyl formation, glass transition temperature, and molecular weight change) and modes of degradation and failure.

TITLE: A Life Prediction Methodology for Encapsulated Solar Cells
AUTHOR: C.D. Coulbert
CORPORATE AUTH: Jet Propulsion Laboratory

MEETING LOCATION: Seminar on Testing Solar Energy Materials and Systems, Gaithersburg, Maryland, May 22-24, 1978, Proceedings. (A79-35038 14-44) Mt. Prospect, Illinois, Institute of Environmental Sciences, 1978, p. 18-23

ABSTRACT: This paper presents an approach to the development of a life prediction methodology for encapsulated solar cells which are intended to operate for twenty years or more in a terrestrial environment. Such a methodology, or solar cell life prediction model, requires the development of quantitative intermediate relationships between local environmental stress parameters and the basic chemical mechanisms of encapsulant aging leading to solar cell failures. The use of accelerated/abbreviated testing to develop these intermediate relationships and in revealing failure modes is discussed. Current field and demonstration tests of solar cell arrays and the present laboratory tests to qualify solar module designs provide very little data applicable to predicting the long term performance of encapsulated solar cells. An approach to enhancing the value of such field tests to provide data for life prediction is described.

TITLE: Environmental Testing of Flat-Plate Solar Cell Modules
AUTHOR: J. Griffith, L. Dumas, and A. Hoffman
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Seminar on Testing Solar Energy Materials and Systems, Gaithersburg, Maryland, May 22-24, 1978, Proceedings. (A79 35038 14-44) Mt. Prospect, Illinois, Institute of Environmental Sciences, 1978, p. 1-11

ABSTRACT: Commercially available flat-plate solar cell modules have been subjected to a variety of environmental tests designed to simulate service conditions. Among the tests are those simulating heat and rain, wind-driven rains, humidity and freezing, humidity and heat, humidity with a voltage bias, salt fog, hail impact, and fungus infestation. Tests for optical surface soiling and the combined effects of temperature, humidity and UV irradiation are under development. A correlation has been demonstrated between degradation caused by the qualification tests and such observed field effects as power loss.

TITLE: A Life Prediction Methodology for Encapsulated Solar Cells
AUTHOR: C.D. Coulbert
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Seminar on Testing Solar Energy Materials and Systems, Gaithersburg, Maryland, May 22-24, 1978, Proceedings. (A79 35038 14 44) Mt. Prospect, Illinois, Institute of Environmental Sciences, 1978, p. 18-23

ABSTRACT: This paper presents an approach to the development of a life prediction methodology for encapsulated solar cells which are intended to operate for twenty years or more in a terrestrial environment . Such a methodology, or solar cell life prediction model, requires the development of quantitative intermediate relationships between local environmental stress parameters and the basic chemical mechanisms of encapsulant aging leading to solar cell failures. The use of accelerated/abbreviated testing to develop these intermediate relationships and in revealing failure modes is discussed. Current field and demonstration tests of solar cell arrays and the present laboratory tests to qualify solar module designs provide very little data applicable to predicting the long term performance of encapsulated solar cells. An approach to enhancing the value of such field tests to provide data for life prediction is described.

TITLE: Actinometric Measurement of Solar Ultraviolet and Development of a Weighted Solar UV Integral Photochemical Reaction Rate Determination
AUTHOR: A. Gupta and C. Coulbert
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Seminar on Testing Solar Energy Materials and Systems, Gaithersburg, Maryland, May 22-24, 1978, Proceedings. (A79-35038 14-44) Mt. Prospect, Illinois, Institute of Environmental Sciences, 1978, p. 253-255

ABSTRACT: An actinometer has been developed to measure outdoor irradiance in the range 295-400 nm. Actinometric measurements of radiation are based on determination of photochemical reaction rates for reactions of known quantum efficiency. Actinometers have the advantage of providing irradiance data over surfaces of difficult accessibility; in addition, actinometrically determined irradiance data are wavelength weighted and therefore provide a useful means of assessing the degradation rates of polymers employed in solar energy systems.

TITLE: A Candidate Low Cost Processing Sequence for Terrestrial Silicon Solar Cell Panel
AUTHOR: D.B. Bickler, B.D. Gallagher, and L.E. Sanchez
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, p. 241-245

ABSTRACT: Manufacturing sequence for Si solar cells using Cz crystal growing techniques in order to produce at a rate of 20 MW/y on a 24-h/day basis is discussed. Cost analysis of the manufacturing is presented and consideration is given to the following processing decision categories of the manufacturing of an unencapsulated solar cell from a Si wafer: (1) treatment of the optical surface; (2) formation of the junction(s); and (3) metallization of electrical collectors. The manufacturing of encapsulated solar modules from solar cells, using two glass plates, a low iron front surface, and a standard float glass back plate, is described. Totaling the three major activities of wafer making, cell manufacturing, and module fabrication, the resulting contribution to module price will be 1.945$/W.

TITLE: Lifetime Cost and Performance Model for Photovoltaic Power Systems
AUTHOR: C.S. Borden
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, p. 925-929

ABSTRACT: This paper describes the approach and procedures of the Lifetime Cost and Performance model for PV power systems. The LCP model is designed to evaluate the impact of alternative initial design and recurrent policy decisions on both cost and power output over the lifetime of a PV power plant. LCP is, therefore, useful to system designers and operators for addressing questions relating to optimal system configuration, installation activities, level of effort and timing of operations/maintenance actions, allowable degradation and replacement options.

TITLE: Product Pricing in the Solar Array Manufacturing Industry - An Executive Summary of SAMICS
AUTHOR: R.G. Chamberlain
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, p. 904-907

ABSTRACT: Capabilities, methodology, and a description of input data to the SAMICS are presented. SAMICS were developed to provide a standardized procedure and data base for comparing manufacturing processes of LSA subcontractors, guide the setting of research priorities, and assess the progress of LSA toward its hundred-fold cost reduction goal. SAMICS can be used to estimate the manufacturing costs and product prices and determine the impact of inflation, taxes, and interest rates, but it is limited by its ignoring the effects of the market supply and demand and an assumption that all factories operate in a production line mode. The SAMICS methodology defines the industry structure, hypothetical supplier companies, and manufacturing processes and maintains a body of standardized data which is used to compute the final product price. The input data includes the product description, the process characteristics, the equipment cost factors, and production data for the preparation of detailed cost estimates. Activities validating that SAMICS produced realistic price estimates and cost breakdowns are described.

TITLE: Mechanisms of Photon Induced Changes in Silicon Solar Cell Parameters
AUTHOR: L.J. Cheng, G.B. Turner, R.G. Downing, C.H. Seaman, and E.Y. Wang
CORPORATE AUTH: Jet Propulsion Laboratory; Wayne State Univ., Detroit, Michigan
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 1333-1336

ABSTRACT: Reversible changes in solar cell performance were induced by AM1 illumination and evaluated by measuring short circuit current, weak light spectral response, and minority carrier diffusion length. In n^+p cells the change manifests itself as a reduced short circuit current, a loss of the red response, and a reduction in minority carrier diffusion length. In p^+n cells there are two photon induced effects: (1) enhancement of the blue spectral response, presumably occurring in the p^+ layer and (2) degradation in open circuit voltage at low light levels due to increased leakage occurring only after the junction edge is exposed to bright light. Most of these photon effects are attributed to defects in the Si.

TITLE: Effect of Copper Impurity on Polycrystalline Silicon Solar Cells
AUTHOR: T. Daud and K.M. Koliwad
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, p. 503-506

ABSTRACT: The presence of copper impurity, up to 10^{15} atoms/cc, in single crystal Si has been shown to have no deleterious effect on the p-n junction solar cell performance. However, in polycrystalline Si, copper atoms tend to migrate to the defect sites because of the structural sensitive properties of copper. This study was undertaken to investigate the influence of this behavior of copper impurity on the performance of p-n junction solar cells fabricated from structurally imperfect Si. Two sets of polycrystalline Si substrates containing copper were examined. In one set of samples, copper was incorporated during growth, whereas in the other, copper was diffused. Solar cells were fabricated on both the sets of substrates by a standard process. Dark and light I-V and spectral response characteristics of the cells were measured and compared with copper-free polycrystalline Si solar cells. The results and the model are discussed.

TITLE: Effect of Multiblade Slurry Saw Induced Damage on Silicon Solar Cells
AUTHOR: T. Daud, J.K. Liu, G.A. Pollock, and K.M. Koliwad
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 142-146

ABSTRACT: A correlation between the optimum etch loss and the depth of damage is established using wafers produced by the MBS and the ID saws. The observations are based on the measurement of the performance of solar cells fabricated on these wafers. Sample preparation and test results are described and the following conclusions are made: (1) the amount of silicon removal necessary for optimum solar cell performance coincides with the depth of saw-induced damage; (2) optimization of cell performance is not affected by the method of Si removal; (3) sawing conditions should be optimized to minimize the extent of saw-induced damage; (4) the MBS saw is found to induce damage to a lesser extent; (5) since the extent of damage in MBS-sawn wafers is in the limit of etch loss required in texture etching, it is possible to achieve optimum improvement in cell performance by merely texture etching the surface of as-sawn wafers.

TITLE: Environmental Qualification Testing of Terrestrial Solar Cell Modules
AUTHOR: A.R. Hoffman and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 835-842

ABSTRACT: The placement of solar cell modules in various climates and locations throughout the world results in different degrees and combinations of environmental stresses. Coupled with a design lifetime goal of 20 yrs, early detection and correction of module design deficiencies can result in significantly better long term economics. This paper describes an environmental test research program for developing qualification requirements and procedures for flat-plate solar cell modules. A multiple iterative approach for establishing and evaluating test requirements is discussed as well as the rationale for the selection of levels and durations for the current qualification tests. The status of study efforts involving optical surface soiling, encapsulation delamination, and voltage bias humidity testing is reviewed.

TITLE: Photovoltaic Design Optimization for Terrestrial Applications
AUTHOR: R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 1067-1073

ABSTRACT: As part of JPL's LSA Project, a comprehensive program of module cost-optimization has been carried out. The objective of these studies has been to define means of reducing the cost and improving the utility and reliability of PV modules for the broad spectrum of terrestrial applications. This paper describes one of the methods being used for module optimization, including the derivation of specific equations which allow the optimization of various module design features. The method is based on minimizing the life-cycle cost of energy for the complete system. Comparison of the life cycle energy cost with the marginal cost of energy each year allows the logical plant lifetime to be determined. The equations derived allow the explicit inclusion of design parameters such as tracking, site variability, and module degradation with time. An example problem involving the selection of an optimum module glass substrate is presented.

TITLE: The Effects of Copper and Titanium on Silicon Solar Cells

AUTHOR: A.M. Salama
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 496-502

ABSTRACT: Copper-doped n/p Si solar cells fabricated from the Cz grown single-crystal wafers were found to have good electrical characteristics, but the titanium doped n/p Si solar cells has considerably lower conversion efficiency. However, in the copper/titanium-doped solar cells, copper seems to mitigate the unfavorable effects of titanium. To explain this behavior, microstructural tests were performed on Si wafers and solar cells doped with copper, titanium and copper/titanium. Dark forward and reverse I-V measurements were performed on the solar cells to correlate the microstructural defects with the p-n junction properties. It was found that copper precipitates were formed in the copper-doped and copper/titanium doped wafers and cells. There was a significant voltage drop in the dark reverse I-V measurements of the titanium solar cells. Also, there were some electronically active defects in the depletion region of some titanium doped cells. Reasons that lead to the above results are given in detail.

TITLE: Some Failure Modes and Analysis Techniques for Terrestrial Solar Cell Modules
AUTHOR: A. Shumka and K.H. Stern
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 824-834

ABSTRACT: Analysis data are presented on failed/defective Si solar cell modules of various types and produced by different manufacturers. The failure mode (e.g., internal short and open circuits, output power degradation, isolation resistance degradation, etc.) are discussed in detail and in many cases related to the type of technology used in the manufacture of the modules; wherever applicable, appropriate corrective actions are recommended. Consideration is also given to some failure analysis techniques that are applicable to such modules, including x ray radiography, capacitance measurement, cell shunt resistance measurement by the shadowing technique, steady state illumination test station for module performance illumination, laser scanning techniques, and the SEM.

TITLE: Effects of Design on Cost of Flat-Plate Solar Photovoltaic Arrays for Terrestrial Central Station Power Applications
AUTHOR: P. Tsou and W. Stolte
CORPORATE AUTH: Jet Propulsion Laboratory; Bechtel International Corp., San Francisco, California
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 1196-1201

ABSTRACT: The paper examines the impact of module and array designs on the balance of plant costs for flat plate terrestrial central station power applications. Consideration is given to the following types of arrays: horizontal, tandem, augmented, tilt adjusted, and E-W tracking. The life cycle cost of a 20-yr plant life serves as the costing criteria for making design and cost tradeoffs. A tailored code of accounts is developed for determining consistent PV power plant costs and providing credible PV system cost baselines for flat-plate module and array designs by costing several varying array design approaches.

TITLE: Evaluations of Candidate Encapsulation Designs and Materials for Low Cost Silicon Photovoltaic Arrays
AUTHOR: G.B. Gaines, D.C. Carmichael, F.A. Sliemers, M. Brockway, A. Bunk, and C.F. Nance
CORPORATE AUTH: Battelle Columbus Labs., Ohio.
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 615-619

ABSTRACT: Three encapsulation designs for Si PV arrays based on cells with silk-screened Ag metallization have been evaluated: transparent polymeric coatings over cells laminated between two films or sheets of polymeric materials; cells adhesively bonded to a glass cover with a polymer pottant and a glass or other substrate component. Silicone and acrylic coatings were assessed, together with acrylic sheet, 0.635 mm fiberglass-reinforced polyester sheet, 0.102 mm polycarbonate/acrylic dual-layer film, 0.127 mm fluorocarbon film, soda lime glass, borosilicate glass, low iron glass, and several adhesives. The encapsulation materials were characterized by light transmittance measurements, determination of moisture barrier properties and bond strengths, and by the performance of cells before and after encapsulation. Si and acrylic coatings provided inadequate protection. Acrylic and fluorocarbon films displayed good weatherability and acceptable optical transmittance. Borosilicate, low iron and soda lime float glasses were found to be acceptable candidate encapsulants for most environments.

TITLE: Performance Degradation Mechanisms and Modes in Terrestrial Photovoltaic Arrays and Technology for Their Diagnosis
AUTHOR: G.T. Noel, F.A. Sliemers, G.C. Derriner, V.E. Wood, K.E. Wilkes, G.B. Gaines, and D.C. Carmichael
CORPORATE AUTH: Battelle Columbus Labs., Ohio
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p.817-823

ABSTRACT: Accelerated life prediction test methodologies have been developed for the validation of a 20-yr service life for low cost PV arrays. Array failure modes, relevant materials property changes, and primary degradation mechanisms are discussed as a prerequisite to identifying suitable measurement techniques and instruments. Measurements must provide sufficient confidence to permit selection among alternative designs and materials and to stimulate widespread deployment of such arrays. Furthermore, the diversity of candidate materials and designs, and the variety of potential environmental stress combinations, degradation mechanisms and failure modes require that combinations of measurement techniques be identified which are suitable for the characterization of various encapsulation system cell structure-environment combinations.

TITLE: Directional Solidification of Crack-Free Silicon Ingots by Heat Exchanger Method
AUTHOR: C.P. Khattak and F. Schmid
CORPORATE AUTH: Crystal Systems, Inc., Salem, Massachusetts
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 137-141

ABSTRACT: Si crystals are being grown for PV applications by a directional solidification casting technique. One of the major problems in casting Si in silica crucibles is the cracking of the ingot during the cooling cycle. Graded crucibles have been developed which delaminate thereby eliminating cracking of the case Si. Boules as large as 3-1/2 Kg have been solidified with a high degree of crystallinity. The origin of Si carbide formed at high temperatures in vacuum has been attributed to the use of silica crucibles in contact with graphite retainers. Solar cells fabricated out of the case Si have shown conversion efficiencies of up to 14% (AM1).

TITLE: Advances in the Dow Corning Process for Solar-Grade Silicon
AUTHOR: L.P. Hunt, V.D. Dosaj, J.R. McCormick, and A.W. Rauchholz
CORPORATE AUTH: Dow Corning Corp., Hemlock, Michigan
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 333-338

ABSTRACT: The Dow Corning process consists of the carbothermic reduction of silica to produce Si that is then purified by unidirectional solidification. The process has produced Si of semiconductor quality with respect to all elements except boron and phosphorus at about 10 ppma and aluminum at 0.1 ppma. Solar cells produced from this Si gave AM0 conversion efficiencies of 11%. A process cost analysis is presented.

TITLE: Development of a Shingle-Type Solar Cell Module
AUTHOR: N.F. Shepard, Jr. and L.E. Sanchez
CORPORATE AUTH: General Electric Co., Philadelphia, Pennsylvania; Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1878, p. 160-164

ABSTRACT: The development of a solar cell module, which is suitable for use in place of shingles on the sloping roofs of residential or commercial buildings, is reported. The design consists of nineteen series-connected 53 mm dia solar cells arranged in a closely packed hexagon configuration. The shingle solar cell module consists of two basic functional parts: an exposed rigid portion which contains the solar cell assembly, and a semi-flexible portion which is overlapped by the higher courses of the roof installation. Consideration is given to the semi-flexible substrate configuration and solar cell and module to-module interconnectors. The results of an electrical performance analysis are given and it is noted that high specific power output can e attributed to the efficient packing of the circular cells within the hexagon shape. The shingle should function for at least 15 yrs, with a specific power output of 98 W/sq m.

TITLE: Growth, Evaluation and Modeling of Silicon-on-Ceramic Solar Cells
AUTHOR: J.D. Zook, S.B. Schuldt, R. Maciolek, and J.D. Heaps
CORPORATE AUTH: Honeywell Corporate Material Sciences Center, Bloomington, Minnesota
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 472-478

ABSTRACT: The SOC process uses inexpensive ceramic substrates to provide supported growth of Si from the melt. The conditions for unidirectional solidification, the grain structure and other properties are quite similar to those of EFG Si ribbon. Solar cells with interdigital electrodes have demonstrated AM1 conversion efficiencies (active area) of 7.8% without AR coatings and 10.1% efficiencies with an AR coating of SiO. Mathematical modeling of the series resistance of cells shows the feasibility of making electrical contact to the base layer of the cell through slots in the substrate. However, series resistance in the base layer sets an upper limit on slot spacing for efficient cell performance.

TITLE: Multiple Silicon Ribbon Growth by EFG
AUTHOR: B.H. Mackintosh, T. Surek, J.P. Kalejs, E.M. Sachs, S. Nagy, and F.V. Wald
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 350-357

ABSTRACT: The background and progress to date of EFG ribbon growth for solar cell applications are briefly reviewed. The design and operation of a multiple ribbon per-operator manufacturing system are then described. Results are presented of cost studies of this system at three stages of development. In the latter stage, believed to be attainable by 1986, conversion costs for polycrystalline Si into wafers are attained which are consistent with manufacture of PV systems at $0.50/$W_p$. Principal technological problems in the ribbon growth process are discussed.

TITLE: The Impact of Defects on the Photovoltaic Potential of RTR Silicon Ribbon
AUTHOR: A. Baghdadi, R.H. Gurtler, R.N. Legge, R.J. Ellis, and B.L. Sopori
CORPORATE AUTH: Motorola, Inc., Phoenix, Arizona
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 363-369

ABSTRACT: Si ribbon grown at a high rate by the RTR method contains a variety of defects and can exhibit an unusual dendritic morphology. This paper is a study of the effect of the defect structure and dendritic morphology on the PV potential of RTR ribbon. Defects found in RTR ribbon include grain boundaries, twin planes, stacking faults and dislocations. The electrical activity of these defects is investigated by measuring the diffusion length in the ribbon; by fabricating small area diodes on the ribbon and evaluating their photoresponse; and by using a scanning electron microscope in the electron beam induced current mode. It is concluded that although grain boundaries serve very effectively as recombination centers, they do not occur frequently enough in RTR ribbons to significantly affect the generation current. Dislocation densities up to 1,000,000/sq cm can be tolerated without strongly reducing the photoresponse. Similarly, linear boundaries such as twin planes or stacking faults do not affect the cell performance up to densities of 1000/sq cm.

TITLE: The Pd_2Si-Pd-Ni-Solder Plated Metallization System for Silicon Solar Cells
AUTHOR: M.G. Coleman, R.A. Pryor, and T.G. Sparks
CORPORATE AUTH: Motorola, Inc., Phoenix, Arizona
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 597-602

ABSTRACT: The rationale and application of a plated metal system, Pd_2Si Pd - Ni - solder, is presented. This metallization system is particularly useful on shallow p n junction solar cells. The advantages of such plated solar cell contacts are discussed. A process sequence for applying the metallization system is outlined. A specific example is presented, including chemical plating solution formulations and detailed process step descriptions. Electrical test data for solar cells metallized with the palladium-nickel-solder system are provided.

TITLE: Analysis of ID Saw Slicing of Silicon for Low Cost Solar Cells
AUTHOR: H. Yoo, R.G. Schwartz, and P.A. Iles
CORPORATE AUTH: Optical Coating Laboratory, Inc., City of Industry, California
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 147-151

ABSTRACT: A brief description of three Si slicing methods using MBS, ID, and MWS saws is given. Attention is given to the ID method because it is considered the baseline method used by most of the Si industry. Mechanical wafer parameters, such as thickness variations, taper, bow and roughness are considerably better for wafers sliced with the ID saw and MWS saw than for those with the MBS saw. Wafers sawn with the ID saw showed slightly better parameters than those with the MWS saw. Cost assessment also indicated that the ID saw slicing is more favorable and its capability of automation adds advantage over the other two methods. Further reduction in wafering cost can be expected by increasing machine productivity and decreasing kerf width by ganging blades, programmed cutting, use of thinner blades and a rotating crystal system.

TITLE: Characterization of Nonideal Silicon in Terms of Lifetime and Diffusion Length
AUTHOR: S. Othmer and S.C. Chen
CORPORATE AUTH: Northrop Research and Technology Center, Palos Verdes Peninsula, California
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 1238-1243

ABSTRACT: Experimental methods have been evaluated for the determination of lifetime and diffusion length in Si intentionally doped with potentially lifetime degrading impurities which may be present in low cost Si intended for use in terrestrial flat-plate arrays. Results obtained with these methods have been compared for mutual consistency. The effects of a number of impurities on bulk lifetime were determined from steady-state photoconductivity, and solar cells fabricated from this material were characterized in terms of diffusion length using a penetrating light technique. Comparison was made with results obtained by others using photoconductivity decay. General agreement was found in terms of the hierachy of impurities to which the lifetime is sensitive. The utility of the steady-state photoconductivity method is established even in the presence of considerable trapping.

TITLE: Test and Evaluation of Silicon Cells Optimized for High Efficiency Under Concentrated Sunlight
AUTHOR: J. Castle, P. Payne, E. Aerni, and P. Stella
CORPORATE AUTH: Spectrolab, Inc., Sylmar, California; Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 810-816

ABSTRACT: An internal Spectrolab development task is being directed at determining performance characteristics of Si n/p concentrator solar cells. The cells being developed utilize advanced design and processing technology, which includes utilization of back surface fields, back surface reflectors, textured front surfaces, improved front contact geometry masks, and dual AR coatings. Selected performance characteristics obtained from this work are presented. Efficiencies of 18.6% at 28 C have been obtained on 2 x 2 cm size cells measured under concentrated simulated sunlight. Efficiencies exceeding 10% at 10 W/sq cm (100 AM1) solar constants) at a cell temperature of 100 C has also been obtained. Other performance characteristics addressed and evaluated in this program include the efficiency temperature coefficient and open circuit voltage sensitivity with concentration and temperature.

TITLE: A 1982 Low-Cost Photovoltaic Module Factory Study
AUTHOR: B.G. Carbajal
CORPORATE AUTH: Texas Instruments, Inc., Dallas, Texas
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 252-256

ABSTRACT: An analysis of a 1982 Solar PV Factory was made to determine the feasibility of achieving a $2.00/W selling price in 1982. The study concluded that an aggressive goal oriented program could achieve the target price with a production rate in the range of 25-30 MW/yr.

TITLE: Preliminary Process Design and Economics of Low Cost Solar-Grade Silicon Production
AUTHOR: W.C. Brenman, E.G. Farrier, and H. Morihara
CORPORATE AUTH: Union Carbide Corp., Sisterville, West Virginia; Union Carbide Corp., Tonawanda, New York
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 339-343

ABSTRACT: This process will produce high purity Si on a high-volume low cost basis. It uses the catalyzed reaction of hydrogen and Si tetrachloride with metallurgical Si to produce trichlorosilane. The trichlorosilane is converted to silane and recycled Si tetrachloride using a disproportionation reaction combined with distillation. The high purity silane is pyrolyzed to Si in either gas phase decomposition or in a fluid-bed reactor which deposits a dense plate of Si on seed particles. The process design, which includes redundant purification techniques to assure product quality, was demonstrated in small-scale apparatus. The product cost is forecast at well under $10/kg at a scale of 1000 MT/yr.

TITLE: Efficient Polycrystalline Solar Cells Made from Low Cost Refined Metallurgical Silicon
AUTHOR: J.I. Hanoka, H.B. Strock, and P.S. Kotval
CORPORATE AUTH: Union Carbide Technical Center, Tarrytown, New York
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 485-489.

ABSTRACT: A key element in reaching the goal of low cost terrestrial solar cells is the availability of an inexpensive substrate material. Polycrystalline substrates made from refined metallurgical Si are an attractive candidate. Accordingly, a low cost process for producing RMS has been developed. The resulting RMS substrate material is p type with resistivity of about 0.1 ohm-cm; major impurities are Fe, Ti, Cu, C, Al, B, and P. Diffused junction solar cells (n^+ p structure) have been fabricated on polycrystalline RMS substrates. AM1 efficiencies as high as 8.5% on cells of 4 sq cm area have been obtained with fill factors of 72% and diode quality factors n = 1.56 and J_o = 1.3 x 10^{-8} A/sq cm. An explanation for the rather high efficiencies obtained is suggested in which impurity segregation at the grain boundaries, including twin boundaries, plays a major role.

TITLE: Design Considerations for Silicon HLE Solar Cells
AUTHOR: F.A. Lindholm, A. Neugroschel, J.G. Fossum, and C.T. Sah
CORPORATE AUTH: University of Florida, Gainesville, Florida; Sandia National Labs., Albuquerque, New Mexico; Illinois Univ., Urbana, Illinois
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 1300-1305

ABSTRACT: The high-low (H-L) junction in the emitter region that defines the high-low-junction emitter (HLE) solar cell suppresses the dark emitter recombination current J_E so that the base recombination current dominates in determining the open-circuit voltage. For Si cells this enables the achievement of considerably larger values of open circuit voltage than those achievable in conven

tional structures. This paper describes experiments that demonstrate the achievement of J_g suppression (to less than 5×10^{-14} A/sq cm) and large open-circuit voltage (640 mV) in HLE test cells of two distinct types. In the first type (the diffused HLE structure) impurity diffusion forms the H-L junction in the emitter; in the second type (the oxide-charge-induced HLE structure) the H-L junction is formed in emitter material of relatively low doping concentration by an oxide-charge-induced electron accumulation layer.

TITLE: Evaluation of Options for Process Sequences in Solar Cell Manufacturing
AUTHOR: M. Wolf, H.M. Goldman, and A.C. Lawson
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania; Jet Propulsion Laboratory
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 271-280

ABSTRACT: A methodology is being developed to ease the comparative evaluation of competing options in the process sequence for the manufacture of PV solar energy utilization systems. This evaluation will largely involve process economic analyses but will place equal emphasis on other characteristics, including energy consumption and environmental effects of the process options. Early analyses have been performed for the energy consumption in the arc furnace reduction of SiO_2, for the costs and energy consumption in Cz crystal pulling and various slicing processes, and for the total energy consumption of process sequence through the completed module.

TITLE: Characterization of the Effects of Metallic Impurities on Silicon Solar Cell Performance
AUTHOR: J.R. Davis, A. Rohatgi, P. Rai-Choudhury, P. Blais, R.H. Hopkins, and J.R. McCormick
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania; Dow Corning Corp., Midland, Michigan
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 490-495

ABSTRACT: The effects of controlled concentrations of secondary impurities (Al, C, Ca, Cr, Cu, Fe, Mg, Mn, Mo, Ta, Ti, V, Zn, and Zr), incorporated alone or in combinations into Cz and float zone crystals, on the performance of Si solar cells were investigated. Impurity concentrations ranged from 10^{11} to 10^{17}/cu cm. Solar cells were fabricated by a conventional diffusion process and characterized by computer reduction of current-voltage data. The data suggest that performance loss primarily results from reduction of the base diffusion length. On the basis of this assumption, a first order analytic model which predicts cell performance as a function of impurity concentrations is developed. Calculated performance parameters are in good agreement with observation, except for some impurities, such as Fe, Cu and Ni, which degrade cells via recombination and defects in the junction space charge region. N-base devices are less affected by impurities, although degradation mechanisms appear to be the same as in p-devices. There seems to be very limited interaction between impurities in multiply doped cells.

TITLE: Computer Modeling of Dendritic Web Growth Processes and Characterization of the Material
AUTHOR: R.G. Seidensticker, R.E. Kothmann, J.P. McHugh, C.S. Duncan, R.H. Hopkins, P.D. Blais, J.R. Davis, and A. Rohatgi
CORPORATE AUTH: Westinghouse Electric Corp., Pittsburgh, Pennsylvania
MEETING LOCATION: 13th IEEE Photovoltaic Specialists Conference, Washington, D.C., June 5-8, 1978, Conference Record. (A79-40881 17-44) New York, 1978, p. 358-362

ABSTRACT: High area throughput rate will be required for the economical production of Si dendritic web for solar cells. Web width depends largely on the temperature distribution on the melt surface while growth speed is controlled by the dissipation of the latent heat of fusion. Thermal models were developed to investigate each of these aspects, and were used to engineer the design of laboratory equipment capable of producing crystals over 4 cm wide; growth speeds up to 10 cm/min were achieved. The web crystals were characterized by resistivity, lifetime and etch pit density data as well as by detailed solar cell I-V data. Solar cells ranged in efficiency from about 10 to 14.5% (AM-1) depending on growth conditions. Cells with lower efficiency displayed lowered bulk lifetime believed to be due to surface contamination.

TITLE: Casting Large Silicon Crystals in Clear Silica Crucibles
AUTHOR: C.P. Khattak and F. Schmid
CORPORATE AUTH: Crystal Systems, Inc., Salem, Massachusetts
PUBLICATION: American Ceramic Society Bulletin, vol. 57, June 1978, p. 609-610

ABSTRACT: None.

TITLE: High-Purity Silicon for Solar Cell Applications
AUTHOR: V.D. Dosaj, L.P. Hunt, and A. Schei
CORPORATE AUTH: Dow Corning Corp., Midland, Michigan; Elkem-Spigerverket A/S (Norway)
PUBLICATION: Journal of Metals, vol. 30, June 1978, p. 8-13

ABSTRACT: The article discusses the production of solar cells from high purity Si. The process consists of reducing the level of impurities in the raw materials, preventing material contamination before and after entering the furnace, and performing orders of magnitude reduction of metal impurity concentrations. The high-purity raw materials are considered with reference to carbon reductants, silica, and graphite electrodes. Attention is also given to smelting experiments used to demonstrate, in an experimental-scale furnace, the production of high purity SoG Si. It is found that high purity Si may be produced from high purity quartz and chemically purified charcoal in a 50 kVA arc furnace. The major contamination source is shown to be impurities from the carbon reducing materials.

TITLE: A Simple Theory of Back Surface Field Solar Cells
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics, vol. 49, June 1978, p. 3503-3511

ABSTRACT: A theory of an n p p^+ junction is developed, entirely based on Shockley's depletion layer approximation. Under the further assumption of uniform doping the electrical characteristics of solar cells as a function of all relevant parameters (cell thickness, diffusion lengths, etc.) can quickly be ascertained with a minimum of computer time. Two effects contribute to the superior performance of a BSF cell (n p-p^+ junction) as compared to an ordinary solar cell (n-p junction). The sharing of the applied voltage among the two junctions (the n p and the p-p^+ junction) decreases the dark current and the reflection of minority carriers by the built in electron field of the p p^+ junction increases the short circuit current. The theory predicts an increase in the V_{oc} with a decrease in cell thickness. Although the short circuit current decreases at the same time, the efficiency of the cell is virtually unaltered in going from a thickness of 200 microns to a thickness of 50 microns. The importance of this fact for space missions where large power to weight ratios are required is obvious.

TITLE: Theoretical Analysis of Heat Flow in Horizontal Ribbon Growth from a Melt - Silicon Metal
AUTHOR: J.A. Zoutendyk
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics, vol. 49, July 1978, p. 3927-3932

ABSTRACT: A theoretical heat flow analysis for horizontal ribbon growth is presented. Equations are derived relating pull speed, ribbon thickness, thermal gradient in the melt, and melt temperature for limiting cases of heat removal by radiation only and isothermal heat removal from the solid surface over the melt. Geometrical cross sections of the growth zone are shown to be triangular and nearly parabolic for the two respective cases. Theoretical pull speed for silicon ribbon 0.01 cm thick, where the loss of latent heat of fusion is by radiation to ambient temperature (300 K) only, is shown to be 1 cm/sec for horizontal growth extending 2 cm over the melt and with no heat conduction either to or from the melt. Further enhancement of ribbon growth rate by placing cooling blocks adjacent to the top surface is shown to be theoretically possible.

TITLE: Emitter Current Suppression in a High-Low-Junction Emitter Solar Cell Using an Oxide-Charge-Induced Electron Accumulation Layer
AUTHOR: A. Neugroschel, F.A. Lindholm, S.C. Pao, and J.G. Fossum
CORPORATE AUTH: University of Florida, Gainesville, Florida
PUBLICATION: Applied Physics Letters, vol. 33, July 15, 1978, p. 168-170

ABSTRACT: None.

TITLE: The Application of Photovoltaic Roof Shingles to Residential and Commercial Buildings
AUTHOR: N.F. Shepard, Jr and L.E. Sanchez
CORPORATE AUTH: General Electric Co., Philadelphia, Pennsylvania; Jet Propulsion Laboratory
MEETING LOCATION: Intersociety Energy Conversion Engineering Conference, 13th, San Diego, California, Aug. 20-25, 1978, Proceedings. Vol. 2 (A79-10001 01-44) Warrendale, Pennsylvania, Society of Automotive Engineers, Inc., 1978, p. 1582-1587

ABSTRACT: The recent development of a shingle type solar-cell module makes it possible to incorporate easily PV power generation into the sloping roofs of residential or commercial buildings. These modules, which use a closely packed array of nineteen 53 mm dia circular solar cells, are capable of producing 101 W/sq m of module area under standard operating conditions. This module performance is achievable by the use of solar cells with an average efficiency of 13.3% at 1 kW/sq m AM1.5 insolation and at a cell temperature of 28 C. When these modules are mounted on a sloping south-facing roof which is insulated on the rear surface, the annual energy generated at the maximum power operating point will vary from 255.6 to 137.3 kWh/sq m of module area depending on the site location, with Albuquerque, New Mexico, and Seattle, Washington, representing the highest and lowest values of the thirteen sites considered.

TITLE: Analysis of the Interaction of an Electron Beam With a Solar Cell. I. II
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Solid-State Electronics, vol. 21, Aug. 1978, p. 1063-1067, 1069 1077

ABSTRACT: The short-circuit current generated by the electron beam of a scanning electron microscope when it impinges on the n p junction of a solar cell is known to be dependent on the configuration used to investigate the cell's response, and the situation for one specific configuration is analyzed. This configuration is the case in which the highly collimated electron beam strikes the edge of a planar junction a variable distance away from the edge of the depletion layer. An earlier treatment is generalized to encompass the ohmic contact at the back surface. The analysis employing Fourier and Wiener-Hopf techniques shows that it is impractical to determine the bulk diffusion length of a solar cell by a SEM used in the studied configuration unless the ohmic contact is partially removed.

TITLE: Defect Distribution Near the Surface of Electron-Irradiated Silicon
AUTHOR: K.L. Wang, Y.H. Lee, and J.W. Corbett
CORPORATE AUTH: General Electric Co., Schenectady, New York; New York State Univ., Albany, New York
PUBLICATION: Applied Physics Letters, vol. 33, Sept. 15, 1978, p. 547, 548

ABSTRACT: The surface-defect distributions of electron-irradiated n type Si have been investigated using a transient capacitance technique. Schottky, p n junction, and MOS structures were used in profiling the defect distributions. Surface depletions of defects observed were attributed to the vacancy distribution, but not that of oxygen, and other capture centers' distributions. The vacancy diffusion length at 300 K was estimated to be about 3-6 microns.

TITLE: Effect of Grain Boundaries in Silicon on Minority-Carrier Diffusion Length and Solar Cell Efficiency
AUTHOR: T. Daud, K.M. Koliwad, and F.G. Allen
CORPORATE AUTH: Jet Propulsion Laboratory; University of California, Los Angeles, California
PUBLICATION: Applied Physics Letters, vol. 33, Dec. 15, 1978, p. 1009-1011.

ABSTRACT: The spatial variation of minority-carrier diffusion length in the vicinity of a grain boundary for a polycrystalline Si sheet has been measured by the use of the EBIC technique. The effect of such a variation on solar cell output has then been computed as a function of grain size. Calculations show that the cell output drops considerably for grain size smaller than three times the bulk diffusion length.

TITLE: Low Cost Encapsulation Materials for Terrestrial Solar Cell Modules
AUTHOR: E.F. Cuddihy, B. Baum, and P. Willis
CORPORATE AUTH: Jet Propulsion Laboratory; Springborn Laboratories, Inc., Enfield, Connecticut
PUBLICATION: Solar Energy, vol. 22, no. 4, 1979, p. 389-396

ABSTRACT: The paper presents the findings of material surveys intended to identify low cost materials which could be functional as encapsulants (by 1986) for terrestrial solar cell modules. Economic analyses have indicated that in order to meet the low cost goal of \$2.70 m^2, some or all of the following material technologies must be developed or advanced: (1) UV screening outer covers; (2) elastomeric acrylics; (3) weatherproofing and water-proofing of structural wood and paper products; (4) transparent UV stabilizers for the UV sensitive transparent pottants; and (5) cost-effective utilization of silicone and fluoro-carbon materials.

TITLE: New Technologies for Solar Energy Silicon - Cost Analysis of UCC Silane Process
AUTHOR: C.L. Yaws, F.C. Jelen, K.-Y. Li, M.P. Patel, and C.S. Fang
CORPORATE AUTH: Lamar University, Beaumont, Texas; Southwestern Louisiana, University, Lafayette, Louisiana

PUBLICATION: Solar Energy, vol. 22, no. 6, 1979, p. 547-553

ABSTRACT: A preliminary process design was performed to provide detailed data for cost analysis. The design was based on a plant size of 1000 MT/yr production of solar cell grade Si. Cost and sensitivity analysis results are presented for producing Si which includes costs for raw materials, labor, utilities, and other items composing product cost. For sensitivity analysis, the order of cost parameter influence on product cost is given by plant investment, raw materials, labor, and utilities. A cost and profitability analysis summary is also presented including sales price of polysilicon at various rates of return on investment.

TITLE: On the Determination of Diffusion Lengths by Means of Angle Lapped p n Junctions
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Solid-State Electronics, vol. 22, Jan. 1979, p. 113, 114

ABSTRACT: A standard procedure for determining the minority carrier diffusion length by means of SEM consists of scanning an angle-lapped surface of a p-n junction and measuring the resulting short circuit current as a function of beam position. The present paper points out that the usual expression linking the short circuit current induced by the electron beam to the angle between the semiconductor surface and the junction plane is incorrect. The correct expression is discussed and it is noted that, for angles less than 10 deg, the new and the old expression are practically indistinguishable.

TITLE: Structural Cost Optimization of Photovoltaic Central Power Station Modules and Support Structure
AUTHOR: P.D. Sutton, W.J. Stolte, and R. Marsh
CORPORATE AUTH: Jet Propulsion Laboratory; Bechtel International Corp., San Francisco, California
MEETING LOCATION: American Society of Mechanical Engineers, Gas Turbine Conference and Exhibit and Solar Energy Conference, San Diego, California, Mar. 12-15, 1979, 8 p

ABSTRACT: The results of a comprehensive study of PV module structural support concepts for PV central power stations and their associated costs are presented. The objective of the study has been the identification of structural cost drivers. Parametric structural design and cost analyses of complete array systems consisting of modules, primary support structures, and foundations were performed. Area related module cost was found to be constant with design, size, and loading. A curved glass module concept was evaluated and found to have the potential to significantly reduce panel structural costs. Conclusions of the study are: array costs do not vary greatly among the designs evaluated; panel and array costs are strongly dependent on design loading; and the best support configuration is load dependent

TITLE: Application of the Superposition Principle to Solar-Cell Analysis
AUTHOR: F.A. Lindholm, J.G. Fossum, and E.L. Burgess
CORPORATE AUTH: University of Florida, Gainesville, Florida; Sandia National Labs., Albuquerque, New Mexico
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-26, Mar. 1979, p. 165-171

ABSTRACT: The superposition principle of differential-equation theory, which applies if and only if the relevant boundary value problems are linear, is used to derive the widely used shifting approximation that the current-voltage characteristic of an illuminated solar cell is the dark current-voltage characteristic shifted by the short circuit photocurrent. Analytical methods are presented to treat cases where shifting is not strictly valid. Well-defined conditions necessary for superposition to apply are established. For high injection in the base region, the method of analysis accurately yields the dependence of the open circuit voltage on the short circuit current (or the illumination level).

TITLE: Considerations for Accurately Determining the Maximum Power Output of Solar Cells
AUTHOR: J.W. Lathrop and J. Prince
CORPORATE AUTH: Clemson University, Clemson, South Carolina
MEETING LOCATION: SOUTHEASTCON '79; Proceedings of the Region 3 Conference and Exhibit, Roanoke, Virginia, April 1-4, 1979. (A79-50026 22-31) New York, Institute of Electrical and Electronics Engineers, Inc., 1979, p. 29-32

ABSTRACT: The most important single electrical parameter characterizing solar cell performance is Pm, the cell's maximum power output. In order to experimentally determine Pm it is necessary accurately to control both illumination and cell temperature during measurements. Two quite different measurement approaches can be used: an equilibrium method and a transient flash method. Both techniques are discussed in the paper in detail.

TITLE: Accelerated Stress Testing of Terrestrial Solar Cells
AUTHOR: J. Prince and J.W. Lathrop
CORPORATE AUTH: Clemson University, Clemson, South Carolina
MEETING LOCATION: SOUTHEASTCON '79; Proceedings of the Region 3 Conference and Exhibit, Roanoke, Virginia, April 1-4, 1979. (A79-50026 22-31) New York, Institute of Electrical and Electronics Engineers, Inc., 1979, p. 33-36

ABSTRACT: A program to investigate the reliability characteristics of unencapsulated low cost terrestrial solar cells using accelerated stress testing is described. Reliability (or parametric degradation) factors appropriate to the cell technologies and use conditions were studied and a series of accelerated stress tests was synthesized. An electrical measurement procedure and a data analysis and management system was derived, and stress test fixturing and material flow procedures were set up after consideration was given to the number of cells to be stress tested and measured and the nature of the information to be obtained from the process. Selected results and conclusions are presented.

TITLE: Design Curves for Non-Linear Analysis of Simply-Supported, Uniformly-Loaded Rectangular Plates
AUTHOR: D. Moore
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Structures, Structural Dynamics, and Materials Conference, 20th, St. Louis, Missouri, April 4-6, 1979, Technical Papers on Dynamics and Loads. (A79-28251 10-39) New York, American Institute of Aeronautics and Astronautics, Inc., 1979, p. 137-144

ABSTRACT: Design curves for the non-linear analysis of simply-supported rectangular plates subjected to uniform normal pressure loads have been developed. These curves yield the center deflection, center stress and corner stress in non-dimensionalized form plotted against a dimensionless parameter describing the load intensity. The results presented are based on extensive non linear finite element analysis employing the ARGUS structural

analysis program. Plates with length to width ratios of 1, 1.5, 2, 3 and 4 are included. The load range considered extends to 1000 times the load at which the behavior of the plate becomes significantly non-linear. Over the load range considered, the analysis shows that the ratio of center deflection to plate thickness for a square plate is less than 16 to 1, whereas linear theory would predict a center deflection 400 times the plate thickness. Likewise, the stress is markedly lower than would be predicted by linear theory. The present results are shown to be in excellent agreement with the classical linear theory up to a central deflection to plate thickness ratio of about one-half. In the non-linear regime the present results for deflection and stress are in very good agreement with the analytical and experimental work of other investigators.

TITLE: Assessment of Low-Cost Manufacturing Process Sequences Photovoltaic Solar Arrays
AUTHOR: R.G. Chamberlain
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: European Congr. on Operations Res., Amsterdam, 9 Apr. 1979

ABSTRACT: An extensive research and development activity to reduce the cost of manufacturing PV solar arrays by a factor of approximately one hundred is discussed. Proposed and actual manufacturing process descriptions were compared to manufacturing costs. An overview of this methodology is presented.

TITLE: Low-Cost, High Efficiency Silicon by Heat Exchanger Method and Fixed Abrasive Slicing Technique for Solar Cells
AUTHOR: C.P. Khattak and F. Schmid
CORPORATE AUTH: Crystal Systems, Inc., Salem, Massachusetts
MEETING LOCATION: Photovoltaic Solar Energy Conference, 2nd, Berlin, West Germany, April 23-26, 1979, Proceedings. (A80-46694 20-44)Dordrecht, D. Reidel Publishing Co., 1979, p. 106-113

ABSTRACT: The paper describes the HEM for growing Si crystals. The problem of ingot cracking was solved by using a graded structure silica crucible, and vacuum processing eliminated expensive high purity argon. Solar cells fabricated from HEM Si demonstrated conversion efficiencies up to 15% (AM1) at low cost, using square cross-section, single crystal Si. A modified multiblade slurry machine was adapted for multiwire fixed abrasive slicing of Si which uses a diamond attached to wires; this method provides a conversion ratio of 1.08 sq m of wafer/Kg of Si ingot, and produces wafers free of edge chipping with a surface damage of 3-5 microns.

TITLE: Progress on the Dow Corning Process for Solar-Grade Silicon
AUTHOR: L.P. Hunt and V.D. Dosaj
CORPORATE AUTH: Dow Corning Corp., Hemlock, Michigan
MEETING LOCATION: Photovoltaic Solar Energy Conference, 2nd, Berlin, West Germany, April 23-26, 1979, Proceedings. (A80-46694 20-44) Dordrecht, D. Reidel Publishing Co., 1979, p. 98-105

ABSTRACT: The Dow Corning approach to increasing the resistivity of solar-grade Si from about 0.04 ohm-cm (40 ppma B) to greater than 0.1 ohm-cm (10 ppma B) involves the use of high-purity raw materials carbothermically reduced in a specially designed electric arc furnace. Final purification occurs during Cz crystal growth of a polycrystalline ingot. This small-scale purification technology has resulted in Si that has been fabricated into solar cells with a maximum AM1 conversion efficiency of 13.4%.

TITLE: A Preliminary Test Case Manufacturing Sequence For 50¢/Watt Solar Photovoltaic Modules in 1986
AUTHOR: D.B. Bickler
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference, 2nd, Berlin, West Germany, April 23-26, 1979, Proceedings. (A80-46694 20-44) Dordrecht, D. Reidel Publishing Co., 1979, p. 835-842

ABSTRACT: The paper describes a test case manufacturing process sequence for solar PV modules which will cost 50¢/W in 1986. The process, which starts with the purification of Si grown into 75-mm wide thin ribbons, is discussed, and the plant layout is depicted; each department is sized to produce 250 MW of modules/yr. The cost of this process sequence is compared to present technology at various companies showing considerable spread for each process; data are tabulated in a composite state of the art cell processing cost summary for these processes.

TITLE: Recent Developments in the Economic Modeling of Photovoltaic Module Manufacturing
AUTHOR: R.G. Chamberlain
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference, 2nd, Berlin, West Germany, April 23-26, 1979, Proceedings. (A80-46694 20-44) Dordrecht, D. Reidel Publishing Co., 1979, p. 851-858

ABSTRACT: Recent developments in the SAMICS are described. Consideration is given to the added capability to handle arbitrary operating schedules and the revised procedure for calculation of one-time costs. The results of an extensive validation study are summarized.

TITLE: Encapsulation Materials for Photovoltaic Arrays
AUTHOR: C. Coulbert
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: The Enigma of the Eighties: Environment, Economics, Energy; Proceedings of the Twenty-fourth National Symposium and Exhibition, San Francisco, California, May 8-10, 1979. Book 2. (A79-43228 18-23) Azusa, California, Society for the Advancement of Material and Process Engineering, 1979, p. 850-865

ABSTRACT: As a part of the LSA Project an encapsulation task has been established to identify, develop, and evaluate new low cost, long-life encapsulation systems capable of meeting the project cost and performance goals. Low cost material system candidates have been identified and are being characterized in laboratory and field tests with detailed evaluation of their environmental stability when subjected to temperature cycling, humidity, ultraviolet radiation, dirt, and various other environmental hazards.

TITLE: Testing Flat Plate Photovoltaic Modules for Terrestrial Environment
AUTHOR: A.R. Hoffman, J.C. Arnett, and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 2nd Photovoltaic Solar Energy Conference, Berlin, West Germany, April 23-26, 1979, Proceedings. (A80-46694 20-44) Dordrecht, D. Reidel Publishing Co., 1979, p. 978-986

ABSTRACT: New qualification tests have been developed for flat-plate PV modules. Temperature cycling, cyclic pressure load, and humidity exposure are especially useful for detecting design and fabrication deficiencies. There is positive correlation between many of the observed field effects, such as power loss, and qualification test induced degradation. The status of research efforts for the development of test methodology for field-related problems is reviewed.

TITLE: Some Characteristics of Low-Cost Silicon Sheets
AUTHOR: K.M. Koliwad, T. Daud, and J.K. Liu
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference, 2nd, Berlin, West Germany, April 23-26, 1979, Proceedings. (A80-46694 20-44) Dordrecht, D. Reidel Publishing Co., 1979, p. 710-717

ABSTRACT: The paper discusses structural defects in low-cost Si sheets and their effect on the electronic properties related to solar cell performance. Experimental data are presented on the influence of grain boundaries on minority carrier diffusion length, impurity defect interaction, and variable surface recombination velocity. An analytical model of the effect of grain boundaries on solar cell performance is constructed based on these results.

TITLE: Low-Cost Processes for Silicon Fabricated for Solar Cells
AUTHOR: R. Lutwack
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference, 2nd, Berlin, West Germany, April 23-26, 1979, Proceedings. (A80-46694 20-44) Dordrecht, D. Reidel Publishing Co., 1979, p. 718-725

ABSTRACT: This paper describes the multiple process development of low-cost processes for manufacture of Si. A support program includes subtasks for the modeling of reactions and reactors, chemical engineering and solid state physics studies, and development of impurity concentration measurement procedures. The preliminary economic analyses indicate total product costs ranging from $5.00 to $8.73/Kg based on 1000 MT/yr plants. In the studies of impurity effects, a model which considers that degradations of solar cell performance by impurities are primarily due to decreases in base diffusion length was constructed from experimental data.

TITLE: Physical/Chemical Modeling for Photovoltaic Module Life Prediction
AUTHOR: J. Moacanin, W.F. Carroll, and A. Gupta
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference, 2nd, Berlin, West Germany, April 23-26, 1979, Proceedings. (A80-46694 20-44) Dordrecht, D. Reidel Publishing Co., 1979, p. 995-1001

ABSTRACT: The paper presents a generalized methodology for identification and evaluation of potential degradation and failure of terrestrial PV encapsulation. Failure progression modeling and an interaction matrix are utilized to complement the conventional approach to failure degradation mode identification. Comparison of the predicted performance based on these models can produce: (1) constraints on system or component design, materials or operating conditions, (2) qualification (predicted satisfactory function), and (3) uncertainty. The approach has been applied to an investigation of an unexpected delamination failure; it is being used to evaluate thermo-mechanical interactions in PV modules and to study corrosion of contacts and interconnects.

TITLE: Potential for Improved Silicon Ribbon Growth Through Thermal Environment Control
AUTHOR: R.W. Gurtler, A. Baghdadi, R.N. Legge, and R.J. Ellis
CORPORATE AUTH: Motorola, Inc., Phoenix, Arizona
MEETING LOCATION: Photovoltaic Solar Energy Conference, 2nd, Berlin, West Germany, April 23-26, 1979, Proceedings. (A80-46694 20-44) Dordrecht, D. Reidel Publishing Co., 1979, p. 145-152

ABSTRACT: The RTR process for growth of Si ribbon is described. This process involves the fabrication of a microcrystalline ribbon of Si and subsequent grain size enhancement through a laser recrystallization process. The microribbon is obtained from a thermal expansion shear separation process which allows a CVD layer of Si to be separated from a temporary molybdenum substrate. Efforts to achieve increased solar cell efficiencies and higher area production rates have been problematical. Furnaces, which are necessary for thermal stress control, have been shown to contribute contamination to substrates resulting in degraded efficiencies. Recent results with a new furnace design indicate efficiencies in excess of 9% will e routine. Limitations to area throughput arise due to fundamental linear velocity limitations and width limitations necessary to prevent the occurrence of thermal buckling. Calculations are reported which show the influence of thermal profile on buckling tendencies, and a proposed electron beam technique is considered which promises high throughput with minimal buckling.

TITLE: Environmental Requirements for Flat-Plate Photovoltaic Modules for Terrestrial Applications
AUTHOR: A.R. Hoffman and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Learning to Use Our Environment; Proceedings of the Twenty-fifth Annual Technical Meeting, Seattle, Washington, April 30-May 2, 1979. (A79-50326 22-42) Mount Prospect, Illinois, Institute of Environmental Sciences, 1979, p. 171-178

ABSTRACT: The environmental test requirements that have been developed for flat-plate modules purchased through Department of Energy funding are described. Concurrent with the selection of the initial qualification tests from space program experience, temperature cycling and humidity, surveys of existing PV systems in the field revealed that arrays were experiencing the following failure modes: interconnect breakage, delamination, and electrical termination corrosion. These coupled with application dependent considerations led to the development of additional qualification tests, such as cyclic pressure loading, warped mounting surface, and hail. Rationale for the selection of tests, their levels and durations is described. Comparisons between field observed degradation and test induced degradation show a positive correlation with some of the observed field effects. Also, the tests are proving useful for detecting design, process, and workmanship deficiencies. The status of study efforts for the development of environmental requirements for field-related problems is reviewed.

TITLE: Encapsulation Materials for Photovoltaic Arrays
AUTHOR: C. Coulbert
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: The Enigma of the Eighties: Environment, Economics, Energy; Proceedings of the Twenty-fourth National Symposium and Exhibition, San Francisco, California, May 8-10, 1979. Book 2. (A79-43228 18-23) Azusa, California, Society for the Advancement of Material and Process Engineering, 1979, p. 850-865

ABSTRACT: As a part of the LSSA Project an encapsulation task has been established to identify, develop, and evaluate new low-cost, long-life encapsulation systems capable of meeting the project cost and performance goals. Low cost material system candidates have been identified and are being characterized in laboratory and field tests with detailed evaluation of their environmental stability when subjected to temperature cycling, humidity, UV radiation, dirt, and various other environmental hazards.

TITLE: MIS Solar Cells on Crystalline, Polycrystal, and Thin Film Silicon
AUTHOR: S.L. Hyland, J.K. Kim, A. Delahoy, W.A. Anderson, and K. Rajkanan
CORPORATE AUTH: Jet Propulsion Laboratory; Rutgers University, Piscataway, New Jersey; New York State University, Buffalo, New York
MEETING LOCATION: Sun II; Proceedings of the Silver Jubilee Congress, Atlanta, Georgia, May 28-June 1, 1979. Volume 3. (A80-33401 13-44) Elmsford, N.Y., Pergamon Press, Inc., 1979, p. 1786-1789

ABSTRACT: The performance characteristics of MIS solar cells using single crystal, polycrystalline, ribbon and thin film Si are investigated. Overall cell efficiencies, open-circuit voltages, short-circuit current densities and diffusion lengths were measured for chromium-Si, oxide-Si cells fabricated on single crystal substrates and the less costly polycrystalline, ribbon, edge defined film fed growth and electron beam deposited silicon. Results reveal cell efficiency to be lower in cells fabricated from the less costly substrates, due to lower short circuit currents arising from recombination near crystal defects and decreased open circuit voltage attributed to surface defects. It is concluded that the use of MIS semiconductor solar cells based on Si, with efficiencies up to 12%, represents progress in attaining PV costing less than 50¢/W.

TITLE: Experimental and Theoretical Studies of I-V Characteristics of Zinc-Doped Silicon p-n Junctions Using the Exact dc Circuit Model
AUTHOR: P.C.H. Chan and C.T. Sah
CORPORATE AUTH: University of Illinois, Urbana, Illinois
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-26, June 1979, p. 937-941

ABSTRACT: None.

TITLE: Thermal and Other Tests of Photovoltaic Modules Performed in Natural Sunlight
AUTHOR: J.W. Stultz
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: American Institute of Aeronautics and Astronautics, Terrestrial Energy Systems Conference, Orlando, Florida, June 4-6, 1979, 15 p

ABSTRACT: The NOCT, an effective way to characterize the thermal performance of a PV module in natural sunlight, is developed. NOCT measurements for more than twenty different modules are presented. Changes in NOCT reflect changes in module design, residential roof mounting, and dirt accumulation. Other test results show that electrical performance is improved by cooling modules with water and by use of a phase change wax. Electrical degradation resulting from the marriage of PV and solar water heating modules is demonstrated. Cost-effectiveness of each of these techniques is evaluated.

TITLE: Photovoltaic Systems Perspective
AUTHOR: P.D. Sutton and G.J. Jones
CORPORATE AUTH: Jet Propulsion Laboratory; Sandia National Labs., Albuquerque, New Mexico
MEETING LOCATION: American Institute of Aeronautics and Astronautics, Terrestrial Energy Systems Conference, Orlando, Florida, June 4-6, 1979, 9 p

ABSTRACT: This paper summarizes the elements of PV power system and clarifies the terminology currently used. The relationship of system efficiency and cost is described particularly for the Balance of PV System (BOPS) area. The current status of the BOPS development activity is described. The PV systems terminology is found to be on the road to standardization. Power conditioning, energy storage, and support structure are found to be BOPS cost and/or efficiency drivers. Although the current BOPS activity has identified low-cost/high-efficiency components, further development work is necessary.

TITLE: Electron Beam Induced Current Characterization of Polycrystalline Silicon Solar Cells
AUTHOR: J.I. Hanoka
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
PUBLICATION: (Photovoltaic Material and Device Measurements Workshop, Arlington, Virginia, June 11-13, 1979.) Solar Cells, vol. 1, Feb. 1980, p. 123-139.

ABSTRACT: The use of the electron-beam-induced current mode of the scanning electron microscope for recombination studies in polycrystalline Si solar cells is reviewed. The potential and some limits of the technique are discussed. Quantitative studies and representative results for EFG ribbon solar cells and other kinds of Si solar cells are presented and compared. Questions concerning recombination by impurities and defects such as dislocations, grain boundaries and SiC particles and the interactive effects of all these are discussed at some length.

TITLE: Grain Boundary Effects and Conduction Mechanism Studies in Chromium Metal-Insulator-Silicon Solar Cells on Polycrystalline Silicon
AUTHOR: W.A. Anderson, J. Rajkanan, A. Delahoy, and S.L. Hyland
CORPORATE AUTH: New York, State University, Buffalo, New York; Rutgers University, Piscataway, New Jersey; Jet Propulsion Laboratory
MEETING LOCATION: (Photovoltaic Material and Device Measurement Workshop, Arlington, Virginia, June 11-13, 1979.) Solar Cells, vol. 1, May 1980, p. 305-310

ABSTRACT: Chromium metal-insulator-Si (MIS) solar cells fabricated on Wacker polycrystalline Si and electron-beam deposited thin film Si were studied to determine current flow mechanisms. Wacker polycrystalline p-type Si was shown to produce MIS solar cells which exhibit surface state controlled current for T greater than 150 K and tunneling controlled current at lower temperatures. MIS cells on unpolished Wacker Si are clearly space charge limited. Electron beam deposited polycrystalline Si 20-30 microns thick has a conductivity which may be limited by the grain boundary trap density or the availability of free carriers. Surface state analysis, laser scan data and diffusion length studies also show the limitations which exist at grain boundaries of polycrystalline Si.

TITLE: Silicon Ribbon for Photovoltaic Cells
AUTHOR: A. Baghdadi, R.W. Gurtler, R.J. Ellis, and I.A. Lesk
CORPORATE AUTH: National Bureau of Standards, Washington, D.C.; Motorola, Inc., Phoenix, Arizona
MEETING LOCATION: Laser 79 Opto-electronics; Proceedings of the Fourth Conference, Munich, West Germany, July 2-6, 1979. (A80-29334 11-36) Guildford, Surrey, England, IPC Science and Technology Press, Ltd., 1979, p. 539-543

ABSTRACT: The ribbon-to-ribbon method (RTR) for Si ribbon growth is presented, in which a pair of scanned, focused CO_2 laser beams is used to establish a molten zone in a preformed polycrystalline ribbon. Large grained Si ribbon is then drawn from the zone at growth rates up to 13.3 cm/min and the Si ribbon purity is maintained by purging gases used to protect the molten zone during growth. The efficiency of RTR solar cells is found to average 9% with the best cell reaching the 12% conversion efficiency needed for economic viability. It is shown that RTR has achieved

the highest growth rates reported for Si ribbon growth and has great promise as a low-cost PV substrate.

TITLE: A Simple Theory of Back-Surface-Field Solar Cells
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics, vol. 50, Aug. 1979, p. 5371-5374

ABSTRACT: An earlier calculation of the I-V characteristics of solar cells contains a mistake. The current generated by light within the depletion layer is too large by a factor of 2. When this mistake is corrected, not only are all previous conclusions unchanged, but the agreement with experiment becomes better. Results are presented in graphical form of new computations which not only take account of the factor of 2, but also include more recent data on material parameters.

TITLE: High-Efficiency p^+-n-n^+ Back-Surface-Field Silicon Solar Cells
AUTHOR: J.G. Fossum and E.L. Burgess
CORPORATE AUTH: Sandia National Laboratories, Albuquerque, New Mexico
PUBLICATION: Applied Physics Letters, vol. 33, Aug. 1, 1979, p. 238-240

ABSTRACT: The design and fabrication of high-efficiency p^+-n-n^+ back-surface-field Si solar cells are described. The fabrication process has been developed to yield maximum attainable carrier lifetimes (about 0.7 msec) in the base region of the cell, thereby allowing the back n-n^+ junction to enhance effectively the cell performance. A surprising conclusion drawn from a study of the device physics supporting the experimental development of the cell is that the front-surface recombination velocity controls the recombination in the emitter. That is, the bulk p^+ emitter is transparent to minority carrier (electron) flow. The recognition of the significance of the front Si surface has led to process modifications that result in improvements in both the short circuit current density and the open-circuit voltage of the cell. With these improvements, the cells exhibit AM1 conversion efficiencies of nearly 17%. The fabrication process is reliable and reproducible with exceptionally high yield.

TITLE: Environmental Testing of Terrestrial Flat-Plate Photovoltaic Modules
AUTHOR: A. Hoffman and J. Griffith
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Intersociety Energy Conversion Engineering Conference, 14th, Boston, Massachusetts, August 5-10, 1979, Proceedings. Volume 1. (A79-51726 23-44) Washington, D.C., American Chemical Society, 1979, p. 230-238

ABSTRACT: The LSA Project at JPL has as one objective: the development and implementation of environmental tests for flat-plate PV modules as part of the Department of Energy's terrestrial PV program. Modules procured under this program have been subjected to a variety of laboratory tests intended to simulate service environments, and the results of these tests have been compared to available data from actual field service. This comparison indicates that certain tests (notably temperature cycling, humidity cycling, and cyclic pressure loading) are effective indicators of some forms of field failures. Other tests have yielded results useful in formulating module design guidelines. Not all effects noted in field service have been successfully reproduced in the laboratory, however, and work is continuing in order to improve the value of the test program as a tool for evaluating module design and workmanship. This paper contains a review of these ongoing efforts and an assessment of significant test results to date.

TITLE: Titanium in Silicon as a Deep Level Impurity
AUTHOR: C.-W. Chen, A.G. Milnes, and A. Rohatgi
CORPORATE AUTH: Carnegie Mellon Univ., Pittsburgh, Pennsylvania
PUBLICATION: Solid-State Electronics, vol. 22, Sept. 1979, p. 801-808

ABSTRACT: Titanium inserted in Si by diffusion or during Cz ingot growth is electrically active to a concentration level of about 4×10^{14}/cu cm. It is reported that Hall measurements after diffusion show conversion of lightly doped p-type Si to n-type due to a Ti donor level at E_c-0.22 eV. In addition, in DLTS measurements of n^+p structures this level shows as an electron (minority carrier) trap at E_c-0.26 eV with an electron capture cross section of about $3 \times 10^{-15}/cm^2$ at 300 K. Finally, a Ti electrically active concentration of about 1.35×10^{13}/cu cm in p type Si results in a minority carrier (electron) lifetime of 50 nsec at 300 K.

TITLE: Analysis of the Interaction of an Electron Beam with a Solar Cell. III - The Effect of Spacial Variations of the Number Density of Recombination Centers on SEM Measurements
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Solid-State Electronics, vol. 22, Sept. 1979, p. 773-778

ABSTRACT: By means of an exactly soluble model the short circuit current generated by a scanning electron microscope in a p-n junction has been determined in cases where the trap density is inhomogeneous. The diffusion length for minority carriers becomes then dependent on the spacial coordinates. It is shown that in this case the dependence of the I_{sc} on characteristic parameters as cell thickness, distance of the beam excitation spot from ohmic contacts, etc., becomes very intricate. This fact precludes the determination of the local diffusion length in the usual manner. Although the model is somewhat simplified in order to make it amenable to exact solutions, it is nevertheless realistic enough to lead to the conclusion that SEM measurements of bulk transport parameters in in homogeneous semiconductor material are impractical since they may lead to serious errors in the interpretation of the data by customary means.

TITLE: Extension of a Theorem Used in the Investigation of p-n Junctions with the Scanning Electron Microscope to Arbitrary Geometries and Arbitrarily Inhomogeneous Material
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Applied Physics Letters, vol. 35, Sept. 1, 1979, p. 408, 409

ABSTRACT: None.

TITLE: Relating Computer Simulation Studies With Interface State Measurements on MIS Solar Cells
AUTHOR: J.K. Kim, W.A. Anderson, S. Hyland
CORPORATE AUTH: RCA David Sarnoff Research Center, Princeton, New Jersey; New York, State University, Buffalo, New York, Jet Propulsion Laboratory
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-26, Nov. 1979, p. 1777-1782

ABSTRACT: A lock-in-amplifier technique has been used to measure interface state density (N_{ss}) values ranging from 2×10^{11} to 3×10^{13} states/sq cm eV depending on energy in the gap, type of Si substrate, and choice of Schottky metal used in MIS diodes. Polycrystalline, ribbon, and (100) single crystal Si substrates with 40-60 interfacial oxides have been tested using Cr, Al, Ti, and Cu as Schottky metal. A computer simulation is used to predict the influence of interface states, interfacial

oxide thickness, and Schottky metal on open circuit voltage. The influence of Schottky metal on open circuit voltage is also clearly seen. Very close agreement is shown between experimental and theoretical values. This study clearly relates experimental and theoretical data to permit design of more efficient MIS solar cells.

TITLE: Silicon Material Task - Low Cost Solar Array Project
AUTHOR: R. Lutwack
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: New Horizons - Materials and Processes for the Eighties; Proceedings of the Eleventh National Conference, Boston, Massachusetts, November 13-15, 1979. (A80-34751 14-23) Azusa, California, Society for the Advancement of Material and Processes Engineering, 1979, p. 437-440

ABSTRACT: The paper describes the Si material task of the LSA Project, which has the objective of establishing a Si production capability equivalent to 400 mW/yr at a price less than $10/Kg (1975 dollars) in 1986. The task program is divided into four phases: technical feasibility, scale-up studies (the present phase), experimental process system development units, and implementation of large scale production plants, and it involves the development of processes for two groups of materials, that is, semiconductor grade and solar cell grade. In addition, the effects of impurities on solar cell performance are being investigated. Attention is given to problem areas of the task program, such as environmental protection, material compatibility between the reacting chemicals and materials of construction of the equipment, and waste disposal.

TITLE: Comparative Resistance of Beta Si_3N_4 Solid Solutions to Molten Silicon Attack
AUTHOR: R.R. Wills, I. Sekercioglu, J.S. Ogden, C.A. Alexander, and D.E. Niesz
CORPORATE AUTH: Battelle Columbus Labs., Ohio
PUBLICATION: American Ceramic Society Bulletin, vol. 58, Dec. 1979, p. 1198

ABSTRACT: None.

TITLE: Structure of Deformed Silicon and Implications for Low-Cost Solar Cells
AUTHOR: N. Mardesich, M.H. Leipold, G.B. Turner, and T.G. Digges, Jr.
CORPORATE AUTH: Spectrolab, Inc., Sylmar, California; Jet Propulsion Laboratory; ARCO Solar, Inc., Chatsworth, California; Virginia Semiconductor, Fredericksburg, Virginia
PUBLICATION: Metallurgical Transactions A - Physical Metallurgy and Materials Science, vol. 10A, Dec. 1979, p. 1831-1835

ABSTRACT: The paper reports on an investigation of the microstructure and minority carrier lifetime of Si in uniaxially compressed silicon samples, the objective of which was to determine if it is feasible to produce Si solar cells from sheet formed by high temperature deformation. It is reported that recrystallization was found to be incomplete in both fine and large grained materials, and that the major mode of recrystallization appears to be migration of existing boundaries into the deformed regions. Also, minority carrier diffusion length was found to be drastically reduced after deformation, perhaps due to contamination or cooling rate, and recovered only slightly with annealing. It is concluded that these results suggest that high temperature deformation of Si for direct production of sheet for high efficiency solar cells is not practical. It is noted that potential may exist for its use as a coarse grained substrate.

TITLE: Low Cost Silicon-on-Ceramic Photovoltaic Solar Cells
AUTHOR: B.G. Koepke, J.D. Heaps, B.L. Grung, J.D. Zook, J.D. Sibold, and M.H. Leipold
CORPORATE AUTH: Honeywell, Inc., Bloomington, Minnesota; Coors Porcelain Co., Golden, Colorado; Jet Propulsion Laboratory
MEETING LOCATION: Energy and Ceramics. (A82-17076 05-27) Amsterdam, Elsevier Scientific Publishing Co., 1980, p. 1146-1158

ABSTRACT: A technique has been developed for coating low cost mullite based refractory substrates with thin layers of solar cell quality Si. The technique involves first carbonizing one surface of the ceramic and then contacting it with molten Si. The Si wets the carbonized surface and, under the proper thermal conditions, solidifies as a large grained sheet. Solar cells produced from this composite SOC material have exhibited total area conversion efficiencies of ten percent.

TITLE: The Effect of Growth Rate, Diameter and Impurity Concentration on Structure in Czochralski Silicon Crystal Growth
AUTHOR: T.G. Digges, Jr. and R. Shima
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Crystal Growth, vol. 50, 1980, p. 865-869

ABSTRACT: It is demonstrated that maximum growth rates of up to 80% of the theoretical limit can be attained in Cz-grown Si crystals while maintaining single crystal structure. Attaining the other 20% increase is dependent on design changes in the grower, to reduce the temperature gradient in the liquid while increasing the gradient in the solid. The conclusions of Hopkins et al. (1977) on the effect of diameter on the breakdown of structure at fast growth rates are substantiated. Copper was utilized as the test impurity. At large diameters (greater than 7.5 cm), concentrations of greater than 1 ppm copper were attained in the solid (45,000 ppm in the liquid) without breakdown at maximum growth speeds. For smaller diameter crystals, the sensitivity of impurities is much more apparent. For solar cell applications, impurities will limit cell performance before they cause crystal breakdown for fast growth rates of large diameter crystals.

TITLE: Materials of Construction for Silicon Crystal Growth
AUTHOR: M.H. Leipold, T.P. O'Donnell, and M.A. Hagan
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Crystal Growth, vol. 50, 1980, p. 366-377

ABSTRACT: The performance of materials for construction and in contact with molten Si for crystal growth is presented. The basis for selection considers physical compatibility, such as thermal expansion and strength, as well as chemical compatibility as indicated by contamination of the Si. A number of new high technology materials are included as well as data on those previously used. Emphasis is placed on the sources and processing of such materials in that results are frequently dependent on the way a material is prepared as well as its intrinsic constituents.

TITLE: Multiple Czochralski Growth of Silicon Crystals from a Single Crucible
AUTHOR: R.L. Lane and A.H. Kachare
CORPORATE AUTH: Kayex Corp., Rochester, New York; Jet Propulsion Laboratory
PUBLICATION: Journal of Crystal Growth, vol. 50, 1980, p. 437-444

ABSTRACT: An apparatus for the Cz growth of Si crystals is presented which is capable of producing multiple ingots from a single crucible. The growth chamber features a refillable crucible with a water-cooled, vacuum tight isola

tion valve located between the pull chamber and the growth furnace tank which allows the melt crucible to always be at vacuum or low argon pressure when retrieving crystal or introducing recharge polysilicon feed stock. The grower can thus be recharged to obtain 100 kg of Si crystal ingots from one crucible, and may accommodate crucibles up to 35 cm in dia. Evaluation of the impurity contents and I-V characteristics of solar cells fabricated from seven ingots grown from two crucibles reveals a small but consistent decrease in cell efficiency from 10.4% to 9.6% from the first to the fourth ingot made in a single run, which is explained by impurity build-up in the residual melt. The crystal grower thus may offer economic benefits through the extension of crucible lifetime and the reduction of furnace downtime.

TITLE: New Technologies for Solar Energy Silicon. Cost Analysis of BCL Process
AUTHOR: C.L. Yaws, K.Y. Li, C.S. Fang, R. Lutwack, G. Hsu, and H. Leven
CORPORATE AUTH: Lamar University, Beaumont, Texas; University of Southwestern Louisiana, Lafayette, Louisiana, Jet Propulsion Laboratory
PUBLICATION: Solar Energy, vol. 24, no. 4, 1980, p. 359-365

ABSTRACT: New technologies for producing polysilicon are being developed to provide lower cost material for solar cells which convert sunlight into electricity. This article presents results for the BCL process, which produces the solar-cell Si by reduction of Si tetrachloride with zinc vapor. Cost, sensitivity, and profitability analysis results are presented based on a preliminary process design of a plant to produce 1000 MT/yr of Si by the BCL process. Profitability analysis indicates a sales price of $12.1 19.4/Kg of Si (1980 dollars) at a 0-25% DCF rate of return on investment after taxes. These results indicate good potential for meeting the goal of providing lower cost material for Si solar cells.

TITLE: An All-Plated, Low Cost Contact System for Silicon Solar Cells
AUTHOR: D.P. Tanner, P.A. Iles, and P. Alexander
CORPORATE AUTH: Applied Solar Energy Corp., City of Industry, California; Jet Propulsion Laboratory
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 800-804

ABSTRACT: The plating sequences Pd-Cr-Cu and Pd-Ni-Cu are demonstrated. The surface was sensitized with a 50 A thick Pd layer obtained from an immersion bath. After 15 min heating at 400 C in N_2, a thin barrier layer of either Cr or Ni was deposited from electroless baths operated at temperatures around 90 C. The sintering process was repeated, and a thin copper layer of 500 A was deposited by electroless means. An electrolytic copper bath was used to build the copper layer to 3-4 micron thicknesses. Cells with good I-V curves were obtained, and the all plated contacts had good adhesion. Preliminary cost estimates show that the process costs approximately 12¢/W excluding the cost of the masking procedure.

TITLE: Evaluation and Optimization of Silicon Sheet Solar Cells
AUTHOR: H. Yoo, P. Iles, D. Tanner, G. Pollock, and F. Uno
CORPORATE AUTH: Applied Solar Energy Corp., City of Industry, California; Jet Propulsion Laboratory
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, January 7-10, 1980, Conference Record. (A81-27076 11-44) New York, Institute of Electrical and Electronics Engineers, Inc., 1980, p. 312-315

ABSTRACT: This paper describes the results and procedures to evaluate and improve the efficiency of solar cells made from various unconventional Si sheets. The performance parameters included PV characteristics, spectral response, dark I-V characteristics, and diffusion length. The evaluation techniques used provided accurate and reliable information on sheet performance, and self-consistent results were obtained from the various measurement techniques used. Minority carrier diffusion length (L) was shown to be the ultimate limiting factor for the sheet cell performance (efficiency) and other back-up measurements confirmed this L-dependence. Limited efforts were made to identify defects which influence cell performance, and to use some improved process methods to increase cell efficiency.

TITLE: Contact Integrity Testing of Stress-Tested Silicon Terrestrial Solar Cells
AUTHOR: J.L. Prince, J.W. Lathrop, and G.W. Witter
CORPORATE AUTH: Clemson University, Clemson, South Carolina; ARCO Solar, Inc., Chatsworth, California
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 952-957

ABSTRACT: A test procedure was developed and applied to terrestrial Si solar cells in order to determine the effect of accelerated environmental and time-temperature aging on metal contact integrity. Quantities of cells of four different manufacturers were given the contact integrity test after being subjected to accelerated stress tests that included forward bias-temperature, thermal cycle and thermal shock, power cycle, and bias temperature humidity tests at two temperature humidity levels. Significant effects due to certain stress tests were found for some cell types. It is concluded that cells fabricated using plated nickel/solder metallization showed significantly more serious contact integrity degradation than silver-metallized cells.

TITLE: Low-cost Conversion of Polycrystalline Silicon into Sheet by HEM and FAST
AUTHOR: C.P. Khattak and F. Schmid
CORPORATE AUTH: Crystal Systems, Inc., Salem, Massachusetts
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, January 7-10, 1980, Conference Record. (A81-27076 11-14) New York, Institute of Electrical and Electronics Engineers, Inc., 1980, p. 484-487

ABSTRACT: The conversion of polycrystalline Si to sheet form (the wafers produced are 10 cm x 10 cm cross section with minimum surface damage) by the HEM and FAST, as a means of reducing the cost of solar arrays for adaptation of PV technology for terrestrial applications, is given. A schematic of a HEM furnace, which includes a silica crucible, and developments in the HEM process are presented. The high speed slicer has been used to slice 19 wafers/cm from 10 cm dia crystals. Both HEM and FAST are low cost processes and they have the potential of giving one of the lowest add-on costs ($6.24 and $6.48/sq meter of sheet respectively, with the combination add-on cost of $14.87/sq meter) of this conversion.

TITLE: Continuous Coating of Silicon on Ceramic
AUTHOR: J.D. Heaps, S.B. Schuldt, B.L. Grung, J.D. Zook, and C.D. Butter
CORPORATE AUTH: Honeywell Corporate Technology Center, Bloomingdale, Minnesota
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 39-48

ABSTRACT: Growth of sheet Si on low cost substrates has been demonstrated by the Si coating with inverted meniscus (SCIM) technique. A mullite-based ceramic substrate is coated with carbon and then passed over a trough of molten Si with a raised meniscus. Solidification occurs at the trailing edge of the downstream meniscus, producing a SOC layer. Meniscus shape and stability are controlled by varying the level of molten Si in a reservoir connected to the trough. The thermal conditions for growth and the crystallographic texture of the SOC layers are similar to those produced by dip-coating, the original technique of meniscus-controlled growth. The thermal conditions for growth have been analyzed in some detail. The analysis correctly predicts the velocity-thickness relationship and the liquid solid interface shape for dip coating, and appears to be equally applicable to SCIM-coating. Solar cells made from dip-coated SOC material have demonstrated efficiencies of 10% on 4 sq cm cells and 9.9% on 10 sq cm cells.

TITLE: Influence of Module Requirements on Flat-Plate Module Design Evolution
AUTHOR: J.C. Arnett and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 1296-1298

ABSTRACT: PV module design features and performance characteristics have undergone significant evolutionary changes between pre 1975 First Generation configurations and current Third Generation design technology. A major contributor to this evolution was an iterative process of continuing design guideline and specification development for major module procurements. Module manufacturers have actively responded to these evolving requirements through progressively improving designs. This iterative/feedback process is described. Interim design guidelines and preliminary design options reflecting the LSA 1982 Module Technical Readiness Specification (November 1979) are described with respect to previous design and performance requirements.

TITLE: A Silicon Sheet Casting Experiment for Solar Cell Wafer Production
AUTHOR: D.B. Bickler, L.E. Sanchez, and W.J. Sampson
CORPORATE AUTH: Jet Propulsion Laboratory.; Applied Solar Energy Corp., City of Industry, California
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p 36-38

ABSTRACT: The casting of Si blanks for solar cells directly without slicing is an exciting concept. An experiment was performed to investigate the feasibility of developing a machine that casts wafers directly. A Cz furnace was modified to accept a graphite ingot simulating fixture. Si was melted in the middle of the ingot simulator in a boron nitride mold. Sample castings showed reasonable crystal size. Solar cells were made from the cast blanks. The performance is reported.

TITLE: Effect of Production Processes on the Fracture Strength of Silicon Solar Cells
AUTHOR: C.P. Chen, E.L. Royal, and H. Klink
CORPORATE AUTH: Jet Propulsion Laboratory; Motorola, Inc., Phoenix, Arizona
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 929-934

ABSTRACT: Fracture of Cz Si wafers during processing is an important factor in solar cell yield and cost. A fracture-mechanics test and analysis program was developed to evaluate fracture strength changes in the in-process wafer-to-cell processing at different stages on a manufacturer's production line. The strength data were described by Weibull statistical analysis and can be interpreted with the surface flaw distribution of each of the process steps.

TITLE: Behavior of Interdigitated Back-Contact Solar Cells
AUTHOR: L.J. Cheng and D.C. Leung
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 72-75

ABSTRACT: This paper presents experimental data concerning operation mechanisms of two versions of interdigitated back contact solar cells: the tandem junction cell and the front-surface field cell. It is shown that a photogenerated forward bias at the front junction of a tandem junction cell is a critical parameter for cell performance which not only causes photogenerated carriers to migrate to the back junction, but also eliminates the reduction in photoresponse over back p^+ metallization regions. However, no similar light effects are observed in the performance of front surface field cells. Finally, a discussion on mechanisms concerning the performance of front-surface field and tandem junction cells along with their merits is given.

TITLE: Circuit Design Considerations for Photovoltaic Modules and Systems
AUTHOR: C. Gonzalez and R. Weaver
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 528-535

ABSTRACT: None.

TITLE: Qualification Test results for DOE Solar Photovoltaic Flat Panel Procurement - PRDA 38
AUTHOR: J.S. Griffith
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 1290-1295

ABSTRACT: Twelve types of prototypes modules for the DOE PV Flat Panel Procurement (PRDA 38) were subjected to qualification tests at the JPL according to a new specification. Environmental exposures were carried out separately and included temperature cycling, humidity, wind simulation, and hail. The most serious problems discovered were reduced insulation resistance to ground and ground continuity of the metal frames, electrical degradation, erratic power readings, and delamination. The electrical and physical characteristics of the newly received modules are also given.

TITLE: Grain Size Dependence of Silicon Solar Cell Parameters
AUTHOR: K.M. Koliwad and T. Daud
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 1204-1208

ABSTRACT: Measurements of the non uniform diffusion length of the minority carriers near grain boundaries in polycrystalline Si have been used to develop an analytical model for the calculation of solar cell output as a function of grain size. Experimental results are presented which verify the theoretical analysis. Variation of open circuit voltage and fill factor with grain size is discussed.

TITLE: Performance of Silicon Solar Cells Fabricated from Multiple Czochralski Ingots Grown by Using a Single Crucible
AUTHOR: A.H. Kachare, F.M. Uno, T. Miyahira, and R.L. Lane
CORPORATE AUTH: Jet Propulsion Laboratory; Kayex Corp., Rochester, New York
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 327-331

ABSTRACT: Results on the performance of solar cells fab ricated on wafers from multiple Si ingots of large diam eter, grown by using a single crucible and a sequential melt replenishment Cz technique are presented. Samples were analyzed for resistivity, dislocation density and impurity content. Solar cells were fabricated from the seed, center and tag end of each ingot to evaluate the growth reproducibility and material quality. The cell efficiency within a given wafer varies by no more than plus or minus 5% of the average value. A small but consistent decrease in the cell efficiency is observed from the first to the fourth ingot grown from a single crucible. This decrease may be related to an increase in impurity content or dislocation density or a combination of both. The efficiency of the cells fabricated from the tag end of the fourth ingot is about 10% lower than that of the control cell. An impurity effects model is employed to correlate this decrease in efficiency with the impurity build-up in the residual melt.

TITLE: Flat-Plate Photovoltaic Array Design Optimization
AUTHOR: R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 1126-1132

ABSTRACT: An analysis is presented which integrates the results of specific studies in the areas of PV structural design optimization, optimization of array series/parallel circuit design, thermal design optimization, and optimization of environmental protection features. The analysis is based on minimizing the total PV system life-cycle energy cost including repair and replacement of failed cells and modules. This approach is shown to be a useful technique for array optimization, particularly when time-dependent parameters such as array degradation and maintenance are involved.

TITLE: A Base-Metal Conductor System for Silicon Solar Cells
AUTHOR: M.G. Coleman, R.A. Pryor, and T.G. Sparks
CORPORATE AUTH: Motorola, Inc., Phoenix, Arizona
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 793-799

ABSTRACT: Solder, copper, and silver are evaluated as conductor layer metals for Si solar cell metallization on the basis of metal price stability and reliability under operating conditions. Due to its properties and cost, copper becomes an attractive candidate for the conductor layer. It is shown that nickel operates as an excellent diffusion barrier between copper and Si while simultaneously serving as an electrical contact and mechanical contact to Si. The nickel-copper system may be applied to the Si by plating techniques utilizing a variety of plating bath compositions. Solar cells having excellent current-voltage characteristics are fabricated to demonstrate the nickel-copper metallization system.

TITLE: A Combined Quantitative EBIC and Ion Microprobe Analysis of SiC Particles in EFG Ribbon
AUTHOR: J.I. Hanoka and B. Bathey
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, Institute of Electrical and Electronics Engineers, Inc., 1980, p. 478-483

ABSTRACT: A detailed study of one of the limiting factors in making higher efficiency EFG ribbon solar cells, namely SiC particles, has been undertaken using both EBIC and the ion microprobe. The distribution and degree of recombination due to different SiC particles is found to vary considerably, and based on this, the SiC particles observed can be grouped into four categories. The spatial extent and identity of the major detectible impurities associated with the SiC particles have been determined to be Al, K, Na, Ca, and O. Their distribution and occurrence are a function of the SiC particle category. The possible connection between these impurities and the recombination patterns found in the EBIC work is also discussed.

TITLE: Progress in the Growth of Wide Silicon Ribbons by the EFG Technique at High Speed Using Multiple Growth Stations
AUTHOR: J.P. Kalejs, B.H. Mackintosh, E.M. Sachs, and F.V. Wald
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 13-18

ABSTRACT: We report here progress in a program designed to examine the feasibility of large scale production of low-cost Si sheet substrates for solar cells by the EFG process. A multiple ribbon EFG station, containing five single ribbon cartridges, has been continuously operated for a period of 15 hours at a duty cycle of 94%. The average width of the ribbon grown was 5 cm, and the average growth speed was 3.4 cm/min. The cartridge concept of ribbon growth has been extended to successfully grow 10 cm wide ribbon at speeds up to 4 cm/min. Large area (approximately 50 sq cm) solar cells with efficiencies in the range from 8% to 11% (AM1) have been made from ribbon grown in the cartridge systems.

TITLE: Low Cost Monocrystalline Silicon Sheet Fabrication for Solar Cells by Advanced Ingot Technology
AUTHOR: G.F. Fiegl and A.C. Bonora
CORPORATE AUTH: Siltec Corp., Menlo Park, California
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 303-308

ABSTRACT: The continuous liquid feed (CLF) Cz furnace and the enhanced I.D. slicing technology for the low-cost production of monocrystalline Si sheets for solar cells are discussed. The incorporation of the CLF system is shown to improve ingot production rate significantly. As demon-

stated in actual runs, higher than average solidification rates (75 to 100 mm/hr for 150 mm 1-0-0 crystals) can be achieved, when the system approaches steady-state conditions. The design characteristics of the CLF furnace are detailed, noting that it is capable of precise control of dopant impurity incorporation in the axial direction of the crystal. The crystal add-on cost is computed to be $11.88/sq m, considering a projected 1986 25 slice/cm conversion factor with an 86% crystal growth yield.

TITLE: Nickel Contacts for Low Cost Solar Cells
AUTHOR: J.R. Anderson and R.C. Petersen
CORPORATE AUTH: Solarex Corp., Rockville, Maryland
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81 27076 11-44) New York, 1980, p. 948 951

ABSTRACT: It is noted that nickel metallization of Si solar cells offers a relatively inexpensive method of making electrical contact with the surface of the cell. More expensive methods, involving precious metals and costly processes, are widely used; these have been developed for space applications, where considerations of reliability predominate over those of cost. Since recent interest in terrestrial applications of solar cells has led to an increased concern over cost, nickel has assumed a position as a major candidate for solar cell metallization. It is shown that sintering can improve the integrity of the nickel Si bond. Evidence that the nickel-Si contact can survive moderate environmental stress is presented.

TITLE: The Influence of Grains and Grain Boundaries on the Device Characteristics of Polycrystalline Silicon Solar Cells
AUTHOR: G.M. Storti, S.M. Johnson, H.C. Hin, and C.D. Wang
CORPORATE AUTH: Solarex Corp., Rockville, Maryland; Maryland, University, College Park, Maryland
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 191-195

ABSTRACT: None.

TITLE: A Low-Cost Photovoltaic Cell Process Based on Thick Film Techniques
AUTHOR: N. Mardesich, A. Pepe, S. Bunyan, B. Edwards, and C. Olson
CORPORATE AUTH: Spectrolab, Inc., Sylmar, California; Jet Propulsion Laboratory
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11 44) New York, 1980, p. 943 947

ABSTRACT: The low cost, easily automated processing for solar cell fabrication being developed at Spectrolab for the DOE LSA program is described. These processes include plasma etching, spray-on diffusion sources and antireflective coating, thick film metallization, aluminum back contacts, laser scribing and ultrasonic soldering. The process sequence has been shown to produce solar cells having 15% conversion efficiency at AM1 which meet the cell fabrication budget required for the DOE 1986 cost goal of $0.70/$W_p$ in 1980.

TITLE: Review of Physics Underlying Recent Improvements in Silicon Solar-Cell Performance
AUTHOR: F.A. Lindholm and J.G. Fossum
CORPORATE AUTH: University of Florida, Gainesville, Florida
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81 27076 11-44) New York, 1980, p. 680 683

ABSTRACT: This paper provides a unifying view of the physics of Si solar cells, and uses it as a basis for explaining how recent improvements in the performance of these cells have been achieved. The unification is facilitated by a region-by-region analysis of the solar cell, which is also used to compare several recently proposed cell structures.

TITLE: Designing Practical Silicon Solar Cells Approaching the 'Limit Conversion Efficiency'
AUTHOR: M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 563 568

ABSTRACT: To facilitate rapid low-cost design studies on multilayer solar cells, an analytical method has been developed to replace, for the low-level injection cases, the cumbersome numerical calculations. The method is based on expressing the minority carrier currents as a product of a carrier density and a transport velocity, and on using the superposition principle to the fullest. Each layer can be separately considered as active, i.e., contributing light generating carriers, or passive, i.e., transporting excess carriers across them. For active layers, the light generated carrier concentrations at their boundaries are determined. The carrier concentrations and transport velocities are transformed across each passive layer to calculate the total light generated and saturation currents.

TITLE: High Efficiency Silicon Solar Cells
AUTHOR: M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 674-679

ABSTRACT: The narrow region design approach for obtaining high open circuit and maximum power point voltages in solar cells is discussed. The design relies heavily on low effective surface recombination velocities in front and back in conjunction with a textured front surface and an optical internally reflecting back surface. The cell design requires a thin cell in the 50-150 micron range with a thicker front region than conventional designs. The low transport velocities at the back of the narrow base layer are attainable by the addition of two layers with one layer including a drift field or a high/low junction, and the other layer having low resistivity with a thickness on the order of one diffusion length. The front region requires surface passivation by an oxide layer. It is noted that high doping effects can be avoided using the proposed design.

TITLE: The Relative Orientations of Grains and the Nature of Grain Boundaries in Polysilicon Solar Cells
AUTHOR: R.W. Armstrong, M.E.Taylor, G.M. Storti, and S.M. Johnson
CORPORATE AUTH: University of Maryland, College Park, Maryland; Solarex Corp., Rockville, Maryland

MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 196-201

ABSTRACT: None.

TITLE: Low Cost Processes for Fabricating Silicon Solar Cells
AUTHOR: H. Goldman and M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 923-928

ABSTRACT: Solar cell fabrication processes, in particular junction formation and metallization, are evaluated in terms of cell efficiencies, process yields, module packing factors, and energy cost effectiveness. It is shown that for junction formation, the diffusion processes provide a relatively low cost approach. The costs per unit cell area can be further reduced by increased wafer area and mechanized wafer handling. The costs for a large number of metallization processes, excluding the costs of the metal, are roughly comparable. However, their varying influence on cell performance leads to a significant spread in the allowable process costs.

TITLE: Solar Cells and Modules From Dentritic Web Silicon
AUTHOR: R.B. Campbell, A. Rohatgi, E. Seman, J.R. Davis, P. Rai Choudhury, and B.D. Gallagher
CORPORATE AUTH: Westinghouse Electric Corp., Pittsburgh, Pennsylvania; Westinghouse Research and Development Center, Pittsburgh, Pennsylvania; Jet Propulsion Laboratory
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p 332-336

ABSTRACT: Some of the noteworthy features of the processes developed in the fabrication of solar cell modules are the handling of long lengths of web, the use of cost effective dip coating of photoresist and AR coatings, selective electroplating of the grid pattern and ultrasonic bonding of the cell interconnect. Data on the cells is obtained by means of dark I-V analysis and deep level transient spectroscopy. A histogram of over 100 dentritic web solar cells fabricated in a number of runs using different web crystals shows an average efficiency of over 13%, with some efficiencies running above 15%. Lower cell efficiency is generally associated with low minority carrier time due to recombination centers sometimes present in the bulk Si. A cost analysis of the process sequence using a 25 MW production line indicates a selling price of $\$0.75/W_p$ in 1986. It is concluded that the efficiency of dentritic web cells approaches that of float zone Si cells, reduced somewhat by the lower bulk lifetime of the former.

TITLE: Theoretical Design Considerations for Back Surface Field Solar Cells
AUTHOR: J.R. Davis and A. Rohatgi
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 569-573

ABSTRACT: A simple analytic model of a solar cell is described which provides optimum design rules for back surface field structures. The model provides useful insight into the relative impact of surface and bulk recombination on device performance. Results agree well with experimental data. An optimum back surface field structure is shown to consist of a passivated surface and a thin p^+ region with constant doping in the mid 10^{18}/cu cm range.

TITLE: Development of Processes for the Production of Low Cost Silicon Dendritic Web for Solar Cells
AUTHOR: C.S. Duncan, R.G. Seidensticker, J.P. McHugh, R.H. Hopkins, M.E. Skutch, J.M. Driggers, and F.E. Hill
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 25-30

ABSTRACT: High area output rates and continuous, automated growth are two key technical requirements for the growth of low cost Si ribbons for solar cells. By means of computer aided furnace design, Si dendritic web output rates as high as 27 sq cm/min have been achieved, a value in excess of that projected to meet a $\$0.50/W_p$ solar array manufacturing cost. The feasibility of simultaneous web growth while the melt is replenished with pelletized Si has also been demonstrated. This step is an important precursor to the development of an automated growth system. Solar cells made on the replenished material were just as efficient as devices fabricated on typical webs grown without replenishment. Moreover, web cells made on a less refined, pelletized polycrystalline Si synthesized by the Battelle process yielded efficiencies up to 13% (AM1).

TITLE: $POCl_3$ Gettering of Titanium, Molybdenum and Iron Contaminated Silicon Solar Cells
AUTHOR: A. Rohatgi, R.B. Campbell, J.R. Davis, R.H. Hopkins, P. Rai Choudhury, H. Mollenkopf, and J.R. McCormick
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania; Hemlock Semiconductor Corp., Hemlock, Michigan
MEETING LOCATION: 14th IEEE Photovoltaic Specialists Conference, San Diego, California, Jan. 7-10, 1980, Conference Record. (A81-27076 11-44) New York, 1980, p. 908-911

ABSTRACT: None.

TITLE: Photovoltaics. II - Flat panels
AUTHOR: M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
PUBLICATION: IEEE Spectrum, vol. 17, Feb. 1980, p. 32, 33

ABSTRACT: The paper discusses the future of solar cell technology with emphasis on high performance and a reduction of present fabrication costs. Methods of producing pure Si are discussed, including the EFG method and the capillary action shaping technique. Attention is given to the major steps in the solar-cell fabrication sequence of junction formation, contact metallization, and application of an antireflection coating.

TITLE: Theoretical Considerations of Soil Retention - Dirtying of Solar Energy Devices
AUTHOR: E.F. Cuddihy
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: (Solar Energy Research Institute and Battelle Memorial Institute, Solar Reflective Materials Workshop, 2nd, San Francisco, California, Feb. 12-14, 1980.) Solar Energy Materials, vol. 3, Sept. 1980, p. 21-33

ABSTRACT: The performance of solar energy devices is adversely affected by surface soiling, and generally, the loss of performance increases with increases in the quantity of soil retained on their surfaces. To minimize performance losses caused by soiling, solar devices should not only be deployed in low soiling geographical areas, but employ surfaces or surfacing materials having low affinity for soil retention, maximum susceptibility to be naturally cleaned by wind, rain and snow, and to be readily cleanable by simple and inexpensive maintenance cleaning techniques. This article describes known and postulated mechanisms of soil retention on surfaces, and infers from these mechanisms that low soiling and easily cleanable surfaces should have low surface energy, and be hard, smooth, hydrophobic and chemically clean of sticky materials and water soluble salts.

TITLE: The Influence of a Voltage Ramp on the Measurement of I-V Characteristics of a Solar Cell
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Solid State Electronics, vol. 23, Mar. 1980, p. 285-288

ABSTRACT: For efficiency and convenience the voltage applied to a Si solar cell is often fairly rapidly driven from zero to the open circuit value typically at a common rate of 1 V/ms. During this time the values of current are determined as a function of the instantaneous voltage thus producing an I-V characteristic. The present paper shows that the customary expressions for the current as a function of cell parameters still remain valid provided that the diffusion length in the expression for the dark current is changed from its steady state value L to the effective diffusion length L1 given by $L1 = L(1 + qV/kT\tau)^{-1/2}$, where V is the ramp rate considered constant and τ is the lifetime of minority carriers. This result is true to a very good approximation provided that low level injection prevails.

TITLE: The Spectral Response of a Front Surface Field Solar Cell
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics, vol. 51, Mar. 1980, p. 1852, 1853

ABSTRACT: A calculation of the short-circuit current as a function of wavelength of the incident light, induced in a front surface field solar cell, is presented. The cell consists of a p^+-p-n^+ junction. The electric field present in the p^+ layer situated at the front surface (the surface exposed to the sun) boosts the minority carrier collection at the p-n^+ junction sufficiently to make this structure a viable alternative to ordinary solar cells. A distinct advantage derives from the placement of all ohmic contacts on the back-surface facilitating array assemblage.

TITLE: Silicon Ribbon Growth Using Scanned Lasers
AUTHOR: A. Baghdadi, R.J. Ellis, and R.W. Gurtler
CORPORATE AUTH: National Bureau of Standards, Washington, D.C.; Motorola, Inc., Phoenix, Arizona
PUBLICATION: Applied Optics, vol. 19, Mar. 15, 1980, p. 909-913

ABSTRACT: The recent demand for low cost PV arrays has renewed the interest in growing Si in ribbon form. The approach used in the present paper for the growth of low cost Si ribbon is shown schematically. A pair of scanned, focused CO_2 laser beams is directed onto both sides of a preformed Si ribbon. A narrow (about 1 mm high) molten zone is formed across the full width of the ribbon. As the Si ribbon is passed through the laser-heated zone, large grains are produced in the recrystallized ribbon. The laser beam path is outlined schematically. As a general rule, the lenses are not positioned so as to bring the laser beams to a fine focus, since highly focused beams would vaporize the Si surface rather than serve to melt the bulk. Si ribbon has been grown at rates up to 13.3 cm/min by this approach. The best solar cell fabricated so far on this material has a conversion efficiency of 12.7%.

TITLE: Theory of Grain-Boundary and Intragrain Recombination Currents in Polysilicon p-n Junction Solar Cells
AUTHOR: J.G. Fossum and F.A. Lindholm
CORPORATE AUTH: University of Florida, Gainesville, Florida
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED 27, Apr. 1980, p. 692-700

ABSTRACT: The physics controlling recombination in polysilicon p n junction solar cells is described. Analytic models characterizing this recombination, whose parameters can be related directly to experiment, are developed. The analysis reveals that, in general, the description of intragrain and grain boundary recombination in a polysilicon solar cell requires the solution of a nonlinear three dimensional boundary-value problem. Cases of practical interest for which this problem is traceable are discussed. The analysis predicts an exp (qV/2kT) dependence (the reciprocal slope factor is exactly two) for carrier recombination at a grain boundary within the junction space charge region of a nonilluminated, forward biased cell. This result, and others of the analysis, are consistent with preliminary experimental data.

TITLE: The Importance of Surface Recombination and Energy Bandgap Narrowing in p-n Junction Silicon Solar Cells
AUTHOR: J.G. Fossum, F.A. Lindholm, and M.S. Shibib
CORPORATE AUTH: University of Florida, Gainesville, Florida
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED 27, Apr. 1980, p. 1294-1298

ABSTRACT: Experimental data demonstrating the sensitivity of open circuit voltage to front-surface conditions are presented for a variety of p-n junction Si solar cells. Analytical models accounting for the data are defined and supported by additional experiments. The models and the data imply that a) surface recombination significantly limits the open circuit voltage (and the short circuit current) of typical Si cells, and b) energy bandgap narrowing is important in the manifestation of these limitations. The models suggest modifications in both the structural design and the fabrication processing of the cells that would result in substantial improvements in cell performance. The benefits of one such modification, the addition of a thin thermal Si-dioxide layer on the front surface, are indicated experimentally.

TITLE: Updating the Limit Efficiency of Silicon Solar Cells
AUTHOR: M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED 27, Apr. 1980, p. 751-760

ABSTRACT: The limit efficiency of a Si solar cell is investigated using an analytical approach. The analytical model is based on the solution of a transport equation for minority carriers derived from the Shockley equations. On the basis of the computations, a 'narrow-region' design approach is suggested for both the front and the back regions of the solar cell. The design relies on low effective surface recombination velocities, a textured front surface, and an optical internally reflecting back surface. With this approach, the limit efficiency is near 25%, and the optimum cell is 50 to 150 microns thick.

TITLE: Impurities in Silicon Solar Cells
AUTHOR: J.R. Davis, Jr., A. Rohatgi, R.H. Hopkins, P.D. Blais, P. Rai-Choudhury, J.R. McCormick, and H.C. Mollenkopf
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania; Hemlock Semiconductor Corp., Hemlock, Michigan
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-27, Apr. 1980, p. 677-687

ABSTRACT: The paper investigates the effects of metallic impurities on the performance of Si solar cells. Cz and polycrystalline ingots were employed with boron and phosphorus as primary dopants and with controlled additions of secondary impurities. The data obtained from over 200 crystals indicate that impurity induced performance loss is primarily due to a reduction of the base diffusion length. Based on this observation, a model is developed which predicts cell performance as a function of secondary impurity concentrations. The model calculations are in good agreement with experimental values except for Cu, Ni, Fe, and to a lesser degree, carbon, which at higher concentrations degrade the cell by junction defect mechanisms.

TITLE: Second Quadrant Effects in Silicon Solar Cells
AUTHOR: R.A. Hartman, J.L. Prince, and J.W. Lathrop
CORPORATE AUTH: Clemson University, Clemson, South Carolina
MEETING LOCATION: SOUTHEASTCON '80; Proceedings of the Region 3 Conference and Exhibit, Nashville, TN, April 13-16, 1980. (A81-43701 20-31) New York, Institute of Electrical and Electronics Engineers, Inc., 1980, p. 119-122

ABSTRACT: A simple model describing the behavior of a solar cell in the second quadrant of the I-V curve is described. In this mode of operation appreciable power is dissipated in the cell leading to thermal breakdown and the formation of hot spots. These hot spots will be stable in a current limited mode of operation. In addition a simple method is described to locate the hot spots.

TITLE: The Effects of Titanium Impurities in n^+p Silicon Solar Cells
AUTHOR: A.M. Salama and L.J. Cheng
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Electrochemical Society, Journal, vol. 127, May 1980, p. 1164-1167

ABSTRACT: Microscopic and electrical measurements were performed to explain the degradation mechanisms associated with the presence of titanium impurities in Si. The measurements included x-ray topography, transmission electron microscopy, and deep level transient spectroscopy, before and after processing. The results indicated the presence of TiO_2 precipitates, the density of which increased after phosphorus diffusion. A majority carrier trapping level was observed in the wafers before processing. It was concluded that 10% of the Ti in the n^+p Si solar cells formed electrically active centers which caused degradation of the cell junction. 14% of the remaining Ti precipitated out as TiO_2, forming electrically active defects, which also caused junction degradation.

TITLE: Effect of Titanium, Copper and Iron on Silicon Solar Cells
AUTHOR: A. Rohatgi, J.R. Davis, R.H. Hopkins, P. Rai-Choudhury, P.G. McCullin, and J.R. McCormick
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania; Hemlock Semiconductor Corp., Hemlock, Michigan
PUBLICATION: Solid-State Electronics, vol. 23, May 1980, p. 415-419, 421, 422

ABSTRACT: The effect of Ti, Cu, and Fe on Si solar cells has been investigated. Ti severely degrades cell performance above a concentration of 10^{11}/cu cm. A higher Ti level results in a 63% loss in cell performance and more than an order of magnitude reduction in carrier lifetime; Ti produces two deep levels in Si at Ev + 0.30 eV and Ec - 0.27 eV. Copper, at concentrations below 10^{16}/cu cm, has negligible effect on cell performance and carrier lifetime. Fe begins to damage the cell performance above a concentration of 2×10^{14}/cu cm; at the concentration of 1.7×10^{15}/cu cm it causes a 46% loss in cell efficiency and about an order of magnitude reduction in lifetime.

TITLE: Fracture Toughness of Silicon
AUTHOR: C.P. Chen and M.H. Leipold
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: (American Ceramic Society, Annual Meeting, 80th, Detroit, Michigan, May 8, 1978) American Ceramic Society Bulletin, vol. 59, Apr. 1980, p. 469-472

ABSTRACT: The paper presents a study to determine the fracture toughness and to characterize fracture modes of Si as a function of the orientation of single crystal and polycrystalline material. It is shown that bar specimens cracked by Knoop microhardness indentation and tested to fracture under four-point bending at room temperature were used to determine the fracture toughness values. It is found that the lowest fracture toughness value of single crystal Si was 0.82 $MN/m^{3/2}$ in the 111 plane type orientation, although the difference in values in the 111, 110, and 100 planes was small.

TITLE: Interactions of Efficiency and Material Requirements for Terrestrial Silicon Solar Cells
AUTHOR: D.L. Bowler and M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
PUBLICATION: (Institute of Electrical and Electronics Engineers and Electronic Industries Association, Electronic Components Conference, 30th, San Francisco, California, May 11-13, 1980.) IEEE Transactions on Components, Hybrids, and Manufacturing Technology, vol. CHMT-3, Dec. 1980, p. 464-472

ABSTRACT: The transport velocity transformation method was used to analyze solar cell designs to determine optimum cell structures. It was found that low resistivity materials should be used up to the onset of Auger recombination; a properly designed three-layer structure permits base region approaching an ideal device in performance; and that higher resistivity front regions will need more sophisticated grid metallization structures than those used now. It was concluded that new features will provide idealized Si cell structures yielding AM1 efficiencies in the 24-26.5% range, with real efficiencies near 22%.

TITLE: Airborne Particulate Soiling of Terrestrial Photovoltaic Modules and Cover Materials
AUTHOR: A.R. Hoffman and C.R. Maag
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Life Cycle Problems and Environmental Technology; Proceedings of the Twenty-sixth Annual Technical Meeting, Philadelphia, Pennsylvania, May 12-14, 1980. (A81-46476 22-38) Mt. Prospect, Illinois, Institute of Environmental Sciences, 1980, p. 229-236

ABSTRACT: Results are presented for the first phase of a PV-module soiling study that was carried out with NASA participation to investigate the problem of the electrical performance degradation of flat-plate PV modules exposed at outdoor sites that is due to the accumulation of airborne particulates on sensitive optical surfaces. The results were obtained in both field and laboratory soiling

experiments, as well as in materials field experiments using candidate encapsulants and top covers. It is concluded that: (1) the electrical performance degradation shows a significant time and site dependence, ranging from 2% to 60% power loss; (2) the rate of particulate accumulation appears to be largely material independent when natural removal processes do not dominate; (3) the effectiveness of natural removal processes, especially rain, is strongly material dependent; (4) top cover materials of glass and plexiglass retain fewer particles than silicone rubber; and (5) high module voltages relative to ground do not appear to affect the rate of dirt accumulation on modules.

TITLE: Grain Boundary Effects and Conduction Mechanism Studies in Chromium Metal-Insulator-Silicon Solar Cells on Polycrystalline Silicon
AUTHOR: W. Anderson, K. Rajkanan, A. Delahoy, and S. Hyland
CORPORATE AUTH: New York State University, Buffalo, New York; Rutgers University, Piscataway, New Jersey; Jet Propulsion Laboratory
MEETING LOCATION: (Photovoltaic Material and Device Measurement Workshop, Arlington, Virginia, June 11-13, 1979.) Solar Cells, vol. 1, May 1980, p. 305-310.

ABSTRACT: Chromium metal-insulator-Si (MIS) solar cells fabricated on Wacker polycrystalline Si and electron beam-deposited thin film Si were studied to determine current flow mechanisms. Wacker polycrystalline p-type silicon was shown to produce MIS solar cells which exhibit surface-state controlled current for T greater than 150 K and tunneling controlled current at lower temperatures. MIS cells on unpolished Wacker silicon are clearly space charge limited. Electron beam deposited polycrystalline Si 20-30 microns thick has a conductivity which may be limited by the grain boundary trap density or the availability of free carriers. Surface state analysis, laser scan data and diffusion length studies also show the limitations which exist at grain boundaries of polycrystalline Si.

TITLE: Forward and Reverse Bias Tunneling Effects in n^+p Silicon Solar Cells
AUTHOR: G.F. Garlick and A.H. Kachare
CORPORATE AUTH: University of Southern California, Los Angeles.; Jet Propulsion Laboratory
PUBLICATION: Applied Physics Letters, vol. 36, June 1, 1980, p. 911-913

ABSTRACT: Excess currents due to field-assisted tunneling in both forward and reverse bias directions have been observed in n^+-p Si solar cells. These currents arise from the effect of conducting paths produced in the depletion layer by n^+ diffusion and cell processing. Forward-bias data indicate a small potential barrier with height of 0.04 eV at the n^+ end of conducting paths. Under reverse bias, excess tunneling currents involve a potential barrier at the p end of the conducting paths, the longer paths being associated with smaller barrier heights and dominating at the lower temperatures. Low-reverse-bias data give energy levels of 0.11 eV for lower temperatures (253 293 K) and 0.35 eV for higher temperatures (293-380K). A model is suggested to explain the results.

TITLE: Minority Carrier Diffusion Lengths and Absorption Coefficients in Silicon Sheet Material
AUTHOR: K.A. Dumas and R.T. Swimm
CORPORATE AUTH: Jet Propulsion Laboratory; University of Southern California, Los Angeles
MEETING LOCATION: Role of Electro-Optics in Photovoltaic Energy Conversion; Proceedings of the Seminar, San Diego, California, July 31, August 1, 1980. (A81-39527 18-44) Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, 1980, p. 16-20

ABSTRACT: Most of the methods which have been developed for the measurement of the minority carrier diffusion length of Si wafers require that the material have either a Schottky or an ohmic contact. The surface photovoltage (SPV) technique is an exception. The SPV technique could, therefore, become a valuable diagnostic tool in connection with current efforts to develop low cost processes for the production of solar cells. The technique depends on a knowledge of the optical absorption coefficient. The considered investigation is concerned with a reevaluation of the absorption coefficient as a function of Si processing. A comparison of absorption coefficient values showed these values to be relatively consistent from sample to sample, and independent of the sample growth method.

TITLE: Experimental and Theoretical Investigations of the Quality Factor for n^+p Silicon Solar Cells
AUTHOR: G.F. Garlick and A.H. Kachare
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Role of Electro-Optics in Photovoltaic Energy Conversion; Proceedings of the Seminar, San Diego, California, July 31-August 1, 1980. (A81-39527-18-44) Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, 1980, p. 30-35

ABSTRACT: Many n^+p Si solar cells made with Si from different growth techniques have current-voltage relations of the form: $I - I(0)\,(\exp(qV/AkT) - 1)$, where the quality factor A is nonintegral, is greater than 1, and shows a temperature dependence. The dark forward characteristics of such cells have been measured over a range of temperatures and the behavior of the factor A derived from them. Lack of agreement with previous models has led to the development of a new model, in which n^+ conduction electrons tunnel to deep levels near that side, these levels being due to junction contamination by impurities. Electron recombination then occurs with holes thermally assisted into the junction prom the p side. This mechanism involves increased I(0) values over those for diffusion diode processes and thus reduces the cell power conversion efficiency.

TITLE: Effects of Grain Boundaries in Polycrystalline Solar Cells
AUTHOR: J.D. Zook
CORPORATE AUTH: Honeywell Corporate Technology Center, Bloomingdale, Minnesota
PUBLICATION: Applied Physics Letters, vol. 37, July 15, 1980, p. 223-226

ABSTRACT: In polycrystalline solar cells, the short-circuit current is reduced (compared to single crystal cells) due to recombination of minority carriers at the grain boundaries. The magnitude of this reduction is calculated for the case of a monochromatic beam of light, assuming that both the light beam and the grain boundaries are perpendicular to a p-n junction. The photoresponse of the junction is calculated in terms of the absorption coefficient of the light, the minority-carrier diffusion length, the surface recombination velocity at the grain boundary and the distance of the light beam from the grain boundary. The analysis gives an expression for an effective grain boundary width which depends on wavelength. This width determines the reduction in short-circuit current of solar cells made from material with columnar-type grains.

TITLE: The Interaction of Molten Silicon with Silicon Aluminum oxynitrides
AUTHOR: R.R. Wills, I. Sekercioglu, and D.E. Niesz
CORPORATE AUTH: Battelle Columbus Labs., Ohio.
PUBLICATION: American Ceramic Society, Journal, vol. 63, July-Aug. 1980, p. 401-403

ABSTRACT: Si aluminum oxynitride solid solutions (sialons)

based on beta Si_3N_4 and Si_2N_2O behave differently in contact with molten Si. The Si_2N_2O-based sialons convert to almost pure Si_3N_4, apparently through a two-step decomposition and solution-precipitation reaction, whereas the beta-Si_3N_4 sialons are preferentially attacked at the grain boundaries. The composition of the grain-boundary phase appears to control the rate of reaction.

TITLE: Minority Carrier Diffusion Lengths and Absorption Coefficients in Silicon Sheet Material
AUTHOR: K.A. Dumas and R.T. Swimm
CORPORATE AUTH: Jet Propulsion Laboratory; University of Southern California, Los Angeles.
MEETING LOCATION: Role of Electro-Optics in Photovoltaic Energy Conversion; Proceedings of the Seminar, San Diego, California, July 31, Aug. 1, 1980. (A81-39527 18-44) Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, 1980, p. 16-20

ABSTRACT: Most of the methods which have been developed for the measurement of the minority carrier diffusion length of Si wafers require that the material have either a Schottky or an ohmic contact. The surface photovoltage (SPV) technique is an exception. The SPV technique could, therefore, become a valuable diagnostic tool in connection with current efforts to develop low-cost processes for the production of solar cells. The technique depends on a knowledge of the optical absorption coefficient. The considered investigation is concerned with a reevaluation of the absorption coefficient as a function of Si processing. A comparison of absorption coefficient values showed these values to be relatively consistent from sample to sample, and independent of the sample growth method.

TITLE: Opto Electronic Properties of Cells Made from Various Silicon Forms
AUTHOR: H. Yoo, P. Iles, and S. Hyland
CORPORATE AUTH: Applied Solar Energy Corp., City of Industry, California; Jet Propulsion Laboratory
MEETING LOCATION: Role of electro-optics in PV energy conversion; Proceedings of the Seminar, San Diego, CA, July 31-Aug. 1, 1980. (A81-39527 18-44) Bellingham, Washington, Society of Photo-Optical Instrumentation Engineers, 1980, p. 21-25

ABSTRACT: Opto electronic properties of the various Si forms were obtained from the solar cell performance. Performance parameters included the PV characteristics, minority carrier diffusion length, spectral response and small light spot scanning. Self consistent results were obtained from the various measurement techniques, which can provide useful information on sheet quality, as a potential for low cost terrestrial applications, and areas where the sheet formation methods can be improved.

TITLE: The Applicability of DOE Solar Cell and Array Technology to Space Power
AUTHOR: J.A. Scott-Monck, P.M. Stella, and P.A. Berman
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Energy to the 21st Century; Proceedings of the Fifteenth Intersociety Energy Conversion Engineering Conference, Seattle, Washington, Aug. 18-22, 1980. Volume 1. (A80-48165 21-44) New York, American Institute of Aeronautics and Astronautics, Inc., 1980, p. 364-370

ABSTRACT: Current trends in terrestrial PV that might benefit future space power needs are reviewed. Emphasis is placed on the LSA Project with attention given to the materials task, the Si sheet task, the production processes and equipment task, and encapsulation. The PV Concentrator Technology Development Project is also discussed. It is concluded that terrestrial PV technology that has either been developed to date or is currently under development will not have any significant effect on the performance or cost of solar cells and panels for space over the near term (1980-1990).

TITLE: Analysis of Forced Convection Heat Flow Effects in Horizontal Ribbon Growth from the Melt
AUTHOR: J.A. Zoutendyk
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Crystal Growth, vol. 50, Sept. 1980, p. 83-93

ABSTRACT: A heat transport analysis which considers forced convective fluid flow induced by the motion of a continuous solid ribbon over a melt has been done for horizontal ribbon growth. A model has been developed which treats both active and passive cooling at the ribbon surface. The results show that heat flow from the melt requires active cooling in the region of the leading growth edge or growth tip. Steady-state liquid-solid interface shape is analyzed and numerical results are given for steady-state pulling of Si ribbon.

TITLE: Degradation of Solar cell Performance by Areal Inhomogeneity
AUTHOR: F.A. Lindholm, J.A. Mazer, J.R. Davis, and J.I. Arreola
CORPORATE AUTH: University of Florida, Gainesville, Florida; Westinghouse Research and Development Center, Pittsburgh, Pennsylvania, Instituto Nacional de Astrofisica, Optica y Electronica, Pueblo, Mexico
PUBLICATION: Solid-State Electronics, vol. 23, Sept. 1980, p. 967-971

ABSTRACT: Calculations have been made that show how severely areal inhomogeneity can degrade solar-cell conversion efficiency. Two general types of areal inhomogeneity are discussed. In the first type, the emitter recombination current controls the I V characteristics for voltages near the maximum power voltage, and areal variations in the structural or material parameters of the emitter are assumed to occur. For this type of areal inhomogeneity, the base recombination current controls the dark I-V characteristics, and areal variations in the base minority-carrier lifetime are assumed to occur. For this type, the poor-quality area again dominates in determining the conversion efficiency, though less strongly than for the first type of areal inhomogeneity. An extension of the method used to demonstrate this behavior can provide a first order solution of the general three-dimensional boundary value problem resulting from areal inhomogeneity; this extension is briefly described.

TITLE: Diagnostic Study of BSF Silicon Solar Cells
AUTHOR: H. Yoo, P. Iles, F. Ho, G. Pollock, and K. Koliwad
CORPORATE AUTH: Applied Solar Energy Corp., City of Industry, California; Jet Propulsion Laboratory
MEETING LOCATION: Symposium on Materials and New Processing Technologies for Photovoltaics, Hollywood, Florida, Oct. 1980, Proceedings. (A82-34076 16-44) Pennington, New Jersey, Electrochemical Society, Inc., 1981, p. 147-158.

ABSTRACT: Solar cells equipped with back surface fields (BSF) were fabricated by means of an aluminum alloy, boron diffusion, and boron ion implantation. The importance of initial thickness, resistivity, orientation, and the crystal growth method were examined. Aluminum in paste form was screen printed on the cell, followed by alloy

formation at 800 C for a minute. Application of the BSFs resulted in open circuit voltage improvements dependent on the substrate resistivity, ranging from 10 mV at 0.3 ohm-cm to 40 mV at 15 ohm-cm. The gains in performance were attributed to a longer penetration depth, a heightened concentration profile at the interface, and higher concentrations in the p^+ layer.

TITLE: Analytical Calculation of Thickness Versus Diameter Requirements of Silicon Solar Cells
AUTHOR: C.P. Chen
CORPORATE AUTHOR: Jet Propulsion Laboratory
MEETING LOCATION: Symposium on Materials and New Processing Technologies for Photovoltaics, Hollywood, Florida, Oct. 1980, Proceedings. (A82-34076 16-44) Pennington, New Jersey, Electrochemical Society, Inc., 1981, p. 187-195

ABSTRACT: It may be more cost-effective to produce larger diameter Si Cz solar cells. However, greater thickness is anticipated to be necessary for larger diameter wafers to withstand wafering, cell processing and handling. No material standard for these dimensional requirements is practical or cost-effective for cell manufacturers. The equations relating wafer thickness and diameter were derived by using fracture mechanics analysis. An analytical model was used as a guideline to estimate thickness versus diameter requirements of Si solar cells in terms of fracture mechanics parameters.

TITLE: Relatively Low-Temperature Pyrolysis of Silane in Free Space
AUTH: H. Leven
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Symposium on Materials and New Processing Technologies for Photovoltaics, Hollywood, Florida, Oct. 1980, Proceedings. (A82-34076 16-44) Pennington, New Jersey, Electrochemical Society, Inc., 1981, p 68-79

ABSTRACT: The continuous flow pyrolyzer is a free-space reactor that is used to study the effects of concentration, flow rate and temperature in making solar-grade Si by pyrolysis of silane gas. Work with the continuous flow pyrolyzer is within the LSA Project. The work has led to a new theoretical treatment of silane pyrolysis in free space at relatively low temperatures (550 C to 750 C). It involves a sequential, three step mechanism of particle growth: first, Si atom generation by homogeneous reaction; second, coagulation to a 0.1 micron particle due to Brownian motion and van der Waals forces; and finally, chemical vapor deposition by heterogeneous reaction to final particle size.

TITLE: Development of a Weatherable Acrylic Elastomer for Solar Cell Encapsulation
AUTHOR: R. Liang, A. Yavrouian, and A. Gupta
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Symposium on Materials and New Processing Technologies for Photovoltaics, Hollywood, Florida, Oct. 1980, Proceedings. (A82-34076 16-44) Pennington, New Jersey, Electrochemical Society, Inc., 1981, p. 261-265

ABSTRACT: Poly-n-butylacrylate (PnBA) will be discussed as a potential candidate to be used in solar cell encapsulation. A new process has been developed in which PnBA can be readily cross-linked from a solvent free syrup by a thermal process to give a highly flexible transparent film which does not creep significantly at temperature of up to 90 C. This process can be automated without the use of high cost capital equipment. Photodegradation of PnBA has also been modeled as a function of wavelengths and intensities. Its photostability will be discussed.

TITLE: Photovoltaic Encapsulation Materials
AUTHOR: B. Baum, P.W. Willis, and E.C. Cuddihy
CORPORATE AUTH: Springborn Laboratories, Inc., Enfield, Connecticut; Jet Propulsion Laboratory
MEETING LOCATION: Symposium on Materials and New Processing Technologies for Photovoltaics, Hollywood, Florida, Oct. 1980, Proceedings. (A82-34076 16-44) Pennington, New Jersey, Electrochemical Society, Inc., 1981, p. 223-260

ABSTRACT: Candidate materials for the construction of cost effective solar cell flat array modules are reviewed. Fabrication goals include electricity production at $.70/W with a lifetime of 20 yr. Research is currently directed toward low cost encapsulants and substrates for the cells, and outer covers which resist weathering. EVA at $.09/sq ft has displayed the most promising results as the encapsulant laminate when subjected to peroxide cross-linking to prevent melting. EVA accepts the addition of antioxidants, quenchers, absorbers, and stabilizers. Wood is favored as the rigid substrate due to cost, while top covers in substrate modules comprise candidate acrylic and polyvinyl fluoride films and a copolymer. Finally, fiberglass mat is placed between the substrate and the EVA pottant as a mechanical support and for electrical insulation.

TITLE: Heterogeneous Decomposition of Silane in a Fixed Bed Reactor
AUTHOR: S.K. Iya, R.N. Flagella, and F.S. Dipaolo
CORPORATE AUTH: Union Carbide Corp., Tonawanda, New York
MEETING LOCATION: Symposium on Materials and New Processing Technologies for Photovoltaics, Hollywood, Florida, Oct. 1980, Proceedings. (A82-34076 16-44) Pennington, New Jersey, Electrochemical Society, Inc., 1981, p. 80-91

ABSTRACT: Heterogeneous decomposition of silane in a fluidized bed offers an attractive route for the low cost production of Si for PV application. To obtain design data for a fluid bed silane pyrolysis reactor, deposition experiments were conducted in a small-scale fixed bed apparatus. Data on the decomposition mode, plating rate, and deposition morphology were obtained in the temperature range 600 to 900 C. Conditions favorable for heterogenous decomposition with good deposition morphology were identified. The kinetic rate data showed the reaction to be first order with an activation energy of 38.8 kcal/mole, which agrees well with work done by others. The results are promising for the development of an economically attractive fluid bed process.

TITLE: Silicon Sheet - A Key to Low Cost Solar Cells
AUTHOR: R.H. Hopkins
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
MEETING LOCATION: Symposium on Materials and New Processing Technologies for Photovoltaics, Hollywood, Florida, Oct. 1980, Proceedings. (A82-34076 16-44) Pennington, New Jersey, Electrochemical Society, Inc., 1981, p. 92-107

ABSTRACT: The levels of advancement of various methods of mass producing Si sheets for solar cells are assessed. Indirect methods involve initial formation of the crystal and then sawing to shape. Growth is produced by either the Cz method or by directional freezing. Direct methods involve forming the finished cell in a one-step process, and include capillary shaping, dendritic web, ribbon to ribbon, Si on ceramic, horizontal ribbon growth, roller quenching, and filament guided ribbon growth. The production of commercially producible cells by indirect methods is not regarded as possible. The Si on ceramic process called SCIM is mentioned to avoid impurities build-up by passing graphitized mullite substrate through molten Si up to a rate of 30 cm/min. An efficiency of 10.5% was

reported in 1980. Automation is noted to be the production snag, especially for Si web and edge defined growth methods. The latter has yielded 14.5% efficient cells.

TITLE: High Efficiency and Radiation Hard Solar Cells from Dendritic Web Silicon Ribbon
AUTHOR: A. Rohatgi, J.R. Davis, P. Rai-Choudhury, R.G. Seidensticker, and R.B. Campbell
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
MEETING LOCATION: Symposium on Materials and New Processing Technologies for Photovoltaics, Hollywood, Florida, Oct. 1980, Proceedings. (A82-34076 16-44) Pennington, New Jersey, Electrochemical Society, Inc., 1981, p. 108-118

ABSTRACT: Features and performance of dendritic web Si solar cells are examined and compared with FZ Si cells. The web is grown between two dendrites withdrawn from molten Si through a freezing slot. Present web grown wafers contain three (111) twin planes parallel to the surface. Sample n-p-p cells were produced with boron doping and a resistance of 1-10 ohm-cm, and FZ cells were grown at 850 C for the front junction and 950 C for the back surface field. Current-voltage characteristics of both kinds of cells were studied at 91.6 mW/sq cm illumination under AM1 conditions. The cells were also examined for radiation resistance by exposure to a 1 MeV electron beam and subsequent observations by spectroscopy. Both cells featured a maximum efficiency of 15%, a figure which was slightly higher after oxide passivation treatment. The web and FZ cells tolerated radiation equally.

TITLE: Current Status of Solar Cell Performance of Unconventional Silicon Sheets
AUTHOR: H.I. Yoo and J.K. Liu
CORPORATE AUTH: Applied Solar Energy Corp., City of Industry, California; Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A82-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1981, p. 548-552

ABSTRACT: It is pointed out that activities in recent years directed towards reduction in the cost of Si solar cells for terrestrial PV applications have resulted in impressive advancements in the area of Si sheet formation from melt. The techniques used in the process of sheet formation can be divided into two general categories. All approaches in one category require subsequent ingot wafering. The various procedures of the second category produce Si in sheet form. The performance of baseline solar cells is discussed. The baseline process included identification marking, slicing to size, and surface treatment (etch-polishing) when needed. Attention is also given to the performance of cells with process variations, and the effects of sheet quality on performance and processing.

TITLE: Screenable All-Metal Solar Cell Electrodes of Nickel and Copper
AUTHOR: B. Ross and D.B. Bickler
CORPORATE AUTH: Bernd Ross Associates, San Diego, California; Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A82-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1981, p. 674-678

ABSTRACT: Screenable thick film solar cell electrodes are made using the all-metal electrode system, which eliminates the commonly used glass frit and substitutes an oxide scavenger such as silver fluoride. The low temperature firing copper metal systems give good results on solar cells obtaining cell efficiencies of 13% AM1, and adhering sintered structures are demonstrated with nickel systems. The potential effect of copper upon cell performance at elevated temperatures over long periods of time is determined, and it is found that the formation of a copper-Si eutectic at 550 C produces needle-like structures with broad bases on the silicon, extending into and occasionally through the metallization layer.

TITLE: Directional Solidification of MG Silicon by Heat Exchanger Method for Photovoltaic Applications
AUTHOR: F. Schmid, M. Basaran, and C.P. Khattak
CORPORATE AUTH: Crystal Systems, Inc., Salem, Massachusetts
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A82-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1981, p. 252-256

ABSTRACT: None.

TITLE: Natural Sunlight Accelerated Weathering of Photovoltaic Modules
AUTHOR: G.A. Zerlaut, T.B. Anderson, and J.C. Arnett
CORPORATE AUTH: DSET Laboratories, Inc., Phoenix, Arizona; Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A82-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1981, p. 751-755

ABSTRACT: PV modules are exposed to the equivalent of ten years of sunlight aging in an accelerated exposure testing and evaluation program, the objective being to determine the long term durability characteristics of flat plate modules in comparatively short periods of time. The modules are illuminated with concentrated sunlight in a large, sun-tracking, Fresnel-reflecting solar concentrator. The effects of the accelerated exposure are assessed by performing periodic visual inspections and electrical measurements. It is found that field-experienced failure modes are duplicated, that acceleration factors of 6x to 8x are readily attainable, and that the test method is feasible as a predictive tool for PV module lifetime durability.

TITLE: Evaluation of Silicon-on-Ceramic Material for Low-Cost Solar Cells
AUTHOR: J.D. Zook
CORPORATE AUTH: Honeywell Corporate Technology Center, Bloomingdale, Minnesota
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A82-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1981, p. 569-573

ABSTRACT: The SOC process produces thin layers of Si on inexpensive ceramic substrates. The layers are produced by unidirectional solidification of molten Si, and are polycrystalline. Solar cells made from SOC material have performed with a conversion efficiency of 10.5%. In connection with the objective to improve the efficiency of SOC solar cells, an investigation was conducted to assess the relative importance of grain boundaries and impurities. In order to separate the two effects, LBIC measurements of the short-circuit current were made using a micron-sized light beam from a monochromator. The LBIC measurements are closely related to solar cell performance since the technique identifies the various spatial and spectral contributions to solar cell current. On the basis of the obtained results, it appears that structural defects are more important than chemical defects in limiting the performance of present SOC solar cells.

TITLE: Low Cost Solar Array Project Progress and Plans
AUTHOR: W.T. Callaghan
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A82-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1981, p. 279-286

ABSTRACT: The considered project is part of the DOE PV Technology and Market Development Program. This program is concerned with the development and the utilization of cost-competitive PV systems. The project has the objective to develop, by 1986, the national capability to manufacture low cost, long life PV arrays at production rates that will realize economies of scale, and at a price of less than $0.70/W. The array performance objectives include an efficiency greater than 10% and an operating lifetime longer than 20 yr. The objective of the Si material task is to establish the practicality of processes for producing silicon suitable for terrestrial PV applications at a price of $14/kg. The large area sheet task is concerned with the development of process technology for sheet formation. Low cost encapsulation material systems are being developed in connection with the encapsulation task. Another project goal is related to the development of economical process sequences.

TITLE: Progress Toward Goals in Silicon Sheet Development
AUTHOR: K.M. Koliwad and M.H. Leipold
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A92-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1981, p. 228-235

ABSTRACT: One of the goals of the national PV program in the U.S. is the establishment of an industry producing PV material which can be sold at a price not exceeding $0.70/W by 1986. A key element concerning the achievement of this goal is the development and utilization of improved methods for producing Si sheet. Specific technologies being investigated in this connection can be divided into two categories. Methods of one category are based on a utilization of sheet growth techniques including film-fed growth, dendritic web, and Si on-ceramic processes. The approaches used by methods of the second category involve ingot and wafering processes, including Cz growth, the heat exchange method, multiblade procedures, and the use of a fixed abrasive multiwire. It is found that using $84/Kg Si, most sheet technologies would yield module prices in the $2.00/$W_p$ to $3.00/$W_p$ range.

TITLE: A U.S. View of Silicon Production Processes
AUTHOR: R. Lutwack
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A82-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1971, p. 220-227

ABSTRACT: One of the objectives of the LSA Project is the demonstration of the practicality of processes for producing Si, suitable for fabricating solar cells for terrestrial applications, at prices less than $14/Kg. Approaches being investigated are related to a metallurgical Si/silane/Si process, a metallurgical Si/dichlorosilane/Siemens-type process, and a Si tetrachloride-zinc reduction process. There is a great probability that the first process will yield semiconductor grade Si at a price less than $14/Kg. The second process appears to be capable of providing polysilicon with a purity equivalent to the present commercial semiconductor grade Si at a price of about $20/Kg. An important part of the program is the investigation of the effects of impurities on the performance of solar cells.

TITLE: Terrestrial Photovoltaic Performance Reference Conditions
AUTHOR: R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A82-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1981, p. 731-735

ABSTRACT: The rationale behind the selection of key PV performance reference (reporting) conditions, including the standard AM1.5 solar spectrum and reference irradiance and cell temperature levels, is investigated. Besides providing a repeatable reference for performance comparisons, it is shown that the choice of reference conditions directly controls the accuracy of array energy output prediction calculations. Conclusions are drawn on the accuracy associated with present reference conditions, and recommendations are made concerning alternative reference conditions with improved accuracy.

TITLE: Multiple EFG Silicon Ribbon Technology as the Basis for Manufacturing Low Cost Terrestrial Solar Cells
AUTHOR: B. Mackintosh, J.P. Kalejs, C.T. Ho, and F.V. Wald
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A82-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1981, p. 553-557

ABSTRACT: Mackintosh et al. (1978) have reported on the development of a multiple ribbon furnace based on the EFG process for the fabrication of Si ribbon. It has been demonstrated that this technology can meet the requirements for a Si substrate material to be used in the manufacture of solar panels which can meet requirements regarding a selling price of $0.70/$W_p$ when certain goals in terms of throughput and quality are achieved. These goals for the multiple ribbon technology using 10 cm wide ribbon require simultaneous growth of 12 ribbons by one operator at average speeds of 4 to 4.5 cm/min, and 13% efficient solar cells. A description is presented of the progress made toward achieving these goals. It is concluded that the required performance levels have now been achieved. The separate aspects of technology must now be integrated into a single prototype furnace.

TITLE: Silicon Solar Cells with Nickel/Solder Metallization
AUTHOR: R.C. Peterson and A. Muleo
CORPORATE AUTH: Solarex Corp., Rockville, Maryland
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Third International Conference, Cannes, France, Oct. 27-31, 1980. (A82-24101 10-44) Dordrecht, D. Reidel Publishing Co., 1981, p. 684-690

ABSTRACT: The use of nickel plus solder is shown to be feasible for contact metallization for Si solar cells by offering a relatively inexpensive method of making electrical contact with the cell surfaces. Nickel is plated on Si solar cells using an electroless chemical deposition method to give contacts with good adhesion, and in some cases where adhesion is poor initially, sintering under relatively mild conditions will dramatically improve the quality of the bond without harming the p-n junction of the cell. The cells can survive terrestrial environment stresses, which is demonstrated by a 1000 h test at 85 C and 85% relative humidity under constant forward bias of 0.45 V.

TITLE: The Impact of Molybdenum on Silicon and Silicon Solar Cell Performance
AUTHOR: A. Rohatgi, R.H. Hopkins, J.R. Davis, R.B. Campbell, and H.C.Mollenkopf
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania; Hemlock Semiconductor Corp., Hemlock, Michigan
PUBLICATION: Solid State Electronics, vol. 23, Nov. 1980, p. 1185-1190

ABSTRACT: Deep level transient spectroscopy coupled with dark and lighted I-V measurements were used to study the electrical properties of Si crystals and solar cells purposely contaminated with controlled amounts of molybdenum. Mo severely degrades minority carrier lifetime, and hence solar cell performance, by inducing a recombination center at Ev + 0.30 eV. Neither HCl nor $POCl_3$ gettering at temperatures as high as 1100 C and times up to five hours mitigate the effects of Mo. Because the Mo segregation coefficient is small, 4.5×10^{-8}, impurity contamination of Si during crystal growth can be kept below the levels for which electrical properties are affected.

TITLE: The Generation of Electron Hole Pairs in Very Thin Solar Cells Possessing an Optical Back-Surface Reflector
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics, vol. 51, Dec. 1980, p. 6426 6428

ABSTRACT: It is pointed out that very thin solar cells (1 micron thick or less) as, for example, amorphous Si or cadmium sulfide cells, possessing a back surface reflector should be regarded as Fabry-Perot cavities as far as the generation of electron hole pairs by light is concerned. The generation rate of electron-hole pairs as a function of distance from the front surface exhibits characteristic interference patterns which are not negligible and must be accounted for in an analysis of the performance of such a cell.

TITLE: Investigation of Contact Metallization Systems for Solar Cells
AUTHOR: R.B. Campbell and A. Rohatgi
CORPORATE AUTH: Westinghouse Electric Corp., Pittsburgh, Pennsylvania
PUBLICATION: Electrochemical Society, Journal, vol. 127, Dec. 1980, p. 2702-2704

ABSTRACT: In conventional solar cells, evaporated Ti Pd-Ag metallization system has been found reliable. However, for low cost terrestrial applications, its cost effectiveness may be questioned. Electroplated Ag and Cu have been investigated as replacements for evaporated Ag and have given results comparable to the evaporated Ti-Pd-Ag system.

TITLE: New Technologies for Solar Energy Silicon - Cost Analysis of Dichlorosilane Process
AUTHOR: C.L. Yaws, K.-Y. Li, T.C.T. Chu, C.S. Fang, R. Lutwack, and A. Briglio, Jr.
CORPORATE AUTH: Lamar Univ., Beaumont, Texas; University of Southwestern Louisiana, Lafayette, Indiana; Jet Propulsion Laboratory
PUBLICATION: Solar Energy, vol. 27, no. 6, 1981, p. 539-546

ABSTRACT: A reduction in the cost of Si for solar cells is an important objective in a project concerned with the reduction of the cost of electricity produced with solar cells. The cost goal for the Si material is about $14/kg (1980 dollars). The process which is currently employed to produce semiconductor grade Si from trichlorosilane is not suited for meeting this cost goal. Other processes for producing Si are, therefore, being investigated. A description is presented of results obtained for the DCS process which involves the production of dichlorosilane as a Si source material for solar energy Si. Major benefits of dichlorosilane as a Si source material include faster reaction rates for chemical vapor deposition of silicon. The DCS process involves the reaction $2SiHCl_3$ yields reversibly $SiH_2Cl_2 + SiCl_4$. The results of a cost analysis indicate a total product cost without profit of $1.29/kg of SiH_2Cl_2.

TITLE: The Properties of Polycrystalline Silicon Solar Cells with Controlled Titanium Additions
AUTHOR: A. Rohatgi, R.H. Hopkins, and J.R. Davis
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-28, Jan. 1981, p. 103-108

ABSTRACT: By coupling the results of electrical measurements, such as spectral response, lighted and dark I-V determinations, and deep-level-transient spectroscopy with optical and laser scan photomicroscopy, the effects of grain boundaries and impurities on Si solar cells were evaluated. Titanium, which produces two deep levels in si, degrades cell performance by reducing bulk lifetime and thus cell short-circuit current. Electrically active grain boundaries induce carrier recombination in the bulk and depletion regions of the solar cell. Experimental data imply a small but measurable segregation of titanium into some grain boundaries of the polycrystalline Si containing high Ti concentration. However, for the titanium-contaminated polycrystalline material used in this study, solar cell performance is dominated by the electrically active titanium concentration in the grains. Microstructural impacts on the devices are of secondary importance

TITLE: The Depletion Layer of Amorphous p-n Junctions
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics, vol. 52, Feb. 1981, p. 1096, 1097

ABSTRACT: It is shown that within reasonable approximations for the density of state distribution within the mobility gap of a-Si, a one-to-one correspondence exists between the electric field distribution in the transition region of an amorphous p-n junction and that in the depletion layer of a crystalline p-n junction. Thus it is inferred that the depletion layer approximation which leads to a parabolic potential distribution within the depletion layer of crystalline junctions also constitutes a fair approximation in the case of amorphous junctions. This fact greatly simplifies an analysis of solid state electronic devices based on amorphous material (i.e., solar cells).

TITLE: Effect of Zinc Impurity on Silicon Solar-Cell Efficiency
AUTHOR: C.T. Sah, P.C.H. Chan, C.-K. Wang, K.A. Yamakawa, R. Lutwack, and R.L.-Y. Sah
CORPORATE AUTH: Illinois Univ., Urbana, Illinois; Jet Propulsion Laboratory
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-28, Mar. 1981, p. 304-313

ABSTRACT: Zinc is a major residue impurity in the preparation of solar grade Si material by the zinc vapor reduction of Si tetrachloride. This paper projects that in order to get a 17% AM1 cell efficiency for the Block IV module of the LSA Project, the concentration of the zinc recombination centers in the base region of Si solar cells must be less than 4×10^{11} Zn/cu cm in the p-base n^+-p-p^+ cell and 7×10^{11} Zn/cu cm in the n-base p^+-n-n^+ cell for a base dopant impurity concentration of 5×10^{14} atoms/cu cm. If the base dopant impurity concentration is increased by a factor of 10 to 5×10^{15} atoms/cu cm, then the maximum allowable zinc concentration is increased by a factor of about two for a 17% AM1 efficiency. The thermal equilibrium electron and hole recombination and generation rates

at the double acceptor zinc centers are obtained from previous high-field measurements as well as new measurements at zero field described in this paper. These rates are used in the exact dc-circuit model to compute the projections.

TITLE: Short Interval Testing of Solar Cells
AUTHOR: C.R. Saylor and J.W. Lathrop
CORPORATE AUTH: Clemson University, Clemson, South Carolina
MEETING LOCATION: SOUTHEASTCON '81; Proceedings of the Region 3 Conference and Exhibit, Huntsville, Alabama, April 5-8, 1981. (A81-44676 21-31) Piscataway, New Jersey, Institute of Electrical and Electronics Engineers, Inc., 1981, p. 561-564

ABSTRACT: A drawback of conventional electrical evaluation procedures regarding solar cells is related to time consuming operations required in the determination of specific parameters, such as the maximum power point, from the plotted curves, and to the transfer of data to a large digital computer for analysis and manipulation. This is especially true when large numbers of cells must be measured. To overcome such drawbacks, a digital short interval tester was designed and constructed. The new tester provides rapid and accurate measurements at constant temperature. The utilization of a light shutter makes it possible to measure up to 200 data points along the I-V curve in less than a sec, thus avoiding thermal effects. Because the system is digital, parameters such as the maximum power may be calculated directly from the data.

TITLE: Development of an Accelerated Reliability Test Schedule for Terrestrial Solar Cells
AUTHOR: J.W. Lathrop and J.L. Prince
CORPORATE AUTH: Clemson University, Clemson, South Carolina
PUBLICATION: National Association of Corrosion Engineers, International Corrosion Forum, Toronto, Canada, Apr. 6-10, 1981, Paper. 20 p

ABSTRACT: An accelerated test schedule using a minimum amount of tests and a minimum number of cells has been developed on the basis of stress test results obtained from more than 1500 cells of seven different cell types. The proposed tests, which include bias-temperature, bias-temperature-humidity, power cycle, thermal cycle, and thermal shock tests, use as little as 10 and up to 25 cells, depending on the test type.

TITLE: A Quantitative Method for Photovoltaic Encapsulation System Optimization
AUTHOR: A. Garcia, III, C.P. Minning, and E.F. Cuddihy
CORPORATE AUTH: Spectrolab, Inc., Sylmar, California; Hughes Aircraft Co., Culver City, California; Jet Propulsion Laboratory
MEETING LOCATION: Material and process applications - Land, sea, air, space; Proceedings of the Twenty-sixth National Symposium and Exhibition, Los Angeles, California, April 28-30, 1981. (A81-44326 21-23) Azusa, California, Society for the Advancement of Material and Process Engineering, 1981, p. 108-118

ABSTRACT: It is pointed out that the design of encapsulation systems for flat plate PV modules requires the fulfillment of conflicting design requirements. An investigation was conducted with the objective to find an approach which will make it possible to determine a system with optimum characteristics. The results of the thermal, optical, structural, and electrical isolation analyses performed in the investigation indicate the major factors in the design of terrestrial PV modules. For defect-free materials, minimum encapsulation thicknesses are determined primarily by structural considerations. Cell temperature is not strongly affected by encapsulant thickness or thermal conductivity. The emissivity of module surfaces exerts a significant influence on cell temperature. Encapsulants should be elastomeric, and ribs are required on substrate modules. Aluminum is unsuitable as a substrate material. Antireflection coating is required on cell surfaces.

TITLE: Transport Velocity Transformation - A Convenient Method for Performance Analysis of Multilayer Solar Cell Structure
AUTHOR: M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-28, May 1981, p. 566-573

ABSTRACT: It is noted that in the case of low-level injection, space charge quasi neutrality, and spatially constant material parameters (including an electrostatic field), the individual layer can be treated analytically and the basic solar cell performance parameters can be evaluated from three equations. The first equation represents the transformation of the transport velocity across the layer from the other layer boundary. The second establishes the light generated current output from the layer interface, under the influence of the transport velocities and minority carrier density at both layer boundaries and of bulk recombination. The third equation describes the flow of these carriers across other layers. The power of the approach is considered to lie in its facility for analysis of the solar cell's performance layer by layer, giving a clear picture of the individual layer's influence on cell efficiency.

TITLE: Accelerated Weathering of Photovoltaic Modules Employing Natural Sunlight
AUTHOR: G.A. Zerlaut, T.E. Anderson, and J.C. Arnett
CORPORATE AUTH: DSET Laboratories, Inc., Phoenix, Arizona; Jet Propulsion Laboratory
MEETING LOCATION: Environmental Stress Impact and Environmental Engineering Methods; Proceedings of the Twenty-seventh Annual Technical Meeting on Emerging Environmental Solutions for the Eighties, Los Angeles, California, May 5-7, 1981. Volume 1 (A83-31476 13-38). Mt. Prospect, IL, Institute of Environmental Sciences, 1981, p. 51-55

ABSTRACT: None.

TITLE: Outdoor and Laboratory Testing of Photovoltaic Modules
AUTHOR: A. Hoffman, P. Jaffe, and J. Griffith
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Environmental Stress Impact and Environmental Engineering Methods; Proceedings of the Twenty-seventh Annual Technical Meeting on Emerging Environmental Solutions for the Eighties, Los Angeles, California, May 5-7, 1981. Volume 1 (A83-31476 13-38). Mt. Prospect, Illinois, Institute of Environmental Sciences, 1981, p. 32-39

ABSTRACT: An overview of outdoor and laboratory testing being applied to terrestrial PV modules is presented. Descriptions of the test procedures, examples of results, and discussion of the advantages and shortcomings of each approach are included. The test program consists of real-time outdoor testing of systems, modules and materials, and accelerated outdoor testing and laboratory testing of modules. The test results suggest that the various types of tests complement each other and contribute toward the

objective of verifying the environmental suitability of the product. A description of representative PV systems operational in the U.S. in 1981 is presented, along with an identification, description, and physical inspection summary of JPL test module sites and a summary of degradation and failure data for the modules.

TITLE: Improved Performance from Solar Cells Made From Candidate Sheet Silicon Materials
AUTHOR: H.I. Yoo, P.A. Iles, D.C. Leung, and S. Hyland
CORPORATE AUTH: Applied Solar Energy Corp., City of Industry, California; Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82 44928 23-44) New York, 1981, p. 598-602

ABSTRACT: Performance of solar cells made from various candidate Si sheets is updated and the results are presented. Solar cells were fabricated using a baseline process and other process variations, and tested under AM1 conditions. Performance of the baseline solar cells indicates that remarkable improvements in material quality have been achieved for most of the sheets, showing efficiencies close to that of the control cells made from conventional Cz Si. Process variations (or additions), in general, have resulted in significant improvements in all performance with a degree of change dependent on the process chosen and to a certain extent the sheet quality.

TITLE: System Design and Reliability Considerations for an Intermediate Size Photovoltaic Power System for a Remote Application
AUTHOR: G.T. Noel, L.H. Stember, and D.C. Carmichael
CORPORATE AUTH: Battelle Columbus Laboratories, Columbus, Ohio
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82 44928 23-44) New York, 1981, p. 725-731

ABSTRACT: The design of a PV power system for remote applications is described. The preliminary requirements placed on the system are high reliability of power and low life-cycle cost, considering equipment, remote installation, and operation and maintenance costs. The design incorporates flat-panel modules assembled onto steel frames and prewired prior to shipment to the site, in order to minimize on-site installation costs, skilled labor requirements, and risk of costly delays and failures. Other components include power conditioning units, battery storage, battery charger, back-up diesel generators, and controls. A methodology for system reliability analysis using the fault-tree technique is illustrated to aid in system design, and an assessment is made of mean time between failures, mean time to restore/repair, and system availability.

TITLE: Large-Area Silicon-on-Ceramic Substrates for Low-Cost Solar Cells
AUTHOR: S.B. Schuldt, J.D. Heaps, F.M. Schmid, J.D. Zook, and B.L. Grung
CORPORATE AUTH: Honeywell Corporate Research Center, Bloomington, Minnesota
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 934-940

ABSTRACT: The SCIM process to produce SOC substrates has been investigated for various growth conditions and substrate velocities (4-30 cm/min). Slotted mullite-based substrates (10-cm-wide by 100-cm-long) have been coated with smooth, continuous Si layers, with thicknesses in the range from 100 to 300 microns. Thermal stress (which can be a problem at low velocities) is prevented by proper thermal design. The highest SCIM-coated SOC cell efficiencies to date are 7.5% (AM1, AR) as compared to 10.5% (AM1, AR) for dip coated SOC cells. Substantial improvements in cell efficiency are expected when high purity parts are installed in the SCIM coater.

TITLE: Thermal and Optical Performance of Encapsulation Systems for Flat-Plate Photovoltaic Modules
AUTHOR: C.P. Minning, J.F. Coakley, C.M. Perrygo, A. Garcia, III, E.F. Cuddihy
CORPORATE AUTH: Hughes Aircraft Co., Culver City, California; Spectrolab, Inc., Sylmar, California; Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 750-755

ABSTRACT: The electrical power output from a PV module is strongly influenced by the thermal and optical characteristics of the module encapsulation system. Described are the methodology and computer model for performing fast and accurate thermal and optical evaluations of different encapsulation systems. The computer model is used to evaluate cell temperature, solar energy transmittance through the encapsulation system, and electric power output for operation in a terrestrial environment. Extensive results are presented for both superstrate-module and substrate-module design schemes which include different types of Si cell materials, pottants, and antireflection coatings.

TITLE: Photovoltaic Module Hot-Spot Durability Design and Test Methods
AUTHOR: J.C. Arnett and C.C. Gonzalez
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 1099-1105

ABSTRACT: As part of the JPL LSA Project, the susceptibility of fat-plate modules to hot-spot problems is investigated. Hot-spot problems arise in modules when the cells become back-biased and operate in the negative voltage quadrant, as a result of short-circuit current mismatch, cell cracking or shadowing. The details of a qualification test for determining the capability of modules of surviving field hot-spot problems and typical results of this test are presented. In addition, recommended circuit-design techniques for improving the module and array reliability with respect to hot-spot problems are presented.

TITLE: Overview - Flat-plate Technology - Review of Low Cost Solar Array Project
AUTHOR: W.T. Callaghan
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Forida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 361-366

ABSTRACT: Progress and continuing plans for the joint NASA/DOE program at JPL to develop the technologies and industrial processes necessary for mass production of low cost solar arrays (LSA) which produce electricity from solar cells at a cost of less than $0.70/W are reviewed. Attention is given to plans for a demonstration Si refinement plant capable of yielding 1000 MT/yr, and to a CVD process with chlorosilane, which will yield material at a cost of $21/kg. Ingot and shaped-sheet technologies,

using either Cz growth and film fed growth methods have yielded AM1 15% efficient cells in an automated process. Encapsulation procedures have been lowered to $14/sq m, and robotics have permitted assembled cell production at a rate of 10 sec/cell. Standards are being defined for module safety features. It is noted that construction of a pilot Si purification plant is essential to achieving the 1986 $0.70/W cost goals.

TITLE: The Application of Fracture Mechanics to Failure Analysis of Photovoltaic Solar Modules
AUTHOR: C.P. Chen and M.H. Leipold
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82 44928 23-44) New York, 1981, p. 1122-1125

ABSTRACT: Cracking of Si solar cells and solar module transparent cover panels such as glass or polymethyl-methacrylate (PMMA) is a major cause of PV solar module failure in field service. Si and cover materials are brittle, and cracking of these materials is expected to result from the extension of preexisting flaws under stress. Study of the cracking mechanisms is therefore an appropriate area for the application of fracture mechanics principles. In this study, fracture mechanics techniques were employed to identify the mode of crack propagation, to examine the fracture-initiating flaw, to estimate the nature and magnitude of fracture stress in the field, and to predict analytically the service lifetime. Recommendations for corrective actions are also made.

TITLE: Surface Recombination Velocity Measurement for Silicon Solar Cells
AUTHOR: T. Daud and L.J. Cheng
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 1183-1188

ABSTRACT: For the design and fabrication of Si solar cells approaching theoretical ultimate conversion efficiencies, surface recombination velocity plays a crucial role. A technique using a scanning electron microscope with pulsed electron beam has been developed for the measurement of this important parameter for Si surfaces. It is shown that the surface recombination velocity(s) increases by an order of magnitude when a freshly etched sample is left out for a few hours, presumably due to generation of surface states. A textured FSF cell with a high-low junction near the surface shows the effect of minority carrier reflection and an apparent reduction of s, whereas a tandem junction cell with n^+-p junction near the surface gives larger s value.

TITLE: Economics of Ingot Slicing with an Internal Diameter Saw for Low-Cost Solar Cells
AUTHOR: T. Daud, J.K. Liu, and G. Fiegl
CORPORATE AUTH: Jet Propulsion Laboratory; Siltec Corp., Menlo Park, California
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 1011-1015

ABSTRACT: Slicing of Si ingots using diamond impregnated internal diameter blade saws has been a standard technology of the semiconductor industry. This paper describes work on improvements to this technology for 10 cm dia ingot slicing. Ingot rotation, dynamic blade edge control with feedback, mechanized blade dressing and development of thinner blades are the approaches tried. A comparison of the results for wafering with and without ingot rotation is also made. A sensitivity analysis of the major cost elements in wafering is performed for 10 cm dia ingot and extended to the 15 cm dia ingot case. Various parameter values such as machine cost, feed rate and consumable materials cost are identified both for single and multiple ingot slicing.

TITLE: Characterization of HEM Silicon for Solar Cells - Heat Exchanger Method
AUTHOR: K.A. Dumas, C.P. Khattak, and F. Schmid
CORPORATE AUTH: Jet Propulsion Laboratory; Crystal Systems, Inc., Salem, Massachusetts
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82 44928 23-44) New York, 1981, p. 954 958

ABSTRACT: The Heat Exchanger Method is a promising low-cost ingot casting process for material used for solar cells. This is the only method that is capable of casting single crystal ingots with a square cross section using a directional solidification technique. This paper describes the chemical, mechanical and electrical properties of the HEM Si material as a function of position within the ingot.

TITLE: Field Failure Mechanisms for Photovoltaic Modules
AUTHOR: L.N. Dumas and A. Shumka
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82 44928 23 44) New York, 1981, p. 1091-1098

ABSTRACT: Beginning in 1976, Department of Energy field centers have installed and monitored a number of field tests and application experiments using current state-of-the art PV modules. On site observations of module physical and electrical degradation, together with in-depth laboratory analysis of failed modules, permits an overall assessment of the nature and causes of early field failures. Data on failure rates are presented, and key failure mechanisms are analyzed with respect to origin, effect, and prospects for correction. It is concluded that all failure modes identified to date are avoidable or controllable through sound design and production practices.

TITLE: A Photovoltaic Industry Overview - The Results of a Survey on Photovoltaic Technology Industrialization
AUTHOR: R.R. Ferber, E.N. Costogue, J.W. Thornhill, and K. Shimada
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 261-266

ABSTRACT: The National PV Program of the United States Department of Energy has the objective of bringing PV power systems to a point where they can supply a significant portion of the United States energy requirements by the year 2000. This is planned to be accomplished through substantial research and technology development activities aimed at achieving major cost reductions and market penetration. This paper presents information derived from a limited survey performed to obtain PV industry attitudes concerning industrialization, and to determine current industry plans to meet the DOE program goals. Si material production, a key PV manufacturing industry, is highlighted with regards to implementation of technology improvement and Si material supply outlook.

TITLE: Some Tests of Flat Plate Photovoltaic Module Cell Temperatures in Simulated Field Conditions
AUTHOR: J.S. Griffith, M.S. Rathod, and J. Paslaski
CORPORATE AUTH: Jet Propulsion Laboratory; State Univ. of New York, Binghamton, New York
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 822-830

ABSTRACT: The nominal operating cell temperature of solar PV modules is an important characteristic. Typically, the power output of a PV module decreases 0.5% per deg C rise in cell temperature. Several tests were run with artificial sun and wind to study the parametric dependencies of cell temperature on wind speed and direction and ambient temperature. It was found that the cell temperature is extremely sensitive to wind speed, moderately so to wind direction and rather insensitive to ambient temperature. Several suggestions are made to obtain data more typical of field conditions.

TITLE: Effects of Shading and Defects in Solar Cell Arrays - A Simple Approach
AUTHOR: A. Gupta and A.G. Milnes
CORPORATE AUTH: Jet Propulsion Laboratory; Carnegie Mellon University, Pittsburgh, Pennsylvania
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 1111-1116

ABSTRACT: Tradeoffs involved in solar cell array arrangements are discussed with the aid of examples and simple numerical calculations. The effect of various shading conditions on different arrays is studied, along with the arrays' tolerance of the effects of open or short-circuit cells. The effects of cell failure and the benefits of providing interconnections between series strings in a module spanned by a bypass diode are considered. It is found that bypass diodes are desirable both for reasons of shading and the possible presence of defects. Power losses caused by partial shading depend on the orientation of the shading relative to the line of the bypass diodes. Open circuit defects or spot shading cause loss of the current in the string, while numerous branch circuits reduces the voltage loss caused by short-circuit cells. Interconnections within a module are not likely to be beneficial in arrays where there may be a large number of bypass diodes.

TITLE: Investigation of Solar Cells Fabricated on Low-Cost Silicon Sheet Materials Using 1 MeV Electron Irradiation
AUTHOR: A.H. Kachare, S.L. Hyland, and G.F. Garlick
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 603-607

ABSTRACT: The use of high-energy electron irradiation is investigated as a controlled means to study in more detail the junction depletion layer processes of solar cells made on various low-cost Si sheet materials. Results show that solar cells made on Cz grown Si exhibit enhancement of spectral response in the shorter wavelength region when irradiated with high-energy electrons. The base region damage can e reduced by subsequent annealing at 450 C which restores the degraded longer wavelength response, although the shorter wavelength enhancement persists. The second diode component of the cell dark forward bias current is also reduced by electron irradiation, while thermal annealing at 450 C without electron irradiation can also produce these same effects. Electron irradiation produces small changes in the shorter wavelength spectral responses and junction improvements in solar cells made on WEB, EFG, and HEM Si. It is concluded that these beneficial effects on cell characteristics are due to the reduction of oxygen associated deep level recombination centers in the n^+ diffused layer and in the junction.

TITLE: The Solar Cell Laser Scanner
AUTHOR: E.L. Miller, S.-S. Chern, and A. Shumka
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 1126-1133

ABSTRACT: As part of the LSA Project at JPL, failure analyses have been performed on over 300 PV modules from thirty different manufacturers and five countries. Because of the volume of work and the variety of module types encountered, it has been necessary to develop non-destructive techniques to rapidly locate the failure sites. This paper will present design details and results obtained with one instrument developed specifically for this purpose, the Solar Cell Laser Scanner (SCLS). The effects of applying a bias current to the modules will also be discussed, based upon experimental observations and computer generated predictions.

TITLE: Defect Design of Insulation Systems for Photovoltaic Modules
AUTHOR: G.R. Mon
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 964-971

ABSTRACT: A defect design approach to sizing electrical insulation systems for terrestrial PV modules is presented. It consists of gathering voltage breakdown statistics on various thicknesses of candidate insulation films where, for a designated voltage, module failure probabilities for enumerated thickness and number-of-layer film combinations are calculated. Cost analysis then selects the most economical insulation system. A manufacturing yield problem is solved to exemplify the technique. Results for unaged Mylar suggest using fewer layers of thicker films. Defect design incorporates effects of flaws in optimal insulation system selection, and obviates choosing a tolerable failure rate, since the optimization process accomplishes that. Exposure to weathering and voltage stress reduces the voltage withstanding capabilit of module insulation films. Defect design, applied to aged polyester films, promises to yield reliable, cost-optimal insulation systems.

TITLE: Photovoltaic Module and Array Reliability
AUTHOR: R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 1157-1163

ABSTRACT: Several statistical reliability studies have been conducted in areas of PV component design covering cell failure, interconnect fatigue, glass breakage and electrical insulation breakdown. This paper integrates the results from these various studies and draws general conclusions relative to optimal reliability features for future modules. The described analysis is based on designing for specified low levels of component failures and then controlling the degrading effects of the failures through the use of fault tolerant circuitry and module

replacement. Means of selecting the cost optimal level of component failures, circuit redundancy, and module replacement are described.

TITLE: A Comprehensive Analysis of the Performance Characteristics of the Mount Laguna Solar Photovoltaic Installation
AUTHOR: A. Shumka and S.G. Sollock
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 1237-1244

ABSTRACT: This paper represents the first comprehensive survey of the Mount Laguna Photovoltaic Installation. The novel techniques used for performing the field tests have been effective in locating and characterizing defective modules. A comparative analysis on the two types of modules used in the array indicates that they have significantly different failure rates, different distributions in degradational space and very different failure modes. A life cycle model is presented to explain a multimodal distribution observed for one module type. A statistical model is constructed and it is shown to be in good agreement with the field data.

TITLE: Laser Processing of Silicon Solar Cells
AUTHOR: J.S. Katzeff, M. Lopez, and D.R. Burger
CORPORATE AUTH: Lockheed Missiles and Space Co., Sunnyvale, California; Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 437-441

ABSTRACT: Results of a study to utilize an Nd:glass laser for production line annealing of ion implantation induced damage in solar cells are reported. Cz-grown and sawn Si wafers 7.6 cm in diam, 0.35 mm thick, were implanted with phosphorus junctions and boron BSFs. Annealing with electron beam, laser, and firing of an Al paste to form the BSFs in different cells was compared. The laser was employed at 1.06 and 0.53 micron and in combination of both, with a 20-50 nsec pulsewidth, and energy densities of 1.2, 1.5, 1.9, and 2.1 J/sq cm. Best optical coupling was observed with the combined wavelengths and a 20 nsec pulse, using energy densities less than 1.5 J/sq cm. Although the Al sintered cells displayed the best characteristics, laser annealing is concluded to offer electrically active, defect-free, shallow junction Si substrates for high efficiency cells.

TITLE: Ribbon Growth-Cell Processing Synergistic Effects for Solar Cells
AUTHOR: K.V. Ravi, R.C. Gonsiorawski, A.R. Chaudhuri, and C.V. Rao
CORPORATE AUTH: Mobil Tyco Solar Energy Corp., Waltham, Massachusetts
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82 44928 23-44) New York, 1981, p. 928-933

ABSTRACT: The influence of ribbon growth conditions and solar cell processing variables on the conversion efficiency of EFG Si ribbon solar cells have been examined. The key variable in crystal growth is the type of crucible employed for containing the molten Si. It is observed that the use of quartz crucibles results in the highest solar cell efficiencies, whereas graphite crucibles result in reduced efficiencies. Processing conditions such as the diffusion temperature and diffusion source also have an important effect. Greater than 14% AMI efficiencies in large area (approximately 50 sq cm) ribbon solar cells have been achieved.

TITLE: A Realistic Comparison of Minimum Photovoltaic Module Cost Projections
AUTHOR: M.G. Coleman and L.A. Grenon
CORPORATE AUTH: Motorola, Inc., Semiconductor Group, Phoenix, Arizona
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 713-717

ABSTRACT: Some long-term cost projections for thin film PV devices indicate a major advantage for these technologies over crystalline Si PV, ultimately replacing silicon as the predominant material. This paper addresses the assumptions made for the thin film cost projections and compares them with the analogous assumptions for Si. Analysis of cell manufacturing, encapsulation, and balance of systems costs are performed to show that it is unlikely that the thin film materials, even if free, will ever realize a cost advantage in PV systems over Si.

TITLE: A Users Evaluation of SAMIS
AUTHOR: L.A. Grenon and M.G. Coleman
CORPORATE AUTH: Motorola, Inc., Phoenix, Arizona
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 985-989

ABSTRACT: The SAMIS computer program was developed by JPL to provide a method whereby manufacturers or potential manufacturers of PV could simulate a solar industry using their own particular approach. This paper analyzes the usefulness of SAMIS to a growing PV industry and clearly illustrates its limitations as viewed by an industrial user.

TITLE: Reliability of Silicon Solar Cells with a Plated Nickel-Copper Metallization System
AUTHOR: L.A. Grenon, N.G. Sakiotis, and M.G. Coleman
CORPORATE AUTH: Motorola, Inc., Semiconductor Group, Phoenix, Arizona
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 522-526

ABSTRACT: In order to achieve the goal of low cost PV, low cost processes that contribute to a long solar cell service life must be established. In this paper, the interactions between the Si and the nickel contact are examined with respect to long term reliability. The effects of heat treatment of the contacts on diode performance are empirically examined by studying changes in electrical parameters of cells as a function of time and temperature. The results show that, utilizing the appropriate plating technique and establishing the appropriate assembly technique, a low cost, highly reliable nickel-copper metallization system can be used on Si solar cells.

TITLE: Recent Advances in Silicon Sheet Growth by the Ribbon-to-Ribbon Process
AUTHOR: K.R. Sarma, R.W. Gurtler, R.N. Legge, R.J. Ellis, and I.A. Lesk
CORPORATE AUTH: Motorola, Inc., Semiconductor Group, Phoenix, Arizona
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 941-948

ABSTRACT: Significant advances are reported in RTR technology using scanned CO_2 laser beams for producing thin sheets of Si for low cost solar cells. Through control of the growth ambient and melt-solid interface shape, ribbons with high purity and very large grain size were obtained. Also, temperature profiles were developed for producing ribbons with no buckling and with low residual stresses. These improvements have led to production of 1 cm x 2 cm solar cells with AM1 conversion efficiencies approaching 13%, with the average being around 11.5%. Electron beams are also being investigated as a possible heat source in the RTR process.

TITLE: Determination of the Bulk Resistivity of Polycrystalline Silicon Wafers Using a Contactless Microwave Reflection Technique
AUTHOR: J.S. Culik
CORPORATE AUTH: Solarex Corp., Rockville, Maryland
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 1170-1173

ABSTRACT: This paper describes a new technique which provides an accurate measurement of the bulk resistivity of polycrystalline Si wafers. The impedance of a thick semiconductor wafer terminating a waveguide is modulated by the generation of free carriers due to an intense laser pulse. The degree of microwave reflectance modulation is related to the bulk resistivity and the thickness of the sample. Hence, a measurement of the reflectance modulation and the thickness of an unknown semiconductor wafer can be used to determine its bulk resistivity. Since this technique is relatively insensitive to grain boundaries it is useful in measuring the bulk resistivity of polycrystalline Si wafers. Also, as it does not require contacts, very little sample preparation is necessary.

TITLE: The Solarex Block IV module Solar Array Design Features
AUTHOR: J.F. Hoelscher
CORPORATE AUTH: Solarex Corp., Rockville, Maryland
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 745-749

ABSTRACT: Several innovative concepts were introduced for the Block IV contract. Semicrystalline Si manufactured by SEMIX Inc. is the basic cell material. A front metallization pattern combined with a wraparound-style interconnect and in-plane stress relief combine to provide a new method to reliably accomplish series-paralleling. Laminated modules using EVA as the encapsulant were manufactured for the first time.

TITLE: The Fabrication of a 17% AM1 Efficient Semicrystalline Silicon Solar Cell
AUTHOR: G.M. Storti
CORPORATE AUTH: Solarex Corp., Rockville, Maryland
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 442-445

ABSTRACT: The results of investigations of the maximum efficiencies available from cast, polycrystalline Si solar cells made from the SEMIX process are reported. High efficiency cells were found to depend on choices of cells with bulk resistivity between 1.5-1.7 ohm-cm and a dislocation density of less than 10,000/sq cm. Maximized cells were fabricated by using slices less than 150 microns thick. The surfaces were texture etched to reduce reflectance and an Al back surface reflector was evaporated onto the slice surface. Photolithographically applied contacts preceded cutting into 2 cm x 2 cm pieces and subsequent evaporation of TaO_2 and MgF_2 layers onto the surface. Testing was undertaken in sunlight and in a xenon simulator. A highest cell efficiency of 17% was observed, with a current density of 36 mW/sq cm. Semicrystalline Si cells are concluded to offer efficiencies equivalent to those of single crystal Si.

TITLE: An Analytical Approach to Photovoltaic Encapsulation System Design
AUTHOR: A. Garcia, III, C.P. Minning, and E.F. Cuddihy
CORPORATE AUTH: Spectrolab, Inc., Sylmar, California; Hughes Aircraft Co., Culver City, California; Jet Propulsion Laboratory
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Forida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 460 465

ABSTRACT: This paper describes a set of analytical methods which have been developed to enable quantitative analysis of encapsulation system designs for terrestrial PV modules. Design factors determined most important include: encapsulant thickness and modules, emissivity of module surface, ribs on substrate modulus, and AR.

TITLE: Contract Resistivities Between Solar-Cell-Type Si and Transition Metal Nitrides
AUTHOR: M. Maenpaa, I. Suni, M.A. Nicolet, F. Ho, and P. Iles
CORPORATE AUTH: Technical Research Centre of Finland, Esbo, Finland; California Institute of Technology, Pasadena, California; Applied Solar Energy Corp., City of Industry, California
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 518-521

ABSTRACT: Contact resistivities of TiN, Ti-TiN, HfN, Hf-HfN, TaN and Ta-TaN metallizations on solar-cell-type n'Si with a shallow p-n junction have been investigated. Metal and nitride layers were sputter-deposited. Linear contact patterns were used for the measurements. The transmission line model was applied to determine the contact resistivities. Contact resistivity values of less than about 0.0001 ohm cm squared have been achieved with all structures. Electrically the structures are stable up to heat treatments of 700 C. The interfacial layers between the substrate and the deposited material have been found to play an important role in the behavior of the contact. The studied metallizations have been estimated to be electrically acceptable for cells with 100 times solar concentrations.

TITLE: Silane Pyrolysis in a Free Space Reactor
AUTHOR: J.R. Lay and S.K. Iya
CORPORATE AUTH: Union Carbide Corp., Tonawanda, New York
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 565-568

ABSTRACT: The Union Carbide process for producing Si for PV applications proceeds via high purity silane as an intermediate. Decomposition of silane is accomplished in a freespace reactor which utilizes recirculating product hydrogen and Si to transfer energy from a heated wall to an entering silane jet. Reaction occurs away from the wall, minimizing problems with wall deposition and contamination. A series of long duration and throughput tests has proven the feasibility of this concept. High

purity powder can be produced at flows up to 4.5 kg/hr (10 lb/hr) in a 0.2 m (8 in.) dia reactor with better than 99.99% conversion efficiency.

TITLE: Significance of Low Temperature Processing in the Fabrication of Silicon Solar Cells
AUTHOR: J.G. Fossum and D.S. Lee
CORPORATE AUTHOR: University of Florida, Gainesville, Florida
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 120-125

ABSTRACT: A theoretical model that describes the dependence of carrier lifetime on doping density, which is based on the equilibrium solubility of a particular defect in non degenerately doped Si, is developed. Comparisons of the model predictions with the longest measured hole and electron lifetimes ever reported for n type and p type Si support the model and imply a possible fundamental defect in Si. The defect is acceptor-type and is more soluble in n-type than in p-type Si, which suggests a longer fundamental limit for electron lifetime than for hole lifetime at a given doping density. The prevalent, minimum density of the defect, which defines these limits, occurs at the processing temperature below which the defect is virtually immobile in the Si lattice. The analysis reveals that this temperature is 300-400 C, and thus emphasizes the significance of low-temperature processing, e.g., annealing, in Si solar cell fabrication.

TITLE: Polycrystal X-ray Topography and the Photoresponse of Grains or Grain Boundaries in Polysilicon
AUTHOR: R.G. Rosemeier, R.W. Armstrong, S.M. Johnson, G.W. Storti, and C.C. Wu
CORPORATE AUTH: University or Maryland, College Park, Maryland); Solarex Corp., Rockville, Maryland); U.S. Navy, Naval Research Laboratory, Washington, DC
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 1331-1336

ABSTRACT: X-ray topographs and optical photoresponse measurements have been matched on a point-by-point basis across the surface of polysilicon solar cells to show the dependence of the PV properties on grain perfection and on the particular boundary structure between adjacent grains. Dislocations, subgrain boundaries, twins and inclusions are revealed within the relatively perfect microstructures of cells by the asymmetric crystal topography method in surface reflection and by the Lang transmission topography method. The decreased photoresponse at particular grain boundaries is attributed to the smaller crystal dislocation portion of the larger total change in orientation across the grains.

TITLE: Characteristics and Performance of Silicon Solar Cells Between Low and High Level Injection
AUTHOR: M.A. Wolf and M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 387-393

ABSTRACT: The operation of Si solar cells utilizing high-low junctions has been studied for injection levels between the validity ranges of normal low-level and high-level injection approximations. The effects of primary influence on the I-V characteristic and their dependence on cell design were investigated in detail. These effects are: ohmic voltage drops, voltages resulting from non-equilibrium carrier distribution fields, and voltages generated across the high low junction, and current variations due to minority carrier lifetime changes. Several quantitative evaluations of cell structures are compared to illustrate the combined effects of different illumination intensities and cell structures.

TITLE: Metallization for Large-Area Solar Cells
AUTHOR: M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82 44928 23-44) New York, 1981, p. 506-511

ABSTRACT: In large area, low cost solar cells of any type, the contact and grid structure metallization is an important factor which has an effect on the efficiency of the solar cell and its reliability. The present investigation is concerned with aspects of solar cell efficiency. An optimized metallization design leads to minimum total power loss, which is related to a simultaneous minimization of ohmic voltage drops and of shading of the front surface of the cell by the overlaid metal. The requirements regarding the design for a low-loss metallization pattern for the front surface of large area solar cells are represented by a set of design rules listed in a table. The total shading and voltage drop on such cells can be held to about 5%. However, not every metallization process is suited for meeting the requirements of the low-cost design. The low losses can be achieved only by use of several bus lines containing a bulk conductor, such as a wire.

TITLE: Thermal Stability of Impurities in Silicon Solar Cells
AUTHOR: M.H. Hanes, R.H. Hopkins, A. Rohatgi, P. Rai Choudhury, R.B. Campbell, and H.C. Mollenkopf
CORPORATE AUTH: Westinghouse Electric Corp., Pittsburgh, Pennsylvania; Hemlock Semiconductor Corp., Hemlock, Michigan
MEETING LOCATION: 15th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 12-15, 1981, Conference Record. (A82-44928 23-44) New York, 1981, p. 520-533

ABSTRACT: Elevated temperatures were employed as an age accelerating mechanism to test the effects of typical impurities on long-term performance of Si solar cells. Cz-grown p type wafers were junction diffused with POCl3 at 850 C and aged at temperatures from 400-800 C from 10 min to 200 hr. The wafers contained Fe, Cu, Ti, Md, Nv, Ni, and Ag contaminants. The degradation mechanism was assumed to be linear in the initial stages and was modeled numerically, including prediction of a time to failure, defined as an efficiency of 90% the original figure. Deep level transient spectroscopy was used to measure carrier trapping centers and dark and light current-voltage measurements to assay junction degradation and shunt and series resistance effects. Metallic impurities were determined to have negligible impact on cell degradation at expected long-term solar cell operating temperatures. However, studies of the more complex effects of Fe and Cu are recommended.

TITLE: Thermal Stability of Titanium Nitride for Shallow Junction Solar Cell Contacts
AUTHOR: N.W. Cheung, H. von Seefeld, M.-A. Nicolet, F. Ho, and P. Iles
CORPORATE AUTH: California Institute of Technology, Pasadena, California; Applied Solar Energy Corp., City of Industry, California

PUBLICATION: Journal of Applied Physics, vol. 52, June 1981, p. 4297-4299

ABSTRACT: To demonstrate the thermal stability of titanium nitride as a high-temperature diffusion barrier, the TiN-Ti-Ag metallization scheme has been tested on shallow-junction (2000 A) Si solar cells. Electrical measurements on reference samples with the Ti-Ag metallization scheme show serious degradation after a 600 C, 10 min. annealing. With the TiN-Ti-Ag scheme, no degradation of cell performance is observed after the same heat treatment if the TiN layer is equal to or greater than 1700 A. The glass encapsulation of cells by electrostatic bonding requires such a heat treatment.

TITLE: Progress in the Development of Standard Procedures for the Global Method of Calibration of Photovoltaic Reference Cells
AUTHOR: R. Whitaker, A.W. Purnell, and G.A. Zerlaut
CORPORATE AUTH: DSET Laboratories, Inc., Phoenix, Arizona
PUBLICATION: (U.S. Department of Energy, Commercial Photovoltaics Measurements Workshop, Vail, Colorado, July 27-29, 1981.) Solar Cells, vol. 7, Nov. 1982, p. 135-146

ABSTRACT: None.

TITLE: The Calibration of Pyrheliometers and Pyranometers for Testing Photovoltaic Devices
AUTHOR: G.A.Zerlaut
CORPORATE AUTH: DSET Laboratories, Inc., Phoenix, Arizona
PUBLICATION: (U.S. Department of Energy, Commercial Photovoltaics Measurements Workshop, Vail, Colorado, July 27-29, 1981.) Solar Cells, vol. 7, Nov. 1982, p. 119-129

ABSTRACT: None.

TITLE: Spectroradiometer Measurements in Support of Photovoltaic Device Testing
AUTHOR: G.A. Zerlaut and J.D. Maybee
CORPORATE AUTH: DSET Laboratories, Inc., Phoenix, Arizona
PUBLICATION: (U.S. Department of Energy, Commercial Photovoltaics Measurements Workshop, Vail, Colorado, July 27-29, 1981.) Solar Cells, vol. 7, Nov. 1982, p. 97-106

ABSTRACT: The spectroradiometer is capable of complete solar spectral measurements approximately 7 min apart in both the global and the direct beam modes, all in the wavelength range 280-2500 nm. Global measurements can be made at any azimuth and altitude position; the field of view of the pyrheliometer comparison tube is 6 deg. Typical spectra show that the resolution is sufficient to identify Fraunhofer absorption bands in the surface of the sun. Data are presented that show the relationship between direct beam spectra and two specific microenvironments. The differences observed are analyzed in terms of the significance of microenvironment haze and pollution to the efficiency of concentrating PV devices.

TITLE: Silicon Photovoltaic Cells
AUTHOR: R.N. Hall
CORPORATE AUTH: General Electric Co., Schenectady, New York
PUBLICATION: Solid-State Electronics, vol. 24, July 1981, p. 595-616

ABSTRACT: The principles governing the performance of Si solar cells are reviewed with emphasis on clarifying the essential concepts. Principal attention is devoted to the planar p-n junction cell and recent developments that have contributed to increased efficiency. Other solar cell structures are also reviewed and their relative advantages and shortcomings are discussed. Important areas where our present understanding is inadequate are pointed out and some common misconceptions are corrected.

TITLE: Experience with Specifications Applicable to Certification of Photovoltaic Modules for Large Scale Application
AUTHOR: R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: (U.S. Department of Energy, Commercial Photovoltaics Measurements Workshop, Vail, Colorado, July 27-29, 1981.) Solar Cells, vol. 7, Nov. 1982, p. 197-201

ABSTRACT: JPL has developed a number of PV test and measurement specifications to guide the development of modules toward the requirements of future large-scale applications. Experience with these specifications and the extensive module measurement and testing that has accompanied their use is examined. Conclusions are drawn relative to three aspects of product certification: performance measurement, endurance testing and safety evaluation.

TITLE: Module and Solar Cell Values as a Function of Efficiency
AUTHOR: M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
PUBLICATION: Solar Cells, vol. 3, July 1981, p. 327-336

ABSTRACT: The determination of solar cell value as a function of efficiency provides a valuable tool for the selection of modules for a given system or for the assessment of the cost effectiveness of solar cell and module fabrication processes. This value efficiency relationship is dominated by the area related balance-of-system costs (ARBOS). Their future magnitude, however, is rather uncertain. An assumption of this magnitude will radically influence the direction of PV module research and development to be undertaken. To illustrate the effect of array installation costs, a graph presents four curves of module value as a function of efficiency with ARBOS costs as parameter.

TITLE: Glass as Encapsulation for Low-Cost Photovoltaic Solar Arrays
AUTHOR: F.L. Bouquet
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: ASME Transactions, Journal of Solar Energy Engineering, vol. 103, Aug. 1981, p. 221-232

ABSTRACT: In PV systems, the encapsulant material that protects the solar cells should be highly transparent and very durable. Glass satisfies these two criteria and is considered a primary candidate for low cost, PV encapsulation systems. In this paper, various aspects of glass encapsulation are treated that are important for the designer of PV systems. Candidate glasses and available information defining the state of the art of glass encapsulation materials and processes for automated, high volume production of terrestrial PV devices and related applications are presented. The desired characteristics of glass encapsulation are (1) low degradation rates, (2) high transmittance, (3) high reliability, (4) low cost, and (5) high annual production capacity. The glass design areas treated herein include the types of glass, sources, prices, physical properties and glass modifications, such as antireflection coatings.

TITLE: Development of Low-Thermal Expansion Mullite Bodies
AUTHOR: M.H. Leipold and J.D. Sibold
CORPORATE AUTH: Jet Propulsion Laboratory; Coors Porcelain Co., Golden, Colorado
PUBLICATION: American Ceramic Society, Journal, vol. 65, Sept. 1981, p. C-147 to C-149

ABSTRACT: A series of ceramic compositions based on variations in the crystal-glass ratio of a mullite body were developed. The thermal expansion of these compositions varies from 3.7 to 5.0 x 10^{-6}/C to 800 C. The materials are particularly useful for application involving Si,

in that an identical thermal expansion is available. The high-temperature creep data for the lower-expansion compositions are inferior as a result of their higher glass contents. Raw material sources and fabrication procedures for specific compositions are given.

TITLE: Analysis of the Photovoltage Decay (PVD) Method for Measuring Minority Carrier Lifetimes in P-N Junction Solar Cells
AUTHOR: O. Von Roos
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics, vol. 52, Sept. 1981, p. 5833-5837

ABSTRACT: The PVD method for the measurement of minority carrier lifetimes in p-n junction solar cells with cell thickness comparable to or even less than the minority carrier diffusion length is examined. The method involves the generation of free carriers in the quasi neutral bulk material by flashes of light and the monitoring of the subsequent decay of the induced open circuit voltages as the carriers recombine, which is dependent on minority carrier recombination lifetime. It is shown that the voltage versus time curve for an ordinary solar cell (n^+-p junction) is proportional to the inverse minority carrier lifetime plus a factor expressing the ratio of diffusion length to cell thickness. In the case of an ideal back-surface-field cell (n^+-p-p^+ junction) however, the slope is directly proportional to the inverse minority carrier lifetime. It is noted that since most BSF cells are not ideal, possessing a sizable back surface recombination velocity, the PVD measurements must be treated with caution and supplemented with other nonstationary methods.

TITLE: Thickness Dependences of Solar Cell Performance
AUTHOR: C.T. Sah
CORPORATE AUTH: University of Illinois, Urbana, Illinois
PUBLICATION: Solid-State Electronics, vol. 25, Sept. 1981, p. 960 962

ABSTRACT: The significance of including factors such as the base resistivity loss for solar cells thicker than 100 microns and emitter and BSF layer recombination for thin cells in predicting the fill factor and efficiency of solar cells is demonstrated analytically. A model for a solar cell is devised with the inclusion of the dopant impurity concentration profile, variation of the electron and hole mobility with dopant concentration, the concentration and thermal capture and emission rates of the recombination center, device temperature, the AM1 spectra and the Si absorption coefficient. Device equations were solved by means of the transmission line technique. The analytical results were compared with those of low-level theory for cell performance. Significant differences in predictions of the fill factor resulted, and inaccuracies in the low-level approximations are discussed.

TITLE: 11% Efficient Single-Crystal Solar Cells and 10% Efficient Polycrystalline Cells Made from Refined Metallurgical Silicon
AUTHOR: J.I. Hanoka, H.B. Strock, and P.S. Kotval
CORPORATE AUTH: Union Carbide Technical Center, Tarrytown, New York
PUBLICATION: Journal of Applied Physics, vol. 52, Sept. 1981, p. 5829-5832

ABSTRACT: The performance of single crystal and polycrystalline solar cells fabricated from a refined form of low-cost metallurgical Si are presented. Cz-pulled single crystal and cast polycrystalline Si solar cells with an n on p structure were made from metallurgical Si processed by Al dissolution followed by Al removal through slagging and directional solidification to obtain material purities in the fractional ppm by weight range. For the single-crystal cells, measurements reveal AM1 efficiencies up to 11.1%, open circuit voltages up to 596 mV and fill factors up to 81%. The cast polycrystalline substrates have yielded cells with efficiencies up to 10.1%, fill factors of 79% and open circuit voltages of 585 mV. The low short circuit current densities are attributed to impurities in the base region in the single crystal cell, and to grain boundary segregation of impurities and grain boundary recombination in the polycrystalline cells.

TITLE: Annealing and Anomalous High-Energy Electron Irradiation Effects in Low-Cost Silicon n^+p solar cells
AUTHOR: G.F. Garlick and A.H. Kachare
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Applied Physics Letters, vol. 39, Sept. 15, 1981, p. 501-503

ABSTRACT: Si solar cells of n^+p type were subjected to 1 MeV electron irradiation (up to 10^{16} electrons/sq cm) and then annealed at 450 C for 20 min or annealed with no elecron irradiation. Electron irradiation resulted in a degradation of longer wavelength cell response, but produced a marked enhancement of response at shorter wave lengths with a peak change of 40% at 0.44 microns. Subsequent thermal anneal at 450 C reduced the long-wavelength degradation, but enhancement at shorter wavelengths persisted. Excitation at the shorter wavelengths was in the n^+ diffused layer and in the junction region of the cell. Anneal of unirradiated cells produced shorter-wavelength enhancement with a similar peaking at 0.44 microns, but with a relative change of only 20%. More enhancement was produced in the longer wavelength region (up to 0.8 microns). These effects in the different cell regions are explained by a decrease in the interstitial oxygen impurity complexes (deep recombination levels) and the formation of substantial oxygen-Si vacancy centers (donors).

TITLE: p^+ n n^+ Solar Cells with Hole Diffusion Lengths Comparable With the Base Width - A Simple Analytic Model
AUTHOR: G.S. Kousik and J.G. Fossum
CORPORATE AUTH: University of Florida, Gainesville, Florida
PUBLICATION: Solar Cells, vol. 5, Dec. 1981, p. 75-79

ABSTRACT: A simple analytic description of the hole current injected into the n n^+ base of a p^+-n-n^+ solar cell under forward bias in the dark is derived for the intermediate case in which the hole diffusion length is comparable with the base width. The derivation is made possible by recognizing a common relationship between the effective surface recombination velocity at the n-n^+ junction and the diffusion velocity in the base.

TITLE: Polymers in Solar Energy Utilization
AUTHOR: R.H. Liang, D.R. Coulter, C. Dao, and A. Gupta
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Polymers in Solar Energy Utilization; Proceedings of the Symposium, Las Vegas, Nevada, March 28 April 2, 1982. Washington, DC, American Chemical Society (ACS Symposium Series, No. 220), 1983, p. 265-273

ABSTRACT: A laser photoacoustic technique (LPAT) has been verified for performing accelerated life testing of outdoor photooxidation of polymeric materials used in solar energy applications. Samples of the material under test are placed in a chamber with a sensitive microphone, then exposed to chopped laser radiation. The sample absorbs the light and converts it to heat by a nonradiative deexcitation process, thereby reducing pressure fluctuations within the cell. The acoustic signal detected by the microphone is directly proportional to the amount of light absorbed by the specimen. Tests were performed with samples of ethylene/methylacrylate copolymer (EMA) reprecipitated from hot cyclohexane, compressed, and molded

into thin (25-50 microns) films. The films were exposed outdoors and sampled by LPAT weekly. The linearity of the light absorbed with respect to the acoustic signal was verified. Correlations were established between the photoacoustic behavior of the materials aged outdoors and the same kinds of samples cooled and heated in a controlled environment reactor. The reactor tests were validated for predicting outdoor exosures up to 55 days.

TITLE: Reduction of Solar Cell Efficiency by Bulk Defects Across the Back-Surface Field Junction
AUTHOR: C.T. Sah, K.A. Yamakawa, and R. Lutwack
CORPORATE AUTH: C.T. Sah Associates; Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics, vol. 53, Apr. 1982, p. 3278-3290

ABSTRACT: The degradation of solar cell performance due to bulk defects distributed across the back-surface field junction is analyzed in terms of a three region developed-perimeter model. Families of curves are computed and their physical significance is discussed in detail with reference to three parameters used to characterize the defects: defect area, defect density, and defect surface recombination velocity. A reduction in the open-circuit voltage due to the presence of a defect is expressed as a function of the defect area, density, cell thickness, and defect surface recombination velocity. Numerical examples are presented to illustrate the importance of the particular defect parameters.

TITLE: Fracture of Directionally Solidified Multicrystalline Silicon
AUTHOR: C.P. Chen, M.H. Leipold, and D. Helmreich
CORPORATE AUTH: Jet Propulsion Laboratory; Heliotronic GmbH., Burghausen (West Germany).
PUBLICATION: American Ceramic Society, Journal, vol. 65, Apr. 1982, p. C-49. Research supported by the U.S. Department of Energy; Bundesministerium fuer Forschung und Technologie

ABSTRACT: Fracture toughness data is given for multicrystalline Si which has been prepared by directional solidification. Results indicated a plane strain fracture toughness of 0.8 to 0.87 MN/m to the 3/2 power, which is consistent with data for single crystal Si.

TITLE: An Effect of Back-Surface Boron Implantation on Silicon Solar Cells
AUTHOR: M.B. Spitzer, S.J. Solomon, and P.R. Younger
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts
PUBLICATION: Journal of Applied Physics, vol. 53, May 1982, p. 3926

ABSTRACT: An experimental study has been carried out to investigate mechanisms responsible for the effect of open-circuit voltage enhancement in back-surface ion-implanted Si solar cells. It is shown that open-circuit voltage enhancement in boron-implanted cells is due to a back-surface field effect, whereas gettering, if present, does not affect cell performance. This result is consistent with the observation that, for equal fluence, the damage produced by boron implantation is less than that produced by heavier ions, and, consequently, boron-implant damage is less effective as a gettering treatment for the implant and anneal conditions reported.

TITLE: Effect of Thickness on Silicon Solar Cell Efficiency
AUTHOR: C.T. Sah, K.A. Yamakawa, and R. Lutwack
CORPORATE AUTH: University of Illinois, Urbana, Illinois; Jet Propulsion Laboratory
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-29, May 1982, p. 903-908

ABSTRACT: A computer-aided-design study on the dependence of the efficiency peak of a back surface field solar cell on the concentrations of the recombination and dopant impurities is presented. The illuminated current-voltage characteristics of more than 100 cell designs are obtained using the transmission line circuit model to numerically solve the Shockley equations. Using an AM1 efficiency of 17% as a target value, it is shown that the efficiency versus thickness dependence has a broad maximum which varies by less than 1% over more than a three-to-one range of cell thicknesses from 30 to 100 microns. An optically reflecting back surface will give only a slight improvement of AM1 efficiency, about 0.7%, in this thickness range. Attention is given to the dependence of the efficiency on patchiness across the back-surface field low high junction in thin cells.

TITLE: Low Cost Solar Array Progress and Plans
AUTHOR: W.T. Callaghan
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Fourth International Conference, Stresa, Italy, May 10-14, 1982 (A83-32176 14-44). Dordrecht, D. Reidel Publishing Co., 1982, p. 369-373

ABSTRACT: It is pointed out that significant redirection has occurred in the DOE Photovoltaics Program, and thus in the FSA, since the 3rd European Communities Conference. The Si Materials Task has now the objective to sponsor theoretical and experimental research on Si material refinement technology suitable for PV flat-plate solar arrays. With respect to the hydrochlorination reaction, a process proof of concept was completed through definition of reaction kinetics, catalyst, and reaction characteristics. In connection with the dichlorosilane chemical vapor desposition process, a preliminary design was completed of an experimental process system development unit with a capacity of 100 to 200 MT/yr of Si. Attention is also given to the Si-sheet formation research area, environmental isolation research, the cell and module formation task, the engineering sciences area, and the module performance and failure analysis area.

TITLE: Critical Technology Limits to Silicon Material and Sheet Production
AUTHOR: M.H. Leipold
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Fourth International Conference, Stresa, Italy, May 10-14, 1982 (A83-32176 14-44). Dordrecht, D. Reidel Publishing Co., 1982, p. 985-989

ABSTRACT: Earlier studies have indicated that expenditures related to the preparation of high-purity Si and its conversion to Si sheet represent from 40 to 52% of the cost of the entire panel. The present investigation is concerned with the elements which were selected for study in connection with the FSA Project. The first of two technologies which are being developed within the FSA Project involves the conversion of metallurgical-grade Si through a silane purification process to Si particles. The second is concerned with the conversion of trichlorosilane to dichlorosilane, and the subsequent production of Si using modified rod reactors of the Siemens type. With respect to Si sheet preparation, efforts have been focused both on the preparation of ingots, followed by wafering, and the direct cyrstallization of molten Si into a ribbon or film.

TITLE: Recent Developments in Multi-Wire Fixed Abrasive Slicing Techniques for Low-Cost Silicon Wafer Production from Ingots
AUTHOR: F. Schmid, C.P. Khattak, M.B. Smith, and L.D. Lynch
CORPORATE AUTH: Crystal Systems, Inc., Salem, Massachusetts

MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Fourth International Conference, Stresa, Italy, May 10-14, 1982 (A83-32176 14-44). Dordrecht, D. Reidel Publishing Co., 1982, p. 980-984

ABSTRACT: Slicing is an important processing step for all technologies based on the use of ingots. A comparison of the economics of three slicing techniques shows that the fixed abrasive slicing technique is superior to the internal diameter and the multiblade slurry techniques. Factors affecting contact length are discussed, taking into account kerf width, rocking angle, ingot size, and surface speed. Aspects of blade development are also considered. A high concentration of diamonds on wire has been obtained in wire packs used for FAST slicing. The material removal rate was found to be directly proportional to the pressure at the diamond tips.

TITLE: Reliability and Performance Experience with Flat-Plate Photovoltaic Modules
AUTHOR: R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Fourth International Conference, Stresa, Italy, May 10-14, 1982 (A83-32176 14-44). Dordrecht, D. Reidel Publishing Co., 1982, p. 169-178

ABSTRACT: Statistical models developed to define the most likely sources of PV array failures and the optimum method of allowing for the defects in order to achieve a 20 yr lifetime with acceptable performance degradation are summarized. Significant parameters were the cost of energy, annual power output, initial cost, replacement cost, rate of module replacement, the discount rate, and the plant lifetime. Acceptable degradation allocations were calculated to be 0.0001 cell failures/yr, 0.005 module failures/yr, 0.05 power loss/yr, a 0 01 rate of power loss/yr, and a 25 yr module wear-out length. Circuit redundancy techniques were determined to offset cell failures using fault tolerant designs such as series/parallel and bypass diode arrangements. Screening processes have been devised to eliminate cells that will crack in operation, and multiple electrical contacts at each cell compensate for the cells which escape the screening test and then crack when installed. The 20 yr array lifetime is expected to be achieved in the near-term.

TITLE: Cost Estimates for Flat-Plate and Concentrator Collector Arrays
AUTHOR: K. Shimada
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: (Japan Society of Applied Physics and Science Council of Japan, Photovoltaic Science and Engineering Conference in Japan, 3rd, Kyoto, Japan, May 19 21, 1982) Japanese Journal of Applied Physics (ISSN 0021-4922), vol. 21, Supplement 21-2, 1982, p. 143-153

ABSTRACT: The current module and installation costs for the U.S. National PV Program's grid-connected systems are significantly higher than required for economic viability of this alternative. Attention is accordingly given to the prospects for installed module cost reductions in flat plate, linear focus Fresnel concentrator, and point focus Fresnel concentrator candidate systems. Cost projections indicate that all three systems would meet near-term and midterm goals, provided that module costs of $2.80/W_p$ and $0.70/W_p$, respectively, are met. The point focus Fresnel system emerges as the most viable for the near term.

TITLE: Non-Mass-Analyzed Ion Implantation From a Solid Phosphorus Source
AUTHOR: M.B. Spitzer and S.N. Bunker
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts
PUBLICATION: Applied Physics Letters, vol. 40, June 1, 1982, p. 976-978

ABSTRACT: A phosphorus ion beam, extracted from a Freeman ion source charged with elemental phosphorus, has been investigated for use in solar cell fabrication. Mass spectroscopy of the beam indicates the absence of both minority carrier lifetime degrading impurities and hydrogen. The ion beam, without mass analysis, was used for ion implantation of solar cells, and performance for all cells was found to be equivalent to mass analyzed controls.

TITLE: Heterogeneous Decomposition of Silane in a Fixed Bed Reactor
AUTHOR: S.K. Iya, R.N. Flagella, and F.S. Dipaolo
CORPORATE AUTH: Union Carbide Corp., Tonawanda, New York
PUBLICATION: Electrochemical Society, Journal, vol. 129, July 1982, p. 1531-1535

ABSTRACT: Heterogeneous decomposition of silane in a fluidized bed offers an attractive route for the low cost production of Si for PV application. To obtain design data for a fluid bed silane pyrolysis reactor, deposition experiments were conducted in a small scale fixed bed apparatus. Data on the decomposition mode, plating rate, and deposition morphology were obtained in the temperature range 600 900 C. Conditions favorable for heterogeneous decomposition with good deposition morphology were identified. The kinetic rate data showed the reaction to be first order with an activation energy of 38.8 kcal/mol, which agrees well with work done by others. The results are promising for the development of an economically attractive fluid bed process.

TITLE: Accelerated Stress Testing of Terrestrial Solar Cells
AUTHOR: J.W. Lathrop, D.C. Hawkins, J.L. Prince, and H.A. Walker
CORPORATE AUTH: Clemson University, Clemson, South Carolina
PUBLICATION: IEEE Transactions on Reliability, vol. R-31, Aug. 1982, p. 258-265

ABSTRACT: The development of an accelerated test schedule for terrestrial solar cells is described. This schedule, based on anticipated failure modes deduced from a consideration of IC failure mechanisms, involves bias temperature testing, humidity testing (including both 85-85 and pressure cooker stress), and thermal-cycle thermal-shock testing. Results are described for 12 different unencapsulated cell types. Both gradual electrical degradation and sudden catastrophic mechanical change were observed. These effects can be used to discriminate between cell types and technologies relative to their reliability attributes. Consideration is given to identifying laboratory failure modes which might lead to severe degradation in the field through second quadrant operation. Test results indicate that the ability of most cell types to withstand accelerated stress testing depends more on the manufacturer's design, processing, and worksmanship than on the particular metallization system. Preliminary tests comparing accelerated test results on encapsulated and unencapsulated cells are described.

TITLE: Photovoltaic Module Reliability Improvement Through Application Testing and Failure Analysis
AUTHOR: L.N. Dumas and A. Shumka
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: IEEE Transactions on Reliability, vol. R-31, Aug. 1982, p. 228-234

ABSTRACT: During the first four years of the DOE National PV Program, the LSA Project purchased about 400 kW of PV modules for test and experiments. In order to identify, report, and analyze test and operational problems with the Block Procurement modules, a problem/failure reporting and analysis system was implemented by the LSA Project with the main purpose of providing manufacturers with feedback from test and field experience needed for the improvement of product performance and reliability. A description of

the more significant types of failures is presented, taking into account interconnects, cracked cells, dielectric breakdown, delamination, and corrosion. Current design practices and reliability evaluations are also discussed. The conducted evaluation indicates that current module designs incorporate damage resistant and fault-tolerant features which address field failure mechanisms observed to date.

TITLE: A Technique for Determining Solar Irradiance Deficits - Photovoltaic Arrays Design
AUTHOR: C.C. Gonzalez and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: IEEE Transactions on Reliability, vol. R-31, Aug. 1982, p. 285-288

ABSTRACT: An analytic technique which determines the variation of solar irradiance from long term averages is presented. The technique involves computer assisted data reduction techniques, and was designed to improve system reliability by determining the amount of storage capability required to supplement a baseline system. Variations in time intervals of up to 60 days can be determined, and 10 years of data collection are reviewed. The technique involves first calculating average monthly irradiance values, then examining the average irradiance deviation over time intervals. The calculation procedure is clarified by determining solar energy level probabilities and the long term solar energy deviation (achieved by repeatedly integrating actual irradiance figures). It is found that a 15% increase in collector area and the addition of energy storage or backup are essential contributions to achieving cost-effectiveness. In addition, one to seven no-sun day storage capacities are required to accommodate weather caused deficits.

TITLE: Qualification Testing of Flat-Plate Photovoltaic Modules
AUTHOR: A.R. Hoffman, J.S. Griffith, and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: IEEE Transactions on Reliability, vol. R-31, Aug. 1982, p. 252-257

ABSTRACT: The placement of PV modules in various applications, in climates and locations throughout the world, results in different degrees and combinations of environmental and electrical stress. Early detection of module reliability deficiencies via laboratory testing is necessary for achieving long, satisfactory field service. This overview paper describes qualification testing techniques being used in the US Department of Energy's flat-plate terrestrial PV development program in terms of their significance, rationale for specified levels and durations, and test results.

TITLE: Photovoltaic Array Reliability Optimization
AUTHOR: R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: IEEE Transactions on Reliability, vol. R-31, Aug. 1982, p. 246-251

ABSTRACT: An overview of the PV array reliability problem is presented, and a high reliability/minimum cost approach to this problem is presented. Design areas covered are cell failure, interconnect fatigue, and electrical insulation breakdown, and three solution strategies are discussed. The first involves controlling component failures in the solar cell (cell cracking, cell interconnects) and at the module level (must be statistically treated). Second, a fault tolerant circuit is designed which reduces array degradation, improves module yield losses, and controls hot spot heating. Third, cost optimum module replacement strategies are also effective in reducing array degradation. This can be achieved by minimizing the life cycle energy cost of the photovoltaic system. The integration of these solutions is aimed at reducing the 0.01% failure rate.

TITLE: Investigating Reliability Attributes of Silicon Photovoltaic Cells - An Overview
AUTHOR: E.L. Royal
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: IEEE Transactions on Reliability, vol. R-31, Aug. 1982, p. 266-269

ABSTRACT: Reliability attributes are being developed on a wide variety of advanced single crystal Si solar cells. Two separate investigations: cell contact integrity (metal to silicon adherence), and cracked cells identified with fracture strength reducing flaws are discussed. In the cell contact integrity investigation, analysis of contact pull strength data shows that cell types made with different metallization technologies, i.e., vacuum, plated, screen printed and soldered, have appreciably different reliability attributes. In the second investigation, fracture strength was measured using Cz wafers and cells taken at various stages of processing and differences were noted. Fracture strength, which is believed to be governed by flaws introduced during wafer sawing, was observed to improve (increase) after chemical polishing and other process steps that tend to remove surface and edge flaws.

TITLE: Analysis of Minority-Carrier Transport in Polysilicon Devices
AUTHOR: J.G. Fossum and R. Sundaresan
CORPORATE AUTH: University of Florida, Gainesville, Florida
PUBLICATION: IEEE Transactions on Electron Devices, vol. ED-29, Aug. 1982, p. 1185-1197

ABSTRACT: An approximate analytic model is presented for the minority electron current injected into the base of a representative grain of a forward biased n^+-p junction. Simplifying assumptions which enable the separation of the grain boundary recombination analysis from the intragrain transport analysis are discussed along with the model limitations they imply. In particular, it is shown that limitations associated with the assumption of quasi-equilibrium are effectively removed by recognizing that when conditions obtain that negate quasi-equilibrium, the minority electrons flow to the grain-boundary surface with velocities about equal to the kinetic-limit velocity. The proposed model provides a better understanding of minority-carrier transport in polysilicon and should be useful in engineering design of optimal polysilicon bipolar devices, including solar cells.

TITLE: Reduction of Solar Cell Efficiency by Edge Defects Across the Back-Surface Field Junction - A Developed Perimeter Model
AUTHOR: C.T. Sah, K.A. Yamakawa, and R. Lutwack
CORPORATE AUTH: C.T. Sah Associates, Urbana, Illinois; Jet Propulsion Laboratory
PUBLICATION: Solid State Electronics, vol. 25, Sept. 1982, p. 851-858

ABSTRACT: Material imperfections, impurity clusters and fabrication defects across the back surface field junction can degrade the performance of high efficiency solar cells. The degradation from defects appearing on the circumference of a solar cell is analyzed using a two-region developed perimeter device model. The width of the defective perimeter region is characterized by the range or the distance-of-influence of the defective edge and this width is about two diffusion lengths. The defective edge is characterized by a surface recombination velocity. Family of theoretical curves and numerical examples are presented to show that significant reduction of open-circuit voltage can occur in high efficiency cells which are thin compared with the diffusion length. In one example, the degradation is decreased from 135 mV to 75 mV when the cell size is increased from 10 to 100 times the diffusion length in a thin cell whose thickness is 1% of the diffusion length.

TITLE: Cost Analyses of Modular Flat Panel and Concentrator Photovoltaic Array Fields
AUTHOR: D.C. Carmichael
CORPORATE AUTH: Battelle Columbus Laboratories, Columbus, Ohio
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 1176-1182

ABSTRACT: Modular designs for a flat-panel array field and for two types of concentrator array fields have been developed which reduce the array field balance of system (BOS) costs and engineering design costs to a fraction of those experienced in previous installations. To achieve the BOS cost reductions, array field subsystem designs were integrated and optimized for minimum life-cycle costs. It is shown that the array field BOS costs for the developed building-block designs contribute only 0.89 to 1.22 ¢/kWh (ac) to the levelized energy cost of the electricity generated by the PV system.

TITLE: An Accelerated Stress Testing Program for Determining the Reliability Sensitivity of Silicon Solar Cells to Encapsulation and Metallization Systems
AUTHOR: J.W. Lathrop, C.W. Davis, and E. Royal
CORPORATE AUTH: Clemson Univ., South Carolina; Jet Propulsion Laboratory
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 1262-1267

ABSTRACT: The use of accelerated testing methods in a program to determine the reliability attributes of terrestrial Si solar cells is discussed. Different failure modes are to be expected when cells with and without encapsulation are subjected to accelerated testing and separate test schedules for each are described. Unencapsulated test cells having slight variations in metallization are used to illustrate how accelerated testing can highlight different diffusion related failure mechanisms. The usefulness of accelerated testing when applied to encapsulated cells is illustrated by results showing that moisture related degradation may be many times worse with some forms of encapsulation than with no encapsulation at all.

TITLE: Development of a Photovoltaic Module Qualification Test Based on Combined Environment Accelerated Stress Data
AUTHOR: S.E. Trenchard, E. Royal, and E.T. Anderson
CORPORATE AUTH: Coast Guard Research and Development Center, Groton, Connecticut; Jet Propulsion Laboratory; Reliability Technology Associates, Lockport, Illinois
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22975 09-44). New York, 1982, p. 1030-1035

ABSTRACT: The U.S. Coast Guard has developed a qualification test to screen PV modules for utilization on marine aids to navigation. The test is based on a combined environment of hot and cold saltwater immersion and air pressurization. The test has demonstrated a very-high acceleration factor and excellent correlation of electrical failures with modules in a concurrent real time marine exposure.

TITLE: Progress in Growth of Silicon Ribbon by a Low Angle, High Rate Process
AUTHOR: D.N. Jewett, H.E. Bates, and J.W. Locher
CORPORATE AUTH: Energy Materials Corp., So. Lancaster, Massachusetts
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 86-89

ABSTRACT: Substantial progress has been achieved in the development of the LASS crystal growth technique since its inception in mid 1979. Continuously grown ribbons of 10 to 30 meters are produced routinely at growth rates of 10 to 80 cm/min. Ribbon widths are 4 to 15 cm and thickness varies from 0.3 to 6 mm with 0.5 mm typical. At an average growth speed of 30 cm/min and a width of 15 cm, productivity of 450 sq cm/min of ribbon has been demonstrated. Solar cells made from LASS material have exhibited up to 12.9% conversion efficiency (AM1) on 4 x 4 cm boron doped blanks.

TITLE: The Design and Development of a Rectangular, Shingle Type Photovoltaic Module
AUTHOR: N.F. Shepard, Jr.
CORPORATE AUTH: General Electric Co., Philadelphia, Pennsylvania
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 828-833

ABSTRACT: A shingle type PV module has been designed and developed to meet the requirements of specifications for residential applications. The module is ideally suited for installation directly to the sheathing of a sloping, south facing roof of a residential, industrial, or commercial building. The design requirements are examined, taking into account also module safety requirements. Aspects of module design and analysis are discussed, giving attention to installation details, solar cells and electrical circuit design, the encapsulation system, substrate lamination, and the module to-module interconnecting cable. Details of module assembly experience and test and outdoor exposure experience are also considered.

TITLE: Empirical Testing of Structural Deflection Modeling of Large Photovoltaic Modules
AUTHOR: L.B. Duncan, C.P. Minning, A. Garcia, III, and E.F. Cuddihy
CORPORATE AUTH: Hughes Aircraft Co., El Segundo, California; Spectrolab, Inc., Sylmar, California; Jet Propulsion Laboratory
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84 22957 09-44). New York, 1982, p. 1256-1261

ABSTRACT: The objective of the structural deflection test was to verify the analytical models used to predict solar cell stress, load bearing layer stress, and module deflection that result from a uniform pressure load on the module surface. The verification process consisted of measuring module deflection, stress in the solar cell, and stress in the load bearing member as a functon of normal pressure load, pottant modulus of elasticity, pottant thickness, and cell location. Four glass superstrate modules, two plain wood substrate modules, two ribbed wood substrate modules, and a steel substrate module were tested. Consistent with analysis predictions, all unribbed specimens exhibited nonlinear load vs. deflection characteristics. With the exception of the steel module, test results and analysis predictions for panel deflectons agreed to within 10 percent. A wider variation of agreement was found for stress in the load-bearing members and cells.

TITLE: Flat Plate Solar Array Progress and Plans
AUTHOR: W.T. Callaghan
CORPORATE AUTH: Jet Propulsion Laboratory

MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 115-118

ABSTRACT: The emphasis of the FSA Project has been shifted from price goals and commercial development toward longer term, higher risk, higher potential-payoff opportunities. The revised objectives, status, and plans of the project are presented and technical progress is noted in the areas of: large area sheet formation; Si feedstock refinement; flat plate module process sequence development; and engineering and environmental testing.

TITLE: Enhanced Diffusion of Phosphorus at Grain Boundaries
AUTHOR: L.J. Cheng, C.M. Shyu, K.M. Stika, T. Daud, and G.T. Crotty
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 554-558

ABSTRACT: Enhanced diffusion of phosphorus at grain boundaries in cast polycrystalline PV materials (Wacker, HEM, and Semix) was studied. It was found that the enhancements for the three materials were the same, indicating that the properties of boundaries are similar, even though they were grown by different techniques. In addition, it was observed that grain boundaries capable of enhancing the diffusion always have strong recombination activities. Both phenomena could be related to dangling bonds existing at the boundaries. The present study gives the first evidence that incoherent second order twins of 111/115 plane type are diffusion-active.

TITLE: Directional Solidification of Silicon in Carbon Crucibles by an Oscillating Crucible Technique
AUTHOR: T. Daud, K.A. Dumas, G.H. Schwuttke, P. Smetana, and K.M. Kim
CORPORATE AUTH: Jet Propulsion Laboratory; International Business Machines Corp., Hopewell Junction, New York
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 63-67

ABSTRACT: The quality of Si cast by present techniques is limited by the presence of dislocations and grain boundaries in unseeded growth and by cellular structures with dislocation networks in the case of the seeded growth. To address these concerns, a new method of directional solidification called the oscillating crucible technique (OCT) is developed. During growth, a carbon crucible is oscillated to provide for effective stirring of the melt. This growth technique (seeded growth only), along with material characterization and solar-cell fabrication and testing, is described. Solar cell efficiencies of up to 13 percent at 100 mW/sq cm area obtained in the single crystalline areas. Minority carrier diffusion lengths exceeding 100 microns are measured even in the polycrystalline areas of the wafers. Limitations of the present setup and possible future improvements are discussed.

TITLE: Characterization of the Electrical Output of Flat Plate Photovoltaic Arrays
AUTHOR: C.C. Gonzalez, G.M. Hill, and R.R. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 384-390

ABSTRACT: The electric output of flat plate PV arrays changes constantly, due primarily to changes in cell temperature and irradiance level. As a result, array loads such as direct-current to alternating-current power conditioners must be able to accommodate widely varying input levels, while maintaining operation at or near the array maximum power point. The results of an extensive computer simulation study that was used to define the parameters necessary for the systematic design of array/power conditioner interfaces are presented as normalized ratios of power-conditioner parameters to array parameters, to make the results universally applicable to a wide variety of system sizes, sites, and operating modes. The advantages of maximum power tracking and a technique for computing average annual power conditioner efficiency are discussed.

TITLE: Interaction Between Cast Silicon Properties and Solar Cell Performance
AUTHOR: S. Hyland, P. Iles, D. Leung, G. Schwuttke, and J.A. Engelbrecht
CORPORATE AUTH: Jet Propulsion Laboratory; Applied Solar Energy Corp., City of Industry, California; International Business Machines Corp., Hopewell Junction, New York
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 68-73

ABSTRACT: Three types of cast silicon, Silso, HEM and UCP were studied for their use as solar cells. Optical microscopy after etching revealed a high density of uniform dislocations (approaching 1,000,000/cm^2), lines of dislocations indicating stress during crystal growth, and precipitates, some of which generate dislocations. Solar cells were fabricated by three processes. Results of solar cell processing revealed that these materials produce cells of lower efficiency than Cz control cells, and that the efficiencies of the three materials were quite close. Diffusion length and spectral response data are shown. Certain structural features are correlated with solar cell efficiency, diffusion length, and spectral response. EBIC and light spot scanning are used to back up other measurements.

TITLE: Design Solutions for the Solar Cell Interconnect Fatigue Fracture Problem
AUTHOR: G.R. Mon and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 1268-1276

ABSTRACT: Mechanical fatigue of solar cell interconnects is a major failure mechanism in PV arrays. A comprehensive approach to the reliability design of interconnects, together with extensive design data for the fatigue properties of copper interconnects, has been published. This paper extends the previous work, developing failure prediction (fatigue) data for additional interconnect material choices, including aluminum and a variety of copper-Invar and copper-steel claddings. An improved global fatigue function is used to model the probability-fo-failure statistics of each material as a function of level and number of cycles of applied strain. Life-cycle economic analyses are used to evaluate the relative merits of each material choice. The copper-Invar clad composites demonstrate superior performance over pure copper. Aluminum results are disappointing.

TITLE: The Measurement of Variations in Minority Carrier Lifetime Due to Microstructural Defects in Large Area Polysilicon Wafers
AUTHOR: S.M. Johnson and J.S. Culik
CORPORATE AUTH: Solarex Corp., Rockville, Maryland
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 548-553

ABSTRACT: This paper describes the measurement and analysis of minority carrier lifetime inhomogeneities in large area polysilicon wafers used to fabricate solar cells. Variations in free carrier lifetime are measured using a contactless microwave technique. The use of a subsequent Secco etch enables structurally related minority carrier lifetime degradation mechanisms to be distinguished from impurity related lifetime decreases.

TITLE: Empirical Testing of an Analytical Model Predicting Electrical Isolation of Photovoltaic Models
AUTHOR: A. Garcia, C.P. Minning, and E.F. Cuddihy
CORPORATE AUTH: Spectrolab, Inc., Sylmar, California; Hughes Aircraft Co., Los Angeles, California; Jet Propulsion Laboratory
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 1014-1019

ABSTRACT: A major design requirement for PV modules is that the encapsulation system be capable of withstanding large DC potentials without electrical breakdown. Pre sented is a simple analytical model which can be used to estimate material thickness to meet this requirement for a candidate encapsulation system or to predict the breakdown voltage of an existing module design. A series of electrical tests to verify the model are described in detail. The results of these verification tests confirmed the utility of the analytical model for preliminary design of PV modules.

TITLE: Non-Mass-Analyzed Ion Implantation Equipment for High Volume Solar Cell Production
AUTHOR: A.J. Armini, S.N. Bunker, and M.B. Spitzer
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 895-899

ABSTRACT: Equipment designed for junction formation in Si solar cells is described. The equipment, designed for a production level of approximately one megawatt per year, consists of an ion implanter and annealer. Low cost is achieved by foregoing the use of mass analysis during the implantation, and by the use of a belt furnace for anneal-ing. Results of process development, machine design and cost analysis are presented.

TITLE: Large Area Space Solar Cell Assemblies
AUTHOR: M.J. Nowlan and M.B. Spitzer
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 150-155

ABSTRACT: Results of the development of a 34.3 sq cm space solar cell and integral glass cover are presented. Average AM1 cell efficiency is 14%. The cell design includes a high performance back surface reflector yielding a thermal alpha of approximately 0.66. A novel process is described which integrates cell fabrication and encapsula-tion thereby achieving a reduction of encapsulation cost. Test results indicate the potential of this new technology.

TITLE: New Implantation Techniques for Improved Solar Cell Junctions
AUTHOR: M.B. Spitzer and S.N. Bunker
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 764-769

ABSTRACT: Ion implantation techniques offering improved cell performance and reduced cost have been studied. These techniques include non-mass analyzed phosphorus implantation, argon implantation gettering, and low temper ature boron annealing. It is found that cells produced by non mass analyzed implantation perform as well as mass analyzed controls, and that the cell performance is largely independent of process parameters. A study of argon implantation gettering shows no improvement over non gettered controls. Results of low temperature boron annealing experiments are presented.

TITLE: Design principles for High-Efficiency Small-Grain Polysilicon Solar Cells, with Supporting Experimental Studies
AUTHOR: F.A. Lindholm, A. Neugroschel, and C.T. Sah
CORPORATE AUTH: University of Florida, Gainesville, Florida; Illinois Univ., Urbana, Illinois
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 644-647

ABSTRACT: Design principles suggested here aim toward high conversion efficiency (greater than 15 percent) in polysilicon cells. The principles seek to decrease the liabilities of both intragranular and grain-boundary surface defects. The advantages of a phosphorus atom concentration gradient in a thin (less than 50 microns) base of a p^+ n x n^+ drift-field solar cell, which produces favorable gradients in chemical potential, minority carrier mobility and diffusivity, and recombina-tion lifetime (via phosphorus gettering) are suggested. The degrading effects of grain boundaries are reduced by these three gradients and by substituting atoms (P, H, F or Li) for vacancies on the grain-boundary surface. From recent experiments comes support for the benefits of P diffusion down grain boundaries and, for quasi-grain-boundary free and related structures. New analytic solutions for the n(x) base include the effect of a power law dependence between P concentration and life-time. These provide an upper-bound estimate on the open circuit voltage. Finite difference numerical solutions of the six Shockley equations furnish complete information about all solar-cell parameters and add insight concerning design.

TITLE: How Will we Get to 20% (AM1) Efficient Si Solar Cells?
AUTHOR: M. Wolf
CORPORATE AUTH: University of Pennsylvania, Philadelphia, Pennsylvania
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 355-360

ABSTRACT: Application of recent more exact modeling methods has indicated the design principles for the achievement of Si solar cells with efficiencies above 20

AMI. These design principles are primarily aimed at reducing the total device minority carrier recombination rate, not so much to improve the collection efficiency, but more to attain higher voltages. The reduction of recombination is attacked along three paths: increased minority carrier lifetime, reduced volume for bulk recombination, and reduced surface recombination. The lifetime control dictates the avoidance of severe Auger recombination anywhere in the device. Simultaneously, bandgap narrowing effects will also be minimized. The cells will be multi-layer structures, which include high/low junctions in the base region as well as in part of the front region. The thickness of each of the layers needs to be designed in accordance to the electronic properties actually achieved in it and in the other layers.

TITLE: Silicon MIS/Inversion-Layer Solar Cells Utilizing SiO Deposition
AUTHOR: L.C. Olsen, F.W. Addis, W.A. Miller, and G.C. Dunham
CORPORATE AUTH: University of Washington, Joint Center for Graduate Study, Richland, Washington
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 1223-1230

ABSTRACT: Results obtained for Si MIS/Inversion-Layer solar cells are discussed. Cells are fabricated using Al and Mg MIS collector grids, and by establishing an inversion layer with an SiO AR layer. The theory of MIS-IL cells has developed by solving the two-dimensional diffusion problem for minority carrier transport. Calculated cell performance explains experimental results well. Studies of the inversion layer formation process have involved studies of MOS devices and in situ measurement of inversion layer sheet resistance. An AMI active area efficiency of 16.1% (13.4% total area efficiency) has been achieved with 0.2 ohm cm single crystal material, while an active area efficiency of 12.8% (10.3% total area) was achieved with Wacker Silso polycrystalline material.

TITLE: Solar Cell Contacts
AUTHOR: D.L. Meier, R.B. Campbell, J.R. Davis, Jr., P. Rai Choudhury, and L.J. Sienkiewicz
CORPORATE AUTH: Westinghouse Electric Corp., Pittsburgh, Pennsylvania
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 904-910

ABSTRACT: Two experimental contact systems were examined and compared to a baseline contact system consisting of evaporated layers of titanium, palladium, and silver and an electroplated layer of copper. The first experimental contact system consisted of evaporated layers of titanium, nickel, and copper and an electroplated layer of copper. This system performed as well as the baseline system in all respects, including its response to temperature stress tests, to a humidity test, and to an accelerated aging test. In addition, the cost of this system is estimated to be only 43 percent of the cost of the baseline system at a production level of 25 MW/yr. The second experimental contact system consisted of evaporated layers of nickel and copper and an electroplated layer of copper. Cells with this system show serious degradation in a temperature stress test at 350 C for 30 min. Auger electron spectroscopy was used to show that the evaporated nickel layer is not an adequate barrier to copper diffusion even at temperatures as low as 250 C. This fact brings into question the long-term reliability of this contact system.

TITLE: Impurities in Polycrystalline Silicon Solar Cells
AUTHOR: A. Rohatgi, J.R. Davis, R.H. Hopkins, and P. Rai-Choudhury
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
MEETING LOCATION: 16th IEEE Photovoltaic Specialists Conference, San Diego, California, Sept. 27-30, 1982, Conference Record (A84-22957 09-44). New York, 1982, p. 411-416

ABSTRACT: The effects of grain boundaries and impurities on silicon solar-cell performance have been studied in single crystal and polycrystalline ingots by intentionally incorporting 2 x 10^{12}/cu cm Mo, 10^{14}/cu cm Ti, and about 10^{15}/cu cm Cr during Cz growth. Mo, Ti, and Cr degrade solar-cell performance by inducing deep levels in silicon. Electrically active grain boundaries also reduce cell performance by inducing carrier recombination in the bulk as well as in the depletion region. At low impurity concentrations, polycrystalline cell performance is controlled by grain-boundary recombination, while at high concentrations, it is dominated by the impurity, resulting in equal efficiencies for single crystal and polycrystalline cells. Impurity/grain-boundary interactions are species dependent and result in a decrese in impurity-induced deep level concentration: Cr exhibits the largest interaction, Ti a weak interaction, and Mo no measurable effect.

TITLE: Optical Absorption Coefficient and Minority Carrier Diffusion Length Measurements in Low-Cost Silicon Solar Cell Material
AUTHOR: R.T. Swimm and K.A. Dumas
CORPORATE AUTH: University of Southern California, Los Angeles, California; Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics, vol. 53, Nov. 1982, p. 7502-7504

ABSTRACT: None.

TITLE: Photothermal Degradation of Ethylene/Vinylacetate Copolymer
AUTHOR: R.H. Liang, S. Chung, A. Clayton, S. DiStefano, K. Oda, S.D. Hong, and A. Gupta
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Polymer Alloys III. New York, Plenum Publishing Corp., 1983, p. 267-278

ABSTRACT: Photothermal degradation studies were conducted on a stabilized formulation of EVA in the temperature range 25-105 C under three different oxygen environments (in open air, with limited access to O_2, and in a dark closed stagnant oven). These studies were performed in order to evaluate the utility of EVA as an encapsulation material for PV modules. Results showed that at low temperature (25 C), slow photooxidation of the polymer occurred via electronic energy transfer involving the UV absorber incorporated in the polymer. However, no changes in the physical properties of the bulk polymer were detected up to 1500 h of irradiation. At elevated temperatures, leaching and evaporation of the additives occurred, which ultimately resulted in the chemical crosslinking of the copolymer and the formation of volatile photoproducts such as acetic acid.

TITLE: Theory of Beam Induced Currents in Semiconductors
AUTHOR: J.D. Zook
CORPORATE AUTH: Honeywell Corporate Technology Center, Bloomington, Minnesota
PUBLICATION: Applied Physics Letters, vol. 42, Apr. 1, 1983, p. 602-604

ABSTRACT: An analytical model is presented for the current flowing in a Schottky diode or shallow p-n junction when the current is generated by an electron beam or light beam. The model represents an exact solution to the three dimensional diffusion equation when the current-collecting junction is at right angles to a grain boundary

or to the semiconductor surface. The finite size of the electron hole generation region is readily included in the analysis. The results are given in terms of one-dimensional integrals which can simply and accurately be evaluated using a programmable hand calculator. The theory provides a basis for using electron-beam-induced currents or light beam induced currents to measure the minority carrier diffusion length and surface recombination velocity at a grain boundary or surface.

TITLE: Assessing Photovoltaic Module Degradation and Lifetime from Long Term Environmental Tests
AUTHOR: D.H. Otth and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Institute of Environmental Sciences, Annual Technical Meeting, 29th, Los Angeles, CA, April 19-21, 1983, Proceedings (A85 26551 11-38). Mount Prospect, Illinois, Institute of Environmental Sciences, 1983, p. 121-126

ABSTRACT: The PV module failure mechanisms related to temperature, humidity, and electrical bias are analyzed using the data collected over a period of 20 yrs from various sites in the U.S. The approach is based on measuring the rate dependence of the mechanisms on site stress levels, and then using the rate data to analytically estimate the field life by means of computer models of the site environment. A correlation is established between the accelerated constant-stress testing and the time-varying field exposures. Test results are presented for two failure mechanisms for a module design featuring PVB encapsulant for the temperature range of 85 to 100 C and 85% relative humidity.

TITLE: Polycrystal X-ray Topography (PXT) of a Cast Silicon Photovoltaic Cell
AUTHOR: R.G.Rosemeier, K.C. Yoo, and S.M. Johnson
CORPORATE AUTH: University of Maryland, College Park, Maryland); Solarex Corp., Rockville, Maryland
PUBLICATION: Materials Letters (ISSN 0167-577X), vol. 1, April 1983, p. 194-196.

ABSTRACT: Contiguous (4 0 4)1 and (4 -4 0)2 polycrystal x ray topographs (PXT) have been obtained simultaneously within a single image for two grains of a cast polycrystalline Si solar cell. A special two-step twinning orientation relationship between the adjacent grains gives a condition of only faint diffraction contrast being observed at the boundary interface. Stereographic projection analysis was employed to identify simultaneous reflection conditions, and a portable image x-ray intensifier was routinely used to align x-ray images in real time.

TITLE: Thermal Stability of Hafnium and Titanium Nitride Diffusion Bariers in Multilayer Contacts to Silicon
AUTHOR: I. Suni, M. Maenpaa, M.-A. Nicolet, and M. Luomajarvi
CORPORATE AUTH: California Institute of Technology, Pasadena, California; Technical Research Centre of Finland, Espoo, Finland; Helsinki, University, Helsinki, Finland
PUBLICATION: Electrochemical Society, Journal (ISSN 0013-4651), vol. 130, May 1983, p. 1215-1218

ABSTRACT: The thermal stability of reactively sputtered hafnium nitride (HfN) and titanium nitride (TiN) thin films is investigated for the application as diffusion barriers in metallic contacts to Si. The temperature range of interest is from 400 800 C. The dominating failure mechanism is associated with loss of adhesion and blistering of the barrier layers. The extent of the failure is related to the compressive stresses in the sputtered nitride layers. With proper constraints imposed on the deposition process, HfN and TiN can perform as effective diffusion barriers up to 800 C.

TITLE: Boron and Phosphorus Determination in Low Resistivity Solar-Grade Silicon
AUTHOR: L.P. Hunt, R.W. Francis, and J.P. Dismukes
CORPORATE AUTH: Exxon Research and Engineering Co., Clinton, New Jersey
PUBLICATION: (Electrochemical Society, Meeting, San Francisco, California, May 8-13, 1983) Electrochemical Society, Journal (ISSN 0013-4651), vol. 131, Aug. 1984, p. 1888-1891

ABSTRACT: The present investigation is concerned with an analytical technique which was developed to measure the concentrations of boron and phosphorus in a special grade of Si intended for use in PV applications. Research and development programs have been conducted with the objective to increase the purity of Si metallurgically produced by the carbothermic reduction of Si in an arc furnace. The technique described for determining boron and phosphorus in the purified metallurgical Si (PMS) is somewhat similar to that employed by the semiconductor industry for analyzing polysilicon produced by the Siemens process. Hall-effect measurements are conducted, and a computational procedure is used to translate the obtained data into boron and phosphorus concentrations.

TITLE: Model Calculations for Silicon Inversion Layer Solar Cells
AUTHOR: W.A. Miller and L.C. Olsen
CORPORATE AUTH: University of Washington, Joint Center for Graduate Study, Richland, Washington
PUBLICATION: Solar Cells (ISSN 0379-6787), vol. 8, May 1983, p. 371-395

ABSTRACT: A theoretical treatment of Si-based inversion-layer (IL) solar cells is presented. IL solar cells consist of a p-type semiconducting substrate with a back contact, a metal grid with a rectifying junction beneath the grid area, and a transparent insulating layer on the front surface containing a fixed charge which functions as an AR coating. The fixed charge creates the IL, i.e., the induced surface junction, in the area between the grid lines. The use of MIS contacts has thus far produced cells with efficiencies up to 15 pct, although calculations show that cells of 19 percent efficiency are possible, with processing temperatures of less than 500 C. The failure to reach the optimized efficiencies has been attributed to high sheet resistances in the IL, and calculations were performed to quantify the resistance as a function of the cell parameters and relate them to the device performance. The formulation of a two-dimensional model led to the conclusion that high efficiency is obtainable with a wide range of insulator charge densities, while the grid line spacing must remain a factor of two or three times that of conventional diffused cells.

TITLE: Electrical Characteristics of Amorphous Iron Tungsten Contacts on Silicon
AUTHOR: M. Finetti, E.T.-S. Pan, M.-A, Nicolet, and I. Suni
CORPORATE AUTH: California Inst. of Tech., Pasadena, California; Consiglio Nazionale delle Ricerche, Bologna (Italy).; Technical Research Centre of Finland, Espoo
PUBLICATION: Applied Physics Letters (ISSN 0003 6951), vol. 42, June 1, 1983, p. 987-989

ABSTRACT: The electrical characteristics of amorphous Fe-W contacts have been determined on both p-type and n-type Si. The amorphous films were obtained by co-sputtering from a composite target. Contact resistivities of 1×10^{-17} and 2.8×10^{-6} were measured on n^+ and p^+ Si, respectively. These values remain constant after thermal treatment up to at least 500 C. A barrier height of 0 61 V was measured on n-type Si.

TITLE: Correlation of Solar Cell Electrical Properties with Material Characteristics of Silicon Cast by the Ubiquitous Crystallization Process
AUTHOR: S. Hyland, D. Leung, A. Morrison, K. Stika, and H. Yoo
CORPORATE AUTH: Jet Propulsion Laboratory; Applied Solar Energy Corp., City of Industry, California
PUBLICATION: Electrochemical Society, Journal (ISSN 0013-4651), vol. 130, June 1983, p. 1373-1376

ABSTRACT: Solar cells were fabricated using a conservative baseline process on 1-3 Omega-cm p type Si from ingots cast by the ubiquitous crystallization process. Conversion efficiencies of the cells were measured, as well as spectral response and minority carrier diffusion length. Adjacent slices from the same ingot were studied for their grain size, dislocation distribution, and impurity distribution. Cell performance was related to the observed structural features, as well as to the chemical structure of the ingot.

TITLE: Analysis of the Interaction of an Electron Beam With Back Surface Field Solar Cells
AUTHOR: O. Von Roos and K.L. Luke
CORPORATE AUTH: Jet Propulsion Laboratory; California State Univ., Long Beach, California
PUBLICATION: Journal of Applied Physics (ISSN 0021 8979), vol. 54, July 1983, p. 3938 3942

ABSTRACT: In this paper the short circuit current I_{sc} induced by the electron beam of a scanning electron microscope in a back surface field solar cell will be determined theoretically. It will be shown that, in a configuration used previously for solar cells with an ohmic back surface, the I_{sc} gives a convenient means for estimating the back surface recombination velocities and thus the quality of back surface field cells. Numerical data will be presented applicable to a point source model for the electron-hole pair generation.

TITLE: Contact Resistivity of TiN on p^+-Si and n^+-Si Measurement for Metal Contact Diffusion Barrier in Solar Cell
AUTHOR: M. Finetti, I. Suni, and M.-A. Nicolet
CORPORATE AUTH: California Institute of Technology, Pasadena, California; CNR, Laboratorio di Chimica e Tecnologia del Material, e Componenti per Electronica, Bologna, Italy; Technical Research Centre of Finland, Espoo, Finland
PUBLICATION: Solar Cells (ISSN 0379-6787), vol. 9, Aug. 1983, p. 179-183

ABSTRACT: The accuracy of the derived value of the contact resistivity of TiN on an n^+-Si solar cell was improved experimentally and compared with values for TiN on a p^+-Si solar cell. The TiN diffusion barrier was deposited on heavily doped cells by RF sputtering and a layer of silver was laid down over the TiN pad. Electrical measurements were performed on two different test patterns. The contact resistivities for the n and p cells were 0.000015 ohm sq cm and 0.00028 ohm-sq cm, respectively. The differences were attributed to the barrier height and the surface dopant concentation. The results indicate that the TiN barrier does not degrade in concentrator contigurations of up to 50 suns for the n-type material and up to 100 suns for the p-type material.

TITLE: Temperature-Dependent Ion Mixing and Diffusion During Sputtering of Thin Films of $CrSi_2$ on Silicon
AUTHOR: U. Shreter, M.-A. Nicolet, and R. Fernandez
CORPORATE AUTH: California Inst. of Tech., Pasadena, California; Jet Propulsion Laboratory
PUBLICATION: California Applied Physics Letters (ISSN 0003-6951), vol. 43, Aug. 1, 1983, p. 247-249

ABSTRACT: Measurements of sputtering yields and composition profiles have been carried out using backscattering spectrometry for samples of $CrSi_2$ on Si irradiated wth 200 keV Xe ions. When the $CrSi_2$ layer is thinner than the ion range, the sputtering yield ratio of Si to Cr increases from 3.5 for room temperature irradiation to 65 at 290 C. For a thick sample, the corresponding increase is from 2.4 to 4.0 only. These changes are explained in terms of a rise in the Si surface concentration ot 290 C. The driving force for this process seems to be the establishment of stoichiometric $CrSi_2$ compound. Transport of Si to the surface is by ion mixing in the thin sample and thermal diffusion through the thick layer.

TITLE: Silicon Material Technology Status Assessment for Electronic and Photovoltaic Applications
AUTHOR: R. Lutwack
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: IECEC '83; Proceedings of the Eighteenth Intersociety Energy Conversion Engineering Conference, Orlando, Florida, Aug. 21-26, 1983. Vol. 3 (A84-30102 13-20). New York, American Institute of Chemical Engineers, 1983, p. 1320-1324

ABSTRACT: Si has been the basic element for the electronic and PV industries. The use of Si as the primary element for terrestrial PV solar arrays is projected to continue. The reasons for this projection are related to the maturity of Si technology, the ready availability of extremely pure Si, the performance of Si solar cells, and the considerable present investment in technology and manufacturing facilities. The technologies for producing semiconductor grade Si and, to a lesser extent, refined metallurgical grade Si are considered. It is pointed out that nearly all of the semiconductor grade Si is produced by processes based on the Siemens deposition reactor, a technology developed 26 years ago. The state of the art for producing Si by this process is discussed. It is expected that efforts to reduce polysilicon process conts will continue.

TITLE: Sheet Silicon Cell/Module Technology
AUTHOR: A.D. Morrison
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: IECEC '83; Proceedings of the Eighteenth Intersociety Energy Conversion Engineering Conference, Orlando, Florida, Aug. 21-26, 1983. Vol. 3 (A84 30102 13-20). New York, American Institute of Chemical Engineers, 1983, p. 1325-1330

ABSTRACT: The cost involved in the performance of the standard operations for the manufacture of Si wafers is insignificant in the case of space PV applications. It is, however, a decisive factor with respect to terrestrial applications of silicon PV devices. In 1975, a program was, therefore, begun to develop low cost Si solar arrays for terrestrial applications. The goal was Si-based PV modules ready for installation at a selling price of $0.50/W (1975$). Sheet and ribbon Si growth held out the promise of reduced cost through continuous operation, high material throughput, high material utilization efficiency, and a product whose shape lent itself to the assembly of high packing density modules. Attention is given to ribbon growth technologies, sheet technology generic problems, and ribbon cell and module technology status. It is concluded that the potential for crystalline ribbon Si appears to be better today than ever before.

TITLE: An EBIC Equation for Solar Cells
AUTHOR: K.L. Luke and O. Von Roos
CORPORATE AUTH: California State Univ., Long Beach.; Jet Propulsion Laboratory
PUBLICATION: Solid-State Electronics (ISSN 0038-1101), vol. 26, Sept. 1983, p. 901-906

ABSTRACT: When an electron beam of a scanning electron microscope impinges on an n p junction, the generation of electron hole pairs by impact ionization causes a characteristic short circuit current I_{sc} to flow. The I(sc), i.e., EBIC depends strongly on the configuration used to investigate the cell's response. In this paper the case where the plane of the junction is perpendicular to the surface is considered. An EBIC equation amenable to numerical computations is derived as a function of cell thickness, source depth, surface recombination velocity, diffusion length, and distance of the junction to the beam cell interaction point for a cell with an ohmic contact at its back surface. It is shown that the EBIC equation presented here is more general and easier to use than those previously reported. The effects of source depth, ohmic contact, and diffusion length on the normalized EBIC characteristic are discussed.

TITLE: Flat-Plate Solar Array Progress and Plans
AUTHOR: W.T. Callaghan and P.K. Henry
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Fifth International Conference, Athens, Greece, Oct. 17-21, 1983 (A85 11301 02-44). Dordrecht, D. Reidel Publishing Co., 1984, p. 455 459

ABSTRACT: The FSA, sponsored by the DOE and managed by the JPL, has achieved progress in a broad range of technical activities since that reported at the Fourth European Communities Conference. A particularly important analysis has been completed recently which confirms the adoption into practice by the U.S. PV industry, of all the low cost module technology elements proposed at the 16th PIM for a $\$2.80/W_p$ (1980 U.S. Dollars) design approach in the fall of 1980. This work presents along with a projection, using the same techniques, for what is believed to be a very credible ribbon-based module design for less that $\$0.55/W_p$ (1980 U.S. Dollars). Other areas to be reported upon include low cost Si feedstock refinement; ribbon growth; process sequence development for cells; environmental isolation; engineering science investigations; and module testing progress.

TITLE: Fracture Behavior in Silicon
AUTHOR: M.H. Leipold and C.P. Chen
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Fifth International Conference, Athens, Greece, Oct. 17-21, 1983 (A85-11301 02-44). Dordrecht, D. Reidel Publishing Co., 1984, p 1014-1018

ABSTRACT: The fracture mechanics of crystalline Si are reviewed, together with known techniques for minimizing the occurences of fracture and/or their effects. The fracture toughness (Kic) of Si varies only 10 percent from cell-to-cell and standard values have been established for different types of crystalline Si cells. A critical flaw size of 10-100 microns has been identified, and also pertains to polycrystalline materials. Chemical polishing is known to double the value of Kic, while edge rounding has no effect. Internal stresses, particularly those caused during ribbon growth, do not exceed 10 percent of Kic. External stresses are imposed by the module hardware and the ambient environment. Multiple contacts reduce the effects of cell fracture and series-parallel wiring in modules in arrays ameliorates the effects of single-cell failures. During manufacturing, maintenance of quality control and removal of sheets displaying aberrations can, depending on the costs and the implementation of the array reliability features, result in arrays delivering any desired level of reliability.

TITLE: Advances in Large Area Polycrystalline Solar Cells
AUTHOR: G.J. Vendura, G. Johnson, and J.F. Hoelscher
CORPORATE AUTH: Pennsylvania State Univ., University Park, Pennsylvania; Solarex Corp., Rockville, Maryland
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Fifth International Conference, Athens, Greece, Oct. 17-21, 1983 (A85-11301 02-44). Dordrecht, D. Reidel Publishing Co., 1984, p. 1075-1084

ABSTRACT: Polycrystaline Si is presently routinely processed into low cost 10 cm by 10 cm solar cells. However, assuming minimal handling difficulties, only minor equipment modifications and no increase in processing complexity, the fabrication of even larger geometries would be economically advantageous. This investigation addressed the feasibility of developing 10 cm by 15 cm solar cells from research through pilot line production stages. The major thrust was to minimize costing by using existing production equipment and proven techniques wherever possible. Accordingly methods were developed to section larger substrates from existing cast ingots, a simple solar cell was designed and low cost processes implemented. After numerous preliminary experiments, pilot line production of 1500 cells was completed. Of these approximately 62% exhibited efficiencies greater than 7.0%, 53% were greater than 8.0% and 15% were greater than 9.0%. Based on this study, the regular production of 10 cm by 15 cm solar cells was determined to be both feasible and cost effective using existing processing methods.

TITLE: Mechanisms Limiting the Performance of Large Grain Polycrystalline Silicon Solar Cells
AUTHOR: J.S. Culik, P. Alexander, K.A. Dumas, and J.W. Wohlgemuth
CORPORATE AUTH: Solarex Corp., Rockville, Maryland.; Jet Propulsion Laboratory; Cabot Corp., Billerica, Massachusetts
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Fifth International Conference, Athens, Greece, Oct. 17-21, 1983 (A85-11301 02-44). Dordrecht, D. Reidel Publishing Co., 1984, p. 1090-1094

ABSTRACT: The open circuit voltage and short-circuit current of large grain (1 to 10 mm grain dia) polycrystalline Si solar cells is determined by the minority-carrier diffusion length within the bulk of the grains. This was demonstrated by irradiating polycrystalline and single crystal (Cz) Si solar cells with 1 MeV electrons to reduce their bulk lifetime. The variation of short-circuit current with minority-carrier diffusion length for the polycrystalline solar cells is identical to that of the single-crystal solar cells. The open-circuit voltage versus short-circuit current characteristic of the polycrystalline solar cells for reduced diffusion lengths is also identical to that of the single crystal solar cells. The open-circuit voltage of the polycrystalline solar cells is a strong function of quasi-neutral (bulk) recombination, and is reduced only slightly, if at all, by grain-boundary recombination.

TITLE: Investigation of Structural Defects Within Grain Volumes that Affect the Efficiency of Polycrystalline Silicon Solar Cell Materials
AUTHOR: K.C. Yoo, W.F. Regnault, S.M. Johnson, and G.M. Storti
CORPORATE AUTH: Solarex Corp., Rockville; Maryland, University, College Park, Maryland
MEETING LOCATION: Photovoltaic Solar Energy Conference; Proceedings of the Fifth International Conference, Athens, Greece, Oct. 17-21, 1983 (A85-11301 02-44). Dordrecht, D. Reidel Publishing Co., 1984, p. 77-84

ABSTRACT: The origin and character of subgrain boundaries generated within large grains of cast polycrystalline Si have been investigated using x-ray topography and electron beam induced current scanning techniques. It has been found that the subgrain structures originate at kinks in

high angle grain boundaries when the material is subjected to thermal stress. Further, whenever adjacent grains have a common rotation axis which satisfies the slip system in both grains, it is possible, under a suitable stress, to generate bundles of dislocations simultaneously in both grains. The resultant dislocations are electrically active and serve to decrease the effective minority carrier diffusion length. By controlling the thermal gradients in the Si bricks, the generation of subgrain boundaries can be minimized.

TITLE: Analysis of an Enhanced Photoresponse Observed at Subgrain Boundaries in Polysilicon Solar Cells
AUTHOR: H.C. Lin and S.M. Johnson
CORPORATE AUTH: University of Maryland, College Park, Maryland; Solarex Corp., Rockville, Maryland
PUBLICATION: IEEE Transactions on Electron Devices (ISSN 0018-9383), vol. ED-30, Oct. 1983, p. 1271-1273

ABSTRACT: In an earlier study (Johnson et al., 1982), an enhanced photoresponse was observed at dislocation-subgrain boundaries in a polysilicon solar cell. The subgrain boundaries were revealed by x-ray topography methods. The enhanced photoresponse was attributed to preferential diffusion along the subgrain boundaries relative to a distance significant with respect to the value of the minority-carrier diffusion length. Using a theoretical model of the carrier collection at the preferentially diffused boundaries, the wavelength dependence of the enhanced carrier collection is calculated. These results generally confirm the earlier experimentally derived model.

TITLE: A Study of Grown-In Impurities in Silicon by Deep Level Transient Spectroscopy
AUTHOR: A. Rohatgi, J.R. Davis, R.H. Hopkins, and P.G. McMullin
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
PUBLICATION: Solid-State Electronics (ISSN 0038-1101), vol. 26, Nov. 1983, p. 1039-1047

ABSTRACT: A description is given of the deep levels caused by various impurities incorporated in Cz silicon ingots during crystal growth. It is found that the largest impurity induced deep level concentration, defined as the electrically active impurity concentration, is a fraction of the metallurgical impurity content of the crystals. For a specific impurity, this fraction depends on the thermal history of the sample and on the ability of the impurity to diffuse. A decreasing electrically active impurity concentration toward the surface of a Si wafer results from the POCl3 gettering of Ti and V. However, there is no observable effect of this heat treatment on the Mo concentration. For Cr, which diffuses much more rapidly than Mo, Ti, or V in silicon, a very significant reduction in the electrically active concentration is seen after heat treatment. In similar fashion, the electrically active Mo concentration in metal-doped polysilicon wafers appears unaffected by grain boundaries; however, the electrically active Cr concentration at or near some grain boundaries is reduced by more than an order of magnitude compared with that at grain centers.

TITLE: Finite Metal-Sheet-Resistance in Contact Resistivity Measurements - Application to Si/TiN Contacts for Solar Cell Applications
AUTHOR: M. Finetti, I. Suni, and M.-A. Nicolet
CORPORATE AUTH: California Institute of Technology, Pasadena, California; CNR, Istituto di Chimica e Tecnologia dei Materiali e Componenti per Elettronica, Bologna, Italy; Technical Research Centre of Finland, Espoo, Finland
PUBLICATION: Solid-State Electronics (ISSN 0038-1101), vol. 26, Nov. 1983, p. 1065-1067

ABSTRACT: Because the finite sheet resistance of the TiN must be accounted for, the standard transmission line model cannot be applied to evaluate the contact resistivity of thin TiN layers on highly doped p+ and n+ substrates. Two ways are presented for including this effect using existing analytical models. It is shown that the results agree with measurements where the effect of the finite sheet resistance of TiN is eliminated with a metallic overlayer. Using these evaluation techniques, it is shown that the contact resistivity of TiN changes in opposite ways for p^+ and n^+ Si after vacuum annealing at 600 C for 15 min. It is pointed out that the result is consistent with an increase of the barrier height of the contact by approximately 0.1 V to near midgap value.

TITLE: Plastic Deformation of Silicon Dendritic Web Ribbons During the Growth
AUTHOR: L.J. Cheng, K.A. Dumas, B.M. Su, and M.H. Leipold
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Crystal Growth (ISSN 0022-0248), vol. 70, 1984, p. 314-318

ABSTRACT: The distribution of slip dislocations in Si dendritic web ribbons due to plastic deformation during the cooling phase of the growth was studied. The results show the existence of two distinguishable stress regions across the ribbon formed during the plastic deformation stage, namely, shear stress at the ribbon edges and tensile stress at the middle. In addition, slip dislocations caused by shear stress near the edges appear to originate at the twin plane.

TITLE: Electron-Beam Induced Current Characterization of Back Surface Field Solar Cells Using a Chopped Scanning Electron Microscope Beam
AUTHOR: K.L. Luke and L.-J. Cheng
CORPORATE AUTH: California State Univ. at Long Beach, California; Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics (ISSN 0021-8979), vol. 55, Jan. 15, 1984, p. 555-559

ABSTRACT: A chopped EBIC technique for the chacterization of BSF solar cells is presented. It is shown that the effective recombination velocity of the low-high junction forming the back surface field of BSF cells, in addition to the diffusion length and the surface recombination velocity of the surface perpendicular to both the p n and low high junctions, can be determined from the data provided by a single EBIC scan. The method for doing so is described and illustrated. Certain experimental considerations taken to enhance the quality of the EBIC data are also discussed.

TITLE: Stress Rate and Proof-Testing of Silicon Wafers
AUTHOR: C.P. Chen and M.H. Leipold
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: (American Ceramic Society, Annual Meeting, 85th, Chicago, Illinois, Apr. 26, 1984) American Ceramic Society, Communications (ISSN 0002-7820), vol. 68, Feb. 1985, p. C-54, C-55

ABSTRACT: Fracture mechanics test methods were applied to evaluate the proof-test characteristics of single-crystal Si wafers. The results indicate that the strength distribution of Si wafers is truncated by proof-testing. No subcritical crack growth occurred during proof-loading, as inferred from the lack of a stress-rate effect on strength. Mechanical proof-testing appears to be an effective method for eliminating weak samples before cell processing.

TITLE: Performance Improvements from Penetrating Back-Surface Field in a Very High Efficiency Terrestrial Thin-Film Crystalline Silicon Solar Cell
AUTHOR: C.T. Sah and F.A. Lindholm

CORPORATE AUTH: University of Illinois, Urbana, Illinois; University of Florida, Gainesville, Florida
PUBLICATION: Journal of Applied Physics (ISSN 0021-8979), vol. 55, Feb. 15, 1984, p. 1174-1182

ABSTRACT: Approximately 100 Si cells are analyzed, each having a different emitter or base dopant impurity distribution selected on the basis of physical anticipated improvements. Computations are made of the four principal performance parameters (open-circuit voltage, short-circuit current, fill factor, and maximum efficiency) using a program which numerically solves the six Shockley equations under AM1 solar illumination at 88.92 mW/sq cm and at an optimum cell thickness of 50 microns. It is found that significant improvements in performance can be effected by extending the back-surface-field layer thickness from 1 microns (18% efficiency) to 40 microns (20% efficiency). It is also found that the immunity of cell performance to recombination defect or impurity center is improved by a factor of 2 to 3 in the recombination center density. A 20-micron back-surface-field penetration is considered sufficient for 20% p^+-n-n^+ cells with a base lifetime of about 20 microsec.

TITLE: Large Area Silicon Sheet Technology Status in United States' Department of Energy Photovoltaics Programs
AUTHOR: R. Ferber, K. Shimada, and E. Costogue
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: International Journal of Solar Energy (ISSN 0142-5919), vol. 2, March 1984, p. 171-187

ABSTRACT: None.

TITLE: A Theoretical Study of the Effects of Interacting Grain Boundaries on Electron-Beam Induced Currents
AUTHOR: K.L. Luke and O. Von Roos
CORPORATE AUTH: California State Univ., Long Beach, California; Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics (ISSN 0021-8979), vol. 55, April 15, 1984, p. 2962-2966

ABSTRACT: The influence of several grain boundaries on the electron-beam induced current in polycrystalline Si is investigated. The simple geometry contemplated here, consisting of two plane parallel grain boundaries possessing different effective, albeit constant, surface recombination velocities, intersecting a planar junction at right angles allows for an exact solution of the corresponding boundary value problem. It is shown that if the distance between the grain boundaries w becomes less than the diffusion length for minority carriers L within the grain, the grain boundary with the smaller effective recombination velocity becomes less and less visible the smaller the ratio w/L.

TITLE: Stress Rate and Proof-Testing of Silicon Wafers
AUTHOR: C.P. Chen and M.H. Leipold
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: (American Ceramic Society, Annual Meeting, 85th, Chicago, Illinois, Apr. 26, 1984) American Ceramic Society, Communications (ISSN 0002-7820), vol. 68, Feb. 1985, p. C-54, C-55

ABSTRACT: Fracture mechanics test methods were applied to evaluate the proof-test characteristics of single-crystal Si wafers. The results indicate that the strength distribution of Si wafers is truncated by proof-testing. No subcritical crack growth occurred during proof-loading, as inferred from the lack of a stress-rate effect on strength. Mechanical proof-testing appears to be an effective method for eliminating weak samples before cell processing.

TITLE: Method for Calculating Multidimensional Electric Fields in Photovoltaic Modules
AUTHOR: J. Kallis, D. Trucker, E. Cuddihy, and A. Garcia, III
CORPORATE AUTH: Hughes Aircraft Co., El Segundo, California; Jet Propulsion Laboratory; Spectrolab, Inc., Sylmar, California
PUBLICATION: Solar Cells (ISSN 0379-6787), vol. 11, May 1984, p. 309-330

ABSTRACT: A finite element method for evaluating the electrical isolation characteristics of PV modules was developed, its accuracy was verified by comparison with an exact solution for a geometry similar to that of solar cells. Tests on a square test coupon, employed in electrical isolation tests, and a group of disc-shaped solar cells illustrated the finite element method's usefulness in evaluating module encapsulation designs. Finite element models had to avoid adjacent large and small elements and elements with large aspect ratios, and the NASTRAN output had to be curve fitted to calculate the maximum field. Geometric limits were indicated: cells with very sharp edges, and cells much thinner or thicker than the dielectric pottant layer.

TITLE: Electrical Characteristics of Amorphous Molybdenum-Nickel Contacts to Silicon
AUTHOR: K.T.-Y. Kung, M.-A. Nicolet, and I. Suni
CORPORATE AUTH: California Inst. of Tech., Pasadena, California; Technical Research Centre of Finland, Espoo
PUBLICATION: Journal of Applied Physics (ISSN 0021-8979), vol. 55, May 15, 1984, p. 3882-3885

ABSTRACT: The electrical characteristics of sputtered, amorphous Mo Ni contacts have been measured on both p- and n-type Si, as functions of composition (30, 54, and 58 at. percent Mo). The contact resistivity on both p^+ and n^+ Si is in the 0.00000 ohm sq cm range. The barrier height for as-deposited samples varies between phi-bp = 0.47-0.42 V on p type Si and between phi-bn = 0.63-0.68 V on n type Si, as the composition of the amorphous layer goes from Ni rich to Mo-rich. The sum phi-bp + phi-bn always equals 1.12 V, within experimental error. After thermal treatment at 500 C for 1/2 h, the contact resistivity changes by a factor of two or less, while the barrier height changes by at most approximately 0.05 V. In light of these results, the amorphous Mo-Ni film makes good ohmic contacts to Si.

TITLE: High Efficiency Ion-Implanted Silicon Solar Cells
AUTHOR: M.B. Spitzer, S.P. Tobin, and C.J. Keavney
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts
PUBLICATION: IEEE Transactions on Electron Devices (ISSN 0018-9383), vol. ED-31, May 1984, p. 546-550

ABSTRACT: The development of solar cells with AM1 conversion efficiency of 18 percent is reported. The cells comprise an n^+ p p^+ structure fabricated from FZ Si having resistivity of 0.3 ohm-cm. The n^+ and p^+ regions are formed by low energy ion implantation and thermal annealing. An important feature of cell fabrication is the growth of SiO_2 passivation for reduction of surface recombination velocity. Details of both cell fabrication and testing are reported.

TITLE: Unifying View of Transient Responses for Determining Lifetime and Surface Recombination Velocity in Silicon Diodes and Back-Surface-Field Solar Cells, With Application to Experimental Short-Circuit-Current Decay
AUTHOR: T.-W. Jung, F.A. Lindholm, and A. Neugroschel
CORPORATE AUTH: University of Florida, Gainesville, Florida
PUBLICATION: IEEE Transactions on Electron Devices (ISSN 0018-9383), vol. ED-31, May 1984, p. 588-595

ABSTRACT: None.

TITLE: I-V Characteristics and Performance of Silicon Solar Cells Between Low- and High-Level Injection. I - The Modeling Method
AUTHOR: M.A. Wolf and M. Wolf
CORPORATE AUTH: Wang Laboratories, Inc., Lowell, Massachusetts; University of Pennsylvania, Philadelphia, Pennsylvania
PUBLICATION: IEEE Transactions on Electron Devices (ISSN 0018-9383), vol. ED-31, May 1984, p. 684-689

ABSTRACT: A relatively simple computational method is reported for studying the operation of solar cells above low level injection. The method is a quasi-numerical extension to the original transport velocity transformation method, and is designed for the modelling of I-V characteristics. The carrier concentrations are approximated by segments of exponential functions, and the electrostatic fields and material parameters by piecewise constant functions. The method achieves good results while representing a cell by relatively few layers. The derivation of the model is shown, and the convergence algorithm and error analysis are discussed.

TITLE: Contact Resistance - Its Measurement and Relative Importance to Power Loss in a Solar Cell
AUTHOR: D.L. Meier and D.K. Schroder
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania; Arizona State University, Tempe, Arizona
PUBLICATION: IEEE Transactions on Electron Devices (ISSN 0018-9383), vol. ED-31, May 1984, p. 647-653

ABSTRACT: The concept of contact resistivity is discussed briefly and a technique for its measurement is presented. This technique allows for resistive contact material and for the possibility that the semiconductor sheet resistance beneath the contact differs from the semiconductor sheet resistance beside the contact. The test pattern is unique in that the effects of contact resistance are accumulated over the pattern, nearly unencumbered by voltage and current probes which might otherwise influence the current flow. Measurements of contact resistivities for typical solar cell metallizations using this technique are reported to be in the mid-10 to the -6th ohm-sq cm range. The relative importance of contact resistance compared to other sources of power loss in a solar cell is determined for a typical contact system. Expressions derived in order to make this comparison are useful for evaluating and optimizing a solar cell contact system. Values of series resistance calculated using these expressions are compared with measured values.

TITLE: Design, Fabrication, and Analysis of 17-18% Efficient Surface Passivated Silicon Solar Cells
AUTHOR: A. Rohatgi and P. Rai-Choudhury
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
PUBLICATION: IEEE Transactions on Electron Devices (ISSN 0018-9383), vol. ED-31, May 1984, p. 596-601

ABSTRACT: A simple analytical model has been developed which provides useful guidelines for fabricating high-efficiency Si solar cells. Consistent with the model calculations, both surfaces of n^+-p-p^+ solar cells were passivated by a thin layer of thermally grown SiO_2. Oxide passivation resulted in 17.2% efficient solar cells on 4 ohm-cm base material. Passivated cells show about 3 mA/sq cm increases in J_{sc}, about 20 mV improvement in V_{oc}, and about 2% increase in absolute cell efficiency compared to the counterpart 15.2% efficient unpassivated cells. The majority of improvement in V_{oc} came from the emitter surface passivation, while both front- and back surface passivation contributed to the increase in J_{sc}. The emitter region should not be regarded as a dead layer because emitter surface passivation can increase the quantum efficiency at short wavelengths from 40% to greater than 75%.

TITLE: Assessing Photovoltaic Module Life from Long Term Environmental Tests
AUTHOR: D.H. Otth and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Environmental Integration Technology Today for a Quality Tomorrow; Proceedings of the Thirtieth Annual Technical Meeting, Orlando, Florida, May 1-3, 1984 (A86-22176 08-38). Mount Prospect, Illinois, Institute of Environmental Sciences, 1984, p. 216-221

ABSTRACT: An assessment is made of results obtained by an experimental program having as its aim the identification of critical temperature humidity bias degradation mechanisms in solar cell modules intended to have an operating lifetime of the order of 20-30 years. These mechanisms are studied in the context of conditions encountered over the course of long term operation in various sites in the U.S. Accelerated tests for the assessment of product lifetime entail the development of a correlation between test and application conditions; this has been accomplished through an analytical procedure for the correlation of time varying field exposures to constant-stress accelerated environments.

TITLE: Effect of Localized Polycrystalline Silicon Properties on Solar Cell Performance
AUTHOR: D. Leung, P.A. Iles, S. Hyland, and A. Kachare
CORPORATE AUTH: Applied Solar Energy Corp., City of Industry, California; Jet Propulsion Laboratory
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 264-270

ABSTRACT: Several forms of polycrystalline Si, mostly from cast ingots, (including UCP, SILSO and HEM) were studied. On typical slices, localized properties were studied in two ways. Small area (about 2.5 sq mm) mesa diodes were formed, and localized PV properties were measured. Also a small area (about .015 sq mm) light spot was scanned across the cells; the light spot response was calibrated to measure local diffusion length directly. Using these methods, the effects of grain boundaries, or of intragrain imperfections were correlated with cell performance. Except for the fine grain portion of SILSO, grain boundaries played only a secondary role in determining cell performance. The major factor was intragrain material quality and it varied with position in ingots and probably related to solidification procedure.

TITLE: The Integration of Bypass Diodes with Terrestrial Photovoltaic Modules and Arrays
AUTHOR: N.F. Shepard and R.S. Sugimura
CORPORATE AUTH: General Electric Co., Philadelphia, Pennsylvania; Jet Propulsion Laboratory
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 676-681

ABSTRACT: Bypass diodes are often required to limit the potential for reverse voltage 'hot-spot' heating in high voltage arrays or in arrays that undergo periodic operation near the short-circuit point. In addition, when properly applied, bypass diodes can minimize the effect of shadowing and various internal module failures on the array energy output. This paper discusses the mechanical and electrical integration of bypass diodes beginning with the array-level considerations which influence the selection of an implementation approach. Concepts for the mounting of these diodes, both internally within the module encapsulant and externally to the exposed rear surface of the module, are described. Factors affecting the reliability of bypass diodes, including the control of junction temperature through adequate heat sinking and the derating of reverse voltage, are discussed.

TITLE: Electrical Isolation Design of Photovoltaic Modules
AUTHOR: J.M. Kallis, D.C. Trucker, R.K. Szeto, E.F. Cuddihy, and A. Garcia, III.
CORPORATE AUTH: Hughes Aircraft Co., El Segundo, California; Jet Propulsion Laboratory; Spectrolab, Inc., Sylmar, California
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 693-699

ABSTRACT: A method was developed for calculating the magnitude and location of the maximum electric field for a family of solar cell-like shapes. Simple formulas for use by photovoltaic module designers were developed. They provide quantitative information on the effects of the cell shape, cell thickness, and pottant thickness on the electrical stress intensification at the cell edge. A method for calculating the lines of force for three-dimensional electric fields was developed and applied to a geometry of interest to the PV program.

TITLE: Flat-Plate Solar Array Progress and Plans
AUTHOR: W.T. Callaghan
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 485-488

ABSTRACT: The results of research into the technology of flat plate solar arrays undertaken in the FSA Project under the sponsorship of DOE are surveyed. Topics examined include Si refinement, ribbon sheet substrate formation, module process sequences, environmental isolation, module engineering and testing, and PV array economics.

TITLE: Mechanical Proof Testing in Cell Processing
AUTHOR: C.P. Chen, M.H. Leipold, and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 1384, 1385

ABSTRACT: Fracture mechanics test methods are applied to evaluate the proof test characteristics of Si Cz wafers. The results indicate that the strength distribution of Si wafers is truncated by proof testing and no subcritical crack growth in Si is observed during proof loading. Mechanical proof testing appears to be an effective method to eliminate weak samples before cell processing.

TITLE: Determination of Hot-Spot Susceptibility of Multistring Photovoltaic Modules in a Central-Station Application
AUTHOR: C.C. Gonzalez, R.W. Weaver, R.G. Ross, Jr., R. Spencer, and J.C. Arnett
CORPORATE AUTH: Jet Propulsion Laboratory; Acurex Corp., Mountain View, California; ARCO Solar, Inc., Woodland Hills, California
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 668-675

ABSTRACT: Part of the effort of the JPL FSA includes a program to improve module and array reliability. A collaborative activity with industry dealing with the problem of hot-spot heating due to the shadowing of PV cells in modules and arrays containing several paralleled cell strings is described. The use of multiparallel strings in large central-station arrays introduces the likelihood of unequal current sharing and increased heating levels. Test results that relate power dissipated, current imbalance, cross-strapping frequency, and shadow configuration to hot-spot heating levels are presented. Recommendations for circuit design configurations appropriate to central station applications that reduce the risk of hot-spot problems are offered. Guidelines are provided for developing hot spot tests for arrays when current imbalance is a threat.

TITLE: Fluidized-Bed Silicon Deposition - Si Production via Silane Pyrolysis
AUTHOR: G. Hsu, A. Morrison, N. Rohatgi, R. Lutwack, and T. MacConnell
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 553-557

ABSTRACT: The growth of Si on seed particles from the pyrolysis of silane in a FBR was studied. The grown particles were shown to be crystalline and to have a structure which has been interpreted to indicate growth by chemical vapor deposition as well as by the collection (scavenging) of Si clusters on seed particle surfaces. Scanning electron microscopy was used to study the product morphology.

TITLE: Predicting Electrochemical Breakdown in Terrestrial Photovoltaic Modules
AUTHOR: G.R. Mon, R.G. Ross, Jr., G. Whitla, and J. Orehotsky
CORPORATE AUTH: Jet Propulsion Laboratory; Wilkes College, Wilkes Barre, Pennsylvania
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-36501 16-44). New York, Institute of Electrical and Electronics Engineers, 1984, p. 682-692

ABSTRACT: Electrochemical corrosion of PV cells can cause a cell to frame short circuit with two undesirable results: (1) catastrophic loss of source-circuit power; and (2) high field maintenance (module replacement) costs. Parameter dependencies are determined and encapsulated two-cell coupons are exposed to a range of voltage differences, temperatures, and relative humidities. Material relative performance is assessed. Nine different metallization-encapsulation combinations are tested.

TITLE: Technology Developments Toward 30-Year-Life of Photovoltaic Modules
AUTHOR: R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 464-472

ABSTRACT: As part of the United States National PV Program, the JPL FSA Project has maintained comprehensive reliability and engineering sciences activity addressed toward understanding the reliability attributes of terrestrial flat-plate PV arrays and to deriving analysis and design tools necessary to achieve module designs with a 30-yr useful life. The considerable progress to date stemming from the ongoing reliability research is discussed, and the major areas requiring continued research are highlighted. The result is an overview of the total array reliability problem and of available means of achieving high reliability at minimum cost.

TITLE: Flammability of Photovoltaic Modules
AUTHOR: R.S. Sugimura, D.H. Otth, R.G. Ross, Jr., K.J. Lewis, and J.C. Arnett
CORPORATE AUTH: Jet Propulsion Laboratory; ARCO Solar, Inc., Woodland Hills, California

MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 489-495

ABSTRACT: A series of Class B burning-brand tests were performed on experimental modules using high-temperature, back surface materials to develop the technology base required to construct fire-ratable modules. Results indicate the existence of synergistic relationships between hydrocarbon encapsulation materials and the experimental module configurations that provide increased fire resistance. These configurations use Kapton, fiberglass, neoprene rubber, stainless steel foil or aluminum foil as the back surface. Successful test results occur when the structural integrity of the module back surface is maintained. Test failures of these modules always occur for one of three reasons: the outermost back cover melts, rips, or is too porous. In each case flammable molten encapsulant, its gaseous byproducts, or both, penetrates the back surface of the module and bursts into flame. Future efforts to complete the technology base will concentrate on the spread-of-flame test, focusing on the more promising configurations identified in the initial series of tests.

TITLE: Backside Damage Gettering in Cast Polycrystalline Silicon
AUTHOR: J. Culik, S. Roncin, and P. Alexander
CORPORATE AUTH: Solarex Corp., Rockville, Maryland; Jet Propulsion Laboratory
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 259-263

ABSTRACT: The technique of backside-damage gettering improves the performance of short minority-carrier diffusion length, large-grain (grain diameter greater than 1 to 2 mm), cast polycrystalline Si. On average, increases of nearly 20 percent in short circuit current, 10 mV in open circuit voltage, and 15 percent in peak power were obtained by heat-treating 300 micron thick polycrystalline wafers at 1000 C in flowing nitrogen for 5 h. Additional measurements of the bulk and space charge recombination current components indicate that this improvement results from a significant increase in the minority-carrier diffusion length due to gettering of impurities from the bulk.

TITLE: Limiting Mechanisms in Large Grain Polycrystalline Silicon Spatial Homogeneity
AUTHOR: J. Culik and K. Grimes
CORPORATE AUTH: Solarex Corp., Rockville, Maryland
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 1137-1142

ABSTRACT: An experiment to investigate the spatial homogeneity of large grain polycrystalline Si shows a number of performance loss mechanisms. Arrays of up to 400 small (about 0.2 sq cm in area) photodiodes were fabricated on a selection of 10 cm x 10 cm polycrystalline Si wafers. Measurements of the illuminated current-voltage (J-V) characteristics were used to generate maps of V_{oc}, J_{sc}, and FF as a function of position; and dark J-V and LBIC analysis were used to determine the cause of low performance in areas with significantly degraded J-V characteristics. In addition to the presence of inclusions, which act as resistive shunts, the performance of many of the cells is limited by quasineutral recombination current, which may vary by up to an order of magnitude across a wafer. The increase is the result of either electrically-active grain boundaries or numerous subgrain boundaries within the grain bulk. In other isolated instances, the open-circuit voltage is reduced by excess space-charge recombination current that is not correlated with either grain or subgrain boundary activity.

TITLE: Mechanisms Limiting Open Circuit Voltage in Silicon Solar Cells
AUTHOR: M.B. Spitzer, C.J. Keavney, S.P. Tobin, F.A. Lindholm, and A. Neugroschel
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts; Florida, University, Gainesville, Florida
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 1218-1224

ABSTRACT: This paper reports the results of research on mechanisms limiting open circuit voltage in conventional p-n junction Si solar cells, with a view toward both the understanding of various heavy-doping effects and the achievement of high conversion efficiency. Experimental and theoretical studies have been conducted in order to correlate heavy-doping effects to actual solar cell performance. The experiments have utilized a variety of emitter configurations with various doping concentrations in order to emphasize a number of concentration-dependent mechanisms. The theoretical modeling addresses the determination of both recombination velocity at the passivated front surface and effects of recombination at the front ohmic contact.

TITLE: Ion Implanted Silicon Solar Cells with 18 Percent Conversion Efficiency
AUTHOR: M.B. Spitzer, C.J. Keavney, S.P. Tobin, and J.B. Milstein
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts; Solar Energy Research Institute, Golden, Colorado
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 398-402

ABSTRACT: The results of research on the basic understanding of high efficiency in Si solar cells are presented. It is shown that through the use of low resistivity silicon, texture-etching, ion implantation, surface passivation, and Ta_2O_5 antireflection coatings, very high performance can be obtained. Cells with 18 % AM1 conversion efficiency (100 mW/sq cm, 28 C) are reported, and research to increase the performance to much higher levels is described.

TITLE: Progress in Developing Ultrathin Solar Cell Blanket Technology
AUTHOR: R.E. Patterson, H.G. Mesch, and J. Scott-Monck
CORPORATE AUTH: TRW, Inc., Redondo Beach, California; Jet Propulsion Laboratory
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 320-325.

ABSTRACT: A program was conducted to develop technologies for welding interconnects to three types of 50-micron-thick, 2 by 2 cm solar cells. Parallel-gap resistance welding was used for interconnect attachment. Weld schedules were independently developed for each of the three cell types and were coincidentally identical. Six 48-cell modules were assembled with 50-micron (nominal) thick cells, frosted fused-silica covers, silver-plated Invar interconnectors, and four different substrate designs. Three modules (one for each cell type) have single-layer Kapton (50-micron-thick) substrates. The other three modules each have a different substrate (Kapton-Kevlar-Kapton, Kapton-graphite-Kapton, and Kapton-graphite-aluminum honeycomb-graphite). All six modules were subjected to 4112 thermal cycles from -175 to 65 C (corresponding to over 40 years of simulated geosynchronous orbit thermal cycling) and experienced only negligible electrical degradation (1.1 percent average of six 48-cell modules).

TITLE: Computer Modeling Results on All Si Cascade Solar Cells
AUTHOR: P.D. Sparks, F.G. Allen, and T. Daud
CORPORATE AUTH: University of California, Los Angeles, Los Angeles, California; Jet Propulsion Laboratory
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 726-728

ABSTRACT: The properties of a cascade solar cell made entirely of Si are investigated numerically with the goal of developing an optimal Si solar cell grown by molecular-beam epitaxy. The cascade cell is modeled as two standard back surface field cells with abrupt junctions connected by a tunnel junction. A cascade cell would have approximately twice the open-circuit voltage of a single cell. If the minority carriers generated in the front cell can be reflected before reaching the tunnel junction, then the cascade cell will show an increase in efficiency over a single cell by a percentage point.

TITLE: Lifetimes in Si CVD-Epitaxial and Other Layers Determined by Spectral LBIC
AUTHOR: M. Wolf, M. Newhouse, and R. Stirn
CORPORATE AUTH: University of Philadelphia, Pennsylvania; Jet Propulsion Laboratory
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 563-568

ABSTRACT: In an effort to evaluate the minority carrier lifetimes in CVD-epitaxially grown layers in their dependence on the CVD process variables, the absolute spectral LBIC method was found to be the only available method capable of yielding both lifetime and surface recombination velocity in layers, independent of the resistivity of this layer or that of the substrate, as long as they are separated by a pn junction. With this method, it was not only possible to determine the minority carrier lifetimes in as grown epi layers, but to observe their changes through the device fabrication processes. In addition, it was possible for the first time to determine the lifetimes in the alloy-regrowth p^+ layers of base high/low junction structures.

TITLE: High Efficiency Silicon MINP Solar Cells
AUTHOR: L.C. Olsen, F.W. Addis, W.A. Miller, and G. Dunham
CORPORATE AUTH: University of Washington, Joint Center for Graduate Study, Richland, Washington
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 403-408

ABSTRACT: Investigations of high-efficiency MINP Si solar cells are discussed. Emphasis is placed on cell characterization to develop a basic understanding of current-transport mechanisms which limit cell efficiency. Fabrication and characterization of cells based on 0.2 ohm-cm substrates, diffused emitters 150-200 nm deep, and with Mg MIS collector grids are discussed. A total-area AM1 efficiency of 16.8 percent has been achieved. Detailed analyses of photocurrent and current-loss mechanisms are presented and utilized to predict future directions of research.

TITLE: The Decisive Impact of Cell Efficiency on the Implementation of Photovoltaic Systems
AUTHOR: E.F. Federmann and A. Rohatgi
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 976-981

ABSTRACT: None.

TITLE: Emitter Formation in Dendritic Web Silicon Solar Cells
AUTHOR: D.L. Meier, A. Rohatgi, R.B. Campbell, P. Alexander, S.J. Fonash, and R. Singh
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania; Westinghouse Electric Corp., Pittsburgh, Pennsylvania; Jet Propulsion Laboratory; Pennsylvania State Univ., University Park, Pennsylvania
MEETING LOCATION: 17th IEEE Photovoltaic Specialists Conference, Kissimmee, Florida, May 1-4, 1984, Conference Record (A85-35601 16-44). New York, 1984, p. 427-433

ABSTRACT: The use of liquid dopants and liquid masks for p-n junction formation in dendritic web solar cells was investigated and found to be equivalent to the use of gaseous dopants and CVD SiO_2 masks previously used. This results in a projected cost reduction of 0.02 1980$/W for a 25 MW/y production line, and makes possible junction formation processes having a higher throughput than more conventional processes. The effect of a low-energy (0.4 keV) hydrogen ion implant on dendritic web solar cells was also investigated. Such an implant was observed to improve V_{oc} and J_{sc} substantially. Measurements of internal quantum efficiency suggest that it is the base of the cell, rather than the emitter, which benefits from the hydrogen implant. The diffusion length for electrons in the p type base increased from 53 microns to 150 microns in one case, with dendritic web cell efficiency being boosted to 15.2 percent. The mechanism by which low-energy hydrogen ions can penetrate deeply into the Si to effect the observed improvement is not known at this time.

TITLE: Photovoltaics - Where Are We Going?
AUTHOR: W.T. Callaghan
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Solar Cells (ISSN 0379-6787), vol. 12, June-July 1984, p. 37-40.

ABSTRACT: The directions that will be followed for solar cell development, production and marketing are projected on the basis of experiences gained during the JPL's FSA Project. It is thought that a billion dollar market for Si ribbons can be established by 1990. Thin film technology will yield a product at $2 U.S./W at the end of the 1980s. R&D is growing more focused on central station PV generators, although the residential market may be the more suitable goal. The intermediate markets, e.g., schools, hospitals and shopping centers may be developed before the central stations.

TITLE: Importance and Considerations of High Efficiency Solar Cells
AUTHOR: A. Rohatgi and E.F. Federmann
CORPORATE AUTH: Westinghouse Research and Development Center, Pittsburgh, Pennsylvania
PUBLICATION: Solar Cells (ISSN 0379-6787), vol. 12, June-July 1984, p. 177-183

ABSTRACT: The impact that solar cell efficiency improvements have on overall system cost is explored. Module costs for widespread use will be about $0.7/$W_p$, with 16% efficiency modules and 18% efficient cells. Experimental crystal cells currently reach that level and production materials will be available in 1990. Improvements in cell technology are needed to reduce cell defects, extend the carrier lifetimes, reduce cell thickness and improve anti-reflective coatings. In early commercialization stages, only half the module costs can be reduced through improvements in the cell performance alone. When production lines are set up, however, module processing will be nearly optimized and the majority of cost reductions will reside with cell efficiency upgrades.

TITLE: Influence of F and Cl on the Recrystallization of Ion-Implanted Amorphous Si
AUTHOR: I. Suni, U. Shreter, M.-A. Nicolet, and J.E. Baker
CORPORATE AUTH: California Institute of Technology, Pasadena, California; Technical Research Centre of Finland, Semiconductor Laboratory, Espoo, Finland; Illinois, University, Urbana, Illinois
PUBLICATION: Journal of Applied Physics (ISSN 0021-8979), vol. 56, July 15, 1984

ABSTRACT: The effect of fluorine and chlorine implantation on the solid phase epitaxial regrowth of amorphized 100 line type Si was studied in intrinsic and heavily boron-doped material. Annealings were performed at 500 and 600 C. Both F and Cl retard the regrowth rate at 500 C. The growth rates are much faster in B-doped than in undoped Si. Complete regrowth in B doped Si is obtained for all investigated doses of fluorine up to 5 x 10^{15}/sq cm at 600 C for 30 min. The same dose of chlorine stops the regrowth at this temperature.

TITLE: Field Funneling and Range Straggling in Partially Depleted Silicon Surface Barrier Detectors
AUTHOR: J.A. Zoutendyk and C.J. Malone
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: (IEEE, U.S. Defense Nuclear Agency, U.S. Department of Energy, and NASA, Annual Conference on Nuclear and Space Radiation Effects, 21st, Colorado Springs, Colorado, July 23-25, 1984) IEEE Transactions on Nuclear Science (ISSN 0018 9499), vol. NS-31, Dec. 1984, p. 1101-1105

ABSTRACT: The effects of field funneling and range straggling have been quantitatively observed in the measurement of charge collected from alpha-particle tracks in Si surface-barrier charged-particle detectors. The method described may be used for the straight-forward measurement of charge collection from heavy ions in these and other semiconductor devices.

TITLE: Recombination-active Defects in Silicon Ribbon and Polycrystalline Solar Cells
AUTHOR: L.J. Cheng
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Metallurgical Society of AIME, International Conference on Defects in Semiconductors, 13th, Coronado, California, August 12-17, 1984, Proceedings. Warrendale, Pennsylvania, Metallurgical Society of AIME, 1984, p. 03-409

ABSTRACT: This paper reports results from a study of recombination-active structural defects in Silicon ribbon and polycrystalline solar cells using the EBIC technique in a scanning electron microscope. It is demonstrated that low temperature EBIC measurements can reveal a range of defects that are not observable at room temperature, including slip dislocations in Si dendritic web ribbons as well as decorated twin boundaries and dislocation complexes in cast polycrystalline Si solar cell materials.

TITLE: Terrestrial Photovoltaic Collector Technology Trends
AUTHOR: K. Shimada and E. Costogue
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: IECEC '84: Advanced Energy Systems - Their Role in Our Future; Proceedings of the Nineteenth Intersociety Energy Conversion Engineering Conference, San Francisco, California, Aug. 19-24, 1984. Vol, 4 (A85-45351 22-44). La Grange Park, Illinois, American Nuclear Society, 1984, p. 2183-2189

ABSTRACT: Following the path of space PV collector development in its early stages, terrestrial PV technologies based upon single crystal silicon have matured rapidly. Currently, terrestrial PV cells with efficiencies approaching space cell efficiencies are being fabricated into modules at a fraction of the space PV module cost. New materials, including $CuInSe_2$ and a Si, are being developed for lowering the cost, and multijunction materials for achieving higher efficiency. Large grid-interactive, tracking flat plate power systems and concentrator PV systems totaling about 10 MW, are already in operation. Collector technology development both flat-plate and concentrator, will continue under an extensive government and private industry partnership.

TITLE: Status of High Efficiency Module Design and Fabrication of Solar Cells
AUTHOR: M.J. Nowlan and M.B. Spitzer
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts
MEETING LOCATION: IECEC '84: Advanced Energy Systems. Their Role in Our Future; Proceedings of the Nineteenth Intersociety Energy Conversion Engineering Conference, San Francisco, California, Aug. 19-24, 1984. Vol. 4 (A85-45351 22-44). La Grange Park, Illinois, American Nuclear Society, 1984, p. 2177-2182

ABSTRACT: The status of an ongoing DOE program to develop an AM1 photoelectric module with 15% conversion efficiency at normal heating temperatures, is reviewed. Emphasis is given to the efforts of a private company to develop a high efficiency module which also has high durability in normal operating conditions. The main design options considered are: high efficiency modules; large area modules; and optimized module fabrication techniques. The design of an automatic system for encapsulating module stacks is described.

TITLE: Discoloration of Poly(vinyl butyral) in Cells Exposed to Real and Simulated Solar Environments
AUTHOR: Q. Kim and A. Shumka
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Solar Cells (ISSN 0379-6787), vol. 12, Sept. 1984, p. 345-352

ABSTRACT: The discoloration of PVB films used in solar cell modules is described. Transmission absorption, Fourier transformation IR absorption and atomic absorption spectroscopy as well as scanning electron microscopy were used for this study. The discoloration of the PVB has been found to be affected by oxygen, moisture, temperature and light. However, the most severe discoloration observed is clearly associated with the migration of positive silver ions, which can be accelerated in the presence of electric fields. The metallization is the source of the silver, and the data are consistent with an interfacial reaction between the silver and PVB followed by transport into the polymer.

TITLE: Investigation of Liquid Dopants for the Production of High-Efficiency Solar Cells from Dendritic Web Silicon
AUTHOR: K.S. Tarneja, R.B. Campbell, and P. Alexander
CORPORATE AUTH: Westinghouse Electric Corp., Pittsburgh, Pennsylvania; Jet Propulsion Laboratory
PUBLICATION: Electrochemical Society, Journal (ISSN 0013-4651), vol. 131, Oct. 1984, p. 2438-2441

ABSTRACT: None.

TITLE: Solar-Cell Interconnect Design for Terrestrial Photovoltaic Modules
AUTHOR: G.R. Mon, D.M. Moore, and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory

PUBLICATION: ASME, Transactions, Journal of Solar Energy Engineering (ISSN 0199 7231), vol. 106, Nov. 1984, p. 379-386.

ABSTRACT: Useful solar cell interconnect reliability design and life prediction algorithms are presented, together with experimental data indicating that the classical strain cycle (fatigue) curve for the interconnect material does not account for the statistical scatter that is required in reliability predictions. This shortcoming is presently addressed by fitting a functional form to experimental cumulative interconnect failure rate data, which thereby yields statistical fatigue curves enabling not only the prediction of cumulative interconnect failures during the design life of an array field, but also the quantitative interpretation of data from accelerated thermal cycling tests. Optimal interconnect cost reliability design algorithms are also derived which may allow the minimization of energy cost over the design life of the array field.

TITLE: Quantification of the Effects of Generation Volume, Surface Recombination Velocity, and Diffusion Length on the Electron-Beam-Induced Current and Its Derivative Determination of Diffusion Lengths in the Low Micron and Submicron Ranges
AUTHOR: K.L. Luke, O. Von Roos, and L. J. Cheng
CORPORATE AUTH: California State Univ., Long Beach, California; Jet Propulsion Laboratory,
PUBLICATION: Journal of Applied Physics (ISSN 0021-8979), vol. 57, March 15, 1985, p. 1978-1984

ABSTRACT: A systematic and quantitative analysis is carried out to investigate the effects of the shape (point, cube, Gaussian) and size of the generation volume, the surface recombination velocity, and the diffusion length on the EBIC and its derivative (DEIC). Thick homogeneously doped samples exhibiting diffusion lengths in the low micron and submicron range are considered. The results are presented in computed EBIC curves as a function of scanning distance and of the ratio true diffusion length/effective diffusion length. Shown using these curves are: (1) a simple and yet rigorous method for the determination of the true diffusion length, taking into consideration all of the factors cited above, (2) a method for the rapid determination of the surface recombination velocity, (3) the condition under which the source shape becomes insignificant, and (4) a new value for the lower limit of the diffusion length which can be determined by the EBIC technique.

TITLE: Lattice Defects within Grain Volumes that Affect the Electrical Quality of Cast Polycrystalline Silicon Solar-Cell Materials
AUTHOR: K.C. Yoo, S.M. Johnson, and W.F. Regnault
CORPORATE AUTH: Maryland, University, College Park, Maryland; Solarex Corp., Rockville, Maryland
PUBLICATION: Journal of Applied Physics (ISSN 0021-8979), vol. 57, March 15, 1985, p. 2258-2266

ABSTRACT: None.

TITLE: Characteristics and Performance of Silicon Solar Cells Between Low- and High-Level Injection. II - Results of the study
AUTHOR: M.A. Wolf and M. Wolf
CORPORATE AUTH: Cadmus Computer Systems, Inc., Lowell, Massachusetts; University of Pennsylvania, Philadelphia, Pennsylvania
PUBLICATION: IEEE Transactions on Electron Devices (ISSN 0018-9383), vol. ED-32, April 1985, p. 800-806.

ABSTRACT: The I-V characteristics of three typical solar-cell structures have been computed by making use of the extended transport velocity transformation method described by Wolf and Wolf (1984). The considered terminal voltages cover a range of injection levels, including levels for which the usual low level assumption is valid and levels for which the usual high-level assumption is satisfied. Attention is given to a structure having a wide base with uniform moderately high doping, a structure having a narrow base with uniform low doping, a structure having a base region including a high low junction, a comparison of the effects of the different cell structures, and solar cell performance studies.

TITLE: Sputtered W-N Diffusion Barriers
AUTHOR: H.P. Kattelus, E. Kolawa, K. Affolter, and M.-A. Nicolet
CORPORATE AUTH: California Inst. of Tech., Pasadena, California
PUBLICATION: (American Vacuum Society, American Society for Metals, International Union for Vacuum Sciences, Techniques, and Applications, et al., International Conference on Metallurgical Coatings, 12th, Los Angeles, California, Apr. 15-19, 1985) Journal of Vacuum Science and Technology A (ISSN 0734 2101), vol. 3, Nov.-Dec. 1985, p. 2246-2254

ABSTRACT: The thermal stability of reactively sputtered tungsten nitrogen alloy thin films is investigated for the application as diffusion barriers in Si contact metallizations. The composition of W-N barriers is varied over a wide range including pure W. Aluminum, gold, and silver are used as low resistivity overlayers. Metallurgical interactions at temperatures ranging from 500 to 900 C are studied. Incorporating nitrogen into tungsten advantageously stabilizes all three systems. The overall failure takes place rapidly above critical temperatures that depend on both the metal overlayer and the microstructure of the barrier. In some cases, W-N alloys can effectively prevent interdiffusion at temperatures as high as 800 C for 30 min.

TITLE: Development of Design Criteria and Qualification Tests for Bypass Diodes in Photovoltaic Applications
AUTHOR: D.H. Otth, R.S. Sugimura, and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Institute of Environmental Sciences, Annual Technical Meeting, 31st, Las Vegas, Nevada, April 30-May 2, 1985, Proceedings (A86-23001 09-38). Mount Prospect, Illinois, 1985, p. 242-248

ABSTRACT: Design criteria have been developed for bypass diodes in p-n and Schottky barrier in PV applications. A test method for assessing conformity to the design criteria is described. Junction temperatures are defined in terms of expected worst-case field conditions, including ambient temperature and solar irradiance on the PV module. The rating criteria address the maximum allowable current and heat sink characteristics of diodes mounted inside or outside the PV module. The method establishes worst-case module to diode thermal interfaces and may be adapted for laboratory or field-site experiments. A list of the design criteria is given.

TITLE: Development and Testing of Advanced Fire-Resistant Photovoltaic Modules
AUTHOR: R.S.Sugimura, D.H. Otth, and R.G. Ross, Jr.
CORPORATE AUTH: Jet Propulsion Laboratory
MEETING LOCATION: Institute of Environmental Sciences, Annual Technical Meeting, 31st, Las Vegas, Nevada, April 30-May 2, 1985, Proceedings (A86-23001 09-38). Mount Prospect, Illinois, 1985, p. 337-343

ABSTRACT: The evaluation of back surface materials flammability in order to identify fire resistant module designs is examined. The fire test apparatus, burning-brand test sequence, and spread of-flame test sequence are described. Video recordings and time temperature profiles of module back surfaces are utilized to study the flammability failure mechanism and identify high-temperature materials. A table of flammability test results for various module designs is provided. The data reveals that 2-mil kapton, fiberglass cloth coated or impregnated with a material to plug pores, and metal foil back-surface materials achieve class A and B fire-resistance levels, and are applicable for PV module designs.

TITLE: Effect of Recombination on the Open-Circuit Voltage of a Silicon Solar Cell
AUTHOR: O. Von Roos and P.T. Landsberg
CORPORATE AUTH: Jet Propulsion Laboratory; Southampton Univ. (England)
PUBLICATION: Journal of Applied Physics (ISSN 0021-8979), vol. 57, May 15, 1985, p. 4746-4751

ABSTRACT: A theoretical study of the influence of band-band Auger, band trap Auger, and the ordinary Shockley-Read Hall mechanism for carrier recombination on the V_{oc} of a solar cell is presented. Under reasonable assumptions for the magnitude of rate constants and realistic values for trap densities, surface recombination velocities and band gap narrowing, the maximum V_{oc} for typical back surface field solar cells is found to lie in the range between 0.61 and 0.72 V independent of base width.

TITLE: Trap Controlled Minority-Carrier Mobility in Heavily Doped Silicon
AUTHOR: A. Neugroschel, F.A. Lindholm, and C.T. Sah
CORPORATE AUTH: University of Florida, Gainesville, Florida; University of Illinois, Urbana, Illinois
PUBLICATION: Solar Cells (ISSN 0378-6787) vol. 14, July 1985, p. 211-217

ABSTRACT: The activation behavior of the minority-carrier mobility and diffusivity in heavily doped (about 10^{20}/cu cm) Si(Si:As) was investigated in the temperature range, 20 to 350K. Experimental results indicate that hole transitions between the valence band and localized shallow states give rise to the observed behavior. The activation energy is about 10 MeV, which suggests that the localized states originate from band tails but does not rule out trapping at boron atoms in the compensated n^+ region.

TITLE: Heavily Doped Polysilicon-Contact Solar Cells
AUTHOR: F.A. Lindholm, A. Neugroschel, M. Arienzo, and P.A. Iles
CORPORATE AUTH: University of Florida, Gainesville, Florida; IBM Watson Research Center, Yorktown Heights, New York; Applied Solar Energy Corp., City of Industry, California
PUBLICATION: IEEE Electron Device Letters (ISSN 0741-3106), vol. EDL-6, July 1985, p. 363-365

ABSTRACT: The first use of a (Si)/heavily doped polysilicon)/(metal) structure to replace the conventional high-low junction or BSF structure of Si solar cells is reported. Compared with BSF and back-ohmic contact (BOC) control samples, the polysilicon back solar cells show improvements in red spectral response (RSR) and open-circuit voltage. Measurement reveals that a decrease in effective surface recombination velocity S is responsible for this improvement. Decreased S results for n-type (Si:As) polysilicon, consistent with past findings for bipolar transistors, and for p-type (Si:B) polysilicon, reported here for the first time. Though the present polysilicon-back solar cells are far from optimal, the results suggest a new class of designs for high efficiency Si solar cells. Detailed technical reasons are advanced to support this view.

TITLE: Microhardness of Carbon Doped (111) p-type Czochralski Silicon
AUTHOR: S. Danyluk, D.S. Lim, and J. Kalejs
CORPORATE AUTH: Chicago Univ., Chicago, Illinois; Mobil Solar Energy Corp., Waltham, Massachusetts
PUBLICATION: Journal of Materials Science Letters (ISSN 0261-8028), vol. 4, Sept. 1985, p. 1135-1137

ABSTRACT: The effect of carbon on (111) p-type Cz Si is examined. The preparation of the Si and microhardness test procedures are described, and the equation used to determine microhardness from indentations in the Si wafers is presented. The results indicate that as the carbon concentration in the Si increases the microhardness increases. The linear increase in microhardness is the result of carbon hindering dislocation motion, and the effect of temperature on Si deformation and dislocation mobility is explained. The measured microhardness was compared with an analysis which is based on dislocation pinning by carbon; a good correlation was observed. The Labusch model for the effect of pinning sites on dislocation motion is given.

TITLE: Attainment of Transparent Boron-Implanted Layers for Silicon Solar Cell Applications
AUTHOR: M.B. Spitzer and C.J. Keavney
CORPORATE AUTH: Spire Corp., Bedford, Massachusetts
PUBLICATION: Applied Physics Letters (ISSN 0003-6951), vol. 47, Oct. 1, 1985, p. 731, 732

ABSTRACT: The formation of boron-doped p^+ layers that are transparent to minority-carrier transport is reported. Ion implantation is used to limit the peak dopant concentration to 5 x 10^{18}/cu cm so as to avoid deleterious heavy doping effects. Solar cell open circuit voltage of 657 mV has been obtained in this way. The importance of surface passivation is indicated.

TITLE: Circuit Analysis Method for Thin-Film Solar Cell Modules
AUTHOR: D.R. Burger
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Solar Cells (ISSN 0379-6787), vol. 15, Dec. 1985, p. 343-351

ABSTRACT: The design of a thin-film solar cell module is dependent on the probability of occurrence of pinhole shunt defects. Using known or assumed defect density data, dichotomous population statistics can be used to calculate the number of defects expected in a module. Probability theory is then used to assign the defective cells to individual strings in a selected series-parallel circuit design. Iterative numerical calculation is used to calcuate I-V curves using cell test values or assumed defective cell values as inputs. Good and shunted cell I-V curves are added to determine the module output power and I-V curve. Different levels of shunt resistance can be selected to model different defect levels.

TITLE: Direct Experimental Determination of Voltage Across High-Low Junctions
AUTHOR: T. Daud and F.A. Lindholm
CORPORATE AUTH: Jet Propulsion Laboratory; Florida Univ., Gainesville, Florida
PUBLICATION: Journal of Applied Physics (ISSN 0021-8979), vol. 59, Jan. 1, 1986, p. 285-287

ABSTRACT: High-low (HL) junctions form a part of many semiconductor devices, including back surface field solar cells. A first experimental determination and interpretation of the voltage across the HL junction under low- and high-injection conditions is presented as a function of the voltage across a nearby p/n junction. Theoretical analysis from first principles is shown to bear well on the experimental results. In addition, a test structure is proposed for measurement of the effective surface recombination velocity at the HL junctions.

TITLE: Dot Junction Solar Cells
AUTHOR: T. Daud and G.T. Crotty
CORPORATE AUTH: Jet Propulsion Laboratory
PUBLICATION: Journal of Applied Physics (ISSN 0021-8979), vol. 59, April 1, 1986, p. 2566-2570

ABSTRACT: A design of solar cells with reduced junction area on the cell surface is investigated for reduction of saturation current and increase in open-circuit voltage. Equidiameter dot junctions distributed across the surface of the cell offer an efficient alternative, with variations in dot diameter and in the spacing between dots giving the required variations in the ratio of junction area to total surface area. A simplified analysis for short-circuit current and other cell parameters, which enables cell design optimization, is presented. Experimental solar-cell performance results, as functions of different area ratios, are presented and compared with the model. It is shown that saturation current reduction is possible for achieving efficiencies as high as 18 % in flat-plate terrestrial applications.

APPENDIX A

LIST OF FSA CONTRACTORS

AEROCHEM RESEARCH LABORATORIES, INC.	Synthesis of Silane and Silicon in a Non-equilibrium Plasma Jet CONTRACT: 954560
AEROCHEM RESEARCH LABORATORIES, INC.	Silicon Halide-Alkali Metal Flames as a Source of Solar Grade Silicon CONTRACT: 954777
AEROCHEM RESEARCH LABORATORIES, INC.	Development of Model and Computer Code for Silicon Reaction CONTRACT: 954862
AEROCHEM RESEARCH LABORATORIES, INC.	Development of Processes for the Production of Solar Grade Silicon from Silicon Halides and Alkali Metals CONTRACT: 955491
AIA RESEARCH CORP.	Integrated Residential Photovoltaic Development CONTRACT: 955893
APPLIED SOLAR ENERGY CORP. (OPTICAL COATING LABORATORY, INC.)	Assessment of Present State-of-the-art Sawing of Large Diameter Ingots for Solar Sheet Material CONTRACT: 954830
APPLIED SOLAR ENERGY CORP. (OPTICAL COATING LABORATORY, INC.)	High-Efficiency, Long-Life Terrestrial Solar Panel CONTRACT: 954831
APPLIED SOLAR ENERGY CORP.	Silicon Solar Cell Process Development, Fabrication and Analysis CONTRACT: 955089
APPLIED SOLAR ENERGY CORP. (OPTICAL COATING LABORATORY, INC.)	Evaluation of Ion-Implanted Silicon Solar Cells CONTRACT: 955118
APPLIED SOLAR ENERGY CORP.	Development of High-Efficiency (14%) Solar Cell Array Module CONTRACT: 955217
APPLIED SOLAR ENERGY CORP.	Development of Low-Cost Contacts to Silicon Solar Cells CONTRACT: 955244
APPLIED SOLAR ENERGY CORP.	Design, Fabrication, Test and Price Analysis of "Third Generation" Design Solar Cell Modules CONTRACT: 955409

APPLIED SOLAR ENERGY CORP.	Laboratory Services to the Low-Cost Solar Project Production Process and Equipment Area CONTRACT: 955423
APPLIED SOLAR ENERGY CORP.	Intermediate Load Modules for Test and Evaluation CONTRACT: 956350
APPLIED SOLAR ENERGY CORP.	Microcrystalline Silicon Growth for Heterojunction for Solar Cells CONTRACT: 956369
APPLIED SOLAR ENERGY CORP.	Development of High-Efficiency Solar Cells CONTRACT: 957098
ARCO SOLAR, INC.	Solar Cell Panel Development Effort CONTRACT: 954751
ARCO SOLAR, INC.	Automated Solar Panel Assembly Line CONTRACT: 955278
ARCO SOLAR, INC.	Vacuum Die Cast of Silicon Sheet for Photovoltaic Applications CONTRACT: 955325
ARCO SOLAR, INC.	Design, Fabricate, Test, Qualification and Price Analysis of "Third Generation" Design Solar Cell Modules CONTRACT: 955402
ARCO SOLAR, INC.	Design of Block V Solar Cell Modules 1981 CONTRACT: 956097
ARCO SOLAR, INC.	Block V Documentation and Solar Cell Modules CONTRACT: 956336
ARCO SOLAR, INC.	Adapt Pulsed Excimer Laser Processing Technology to Fabricate Cost-Effective Solar Cells CONTRACT: 956831
ARIZONA STATE UNIVERSITY	Evaluation/Calibration of a Czochralski (Cz) Crystal Growth System CONTRACT: 956876
ASTROSYSTEMS, INC.	Silicon Film Solar Cell Process CONTRACT: 956769
BATTELLE MEMORIAL INSTITUTE, COLUMBUS LABORATORIES	Module Encapsulation Task of Low-Cost Silicon Solar Array Project CONTRACT: 954328

BATTELLE MEMORIAL INSTITUTE, COLUMBUS LABORATORIES	Part 1-Evaluation of Silicon Production Suitable for Solar Cells CONTRACT: 954339
BATTELLE MEMORIAL INSTITUTE, COLUMBUS LABORATORIES	Study Program to Develop and Evaluate Die and Container Materials CONTRACT: 954876
BATTELLE MEMORIAL INSTITUTE, COLUMBUS LABORATORIES	Study Program to Develop & Evaluate Die & Container Materials CONTRACT: 955582
BECHTEL NATIONAL, INC.	Development of Requirements for Terrestrial Solar Arrays CONTRACT: 954698
BECHTEL NATIONAL, INC.	Terrestrial Central Power Utility Array Life-Cycle Analysis CONTRACT: 954848
BERND ROSS ASSOCIATES	Economical Improved Thick Film Solar Cell Contact CONTRACT: 955164
BERND ROSS ASSOCIATES	Development of an All Metal Thick Film Cost Effective Metallization System for Solar Cells CONTRACT: 955688
BURT HILL KOSAR RITTELMANN ASSOC.	Residential Photovoltaic Modules Requirements Study CONTRACT: 955149
BURT HILL KOSAR RITTELMANN ASSOC.	Commercial/Industrial Photovoltaic Modules Requirements Study CONTRACT: 955698
BURT HILL KOSAR RITTELMANN ASSOC.	Operation & Maintenance Cost Data for Residential Photovoltaic Modules/Panels CONTRACT: 955614
C.T. SAH ASSOCIATES	A Study of Effects of Impurities in Silicon Material CONTRACT: 954685
C.T. SAH ASSOCIATES	Conduct a Study of Relationships of Material Properties and High Efficiency Solar Cell Performance on Material Composition CONTRACT: 956289
CARNEGIE-MELLON UNIVERSITY	An Exploratory Study of Product Safety and Product Liability Considerations for Photovoltaic Module/Array Devices CONTRACT: 955846

CASE WESTERN RESERVE UNIVERSITY	Encapsulation System Studies for Low Cost Silicon Solar Array CONTRACT: 954738
CHRONAR CORP.	Amorphous Silicon Module Research CONTRACT: 957297
CLEMSON UNIVERSITY	Investigation of Reliability Attributes and Accelerated Stress Factors on Terrestrial Solar Cells CONTRACT: 954929
COORS PORCELAIN CO.	Study Program to Develop and Evaluate Substrate and Container Materials CONTRACT: 954878
CORNELL UNIVERSITY	Characterization of Structural, Electrical and Chemical Properties of Silicon Sheet Material Produced Under the Large Area Silicon Sheet Task of the Low Cost Silicon Solar Array Project CONTRACT: 954852
CORNELL UNIVERSITY	Investigation of Physical Structure and the Chemical Nature of Defects in the Silicon Sheet Material Developed by the LSA Project CONTRACT: 956046
CRYSTAL SYSTEMS, INC.	Heat Exchanger-Ingot Casting/Slicing Process, Silicon Sheet Growth Development for the Large Area Silicon Sheet Task of the Low-Cost Silicon Solar Array Project CONTRACT: 954373
CRYSTAL SYSTEMS INC.	Multi-Wire Wafering Technology Development by a Fixed Abrasive Slicing Technique (FAST) CONTRACT: 956073
DOW CORNING CORP.	Task I - Silicon Material Part 3 CONTRACT: 954559
DOW CORNING CORP.	Develop Silicon Encapsulation Systems for Terrestrial Silicon Solar Arrays CONTRACT: 954995
EAGLE-PICHER INDUSTRIES, INC.	Study Program to Develop and Evaluate Die and Container Material CONTRACT: 954877

ELECTRINK, INC.	Laboratory Services for the Development and Characterization of Screenable Materials Utilized in the Fabrication of Solar Cells CONTRACT: 956985
ENDUREX CORP.	Solar Cell Module Ion-Plating Process and Testing CONTRACT: 954728
ENERGY MATERIALS CORP.	Gaseous Melt Replenishment System CONTRACT: 955269
ENERGY MATERIALS CORP.	Low-Angle Silicon Sheet Growth CONTRACT: 955378
ENERGY MATERIALS CORP.	Electrochemical Production of Silicon CONTRACT: 956553
ENERGY MATERIALS CORP.	Technology Development for Low-Angle Silicon Sheet (LASS) Growth Technique for Photovoltaic Applications CONTRACT: 956822
GENERAL ELECTRIC CO.	Floating Substrate Sheet Growth Process, Silicon Sheet Growth Development for the Large Area Silicon Sheet Task of the Low Cost Silicon Solar Array Project CONTRACT: 954350
GENERAL ELECTRIC CO.	Development and Testing of Shingle-Type Solar Cell Modules CONTRACT: 954607
GENERAL ELECTRIC CO.	Design, Fabrication, Test, Qualification and Price Analysis of "Third Generation" Design Solar Cell Modules CONTRACT: 955401
GENERAL ELECTRIC CO.	Integrated Residential Photovoltaic Array Development CONTRACT: 955894
GENERAL ELECTRIC CO.	Design of Block V Solar Cell Module 1981 CONTRACT: 956098
GENERAL ELECTRIC CO.	Research Associated with Requirements for the Encapsulation of Protective Bypass Diode Diode Chips in Photovoltaic Modules with Current Ratings from 2 to 20 amps CONTRACT: 956254
GNOSTIC CONCEPTS	Industrialization Study CONTRACT: 954899

HEMLOCK SEMICONDUCTOR CORP.	Development of a Polysilicon Process Based on Chemical Vapor Deposition CONTRACT: 955533
HONEYWELL, INC.	Dip Coating Process, Silicon Sheet Growth Development for the Large Area Silicon Sheet Task of the Low Cost Silicon Solar Array Project CONTRACT: 954356
IBM CORP.	Silicon Ribbon Growth Using a Capillary Action Shaping Technique CONTRACT: 954144
IIT RESEARCH INSTITUTE	Technical Support in Reliability Engineering of Photovoltaic Modules CONTRACT: 955720
ILLINOIS TOOL WORKS, INC.	Demonstration of Capability to Deposit Anti-Reflective (AR) Coatings by Ion-Plating CONTRACT: 955506
J.C. SCHUMACHER CO.	High Velocity Continuous-Flow Reactor for Production of Solar Grade Silicon, Under the Low Cost Silicon Solar Array Project CONTRACT: 954914
KAYEX CORP.	Development of Advanced Methods for Continuous Czochralski Growth, Silicon Sheet Growth Development for the Large Area Silicon Sheet Task of the Low Cost Silicon Solar Array Project CONTRACT: 954888
KAYEX CORP.	Low-Cost Czochralski Crystal Growing Technology CONTRACT: 955270
KAYEX CORP.	Development of an Advanced Czozhralski Growth Process to Produce Low-Cost 150 Kg Silicon Ingots from a Single Crucible Technology Readiness CONTRACT: 955733
KINETIC COATING, INC.	Phase 2 of the Array Automated Assembly Task for the Low-Cost Silicon Solar Array Project CONTRACT: 955079
KULICKE AND SOFFA INDUSTRIES, INC.	Automated Solar Module Assembly Line CONTRACT: 955287

LAMAR UNIVERSITY	Process Feasibility Study in Support of Silicon Material, Task I CONTRACT: 954343
LOCKHEED MISSILES & SPACE CO., INC.	Spraylon Fluorocarbon Encapsulation for Silicon Solar Cell Arrays CONTRACT: 954410
LOCKHEED MISSILES & SPACE CO., INC.	Transparent Solar Cell Module Development Effort CONTRACT: 954653
LOCKHEED MISSILES & SPACE CO., INC.	Phase 2 of the Array Automated Assembly Task for the Low Cost Silicon Solar Array Project CONTRACT: 954898
LOCKHEED MISSILES & SPACE CO., INC.	Evaluation of Laser Annealing of Solar Cells CONTRACT: 955696
MASSACHUSETTS INSTITUTE OF TECHNOLOGY	Investigation of the Hydrogenation of $SiCl_4$ CONTRACT: 955382
MASSACHUSETTS INSTITUTE OF TECHNOLOGY	Study and Analysis of High-Speed Growth of Silicon Sheet in Inclined Meniscus Configurations CONTRACT: 956919
MATERIALS RESEARCH, INC.	Analysis of Defect Structure in Silicon CONTRACT: 956406
MATERIALS RESEARCH, INC.	Quantitative Analysis of Defects in Silicon CONTRACT: 954977
MATERIALS RESEARCH, INC.	Analysis of Defect Structure in Silicon CONTRACT: 955676
MOBIL SOLAR ENERGY CORP. (TYCO LABORATORIES, INC.)	Thick Film Silicon Growth Techniques CONTRACT: 953365
MOBIL SOLAR ENERGY CORP. (MOBIL TYCO SOLAR ENERGY CORP.)	Edge-Defined Film-Fed Growth (EFG) Process for Silicon Sheet Growth Development for the Large Area Silicon Sheet Task of the Low Cost Silicon Solar Array Project CONTRACT: 954355
MOBIL SOLAR ENERGY CORP. (MOBIL TYCO SOLAR ENERGY CORP.)	Solar Modules CONTRACT: 954999
MOBIL SOLAR ENERGY CORP. (MOBIL TYCO SOLAR ENERGY CORP.)	Design of Block V Solar Cell Modules 1981 CONTRACT: 956099

MOBIL SOLAR ENERGY CORP.	Crystal Growth by Edge-Defined Film-Fed Growth Technique (EFG) CONTRACT: 956312
MOBIL SOLAR ENERGY CORP.	Block V Documentation and Solar Cell Modules CONTRACT: 956335
MONSANTO RESEARCH CORP.	Silicon Material Task of the Low-Cost Silicon Solar Array Project, Part 2 CONTRACT: 954338
MOTOROLA, INC.	Phase I of the Automated Array Assembly Task of the Low Cost Silicon Solar Array Project CONTRACT: 954363
MOTOROLA, INC.	Laser-Zone Growth in a Ribbon-to-Ribbon (RTR) Process, Silicon Sheet Growth Development for the Large Area Silicon Sheet Task of the Low Cost Silicon Solar Array Project CONTRACT: 954376
MOTOROLA, INC.	Silicon Material Task Low Cost Silicon Solar Array Project Part I CONTRACT: 954442
MOTOROLA, INC.	Metallization of Large Silicon Wafers CONTRACT: 954689
MOTOROLA, INC.	Solar Cell Modules with Parallel-Oriented Interconnections CONTRACT: 954716
MOTOROLA, INC.	Studies and Testing of Antireflective Coatings for Soda-Lime Glass CONTRACT: 954773
MOTOROLA, INC.	Phase 2 of the Array Automated Assembly Task for the Low Cost Silicon Solar Array Project CONTRACT: 954847
MOTOROLA, INC.	The Development of a Method of Producing Etch Resistant Wax Patterns on Solar Cells CONTRACT: 955324
MOTOROLA, INC.	The Establishment of a Production-Ready Manufacturing Process Utilizing Thin Silicon Substrates for Solar Cells CONTRACT: 955328

MOTOROLA, INC.	Anti-reflective Coatings on Large Area Glass Sheets CONTRACT: 955339
MOTOROLA, INC.	Photovoltaic Module Electrical Termination Design Requirements Study CONTRACT: 955367
MOTOROLA, INC.	Anti-Reflective Coatings Applied by Acid-Leaching Process CONTRACT: 955387
MOTOROLA, INC.	Design, Fabrication, Test, Qualification and Price Analysis of "Third Generation" Design Solar Cell Modules CONTRACT: 955406
MOTOROLA, INC.	Processing Experiments on the Non-Czochralski Silicon Sheet (MEPSDU Support Contract) CONTRACT: 955844
NATIONAL RESEARCH FOR GEOSCIENCES LABORATORIES, INC.	Evaluation of LSA Test and Performance Methods CONTRACT: 956083
NORLIN INDUSTRIES, INC. (P.R. HOFFMAN CO.)	Slicing of Single Crystal and Polycrystalline Silicon Ingots using Multi-Blade Saws CONTRACT: 955563
NORTH CAROLINA A&T UNIVERSITY FOUNDATION, INC.	Study of the Effects of Row-to-Row Shading on Photovoltaic Arrays CONTRACT: 957021
NORTH CAROLINA STATE UNIVERSITY	Rapid Thermal Processing of Ion-Implanted Silicon CONTRACT: 957175
NORTHROP CORP.	Lifetime Measurement Analysis CONTRACT: 954614
OREGON STATE UNIVERSITY	Development of Fluidized-Bed Silicon Technology CONTRACT: 956133
PENNSYLVANIA STATE UNIVERSITY	Use of Low Energy Hydrogen Ion Implants in High Efficiency Crystalline Silicon Solar Cells CONTRACT: 957126
PHOTOWATT INTERNATIONAL, INC. (SENSOR TECHNOLOGY, INC.)	Low Cost Silicon Solar Array Project, Large Scale Production Task, Eight (8) Kilowatts of Solar Cell Modules CONTRACT: 954387

PHOTOWATT INTERNATIONAL, INC. (SENSOR TECHNOLOGY, INC.)	Low Cost Silicon Solar Array Project, Large Scale Production Task, 40 Kilowatts Solar Cell Modules CONTRACT: 954565
PHOTOWATT INTERNATIONAL, INC. (SENSOR TECHNOLOGY, INC.)	Development of Low-Cost, High-Energy-Per-Unit-Area Solar Cell Modules CONTRACT: 954605
PHOTOWATT INTERNATIONAL, INC. (SENSOR TECHNOLOGY, INC.)	Phase 2 of the Array Automated Assembly Task for the Low Cost Silicon Solar Array Project CONTRACT: 954865
PHOTOWATT INTERNATIONAL, INC. (SENSOR TECHNOLOGY, INC.)	Development of Low-Cost Polysilicon Solar Cells CONTRACT: 955265
PHOTOWATT INTERNATIONAL, INC. (SENSOR TECHNOLOGY, INC.)	In-Depth Study of Silicon Wafer Surface Texturing CONTRACT: 955266
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