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Silicon-Sheet and Thin-Film Cell and Module Technology Potential

Issue Study

K. Shimada
E.N. Costogoue
R.R. Ferber



December 31, 1984

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

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ABSTRACT

The development of high-efficiency low-cost crystalline silicon ribbon and thin-film solar cells is a key element in achieving the goals of the U.S. Department of Energy National Photovoltaics Program. This report summarizes the findings of an issue study conducted by the Photovoltaics Program Analysis and Integration Center at the Jet Propulsion Laboratory, with assistance from the Solar Energy Research Institute and the Flat-Plate Solar Array Project at the Jet Propulsion Laboratory. The study team interviewed leading researchers in crystalline-silicon ribbon and thin-film solar-cell technologies from Federal agencies and industry that conduct research funded both by the government and by private investment. The collected data identified the status of the technology, future research needs, and problems experienced. The data were also studied and evaluated to assess the potentials of present research activities to meet the Federal/industry long-term technical goal of achieving 15¢ per kilowatt-hour levelized PV energy cost. Recommendations for future research needs related to crystalline silicon ribbon and thin-film technologies for flat-plate collectors are also included.

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PART ONE
EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

The primary research emphasis of the U.S. Department of Energy (DOE) National Photovoltaics Program is the development of promising new approaches to photovoltaic (PV) cells, such as thin-film and multijunction concepts. Emphasis also is placed on completing the development of designs based on flat-plate silicon technologies that yield improved conversion efficiencies and are amenable to automated production. These cells, when used in flat-plate collectors, should be capable of achieving the following Federal-industry long-term technical goals for flat-plate collectors:

Module efficiency	13% to 17%
Module cost	\$40 to \$75/m ²

The Solar Energy Research Institute (SERI) and the Jet Propulsion Laboratory (JPL) manage the Program's research on thin-film and silicon-ribbon cells and modules, which are potentially lower in cost than today's Czochralski ingot and cast-polycrystalline silicon cells and modules.

The specific Program milestones listed in the DOE Five-Year Research Plan are:

	FY85	FY86	FY87	FY88
Single-junction polycrystalline thin-film cells			15% 100 cm ²	
Single-junction amorphous silicon cells		8% 1000 cm ²		12% 100 cm ²
Multijunction amorphous thin-film cells	12% 1 cm ²			18% 1 cm ²
Flat-plate crystalline-silicon collectors	12% \$100/m ²		14% \$90/m ²	15% \$90/m ²
Flat-plate thin-film collectors				12% \$70/m ²

The research involves strong Government-industry partnerships using multidisciplinary teams as well as in-house research to support the contracted efforts.

To assess the status of the research efforts, progress and problems experienced, and potentials for achieving the projected goals, an issue study was conducted by the JPL Program Analysis and Integration (PA&I) Center with the support of key persons at SERI and the Flat-Plate Solar Array Project (FSA) at JPL. The study involved an industry survey to (1) review current progress compared with the objectives and goals, (2) examine the problems and prospects for meeting the goals, and (3) analyze the collected data to better define the research needs to achieve the goals.

Highlights of the study findings are:

- (1) Unlike the present-day silicon sheet technologies, both the silicon-ribbon and the thin-film cell and module technologies have the potential to achieve the long-range goals for flat-plate modules.
- (2) Among the silicon-ribbon cell and module technologies, the web-process and EFG-process cells are most promising.
- (3) The amorphous-silicon cell efficiency goal of 12% with 100 cm² cells appears to be achievable in 1988 without depending on any breakthroughs. However, achievement of module efficiency in the 15% range is unlikely with single-junction amorphous silicon cells.
- (4) Some degree (≈5%) of photon-induced degradation may be unavoidable with a-Si cells.
- (5) Polycrystalline thin-film technologies have made remarkable progress. Large-area (>100 cm²) cells are showing efficiencies in the 6% range.
- (6) The achievement of 15% efficiency small-grain polycrystalline thin-film and amorphous-silicon modules requires considerable research effort and almost certainly requires multijunction devices.
- (7) Extensive research efforts are still required in the areas of materials and materials property theory and analysis, as well as measurement techniques and standardization for reliable evaluation of cell and module performance.

Future PV research needs based on the PA&I Center issue-study data are summarized for three projected module technologies:

- (1) Ribbon Silicon Sheet
 - (a) Establishment of high growth rate with minimum stress buildup in ribbons. Growth dynamics modeling and experimental growth rate verification require continued research.
 - (b) Improvement of ribbon quality in both crystallographic and electrical properties. Better control of grain boundaries and twin-plane formation must be achieved. Reduction of grain boundaries, defects, and impurity effects by passivation or otherwise will further improve ribbon-cell efficiency.
 - (c) Continuous ribbon growth using continuous melt replenishment and closed-loop growth control should be demonstrated jointly with industry.

(2) Amorphous Silicon

- (a) Amorphous-silicon alloys with high band gap and amorphous alloys with low band gap require continued research for eventual integration into high-efficiency tandem cells.
- (b) Transparent conducting oxide (TCO) materials require increased attention to improve optical and electrical properties. The interaction between TCO and a-Si should be carefully considered to ascertain device durability.
- (c) Early establishment of baseline film deposition processes with standardized deposition parameters is highly desirable. Cell performance with respect to fabrication processes can be readily calibrated, and the direction for future advancement can also be determined with relative ease.
- (d) Analytical efforts for cell and material modeling must be continued to understand cell performance and to identify areas for improvements. Photon-induced degradation is one such area.
- (e) Experimental work in multijunction amorphous silicon cells should be increased. The work can be done in parallel with single-junction work, since synergism may be expected to accelerate the progress.
- (f) Module-related research should continue steadily at an increasing rate with strong joint funding by industry. The timing should be such that a-Si technology industrialization for power applications can be achieved smoothly in the early 1990's.

(3) Polycrystalline Thin Films

- (a) Research efforts focused on CuInSe_2 and CdTe cells must be continued so that consistent results are experimentally achievable. Clean deposition systems, well-defined source materials, and well-controlled deposition processes are required for consistency.
- (b) Analytical effort coupled with theoretical and diagnostic activities must be strengthened. Polycrystalline materials are obviously complex in crystallographic and electronic properties. Stoichiometry, impurity content and grain structures of polycrystalline materials all have strong, and hitherto unexplained effects on cell performance.
- (c) Research toward high-efficiency tandem polycrystalline thin-film cells requires strengthening, since tandem cells are almost certainly needed to achieve high module

efficiency with polycrystalline thin films. Combinations of differing polycrystalline cell technologies as well as polycrystalline and amorphous combinations should be researched.

The issue study team findings regarding the development of silicon sheet, polycrystalline thin-film and amorphous-silicon technologies are consistent with those developed by the Electric Power Research Institute (EPRI) in a report by an ad hoc advisory committee*. Conclusions of that report are summarized in Table E-1.

Table E-1. Development Characteristics of Photovoltaic Technologies

Development Characteristic	Tandem Amorphous Silicon	Crystalline Silicon Sheet	Polycrystalline Thin Films
Probability of Meeting Cost Targets	high	medium	high
Probability of Meeting Efficiency Targets	medium	high	low
Probability of Meeting Reliability Targets	medium	high	medium
Margin for Meeting Targets	high	low	low
Time to Resolve Technical Uncertainties	10 years	10 years	20 years
Level of Complementary Development Efforts	high	high	low
Degree of Private R&D Investment	high	medium	low
Availability of Near-Term Markets	high	high	medium

Based on EPRI's projections, the crystalline-silicon sheet technology has the highest probability of meeting within 10 years the efficiency and reliability requirements for utility applications that are consistent with the long-term technical goals.

*Photovoltaic Power System Research Evaluation, a report of the EPRI Ad Hoc Photovoltaics Advisory Committee, EPRI AP-3351, Electric Power Research Institute, Palo Alto, California, December 1983.

Inasmuch as the silicon-sheet technology is the most mature, the uncertainty level in predicting its probability of success is lower than that of other technologies. The result is that all elements of the technology, from low-cost silicon material production to the fabrication of highly reliable modules, must achieve individual goals to reach the overall target.

Thin-film technologies, on the other hand, are not likely to have a strong impact on the electric utility market until after 1995, as these technologies are relatively new and are still considered to be in a research status. Their potentials for success, therefore, are projected on a basis of a number of uncertainties and long-range expectations. Thus, the probability of meeting the targets is high for tandem-junction a-Si technology, but the attainment of this potential requires significant continued research to solve a number of technology problems for thin-film modules.

PART TWO
ISSUE STUDY

SECTION I

INTRODUCTION

Photovoltaic (PV) power systems have a number of advantages that make them an appealing option for grid-connected power generation. These include the potential for low maintenance requirements, low noise, no pollution and no fuel requirement. The primary factors now limiting the use of PV systems are low module efficiency and high cost.

The U.S. Department of Energy (DOE) National Photovoltaics Program has undertaken to develop PV systems that can become cost-competitive with other grid-connected power-generating systems. The goal of this program is to develop, for industry commercialization, PV systems that can generate electricity at a 30-year levelized cost of 15¢ per kilowatt hour. Two photovoltaic collector approaches have emerged with the potential to achieve this goal: flat-plate collectors and concentrator collectors. The Federal-industry long-term technical goals for these collectors are:

	Flat-Plate	Concentrator
Collector efficiency	13% to 17%	23% to 29%
Collector cost	\$40 to \$75/m ²	\$90 to \$160/m ²
System life expectancy	30 years	30 years

These goals can only be achieved with low-cost, high-efficiency solar cells for collectors. For flat-plate collectors, silicon ribbon and thin-film multijunction cells with efficiency in the 15% to 20% range will be required. For concentrating collectors, the most viable options are high-efficiency (25% to 35%) multijunction cells, produced at relatively low cost. Current single-junction laboratory cell efficiency, theoretical efficiency and the projected and potential efficiency in the future are listed in Table 1 for a number of cell materials. As can be seen from the projected and potential efficiencies, thin-film and amorphous single-junction cells are marginal for achieving module efficiency goals.

Over the past eight years the Solar Energy Research Institute (SERI) and the Flat-Plate Solar Array project (FSA) at the Jet Propulsion Laboratory (JPL) have been engaged in the research of silicon-ribbon, single-junction and thin-film multijunction cell technologies and related module research to achieve the flat-plate collector long-range goals. To assess the status of silicon-sheet and thin-film technologies and the potentials for meeting the flat-plate solar-cell and collector goals, an issue study was made by the JPL Program Analysis and Integration (PA&I) Center with the assistance and support of SERI and FSA. The study team members are:

Table 1. Single-Junction Photovoltaic Cell Performance Potentials

Cell Materials	Small-Area Laboratory Cell Efficiency, % ^a			
	(1984)	Theory ^b	Projected (1986-88)	Possible (1990's)
Single-Crystal				
Silicon	19	26	21	22
Silicon (100X)	21	30	24	26
GaAs (1 sun)	22	28	22-24	25
GaAs (500X)	24	34	26-28	30
Amorphous Silicon	11	16-20	13-14	15
CuInSe ₂ /CdS	11	25	12-14	15
CdTe/CdS	11	28	12-14	15

^aConcentration Ratio = 1 sun (1X) unless designated otherwise (500 sun concentration ratio = 500X)

^bBest estimates for single-crystal cells except for amorphous silicon

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The purposes of this issue study are to assess the status of silicon-sheet and thin-film technologies, to examine their potentials for meeting the DOE program goals for flat-plate collectors, and to identify research needs for continued development.

The team's approach included compilation of silicon ribbon and thin-film cell and module research status through industry visits and/or teleconference interviews; analysis of data to determine technological progress, and identification of technological problem areas and continuing research needs. Following is a list of interviews conducted by PA&I Center team members:

Visits:

Boeing Co.	8/9/84	Roger Gillette
Electric Power Research Institute	8/10/84	Roger Taylor, Ed DeMeo
Stanford University	8/10/84	Richard Swanson
Energy Conversion Devices, Inc./ Sovonics	8/15/84	Maset Izu, others (see Appendix A)
Westinghouse Electric Corp.	8/16/84	Don Roberts, others (see Appendix A)
Solarex Corp.	8/17/84	John Corsi
Chronar Corp.	8/17/84	George Self, Alan Delahoy
ARCO Solar, Inc.	9/18/84	Don Morel

Teleconferences:

Ametek, Inc.	9/11/84	P. Meyers
Eastman Kodak, Co.	9/11/84	Y. Tyan
Institute of Energy Conversion	9/12/84	J. Meekin
Southern Methodist University	9/12/84	T. Chu
Spire Corp.	9/10/84	J. Delal
Minnesota Mining and Manufacturing Co.	9/16/84	F. Jeffrey
Mobil Solar Energy Corp.	9/13/84	K. Ravi
Arthur D. Little, Inc.	9/13/84	E. Sachs
Energy Materials Corp.	9/13/84	D. Jewett
Solavolt International	9/12 & 9/19/84	A. Lesk, W. O'Connor
Monosolar, Inc./Standard Oil Co. of Ohio	9/11/84	B. M. Basol
Exxon Research and Engineering Co.	10/11/84	T. Moustakas
University of Illinois	10/18/84	J. Thornton

This survey involved the participation of a wide cross section of the photovoltaics community, including technical managers and researchers from photovoltaics companies, university researchers, governmental researchers and Government R&D project managers. The opinions and recommendations of the persons interviewed are reflected in this report. The interviewees are intimately familiar with the silicon-ribbon and thin-film technologies, and with their problems and their potentials for meeting the DOE goals.

SECTION II

OBJECTIVES AND APPROACH

The DOE National Photovoltaics Program objectives are to develop PV technologies that can become competitive for grid-connected power generation. A long-range goal of the Program is to prepare industry for commercialization of photovoltaic systems that can generate electricity at a 30-year levelized cost of 15¢ per kilowatt-hour. The PV systems that have the potential of meeting the program objectives are flat-plate collectors and concentrator collectors.

For flat-plate silicon collectors, the most common approach today uses wafers of single-crystal silicon that are processed into cells, which are assembled into modules. Single-crystal silicon wafers are produced today by the Czochralski method, in which a single crystal of silicon is grown in cylindrical shape and sliced into individual wafers. To reduce the cost of producing PV devices, a number of new processes are being developed, such as silicon ribbon processes that produce a planar sheet directly from the melt, and thin-film PV cell deposition techniques. These sheet and thin-film cell technologies are compatible with projected large-area, low-cost production processes.

Over the past few years, significant technical advances have been made in flat-plate collectors due to the large and direct financial investment made in R&D by both government and industry. These technical advances have made possible the development and sales of PV products in a rapidly growing number of applications.

Widespread grid-connected applications can only become a reality when the following technical goals, which are specific PV Program milestones, for flat-plate collectors are achieved:

	FY85	FY86	FY87	FY88
Single-junction polycrystalline thin-film cells			15% 100 cm ²	
Single-junction amorphous silicon cells		8% 1000 cm ²		12% 100 cm ²
Multijunction amorphous thin-film cells	12% 1 cm ²			18% 1 cm ²
Flat-plate crystalline-silicon collectors	12% \$100/m ²		14% \$90/m ²	15% \$90/m ²
Flat-plate thin-film collectors				12% \$70/m ²

Two research centers in the National Photovoltaics Program organizations, SERI and FSA, have the responsibility for conducting research to advance the state of the art for flat-plate collectors.

A. SERI ADVANCED RESEARCH AND DEVELOPMENT CENTER

SERI's research activities are directed toward advanced photovoltaic material technologies, which include research on amorphous materials, polycrystalline thin films, cadmium sulfide/copper binary and ternary materials, combinations of gallium arsenide and other III-V high-efficiency materials, polycrystalline silicon, and other PV materials and devices. The two major tasks related to the issue study are the Amorphous Thin-Film Research Task and the Polycrystalline Thin-Film Research Task. Another relevant task is the High-Efficiency Concepts Task; almost half of its budget is devoted to high-efficiency III-V thin films for flat-plate collectors. The specific activities in each task involve management of subcontracted research and coordination of in-house research activities complementary to subcontracted efforts.

The research activities involve strong government-industry partnerships using multidisciplinary teams. The requirements for such research are based on the fact that various parts of thin-film PV devices are strongly interdependent and cannot easily be isolated. This is a consequence of the thin-film nature of the technology; surfaces and interfaces play a major role in the properties of the devices. Research in single-junction solar cells is expected to meet the near-term DOE goals for thin-film PV modules and also to provide the basis for the longer-term development of multijunction stacked solar cells. Multijunction stacked solar cells have the potential of meeting higher efficiency goals.

The Amorphous Thin-Film Research Task performs research in accordance with the plans of the Amorphous-Silicon Research Project (ASRP) office at SERI. The research activities are grouped into five major areas: Material Research, Cell R&D, Submodule R&D, Process Development and Module R&D. The ASRP project is organized into two primary and five secondary research activities. The primary research activities are single-junction solar cells and multijunction stacked solar cells. The five secondary research activities are material deposition rate, alternative material deposition methods, light-induced effects, device testing and reliability, and supporting research such as theory development, plasma kinetics and transparent conductors.

A number of amorphous-silicon deposition processes are being evaluated at SERI. One experimental system is a capacitance-coupled glow-discharge apparatus that is being used for developing new types of alloys such as a-SiSn, a-Si:N and others. Another deposition system is a standard glow-discharge apparatus that has been extensively modified for device work. Still another is an R&D-type multichamber deposition apparatus.

The Amorphous-Silicon Research Project office conducts research and development through industry contracts, to understand and improve photovoltaic properties and to increase conversion efficiency of single-junction and multijunction amorphous-silicon cells.

The objective of the Polycrystalline Thin-Film Research Task is to support research directed toward the achievement of high (near 15%) efficiency in polycrystalline thin-film CuInSe_2 -based cells, in thin-film CdTe cells, or in thin-film cascade cells based on these families of materials. These cells are to be deposited by a method that is potentially scalable to high-throughput production. An additional objective is to demonstrate the long-term stability of these thin-film cells. The SERI in-house effort objectives are to develop promising polycrystalline thin-film solar-cell materials and devices by: (1) studies on stoichiometry, carrier concentration and crystallographic structure for CuInSe_2 thin films; (2) studies of diffusional processes between the two layers of CuInSe_2 ; (3) fabrication of $\text{CuInSe}_x\text{S}_{2-x}$ thin films to gain an increase in V_{oc} , as compared with that of CuInSe_2 ; (4) fabrication of state-of-the-art CdS/CuInSe_2 devices; (5) exploration of new ternary materials from II-IV-V₂ compounds by initiating studies of thin-film evaporation and its stoichiometric control, and of the optical and electrical properties of promising candidates; (6) exploration of CdTe thin-film deposition work by hot-wall evaporation techniques.

The efforts are expected to produce the following results: (1) understanding of the mechanisms controlling the near stoichiometric growth of CuInSe_2 thin films; (2) understanding of the necessary stoichiometry and structure of CuInSe_2 to achieve high efficiency; (3) understanding of the role, if any, of the two CuInSe_2 layers; (4) increasing the photovoltage above 0.45 V by modified CuInSe_2 material; (5) identification of new thin-film materials that have promising PV properties.

B. FLAT-PLATE SOLAR ARRAY PROJECT

The Flat-Plate Solar Array Project makes continuing efforts in advanced silicon-sheet technology and has initiated efforts in amorphous-silicon and other thin-film technologies, which include deposition scale-up research and exploratory testing of thin-film amorphous-silicon cells and modules. Work is also being done to identify generic thin-film cell and module reliability issues to enhance performance, repeatability of measurement and understanding of degradation. Specific activities involve management of small subcontracted efforts and the conduct of in-house research complementary to subcontracted efforts.

The primary objectives of FSA's Advanced Silicon Sheet Task are to resolve generic impediments to improvement of ribbon growth speed and quality. The critical problems remaining in achieving high-speed growth of shaped silicon sheet by the dendritic web and edge-defined film-fed growth (EFG) methods include the limitations of crystallization rate. A key problem is residual thermal stresses and subsequent strain associated with high growth speed, large ribbon width and minimum ribbon thickness. The tasks also include development of ribbon technologies that show promise though the experimental research activities at SERI such as low-angle silicon sheet growth (LASS), developed by Energy Materials Corp. (see FSA Project Management Reports for lists of active relevant contracts).

The objective of the Amorphous-Silicon Deposition Task, which is primarily an in-house effort, is to develop and construct a large-area

multichamber amorphous-silicon deposition system to assist in the development of electrodes and plasma-controlling systems and to evaluate and control chamber-to-chamber cross contamination. The testing and reliability assessment activities include a variety of environmental and endurance tests of thin-film cells and modules and definition of key failure mechanisms and possible research avenues for achieving accurate repeatable measurements for reliability improvements and assessment of degradation. Both tasks are conducted in cooperation with the Amorphous-Silicon Research Project Office at SERI.

SECTION III

SILICON-RIBBON SHEET RESEARCH STATUS

To reduce the cost of producing crystalline-silicon photovoltaic devices, several advanced silicon-sheet production processes are being developed. Generically referred to as ribbon processes, they produce crystalline-silicon sheet directly in the form of a planar sheet instead of in the form of a cylindrical ingot that must be subsequently cut into planar form, as with the Czochralski method. These include the dendritic-web (commonly referred to simply as the web) process, ribbon-to-ribbon (RTR), edge-defined film-fed growth (EFG), edge-supported ribbon (ESR) and low-angle silicon sheet (LASS) processes. Excepting the web process, the silicon sheets produced are polycrystalline in form, being composed of numerous large (i.e., centimeter-size) single crystals of silicon. It is hoped that the resulting polycrystalline sheets can be as attractive economically as those that are strictly single-crystal, as it appears that there is a trade-off between crystal size, cell efficiency, and production cost.

Cell efficiencies as high as 16.7% have been reported¹ with material produced by the dendritic-web process, the only ribbon-growth process that produces single-crystal sheet. The developers of this process have projected a production cost of \$0.48/W_p (\$75.8/m², 1980 \$) at production levels of 25 MW_p/year. Such efficiencies and costs, if realized in large-scale production, would make these modules very attractive when compared with the U.S. PV Program cost and performance targets.

The ribbon technologies examined in this study are edge-defined film-fed growth (EFG) as developed by Mobil Solar Energy Corp. (MSEC, or Mobil); dendritic-web silicon, developed at Westinghouse Electric Corp; edge-supported ribbon, being developed by Arthur D. Little, Inc. (ADL); ribbon-to-ribbon (RTR), being developed by Solavolt International; and low-angle silicon sheet, being developed by Energy Materials Corp. (EMC). Other ribbon technologies are being developed, primarily outside the United States, such as ribbon-against-drop (RAD), variants of silicon-on-ceramic (SOC), meniscus-coated substrates, etc. None of these, however is likely to achieve cell and module performance and costs within the envelope provided by the five presently or formerly National Photovoltaics Program-supported technologies that are examined in this study.

All of the ribbon-growth processes have certain generic technology issues associated with them that are the principal foci of current PV Program ribbon R&D. Chief among these technology issues is ribbon stress and resultant buckling. Other concerns are impurity, defect-related minority carrier lifetime limitations and growth-furnace throughput limitations. Satisfactory solutions to these R&D problems must be developed soon for ribbon technologies to become major components of the 1990's PV product-offering mix. Summaries of the ribbon technologies examined are presented in the following paragraphs. See Appendix A for information collected from the interviews.

¹R. Campbell, Westinghouse Electric Corp., private communication, August 16, 1984.

A. DENDRITIC-WEB SILICON

Dendritic-web silicon sheet, developed by Westinghouse Electric Corp. (see Reference 2), is the only one of the ribbon processes that has the potential to produce an effectively single-crystal silicon sheet. In this process, two single-crystal silicon dendrites formed from a single-crystal seed are propagated downward in the $[211]$ crystalline direction into a supercooled melt at the rate of ribbon withdrawal. A liquid silicon film forms between the two dendrites, which are both part of the same single crystal. This film freezes a few millimeters above the melt with the same single-crystal structure as possessed by the growing dendrites. For stable growth, a set of twin planes forms in the plane of the web surface, but buried in the interior of the web. The web surfaces are both (111) crystallographic planes, as shown in Figure 1.

Temperature control in the growth region is extremely critical in this process. There must be supercooled regions extending well down into the melt in the regions where the dendrites are growing. The supercooling region at and near the surface where the web forms must be very small to enable smooth meniscus-controlled liquid-web takeup without any spontaneous crystallite nucleation. All nucleation must occur on the leading-edge surface of the freezing web itself if stable single-crystal web growth is to occur. Typically, ribbon widths of 5 to 6 cm are grown at a linear rate of 1 to 1.5 cm/min with a thickness of 150 μm . Peak web-growth speeds of 3 cm/min have been demonstrated recently at the same width and ribbon thickness.

Recently a three-year web-growth R&D program has been initiated with Westinghouse to resolve generic growth impediments and to demonstrate capabilities consistent with DOE and electric-utility requirements. The

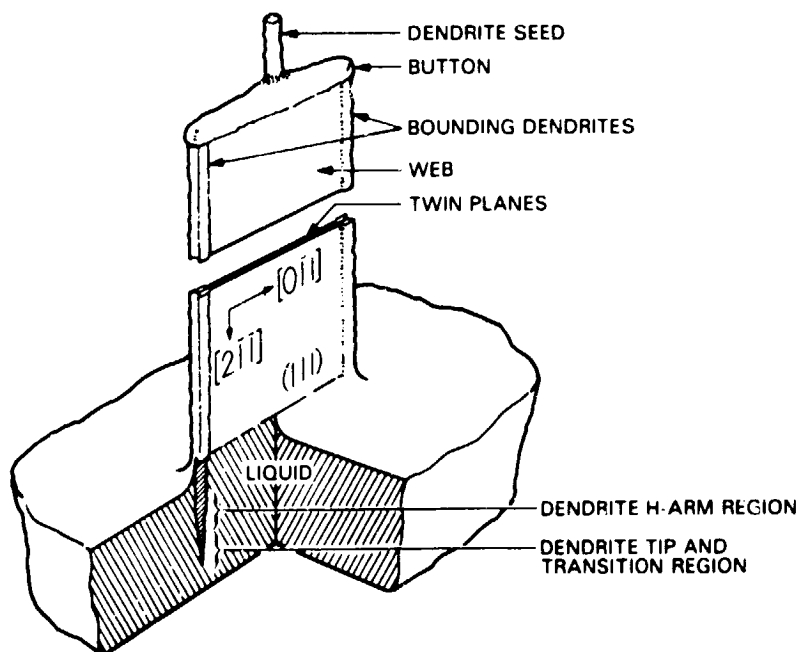


Figure 1. Westinghouse Electric Corp. Dendritic-Web Process

program is supported jointly by DOE, through FSA; by the Southern California Edison Co., by EPRI, and by the Pacific Gas and Electric Co. Late in March 1984, ribbon was grown for 8 1/2 hours with continuous melt replenishment (constant melt level), producing a piece of single-crystal ribbon a little more than 6 meters in length (the longest previous continuous growth was for about three hours). In the same time period, another test was made in which a 9.6-m ribbon was grown without melt replenishment, the longest to date. In this test, the ribbon was grown using a growth configuration that has been well characterized but which tends to produce material with higher stresses than later growth configurations. Using the latest growth configuration (J460L), a 6-m ribbon was grown with melt replenishment. An initial check was made at the center of the ribbon and it was found to have negligible residual stress. Work continues to define the growth-control parameters that can lead to resolving the generic growth impediments. Two different growth configurations have been extensively modelled, one having a vertical radiation shield as the top element of the thermal control and the other having a thinner lid configuration, in which the second lid is replaced by a hot cavity.

Although only modest reduction in stress was obtained using the vertical element, the results indicate that such elements can be used for thermal control. New growth configuration were also tested using both static and dynamic shield configurations. The results are in general agreement with model predictions.

B. EDGE-SUPPORTED RIBBON

One other type of ribbon growth, ESR (see Reference 3), developed by ADL, is similar to web growth. For web, as described above, a pair of elongated silicon crystallites, or dendrites, extends into a silicon melt. As the dendrites are raised, a web forms between them and solidifies. In edge-supported ribbon, graphite (or a similar material) replaces the silicon dendrites.

Edge-supported ribbon growth has been done in both an unseeded and a seeded mode. Unseeded ESR occurs when no single-crystal silicon seed is originally in contact with the melt. This has not been successful, mainly because grain boundaries form at the graphite filaments and propagate horizontally across the web. A seeded version of ESR has been developed (Figure 2) in which the seed crystal is oriented to cause vertical grain boundaries to propagate downward from the seed into the web. The crystallographic boundaries adjacent to the filament block the growth of horizontal grain boundaries emanating from the graphite. Thus, large grains (about 1 cm wide) grow vertically and cells were obtained with up to 13.8% efficiency in research samples. The ribbon growth, as demonstrated by Arthur D. Little, Inc., has been stable with no critical temperature-control requirements and no die problems. The ribbon grown was 5.5 cm wide at 2.5 cm/min growth rate. Cells fabricated from this material have measured 12.5% efficiency. This effort is presently receiving no government funding and corporate support is continuing at a relatively low level. Arthur D. Little, Inc., plans to commercialize the process.

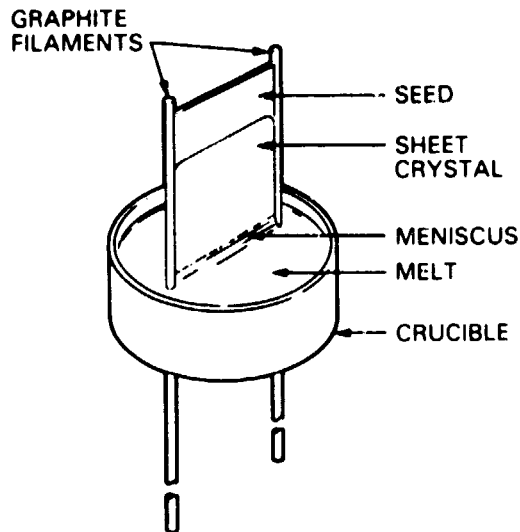


Figure 2. Edge-Supported Ribbon Process

C. RIBBON-TO-RIBBON

The RTR sheet process developed by Solavolt (see Reference 4) is not in the same ribbon category as the other ribbon processes, since the initially formed silicon sheet is not crystallized directly from a melt. In this process, a thin sheet of fine-grained polycrystalline silicon is formed by chemical vapor deposition from chlorosilanes onto a foreign substrate such as molybdenum. However, as-deposited silicon sheet or ribbon does not have satisfactory electronic properties, due to its grain structure, for good solar cells.

Subsequently, the as-grown ribbon is subjected to a second processing step, as shown in Figure 3, in which a very narrow region is melted by a scanning laser beam or electron beam. As the ribbon is passed through this melt zone, which is similar in some respects to a float-zone crystal remelt process, a large-grain polysilicon ribbon with the desired electronic properties is grown from the melted region.

Photovoltaics Program support of this process ended in 1980 and development continues on a proprietary basis. Therefore, information on current technical performance of the process in terms of material quality and throughput rates is not publicly available. Solavolt International claims to have made enough progress, however, that it plans to introduce RTR module products in 1985.

D. EDGE-DEFINED FILM-FED GROWTH

Mobil Solar (previously Tyco Solar Energy Corp. and Mobil Tyco Solar Energy Corp.) has been developing the EFG ribbon process for more than 10 years. At this point, the EFG ribbon process is the only ribbon process that can be considered to be commercial. Mobil Solar is now manufacturing and supplying EFG modules to the user community at nearly 200 kW per year.

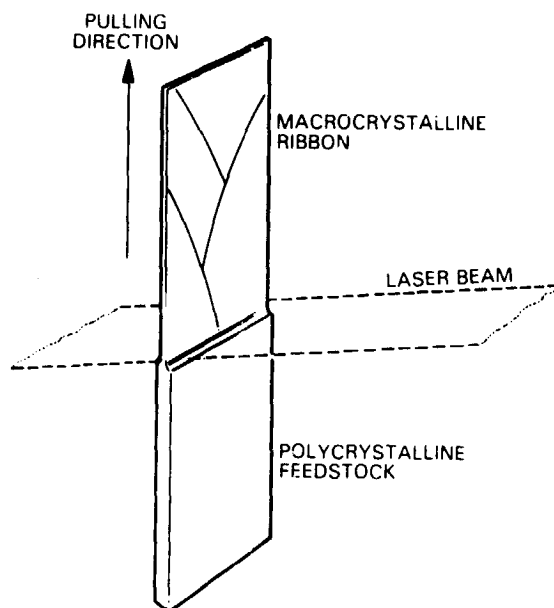


Figure 3. Solavolt International Ribbon-to-Ribbon Process

The EFG process depends on a silicon-wetted graphite capillary die, as shown in Figure 4. This die is immersed in the silicon melt, which is typically contained in a graphite crucible. To start ribbon growth, a seed ribbon crystal is brought into contact with the top of the wetted die and vertical withdrawal is begun at 1 to 2 cm/min.

Ribbons of 5 cm and 10 cm width are routinely pulled in single and multiple die pullers developed with the help of Photovoltaics Program R&D funds. Mobil Solar has developed, using corporate funds, a variant of the process that has become the preferred production growth approach. In this process, a single closed-form nine-sided die is used. With this arrangement, all ribbon-growth edge effects are eliminated and a closed, nine-sided silicon tube is pulled (Reference 5). Currently, nonagons 5 cm on a side can be pulled up to 5.5 m long; typical thickness is 13 mils at a growth rate of 100 cm^2/min . Cells produced from the ribbon measured an average efficiency of 11% with highest efficiencies up to 14%.

Approximately 150 m of ribbon (three 5.5 m nonagon tubes) can be grown from a given crucible setup before replacement of the crucible assembly is necessary. Nonagon facets are now cut into wafers by laser or diamond saw, with diamond saw giving the best results. At present, EFG sheet is grown from non-symmetric dies so that the carbon inclusions (SiC) are concentrated near the rear surface of the sheet. Mobil Solar claims that EFG growth rates can be tripled in the future by going to 10 cm nonagon facets and by increasing linear pull speed by 50%.

The EFG growth objectives are similarly hampered by ribbon stress problems. Construction of a simplified ribbon-growth system has been

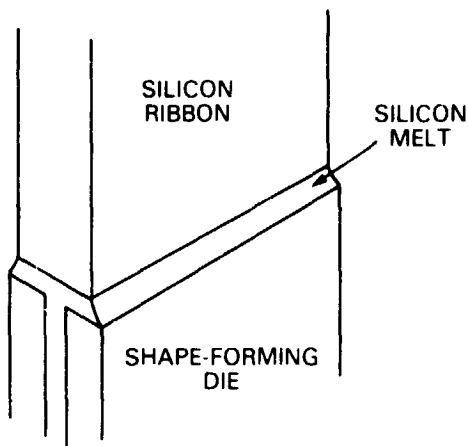


Figure 4. Mobil Solar Energy Corp. Edge-Defined Film-Fed Growth Process

completed to test the stress model and to investigate means of achieving low-stress growth configurations. Preliminary trials and several successful growth runs have been achieved. Ribbon widths were 5 cm, and growth speeds were of the order of 1 cm/min. Additional measurements of stress distributions in EFG material have been obtained at the University of Illinois at Chicago using shadow-moire interferometry. Preliminary characterizations of defects in ribbon grown at speeds of less than 1 cm/min shows that the dislocation density is very low over significant regions of cross section and that regions of high dislocation density occur in bands. Stress studies have shown that stress distributions at distances greater than 1 mm from the melt interface are independent of growth interface conditions. A fiber-optic probe that Mobil has designed, constructed, and calibrated may be used for detailed temperature profile measurements during growth.

E. LOW-ANGLE SILICON SHEET

This method of horizontal ribbon pulling (Figure 5) is being developed by Energy Materials Corp. (Reference 6), based in part on work initiated in Japan (Reference 7). The efforts at EMC are funded by DOE and by private investors. One advantage of the LASS method is that the extended interface between the melt and ribbon aids in the potentially high-speed production of a stable, uniform silicon sheet. Another is that simple passive thermal controls are used, replacing the complex and sensitive active heating and cooling elements used to stabilize growth in other methods. Linear rates of more than 55 cm/min and area rates of more than 400 cm²/min have been attained for short periods during the pulling of a ribbon 33 m long, 5 cm wide, and 0.5 mm thick; 10% cell efficiency has been demonstrated.

Attaining adequate ribbon smoothness is a major problem. Most ribbon surfaces are covered with dendritic structures. Small areas of planar growth are now being achieved and it is hoped that these areas can be made to grow stably over the entire ribbon surface. If this is accomplished, there is also some hope for single-crystal ribbon growth in the future. A clean-room facility has recently been constructed at EMC for better growth control.

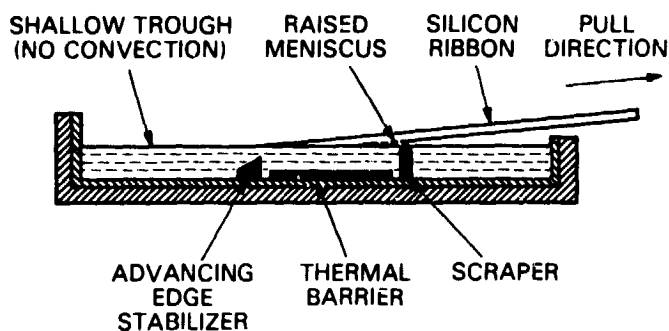


Figure 5. Low-Angle Silicon Sheet Growth

F. RIBBON CHARACTERISTICS SUMMARY

Tables 2 and 3 summarize the 1984 status of the ribbon technologies.

Table 2. Ribbon Characteristics: 1984 Status

Characteristics	EFG	RTR	Web	ESR	LASS
Growth Rate, mm/min	10-30	30-90	10-30	10-90	90-700
Maximum Width, mm	100 ^a	75	60	50	50
Minimum Thickness, μm	150	100	80	80	300
Maximum Length, cm	600 (nonagon)	?	>1000	>100	>1000
Crystal Structure	≈ 4 mm poly-silicon inclusions	≈ 2 mm poly-silicon $\approx 10^4 \text{D/cm}$	single-crystal with twins	large-grain poly-silicon	dendritic poly-silicon
Solar-Cell Efficiency, %	7-14 (11 avg)	10-13 (11.5 avg)	13-16 (14.5 avg)	10-14	9-13
Technology/Skill	high	high	high	low	-----

^aEFG sheet is now grown by Mobil Solar Energy Corp. in a closed nonagon tube with each facet 50 mm wide.

Table 3. Ribbon-Growth Parameters

	EFG	RTR	Web	ESR	LASS
Meniscus Height, mm	0.3	1	7	7	---
Thermal Control, °C	2, crucible and die	---	0.2, Profile Critical	5	---
Surface Morphology	SiC incl: rippled	smooth	very smooth	smooth, bowing	irregular, dendritic
Impurity Sources	die, crucible	feed ribbon	hot zone parts	filaments, crucible	crucible
Impurity Segregation ^a	$K_G \approx 1$	$K_G \approx 1$	$K_0 < K_G < 1$	$K_0 < K_G < 1$	$K_0 < K_G < 1$
Use of Impure Solar- Grade Silicon	no	no	possibly	possibly	possibly
Areas of Concern	freezes, stresses	feed silicon sheet purity	growth rate, stresses	bowing, contamina- tion	crystal- growth control for smooth surface

^a K_G : effective segregation coefficient

K_0 : equilibrium segregation coefficient

SECTION IV

THIN-FILM RESEARCH STATUS

A. AMORPHOUS-SILICON ALLOYS

1. Background

Research on amorphous-silicon properties has been conducted in U.S. laboratories and abroad since 1968. It was demonstrated experimentally that, contrary to general opinion, amorphous materials, particularly hydrogenated amorphous silicon, can be grown that have the optical-electronic properties necessary for use in thin-film solar cells. The first hydrogenated amorphous silicon PV cell was produced in 1974 by RCA, and was the subject of a 1977 U.S. patent (Reference 8). In July 1976, DOE issued a subcontract to RCA to support the research and development of amorphous silicon for applications in photovoltaics.

One type of p-i-n amorphous-silicon (a-Si) solar cell and interconnection scheme is shown in Figures 6 and 7. The p layer used in recent a-Si cells generally consists of hydrogenated amorphous silicon carbide doped with boron. The intrinsic or i layer is normally undoped and consists of hydrogenated amorphous silicon deposited to a thickness of 0.5 to 1.0 μm (1 μm = 0.00004 in.). The intrinsic layer is the active layer, where the absorbed solar radiation generates charge carriers (electrons and holes). The n layer consists of hydrogenated amorphous silicon doped with phosphorus and is typically 0.1 μm in thickness. The doped layers contribute little to the electrical current of the solar cell, but are responsible for determining the voltage of the device and providing low-resistance contacting layers. The total thickness of the different layers shown in Figure 7 (except for the glass and metal layers) is quite small, approximately 1 μm .

Thin-film amorphous-silicon devices can be deposited on large-area, low-cost substrates (e.g., glass, plastics, and metals). Current techniques for depositing thin films include glow discharge, reactive sputtering, and chemical vapor deposition. Figure 7 is an artist's conception of series-connected cells as components of a large-area photovoltaic module produced on a single substrate.

The principal materials being examined in current amorphous-materials R&D activities (see Reference 9) are hydrogenated amorphous silicon, amorphous silicon-carbon and silicon-germanium alloys, microcrystalline phosphorus-silicon-hydrogen, and microcrystalline boron-silicon-hydrogen. The baseline device structures are p-i-n cells. Thin-film preparation approaches are currently glow-discharge (dc and ac) deposition. Glow-discharge deposition using higher-order silane gas is also being investigated for high growth rates. Chemical vapor deposition (CVD) using higher-order silane gases is the only other preparation method currently supported by the DOE-SERI program. The optoelectronic properties of amorphous materials are being studied by several methods, with an emphasis on minority carrier diffusion length and photon-induced instability.

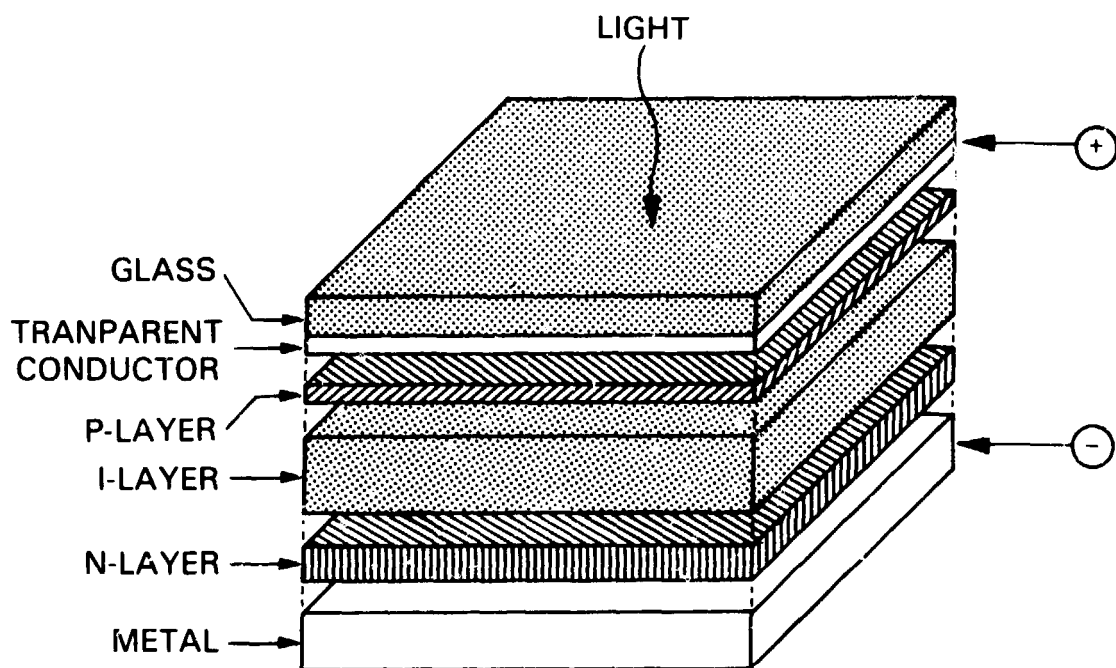


Figure 6. A-Si:H Solar-Cell Structure

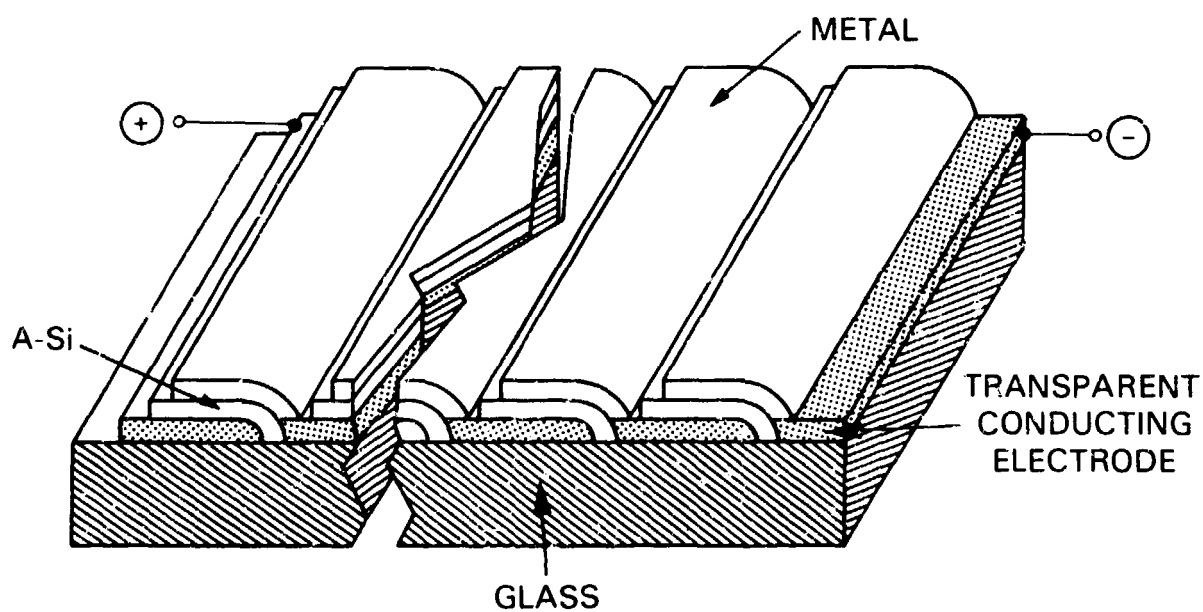


Figure 7. Series-Connected a-Si Cells

2. Efficiency Status

The historical trend of the efficiency of p-i-n solar cells for small and large areas is shown in Figure 8. The most rapid progress in cell efficiency has occurred since 1978. For small-area (1 cm^2) solar cells, the cell efficiency was 4% in 1973, reached 10.1% in July 1982, and in 1984 was reported to be at 10.7% (Reference 10). (More recently, and not shown on the figure, achievement of an 11.5%-efficient cell was reported by Sanyo Electric Co. in October 1984). These achievements were for p-i-n type solar cell structures with the amorphous material grown by glow-discharge deposition. For larger-area solar cells, the p-i-n cell efficiency was 2% in 1979 for an area of 30 cm^2 , and it is now greater than 6% for a total area of 107 cm^2 . United States companies not under government contract have reported conversion efficiencies greater than 8% for an area of 100 cm^2 .

Table 4 gives performance data on the best reported single-junction p-i-n amorphous silicon solar cells having an area of at least 1 cm^2 . The cell structure used by all four groups is the same. Four other research groups -- Komatsu Electronic Metals Co., Ltd., Kyoto Ceramic Co., Ltd. (Kyocera), Sanyo, and Taiyo Yuden Co., Ltd. -- have reported efficiencies

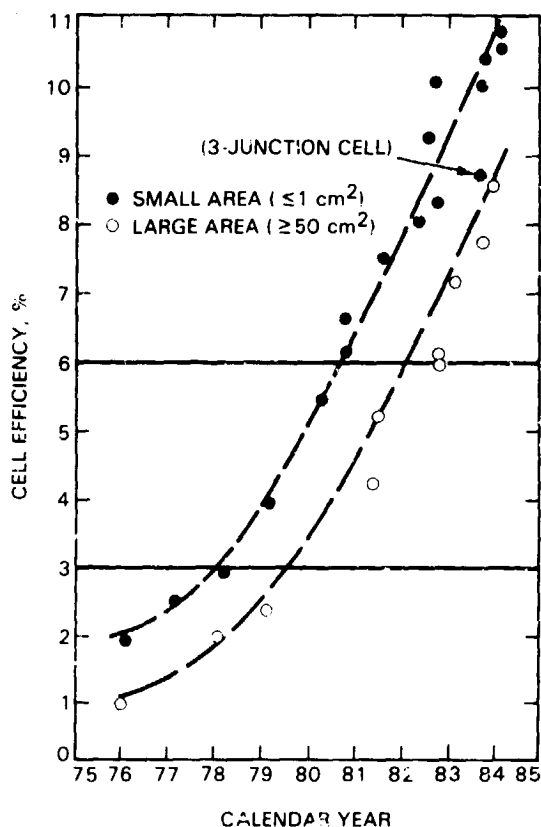


Figure 8. Efficiency of a-Si p-i-n Solar Cells Prepared by Glow Discharge

Table 4. Performance of Best Reported Single-Junction p-i-n Amorphous-Silicon Solar Cells at Least 1 cm² in Area (Reference 9)

Structure	V _{oc} , mV	J _{sc} , mA/cm ²	FF, %	Eff., %	Area, cm ²	
Glass/TCO/p(a-SiC:H)- i-n(a-Si:H)/Me	830	18.3	68.9	10.5	1.05	Tokyo Denki Kagaku Co., Ltd.
Glass/TCO/p(a-SiC:H)- i-n(a-Si:H)/Me	840	17.8	67.6	10.1	1.09	RCA
Glass/TCO/p(a-SiC:H)- i-n(a-Si:H)/Me	850	16.1	71.0	9.7	4cm ²	ARCO Solar, Inc.
Glass/TCO/p(a-SiC:H)- i-n(a-Si:H)/Me	870	15.5	68.4	9.2	1.0	Fuji Electric Co.

Note: In addition to the above, recent information from Japan indicates that Fuji Electric Co. has produced 11.1% efficient 1 cm² cells and Sanyo Electric Co. has produced a cell with 11.5% efficiency.

above 10%, but over smaller areas. The highest efficiency is 10.5%, reported by Tokyo Denki Kagaku Kogyo Co., Ltd., for an area of 0.032 cm². In Table 5, the best individual PV parameters achieved in different years, with calculated efficiencies using these parameters and a range of actual experimental efficiency values achieved in that year, are shown.

These data have been one of the better barometers for predicting future trends. According to E. Salsky of SERI, the calculated efficiency obtained in this manner was 6.7% in 1979 and is now over 14% -- a doubling in potential efficiency. This can be compared with actual experimental values of 4.3% in 1979 and 10.7% in 1984 -- again, a doubling in actual efficiency. The short-circuit current density (J_{sc}) remained near 14 mA/cm² for 1979, 1980, and 1981.

The increase in J_{sc} that occurred from 1981 to 1982 was caused by two developments. The first was the successful use of a new p-type material (boron-doped hydrogenated amorphous silicon carbide), which increased the collection efficiency in the optical wavelength region of less than 0.3 μm. The p-type material previously used (boron-doped hydrogenated amorphous silicon) absorbed some of the incoming light without contributing to the conversion efficiency. The second development was the integration into the cell structure of a highly reflective back-surface electrode such as an n-type microcrystalline-silver back contact. This permitted more optical absorption in the cell by increasing the equivalent path length for the longer-wave-length photons.

Table 5. Best Individual Parameters of Single-Junction p-i-n Amorphous-Silicon Solar Cells

Best Parameters			Calculated Possible Efficiency, %	Year	Experimental Efficiency, %
V_{oc} , mV	J_{sc} , mA/cm ²	FF, %			
990	18.8	76	14.1	1984	10.0 - 10.7
950	16.7	74	11.7	1982	7.5 - 10.1
910	14.0	70	8.9	1981	6.6 - 7.5
900	14.0	66	8.3	1980	5.0 - 6.6
800	14.0	60	8.7	1979	4.0 - 5.0

Other research advances were also responsible for the increase in J_{sc} from 1982 to 1984. One was the successful integration in the cell structure of a thin, texturized surface layer between the transparent conductor and the amorphous silicon. The texturized layer provides better utilization of incoming light by reducing reflection and lengthening optical paths in the amorphous-silicon material. In addition, researchers demonstrated that a thick, intrinsic amorphous-silicon layer of at least 1 μm , rather than the conventional thickness of 0.6 μm , improved cell efficiency. As a result, the present cells have better photovoltaic properties than those previously used. The successful use of thicker intrinsic amorphous silicon layer decreases the need for a highly reflective back contact. As experimental values of current density have recently reached as high as 19 mA/cm² (very close to theoretical values of 20-22 mA/cm² for an optical band gap of 1.7 eV), there is little room for further increase in short-circuit current density.

Recent improvements in solar-cell conversion efficiencies result from intrinsic amorphous-silicon material with better transport properties. Table 6 shows (a) the electron drift mobility was 10^{-1} - 10^{-2} cm²/V-s in 1970 and is now 2.5 cm²/V-s and (b) the hole diffusion length was 0.02-0.2 μm in 1980 and is now near 1.3 μm (Oct. 1984). Also, the early consensus of device modelers was that holes were collected only from those generation regions of high electric field. The reason for the significant improvement in transport properties and solar cell performance is being investigated. There is no doubt that the level of impurities has been reduced and that this accounts for some improvement. However, it is more plausible that the major influence on material properties is changes in the microscopic structure.

3. New Multiyear Amorphous-Silicon Research Contracts

The DOE Amorphous-Silicon Research Plan calls for advancing the state of the art by means of multiyear subcontracts based on strong Government-industry partnerships. Implementation of the plan began early in 1983 when multiyear, competitive procurements were issued for single-junction

Table 6. Transport Properties of Undoped Amorphous Silicon

	Year			
	1970	1977	1980	1983
Electron Drift Mobility, cm ² /V · s at 300K	10 ⁻¹ to 10 ⁻² (note 1)		10 ⁻¹ to 10 ⁻² (note 2)	2.5 (note 3)
Hole Drift Mobility, cm ² /V · s at 300K				10 ⁻² to 3 x 10 ⁻³ (note 4)
Hole Diffusion Length, μm		0.02 to 0.2 (note 5)	0.02 to 0.2 (note 5)	1.2 to 1.3 (note 6)

Note 1: P. LaComber, W. Spear

Note 2: R. Crandall

Note 3: R. Street

Note 4: Depends on field; R. Street

Note 5: Staebler, Crandall, Wronski

Note 6: Cresner, Moore, Goldstein, Szeszak

cells and submodules, and for multijunction cells. The procurements were weighted toward the near-term single-junction solar cell technology. The objective of the single-junction initiative is to improve the understanding of and the efficiency of cells and submodules using single-junction p-i-n type cells based on material grown by the glow-discharge deposition method. The objective of the multijunction initiative is to establish a base of knowledge that can help achieve efficiencies greater than 20%, in the long term, in amorphous-silicon alloy materials in stacked cells.

The competitive procurement process was completed on February 1, 1984, when the final subcontract was signed. Subcontracts were awarded to four organizations: Chronar Corp., Minnesota Mining and Manufacturing Co. (3M), Solarex Corp., and Spire Corp.

Figure 9 shows the different technical approaches taken by the companies to achieve the program goals. Amorphous silicon material for single-junction solar cells will be deposited using three-chamber reactors, and material for multijunction solar cells will be deposited using six-chamber reactors. Direct-current or RF glow discharge with two or three electrodes will be used to generate the plasma.

The total program cost over the three-year life of the subcontracts is \$18.8 million, with approximately 70% of the total cost contributed by the Government and about 30% contributed by the industrial subcontractors. Some

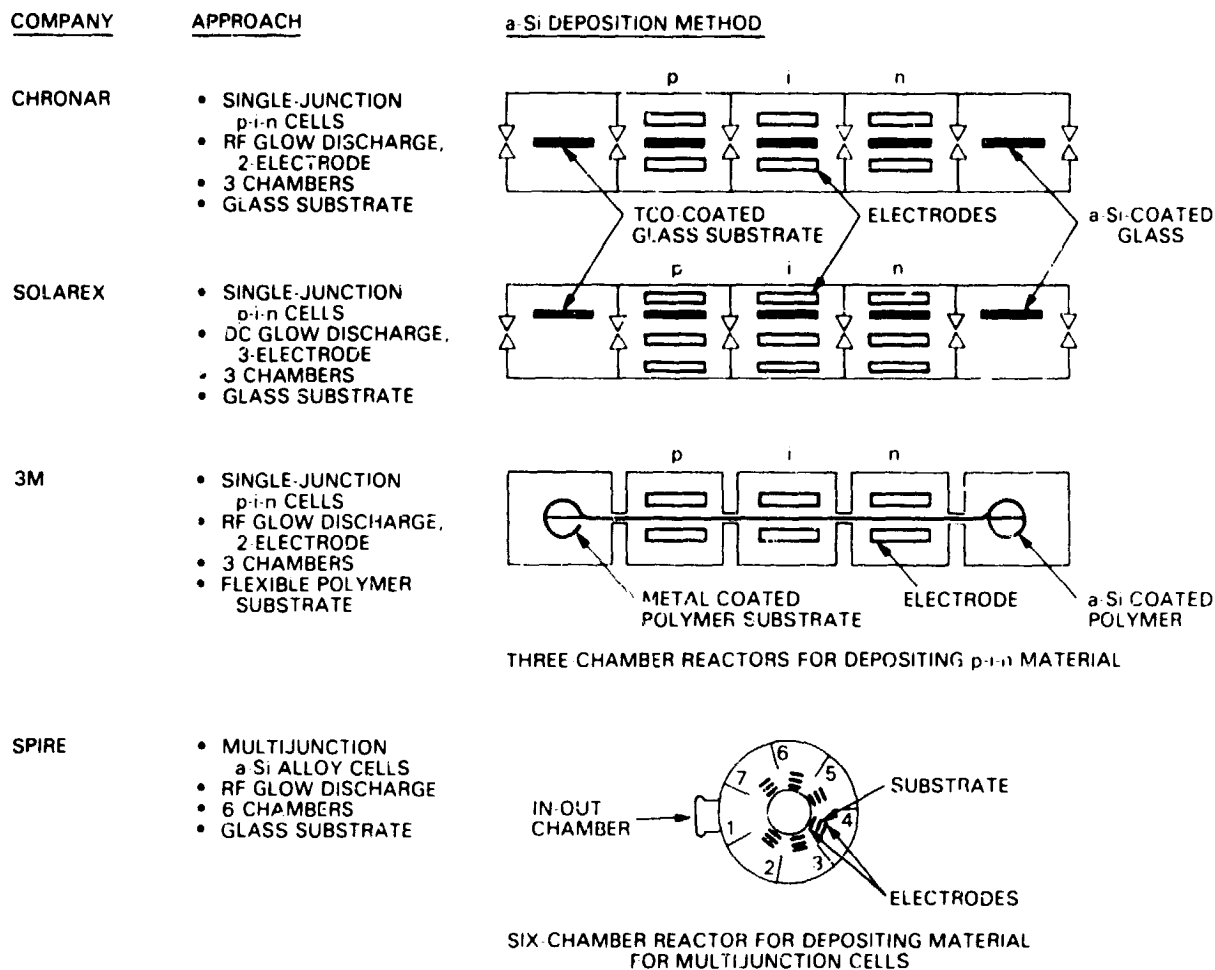


Figure 9. Technical Approaches of New Multiyear Initiatives in Amorphous Silicon

subcontractors are developing multichamber deposition systems to fabricate the solar cells entirely with company funds, and the cost of this work is not included in these values. The SERI/DOE program goals are to demonstrate stable p-i-n solar cells of at least 12% (AM1) efficiency with areas of at least 1 cm² in 1986, a stable submodule of at least 8% (AM1) efficiency having a total area of at least 100 cm², and proof-of-concept multijunction amorphous-silicon alloy thin-film solar cells that will lead to achieving an 18% efficiency goal by 1988.

The enhanced U.S. Government program plays a major leadership role in continuing the technological development of thin-film amorphous-silicon solar cells. Companies such as 3M have now joined with the Government to develop single-junction solar cells, and Polaroid Corp. is providing Spire Corp. with additional resources in its research into multijunction amorphous-silicon alloy solar cells. The significant amorphous-silicon

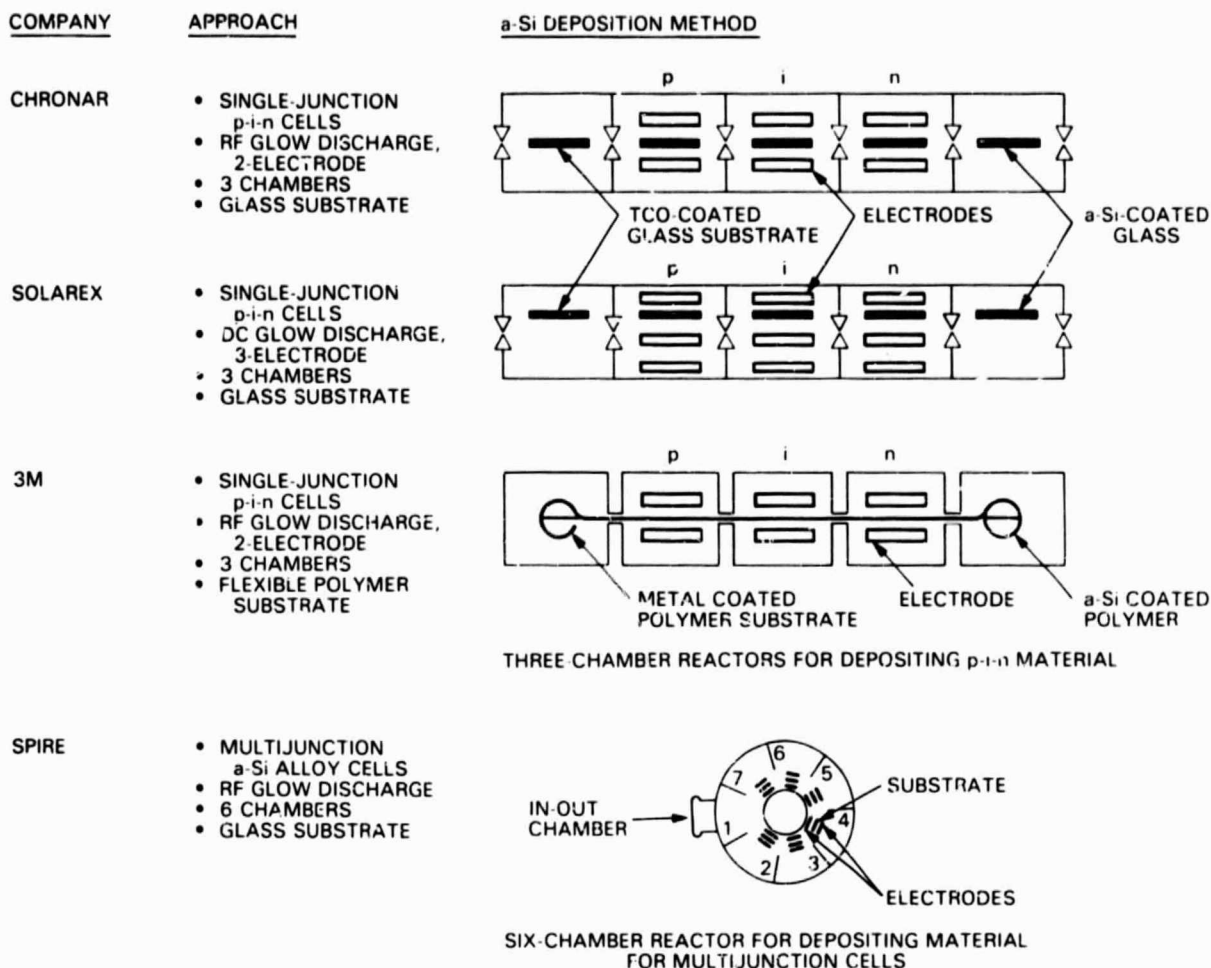


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technology developed at RCA, under long-term Government and RCA support, has been successfully transferred to Solarex Corp. to continue the development of single-junction solar cells under subcontract to SERI. In addition, two small businesses, Chronar Corp. and Spire Corp., are included in this Government-industrial effort.

4. Other Amorphous-Silicon Research Activities

In addition to the research activities covered in the previous section, other research efforts include the investigation of the basic properties of hydrogenated amorphous silicon and amorphous-silicon alloy materials, light-induced effects, high deposition rates, and alternative deposition options. These efforts are funded either by DOE or by corporate resources.

Glow-discharge (GD) deposition of amorphous silicon using higher-order silane gases is being carried out at Brookhaven National Laboratory and Vacronics Corp. The program is investigating optical and electronic properties of amorphous silicon produced at a deposition rate of at least 20 A/s. The intrinsic amorphous-silicon material now being produced by glow discharge using silane gas is deposited at a typical rate of 2 to 4 A/s. A deposition rate of 4 A/s required 42 min to grow a 1- μ m-thick film, whereas a deposition rate of 20 A/s would require only 9 min to grow the same film. Experimental data have already shown that glow-discharge deposition using higher-order silane gases can produce high-quality material at high deposition rates.

Light-induced effects are being studied at the University of Oregon, Massachusetts Institute of Technology (MIT), and Xerox Corp. The effect of light soaking in a-Si:H samples deposited either in an ultra-high-vacuum (UHV) system or in a conventional deposition system has been studied by measuring the change in dangling-bond density using electron-spin resonance (ESR). Although the UHV-deposited samples have lower impurity levels (by one to two orders of magnitude) than the impurity concentrations in conventionally deposited samples, the light-soaking effect was found to be nearly identical. This indicates that impurities play a minimal role in generating the light-induced effects in a-Si:H samples with normal impurity levels. The contribution of impurities to the density of light-induced defects is significant only when the impurity level in a-Si:H is higher than about 1%. Recent data presented by Sanyo Electric Co. (Japan) are somewhat at variance with this finding. Sanyo has shown a strong relationship between light-induced change and oxygen content. A lesser effect has also been correlated with the nitrogen content in the film.

The potential of chemical vapor deposition (CVD) is also being evaluated. Both low-pressure (LPCVD) and atmospheric-pressure (APCVD) deposition methods are being investigated at Chronar, at the Institute of Energy Conversion (IEC), and at Harvard University. Current studies are restricted to CVD using higher-order silane gases. The higher-order silane gases decompose at relatively low temperatures (below 300°C), and, as a result, the films contain large amounts of hydrogen and can also be deposited

at very high deposition rates. APCVD-prepared films have been grown at deposition rates above 30 Å/s, and LPCVD-prepared films were grown at rates up to 15 Å/s. Diagnostic Schottky barrier cells and p-i-n type cells were fabricated using material grown by both LPCVD and APCVD. Short-circuit current densities of 10 mA/cm² have been achieved, demonstrating a good quality of material. In addition, the optical band gap of presently prepared material is reported to be 0.1 to 0.2 eV below that of glow-discharge-prepared material. Lower-band-gap material not obtained by the glow-discharge process is probably better suited for high-efficiency cells. Light-induced effects in CVD-prepared films appear to be less than for glow-discharge-prepared films, although the film quality has not yet reached that of glow-discharge-deposited films. CVD is widely used in the semiconductor industry, is readily scalable, and is a simpler process than the glow-discharge process. Thus the use of this process could reduce costs substantially.

Stacking solar cells with different band gaps in series optically and electrically can potentially convert more solar radiation to electricity. Individual cells in the stack can be made of various amorphous-silicon-alloy materials with passivators such as hydrogen or fluorine to achieve different optical band gaps. Hydrogenated amorphous silicon has been studied extensively and is the basis on which the standard amorphous-silicon stacked cell is designed. Materials being considered include a-SiGe:H and a-SiSn:H (both for the low-band-gap cell) and a-SiN:H (for the high-band-gap cell). A two-layer a-Si:H material with two different-thickness layers in series, and with a a-SiGe:H low-band-gap cell, produced the best results. The results reported are 8.5% efficiency for an area of 100 cm² ($V_{oc} \approx 2.22$ V, $J_{sc} \approx 6.41$ mA/cm², FF ≈ 0.604). Theoretical conversion efficiencies for the multiband-gap cell are above 20%.

A newer type of solar device that is an outgrowth of the conventional thin-film materials has recently been proposed. This new structure is composed of amorphous materials consisting of an amorphous superlattice of alternating layers (30 to 1000 Å thick) of hydrogenated amorphous silicon alloys. The amorphous and thin-film nature of these materials opens research to a whole new class of compound materials not readily available in the past. This new technology has great potential in many areas, including highly efficient PV devices. Research in amorphous silicon alloy materials is being conducted at Harvard University, Xerox Corp., North Carolina State University, and SERI.

Harvard University is developing materials that can reduce the electrical contact resistance between the transparent conducting oxide and the amorphous layers. Diffusion barriers are also being developed to prevent contaminants in glass substrates from affecting the performance of the transparent conducting layer. The Naval Research Laboratory is conducting nuclear magnetic resonance (NMR) and electron-spin resonance experiments on amorphous materials to determine the bonding configurations of boron and phosphorus in the doped amorphous materials. The University of Colorado is characterizing the plasma in glow-discharge reactors to correlate various ions and radical species with film properties.

5. Industry Survey Highlights

Highlights of the industry survey conducted by the study team are summarized in Table 7. For detailed information, see Appendix B. Based on the data collected, single-junction a-Si:H solar cells are now repeatably fabricated to show 10% to 11% efficiency in small-area ($<1 \text{ cm}^2$) cells by Solarex and Arco Solar, Inc. These cells are fabricated by a glow-discharge deposition process in multichamber systems. Chronar, 3M and Spire, which currently fabricate their cells in a single-chamber glow-discharge deposition system are all constructing multichamber deposition systems in which cross-doping of p, i, and n layers can be greatly reduced. Energy Conversion Devices, Inc. (ECD), has already developed and marketed its Ovonic Processors with multiple chambers. One such unit in Japan fabricates multijunction cells for pocket calculators.

Large-area ($>100 \text{ cm}^2$) single-junction series-connected solar cells also are being fabricated by most organizations to develop technologies required for the fabrication of practical a-Si modules. Chronar recently succeeded in fabricating 100-cm^2 submodules having 6% efficiency (DOE/SERI goal for 1984). Such submodules typically consist of series-connected subcells using laser patterning. Chronar has also initiated marketing of $10 \times 10 \text{ cm}$ battery-charger modules. Efficiency of $10 \times 10 \text{ cm}$ submodules that are currently being fabricated by Chronar, ARCO Solar and ECD appear to be in the 5% efficiency range. The DOE/SERI a-Si Project schedules of 12%, 1 cm^2 in 1986, 7%, 100 cm^2 in 1985, and 8%, 1000 cm^2 in 1986 appear to be realizable by a better use of optical trapping, improvement of TCO films, better control of doping profiles and advancement in laser-patterning technology. Amorphous-silicon cell fabrication on a flexible substrate, which is being pursued by 3M, is also making a good progress; experimental cells are now being fabricated in its single-chamber glow-discharge deposition system.

Industry opinions were that the near-term market for stand-alone applications could be competitively shared by a-Si modules of 10% efficiency provided that their costs become lower than those of crystalline-silicon modules, which already have efficiencies higher than 10%. ARCO Solar emphasizes the importance of achieving this a-Si cost-competitiveness with crystalline-silicon technology within five years. Other a-Si companies appear to share that opinion.

The large long-term market, on the other hand, should be for grid-interactive systems where module efficiencies in the range of 15% are required. Here the multijunction a-Si cells become the key element for success.

Currently, multijunction cell research is in a very early stage. A combination of a-Si or a-SiC and a-SiGe is by far the most actively investigated. In fact, ECD-Sovonics has already commercialized similar multijunction cells for pocket calculators where only a modest efficiency improvement over the single-junction cell efficiency would suffice. The corporate multijunction cell-efficiency goal of ECD-Standard Oil Co. of Ohio (Sohio) is 15% in three to five years, and Spire is aiming toward similar efficiencies in two to three years under the SERI subcontract. If the current progress in low-band-gap material research and the baseline a-Si cell research

Table 7. Amorphous-Silicon Cell Technology

Organization	Materials	Deposition Process	Cell Structure	Progress	Plan
ARCO	a-Si:H	Glow Discharge (GD)	single-junction & multijunction	10 to 11% eff. with 1 cm ² single-junction. 5% eff. with SiGe single-junction	10% module at salable price
Chronar	a-Si:H	GD	single-junction	1 ft ² modules pilot production; 6% eff., 107 cm ²	12% eff. 1 cm ² and 8% eff. 1 ft ² in '86
ECD/Sohio (Sovonics)	a-Si, a-SiGe	GD	single-junction & multijunction	3 MW/yr Ovonic Processor at Sharp, Japan. Multijunction module production to begin at Sovonics, Fall 1984	15% eff. cell in 3 to 5 years
3M	a-Si:H on flexible substrate	GD	single-junction	Single-chamber GD deposition system in operation. 4.5% eff., 5 mm ² achieved	12% eff., 1 cm ² 8% eff., 100 cm ²
Solarex	a-Si:H	GD	single-junction	Pilot production and marketing started for calculator cells	10% eff. modules at \$0.50/W in 1990
Spire	a-Si, a-SiGe	GD	multijunction	6% to 6.5% eff., single-junction achieved; a-SiGe with E _g = 1.45 eV fabricated	16% eff. in 2 to 3 years
Exxon Research	a-Si	GD	single-junction	5.5% eff. with 1 cm ²	Current research emphasizes III-V materials and superlattices

continues, and if the commitment made by DOE and U.S. corporations continues, multijunction cell efficiencies in the 15% range can indeed be realized in three to five years. However, the achievement of 15% a-Si modules in five years is difficult to project, since module technology is still in a very early stage of development.

B. POLYCRYSTALLINE THIN FILMS

1. Background

Polycrystalline thin-film PV cells are candidates to achieve the Federal-industry long-term (late 1990's) technical goals for flat-plate modules. Among several polycrystalline materials that have been considered for PV applications, CuInSe_2 and CdTe are the most vigorously investigated under DOE-SERI and PV industry funding. Those materials are known to have a large light-absorption coefficient, one to two orders of magnitude larger than that of crystalline silicon, for the wavelengths of PV interest (Figure 10). Therefore, the cells can be made in thin-film form, requiring considerably less semiconductor material than crystalline silicon. Typically the films are deposited on inexpensive substrates by vacuum or electrodeposition or by CVD, all of which are amenable to low-cost processes.

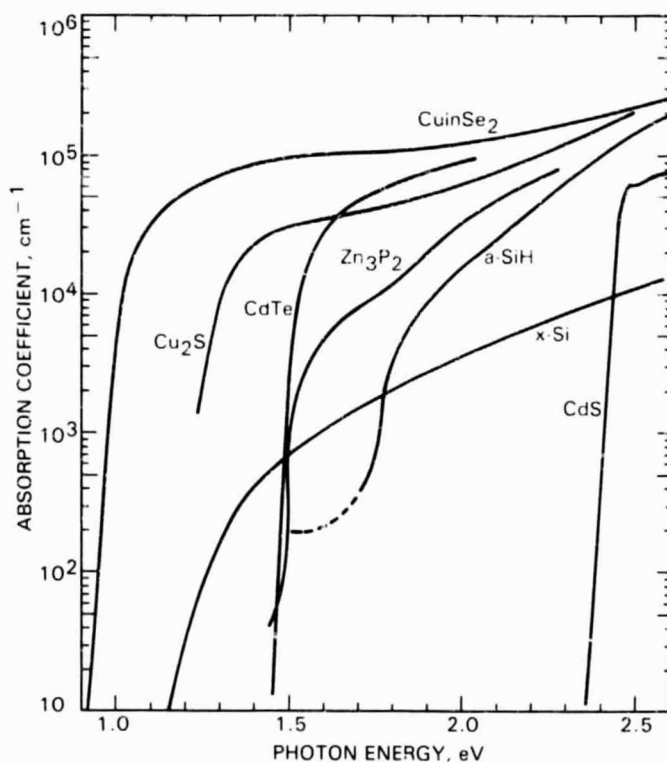


Figure 10. Absorption Coefficient versus Photon Energy

Typical single-junction cells have a CdS window on top of CuInSe₂ or CdTe, as shown in Figure 11. The band-gap energies (E_g) of those two materials are such that the cascading of cells could increase the resultant cell efficiency substantially. A possible cascaded multijunction cell consists of CdS/CdTe and CdS/CuInSe₂, as shown in Figure 12. Other combinations, including amorphous silicon/CuInSe₂ and CdTe/amorphous-silicon germanium, can also be considered.

The 1987 SERI efficiency goal of 15% with 100 cm² cells is considered achievable by further improving the electronic and material properties of existing polycrystalline thin films. For example, an increase of band-gap energies and corresponding open-circuit voltages has been proposed to increase CuInSe₂ cell efficiency. Open-circuit voltages of 570 mV, short-circuit current densities of 35 mA/cm², and fill factors of 0.75 should be attainable in CuInSe₂-alloy-based cells. Similar improvement should be attainable for CdTe-alloy-based cells, with which open-circuit voltages of 850 mV, short-circuit current densities of 23 mA/cm² and fill factors of 0.75 are considered possible. Successful cascading of cells would further increase the probability of achieving the 15% efficiency goals.

2. Copper Indium Diselenide

Research on copper indium diselenide (CuInSe₂) cells is being conducted at The Institute of Energy Conversion (IEC), University of Delaware, Poly Solar and the University of Illinois in addition to Boeing Co. The 11% efficiency of small-area cells is comparable with that of amorphous-silicon thin-film cells. The stability of the CuInSe₂ cell is known to be excellent;

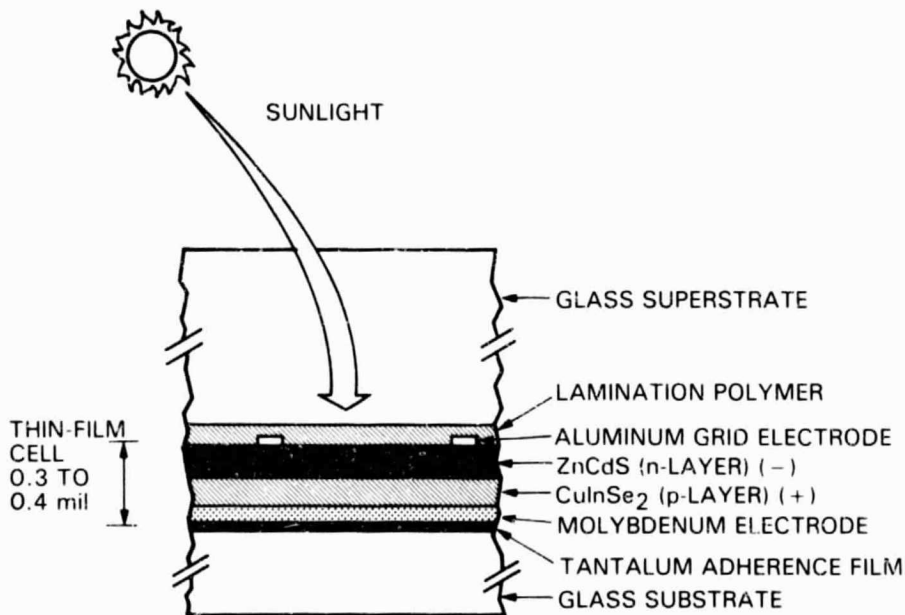


Figure 11. Thin-Film Cell Design

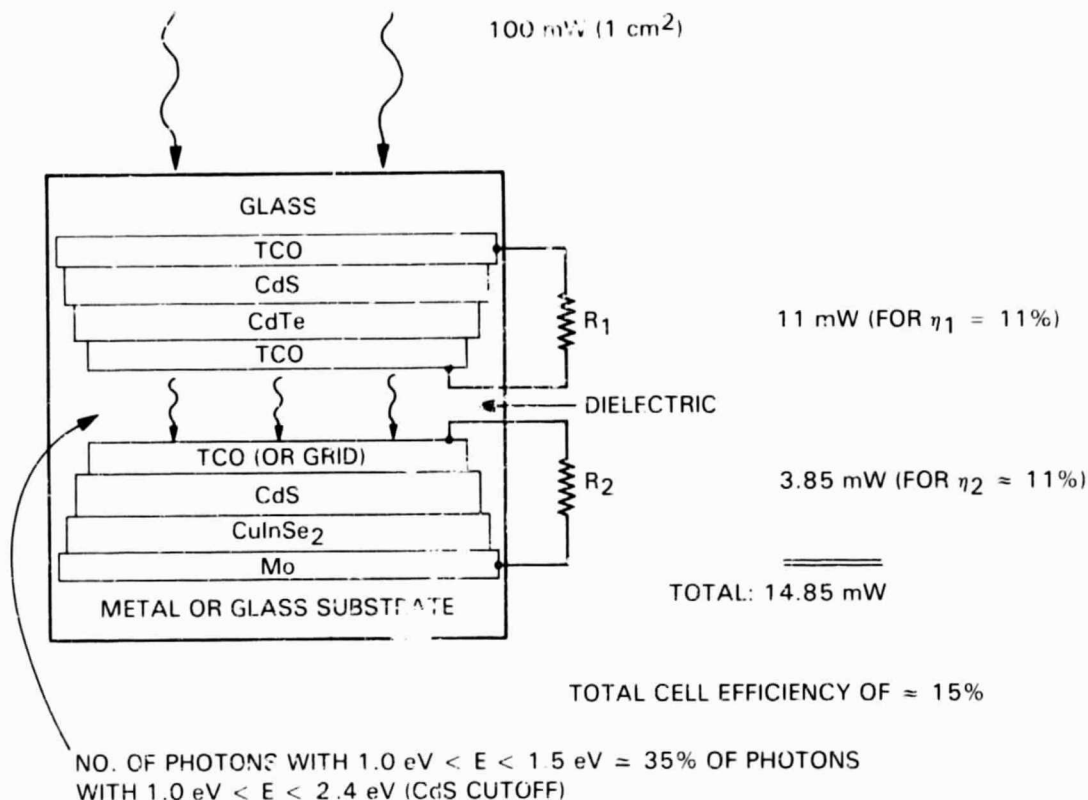


Figure 12. Cascaded Multijunction Polycrystalline Thin-Film Cell

the degradation of the CuInSe₂ cell has already been shown to be minimal in a simulated environmental test conducted at Boeing under constant illumination and elevated temperature for 9000 hours. Encouraged by the cell-efficiency improvements and the good cell-stability data, Boeing has envisioned the fabrication of polycrystalline thin-film modules consisting of submodules, each of which contains 12 subcells that are series-connected, as shown schematically in Fig. 13. Recently, Boeing successfully fabricated a 4 x 4 in. CuInSe₂ cell having an effective area efficiency of 6.1%. Plans for production and marketing of modules, which were considered by the Boeing-Sovolco joint venture, were suspended because the Sovolco joint venture with Reading & Bates, Inc., was dissolved in May 1984. Boeing is continuing commercialization R&D, using its own funds, and may license the manufacturing in the future.

Boeing's vacuum-evaporated cell is a thin-film polycrystalline heterojunction with a CuInSe₂ absorber and a large-band-gap (2.5 eV) (CdZn)S window (Reference 11). The CuInSe₂ layer is deposited in a two-layer (high-resistivity and low-resistivity) configuration, but mixing takes place during deposition. The layers in the final CuInSe₂ cell are homogeneous

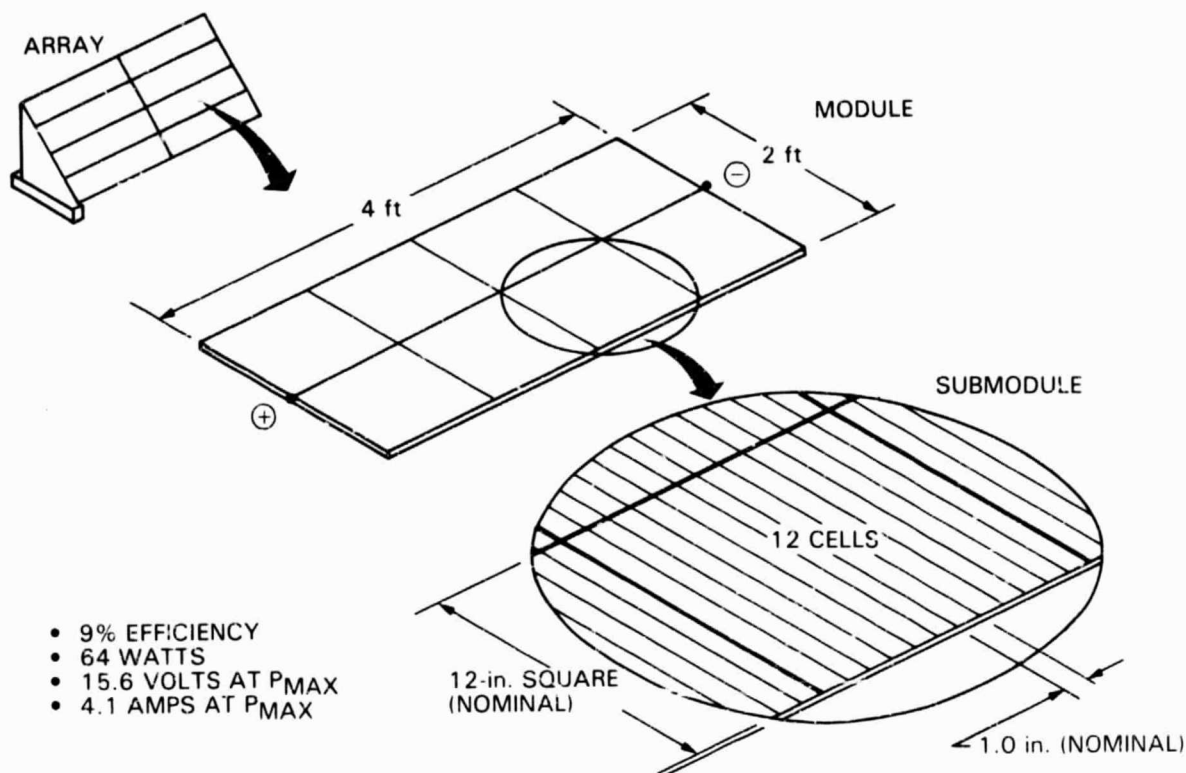


Figure 13. Baseline Photovoltaic Module (Boeing Co.)

within 0.5 atomic-percent measurement error. However, sub-percentage inhomogeneities (if they exist) could be responsible for significant variations in electronic properties. The final cell-layer composition and electronic properties are now under close study.

Boeing fabricates CuInSe_2 films by means of an open-boat vacuum-evaporation system. The elemental flux from the heated boats is measured by electron-impact emission spectroscopy, and a feedback loop is used to control the temperature of the boats and the evaporation rates.

The Institute of Energy Conversion is also fabricating high-efficiency CuInSe_2 devices, using a feed-forward system of controlled Knudsen cell effusion sources, wherein temperature and aperture are carefully calibrated and designed to deposit the desired films. The effusion cell design has demonstrated large-area scalability, which is important for the future commercial scaleup of CuInSe_2 manufacturing. A small-area (0.09cm^2) CdS/CuInSe_2 cell fabricated by the effusion system has achieved 9.6% efficiency.

Recently, IEC also fabricated a 3.0% efficient, multijunction, CdTe/CuInSe_2 cell, and is the first organization that has actually cascaded two thin-film polycrystalline cells in a two-terminal configuration.

3. Cadmium Telluride

Cadmium telluride (CdTe) is a prime PV cell candidate, due to its ideal direct band gap (near 1.5 eV), high optical absorption coefficient (greater than $3 \times 10^4/\text{cm}$ at the edge of the energy band), and relative ease of deposition.

In 1982, Eastman Kodak Co. reported a polycrystalline thin-film CdS/CdTe device with 10.9% efficiency. The Kodak experimental cell, which had the structure shown in Figure 14, was such that it would be mass-producible by using steps shown in Figure 15. The experimental Kodak cell was fabricated by a close-spaced sublimation (CSS) system in which the sublimation source and a heated substrate were placed with a small gap between them.

Ametek, Inc., has been developing CdTe cell technology for a number of years. The technique used is to fabricate cells in an electrolytic tank using electrodeposition. Small-area (2 mm^2) cell efficiency of 8.6% and large-area (10 cm^2) cell efficiency of 6.2% have been reported. The cell structure is metal-insulator-semiconductor (MIS). A similar CdTe electroplating process is being developed by Monogram Industries Research Laboratory (Monosolar). Recently, Monosolar was purchased by Sohio/British Petroleum Co. Ltd. for possible future commercialization of the CdTe cell and module technology.

A Japanese company, Matsushita Electric Industrial Co., reports an active-area efficiency of 12.8% for small-backwall n-CdS/p-CdTe cells made by screen printing. However, due to the placement of electrodes, the actual total-area efficiency is substantially less. According to the recent report (October 1984), an all-screen-printed multicell module, $30 \times 30 \text{ cm}$, achieved module efficiency of 5.4%.

Under SERI sponsorship, Southern Methodist University (SMU) is developing indium tin oxide (ITO)/p-CdTe heterojunction cells. Cell efficiency of 8.2% has been achieved for cell areas of 1 cm^2 (Reference 12). The CdTe was deposited by CVD on a Sb/W/graphite substrate, and the ITO was ion-beam deposited. Further improvement is expected in the area of ohmic contact with p-CdTe, and in use of lower-cost substrates.

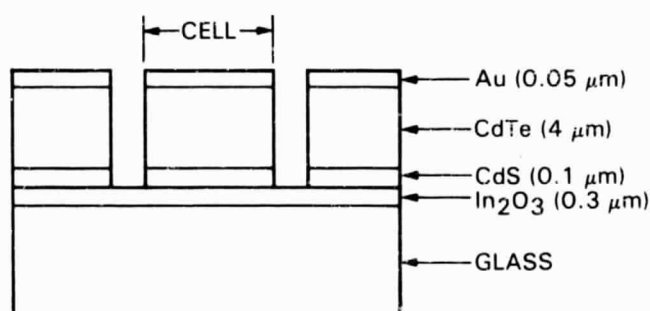


Figure 14. Thin-Film CdS/CdTe Solar Cell (Eastman Kodak Co.)

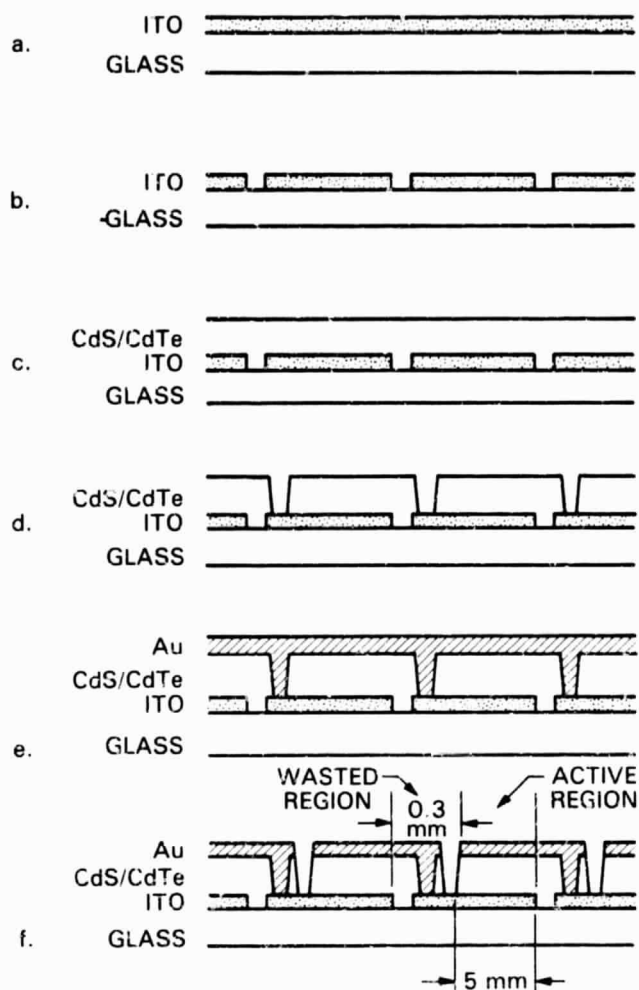


Figure 15. Fabrication Steps for an Integrated Cell

P-CdTe/n-CdS devices have also been fabricated at Stanford University and in-house at SERI using hot-wall vacuum evaporation (HWVE). The most recent results from Stanford have shown 4.7% efficient CdS/CdTe heterojunctions in which both materials were deposited by HWVE.

A major objective in the SERI-DOE program is to make a stable low-resistance contact to p-CdTe. One possible solution is the use of an antimony-doped CdTe interlayer incorporated between the p-CdTe and the back contact. Interface resistance has been reduced to about 3.5 ohm-cm^2 using this method.

Additionally, a new electroless method for the deposition of p-CdTe films has been developed. The electroless method is based upon short-circuiting the thin-film substrate to an easily oxidizable redox component (e.g., Al, Cd) in the electrolytic bath. This method shows promise for routine low-cost film deposition, since it obviates the instrumentation for potentiostatic or galvanostatic control.

4. Industry Survey Highlights

The industry survey results are presented in Appendix A, with highlights in Table 8. It is apparent that current R&D work is concentrated on conversion efficiency improvement using relatively small-area cells ($<1 \text{ cm}^2$), and that the module-related work is still in the planning stage. Highest cell efficiencies achieved are 11.5% with a 0.2 cm^2 CuInSe₂ cell and 10.9% with a 1 cm^2 CdTe cell (DOE-SERI's 1984 goal is 12.5%, with 1 cm^2 cells). Pertinent data for these cells are shown in Table 9.

A number of researchers surveyed believe that most thin-film research has been based on empirical results, and better understanding of the materials physics and chemistry involved is required to achieve reliable high-efficiency devices. There was general agreement that for high-efficiency modules above 12%, multijunction cells such as CdTe/CuInSe₂ will be required in tandem structures. Optimism exists that a thin-film polycrystalline cell (CuInSe₂) with 12% efficiency is achievable in the near future. Such a cell technology could be capable of producing a 9%-efficient large-area single-junction module.

Table 8. Polycrystalline Thin Film Technology

Organization	Materials	Deposition Process	Cell Structure	Progress	Plan
Ametek	CdTe	electro-deposition	MIS, single-junction	8.6% eff., 2 mm dia 6.2% eff., 10 cm ²	Production of 5% eff. 10 x 10 cm cells at 70% yield
Boeing	CuInSe ₂ / CdZnS	boat evaporation	hetero-junction	11% eff., 1 cm ² 10 x 10 cm submodules with effective area efficiency of 6.2%	12% eff. cell by 84 13% eff. cell by 85 9% eff., 5 x 10 cm module fabrication; P _{max} = 64W
Kodak	CdTe/CdS	close-spaced sublimation	hetero-junction	10.9% eff., 1 cm ² in 1982; further work suspended by Kodak	Kodak would resume PV R&D if market outlook improves
IEC	CuTnSe ₂ / CdS	effusion source system	hetero-junction	9.6% eff., 0.09 cm ² single-junction 3.0% eff., 0.09 cm ² multi-junction	subcells for 15% eff. multi-junction module; scaleable deposition
SMU	ITO/CdTe	chemical vapor deposition	hetero-junction	7.2% eff., 1 cm ² ITO/p-CdTe with Sb/W/graphite substrate	cell efficiency of 11% in '85 and 12% in 3 years
Monosolar/ Sohio	CdTe/CdS	electro-deposition	hetero-junction	9.34% eff., 1.4 cm ² 8.7% eff., 2.1 x 2.1 cm	10% or higher eff., commercialize thin- film cell/module

Table 8. Polycrystalline Thin Film Technology (Cont'd)

Organization	Materials	Deposition Process	Cell Structure	Progress	Plan
U. of Ill. (Telic)	CuInSe ₂ / CdS	magnetron reactive sputtering	hetero- junction	4% eff., 0.09 cm ² single-junction 10-ft- long, in-line deposition systems	advanced magnetron sputtering technology
ARCO Solar	CdS/ CuInSe ₂	boat evaporation	hetero- junction	11.5% eff., 0.18 cm ²	

Table 9. Polycrystalline Thin Films 1984 Status

Cell	V_{oc} , V	J_{sc} , mA/cm ²	FF	Efficiency, %	Stability
(Cd, Zn)S/ CuInSe ₂ (Boeing)	0.437	38.5 ^a	0.65	11	Excellent: Boeing Battelle SERI outdoor
CdS/CdTe (Kodak)	0.755	16.7	0.648	10.9	Back contact photodegradation not solved

^aHighest current of any PV cell

SECTION V

FUTURE RESEARCH NEEDS

A. RIBBON SILICON SHEET

Several silicon-ribbon processes have been under development by the National Photovoltaics Program and by industry for more than 10 years. Extensive research efforts are continuing on the more promising of these technologies, which include EFG, web, RTR, ESR and LASS. At this point, modules made by the EFG process have been commercially available for more than a year and RTR modules are expected to be available to the marketplace in 1985.

Continuing research is still needed in support of all of the ribbon-silicon technologies, however. Among the remaining research issues are: (1) minimization of ribbon stress, especially at high growth rates; (2) the value of and stability of hydrogen passivation in ribbon materials; (3) understanding and minimization of twin-plane and grain-boundary electrical activity; (4) understanding of and minimization of impurity and inclusion problems, such as SiC inclusions in material grown from graphite boats or dies, and (5) the development of growth monitoring and controls that allow full closed-loop ribbon growth. All of these factors should lead to high cell efficiency in production. The following paragraphs touch briefly on needed research in these areas.

Ribbon stress is being studied extensively under current contracts with the University of Kentucky, Westinghouse, and others. Considerable progress has been made in understanding of the cooldown dynamics of both the plastic and the elastic regions for typical EFG and web ribbon-growth geometries. The region starting at the solidification interface and proceeding through the plastic region to the beginning of the elastic region still needs much study to develop an understanding sufficient to guide experimental growth researchers in improving the growth process throughput to an economic position. For example, web ribbon typically is now grown at 6 to 8 cm^2/min . Steady-state growth of low-dislocation, low-stress web ribbon must achieve 20 to 30 cm^2/min in automated, closed-loop-controlled furnaces to achieve DOE targets and economic application. Research is needed on the formation of dislocations at the growth interface, the movement or annealing of dislocations throughout the plastic region, and the formation of or annealing of dislocations during ribbon cooldown.

Hydrogen passivation using a Kauffman ion engine has been shown to improve efficiency significantly for EFG, RTR and web ribbon cells. The detailed improvement mechanisms are not yet well understood. In some cases, it is clear that grain-boundary electrical activity is being passivated, but in others, such as in the treatment of web cells, the mechanisms are not yet understood. In the web case, hydrogen-passivated cells have shown a markedly increased red response, indicating an apparent bulk material minority carrier lifetime improvement of a factor of two or more. Is this real? and if so, how did the hydrogen diffuse through the bulk of this single-crystal material? Can hydrogen-passivated cells retain their hydrogen-enhanced performance for a

20-year or 30-year module life? If the answers to these research questions verify the value of hydrogen passivation, then research is also needed to develop practical, scalable, continuous hydrogen treatment processes.

Research leading to an understanding of the electrical behavior of grain boundaries has been under way for some years. Much has been learned, but there are still many unanswered questions. Since all ribbons but web are polycrystalline, a good knowledge of grain boundaries, their activity, and passivation is essential. All ribbon materials also contain twin planes within crystallites. Moreover, the web process requires the presence of buried twin planes parallel to the ribbon surfaces. Little research has been done on the electrical and crystallographic properties of these twin planes. Can the twin planes effectively getter, pin, or terminate dislocations during cell processing? Do they serve as a getter for impurities? Can these twin planes be used to advantage in cell efficiency improvement? There is some evidence to suggest that, at least for web, these twin planes can serve to getter both unwanted impurities and dislocations. If these twin planes can be deliberately grown near the rear surface of the ribbon, can cell efficiency be improved through twin-plane gettering? Much research remains to be done to gain sufficient understanding to answer these questions.

Inclusions in silicon ribbons, particularly in those grown in furnace environments containing graphite, have been a significant problem in the past. In particular, EFG ribbon has had significant problems with μm -sized SiC precipitates, which tend to shunt p-n junctions and lower minority-carrier lifetime. Unfortunately, graphite seems to be the only die material that wets adequately for this ribbon process. Recent research progress (by use of asymmetric dies, for example) has been good in minimizing the inclusions and shifting them toward the back side of the ribbon. More research is needed, however, to develop ways to eliminate such inclusions completely. As long as any precipitate inclusions exist in ribbon materials, they will tend to limit cell performance significantly.

Automatic growth monitoring and control for continuous closed-loop ribbon growth is essential. This is an especially critical R&D issue for those ribbons that have very tight thermal management requirements and relatively slow growth rates. The web growth process is an example with both of these characteristics -- slow growth rate and extremely tight growth temperature-profile control requirements. Without automatic monitoring and control, it is doubtful that web can ever be commercialized. The National Photovoltaics Program has recently initiated a task-force effort at JPL to address the monitoring and control issue. This task force is composed of an FSA team with instrumentation and sensing expertise drawn from the JPL spacecraft-related sensing-specialist corps. It is expected that this R&D team will function over the next year to accomplish the task objectives.

An additional R&D task, which applies to all crystalline silicon sheet and cell technologies, is high-efficiency cell R&D. High-efficiency performance is essential for ribbons. Most polysilicon ribbons should have the potential to produce cells about 1% to 2% lower in efficiency than those produced on Czochralski wafers. Significant research efforts are essential to tailor the high-efficiency cell processes now being developed for the less-than-ideal sheet material typically produced by most ribbon processes.

For silicon ribbon technologies to reach their potential, the research efforts described above must be funded at an adequate level over the next two or three years. If research funding in ribbon-related areas drops below present levels, the necessary technology base may not develop in time to achieve the Program goals.

B. AMORPHOUS-SILICON DEVICES

National Photovoltaics Program R&D activities and plans for a-Si as outlined in the SERI Amorphous-Silicon Five-Year Research Plan are considered satisfactory for achieving the DOE Five-Year Research Plan objectives, based on the data collected for the issue study. However, if lower-than-planned research allocations occur in this area, the program may not acquire important knowledge needed for the a-Si technology base.

Both the DOE Five-Year Research Plan and the SERI Amorphous-Silicon Research Project Five-Year Research Plan have established goals of 12% efficiency for 100 cm² single-junction cells and 18% for 1 cm² multi-junction cells by the end of FY88. Although 18% may not be achieved by 1988, considering the present level of funding of the Program, successful multijunction cells of greater than 15% should be available by that time. Appendix B contains abstracted sections from the Amorphous-Silicon Research Project Five-Year Plan. This appendix outlines the National Photovoltaics Program approach to goals accomplishment. Once these goals are achieved, additional R&D effort will be needed to complete the understanding of module performance and expected module service life. Additional effort to develop successful large-area high-efficiency modules will also be required in the 1988-1990 period. The thin-film module R&D needs and projections are further addressed in Section VI.

Five major technical needs must be met before any PV technology can be expected to produce significant amounts of power in the U.S. electric grid:

- (1) Higher conversion efficiencies.
- (2) Stable, durable devices.
- (3) The ability to scale up to larger unit device sizes.
- (4) Field demonstrations over several years.
- (5) A cost-competitive product.

These issues indicate that a significant amount of research is needed before amorphous silicon technology can hope to affect the U.S. electrical-energy economy, even though a-Si products based on current technology may represent profitable business activities in consumer electronic applications.

A task force was convened early in FY83 to address the technical issues and to recommend the Federal effort in a-Si R&D through 1986. The research budget allocations are shown in Table 10.

Table 10. Amorphous-Silicon Budget Recommendations, Millions of Dollars

	Fiscal Year		
	1984	1985	1986
<u>R&D Category</u>			
Materials Research	3.4 (2.4)	3.7	3.1
Cell R&D	4.3 (3.3)	4.4	4.6
Submodule R&D	1.2 (0.5)	1.4	1.8
Module R&D	0.3 (0.1)	0.5	0.6
Process Development	0.4 (0.2)	0.7	1.2
Module Pilot Plant	0.0 (0)	0.0	0.0
Federal Amorphous-Silicon Budget, Annual Totals	9.6 (6.5)	10.7	11.3

(Actual budget allocations in parentheses)

Examination of the PV Program FY84 amorphous silicon research allocations, shown in parentheses in Table 10, shows that the total is less than that recommended by the task force, but the task force recommendations were based on a significantly larger total PV Program R&D budget than was actually the case for FY84. The relative distribution of funds is consistent with Task Force recommendations. Milestone accomplishment, however, will probably be delayed under this level of funding.

The Issue Study staff has come to the conclusion that current PV Program R&D activities and plans for a-Si are reasonable as outlined in the SERI Amorphous-Silicon Research Project Five-Year Research Plan.

The five major R&D activity areas identified in the Amorphous Silicon Research Project plans are:

- (1) Materials Research.
- (2) Cell R&D.
- (3) Submodule R&D.
- (4) Module R&D.
- (5) Process Development.

Based on issue-study collected data, specific future research needs in these activity areas are:

(1) Materials Research

- (a) Low bandgap materials including a-SiGe and other alloys.
A-SiGe has already been used for a bottom cell of tandem amorphous cells. It has desirable characteristics, and the effects of Ge addition for lowering the band gap are already under investigation. With a-SiSn, it has been established that the band gap can be lowered from 1.8 eV to 1.1 eV by the addition of a relatively small amount (10%) of tin, but electronic properties of the resultant material are very poor. Continued research with low-band-gap amorphous alloy materials is needed for eventual development of efficient multijunction cells.
- (b) Impurity effects in p, i, and n amorphous materials.
Systematic investigation of impurity and alloying effects with elements such as C, O and N is required in amorphous-silicon-alloy p, i and n materials that are prepared in a clean and well-characterized deposition system.
- (c) Transparent conducting oxide (TCO) materials. Research should be strengthened on TCO materials, which are currently limited to ITO and SnO_x , mainly because of existing experience. New materials require exploration, and problems with existing materials, such as the indium diffusion from ITO into a-Si, must be investigated.
- (d) Film deposition processes. It is important to obtain good characterization of gas and reaction kinetics in deposition system, as well as the film property characterization.

(2) Cell Research and Development

- (a) Establishment of clean cell deposition systems.
Contaminant-free and cross-doping-free deposition systems must be developed to obtain understanding of the effects of different contaminants on cell performance.
- (b) Establishment of cell-performance measurement standards.
Early establishment of consensus standards is desirable because it provides agreed-upon cell performance measurement procedures.
- (c) Effects of microcrystalline layers. Microcrystalline silicon layers have shown good optical properties as a window, and have also exhibited good electrical properties for ohmic contact. Relationships between microcrystalline film properties and deposition parameters require further research.

- (d) Improved understanding of photon-induced performance degradation. Continue research on the Staebler-Wronski effect to minimize cell-performance degradation.
- (e) High-efficiency, multijunction cell research. It is necessary to develop multijunction thin-film cells to achieve cell efficiencies of 18% or higher. An early increase in multijunction cell research effort is recommended.

(3) Submodule R&D

Trade-off studies between large-area single cell and integrally connected small subcells. Although such a study presently has a low priority, future definition of the subject trade-off and its experimental verification is needed for subsequent module development. Such factors as fabrication cost, yield, submodule performance, module integration and long-term durability must be considered.

(4) Process Development

Process development has low priority at present, as its directions will be contingent upon progress in areas discussed above. In addition, process development in the PV industry and in related a-Si industries (xerography, for example) should be tapped so that related, well-developed technologies can be integrated in the process-development phase of the Amorphous-Silicon Research Project.

(5) Module R&D

Module R&D must be considered in a similar manner as process development. However, the module cost-estimate studies should continue at low level to provide information for materials, cell, and submodule R&D. Another issue to be examined is the long-term interaction of available organic pottants such as EVA with active amorphous cell layers.

C. POLYCRYSTALLINE THIN-FILM DEVICES

It is believed that the role of DOE in the R&D of a-Si should also apply to the other two leading thin-film photovoltaic technologies, CdTe and CuInSe₂. Specifically, the bulk of the efforts for these two technologies should also emphasize primarily materials research, cell R&D, and submodule R&D through 1986. For the II-VI and II-IV-V₂ related thin-film polycrystalline technologies, Figure 16 displays the expected research directions. CdTe alloy and CuInSe₂-based heterojunction structures form the basis for the projected continued research efforts. These efforts include:

- Optimization of single-junction cells by investigating CuInSe₂, CdTe, and selected alloys of each.
- New research into complex cell geometries such as polycrystalline cascade devices for flat-plate applications.

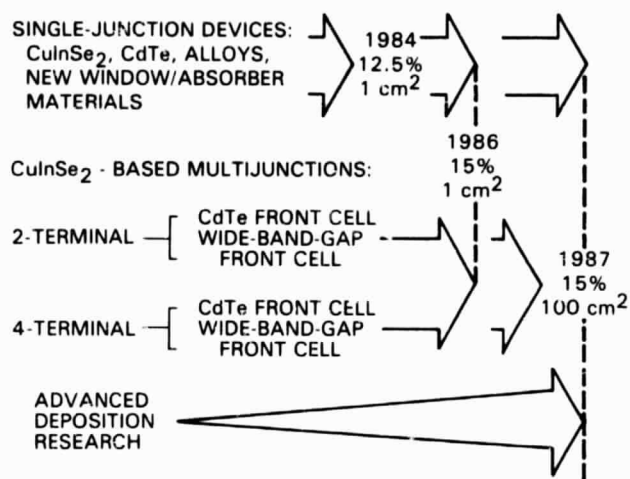


Figure 16. Opportunities in Polycrystalline Thin-Film Solar Cells

- The development of alternative heterojunction-partner (window) materials, including n-ZnO, n-CdO, n-SnO₂ and new p-type materials.
- The development of improved low resistance contacts, especially to p-CdTe.
- The development of low resistivity p-type CdTe.
- Advanced deposition research, including fundamental studies and studies of area-scalable device deposition techniques such as sputtering or electroplating.

1. Single-Junction Cells

At present the most promising single-junction cells are CuInSe_2 and CdTe, which have achieved efficiencies above 10%; other materials (Zn_3P_2 , Cu_2Se) have not been very successful. Therefore, current program priorities embrace CuInSe_2 and CdTe.

To achieve a 15% CuInSe_2 device it is necessary to enhance fill factor from about 65% to 75% to improve open-circuit voltage from 0.44 V to about 0.57 V. A major research direction that can be pursued to reach these goals is to produce CuInSe_2 alloys that have band gaps of 1.2 to 1.4 eV. If present CuInSe_2 materials properties (defects, composition) can be maintained or bettered, a higher V_{oc} should be produced. Given the high absorption coefficient of selected CuInSe_2 alloys, short-circuit current should remain near the optimum. With a large band-gap window (perhaps wider than the 2.5 eV gap of CdZnS) and wider-band-gap cells, current densities could be about 35 mA/cm^2 or more.

Progress with CdTe requires a different strategy. Major problems with CdTe are poor contacting and high bulk resistivity. High resistivity is thought to be due to electrically active grain boundaries and low carrier concentrations in the p-type material. Significant progress should be expected if these problems can be solved or reduced. One approach is the introduction of Hg or Sb to produce higher p-type conductivity and better contacting. This also lowers the bandgap, forcing a trade-off between reduced V_{oc} and greater current.

2. Multijunction Cells

Multijunction polycrystalline cells have not been investigated adequately. Only recently IEC successfully demonstrated a two-terminal CdTe/CuInSe₂ two-cell stack, showing both voltage addition (more than 1 V) and an increase of several mA/cm² current density.

Two-terminal and four-terminal stacked polycrystalline cells have trade-offs similar to single-crystal analogs. In two-terminal devices, current must be matched, and deposition process limitations may be significant. In four-terminal devices, the cells must be separately contacted, intercell reflection may need to be reduced, and extra insulating layers may be required.

For four-terminal devices, where current-matching is not necessary, the total achievable efficiency of a two-cell device is the efficiency of the top cell plus a fraction of the normal AM1 efficiency of the bottom cell. To a first approximation (if the spectral response of the bottom cell is flat), the efficiency of the bottom cell is its normal (AM1) efficiency times the fraction of the sunlight that reaches it when it is under the top cell. For instance, at AM1, a CuInSe₂ cell beneath a CdTe cell can receive about 35% of the incident solar photons². Thus, the achievable efficiency of a CdTe/CuInSe₂ four-terminal device would be the AM1 efficiency of the CdTe cell plus 35% of the AM1 efficiency of the CuInSe₂ cell. If the band gap of the top cell could be raised to near 1.75 eV without sacrificing efficiency, about 50% of the light could reach the bottom cell, raising the combination's total efficiency substantially.

Figure 17 shows a simple estimate of the practical, achievable efficiencies of CdTe/CuInSe₂ four-terminal devices. Note that efficiencies near 15% are within reach, given separate cells that are 11% efficient.

The performance of two-terminal devices is limited by the need to equalize the currents generated in the cells to achieve optimal performance. One might consider that allowing 50% of the spectrum to reach the bottom cell would equalize currents, but CuInSe₂ is such a good current generator that

²This is a conservative estimate based on counting photons between given intervals (the various band gaps) in the AM1 direct normal solar spectrum. The actual percentage of photons reaching the CuInSe₂ cell may vary between 35% and 45%, depending on spectral content. At AM1.5, similar photon counting suggests a 40% spectral fraction.

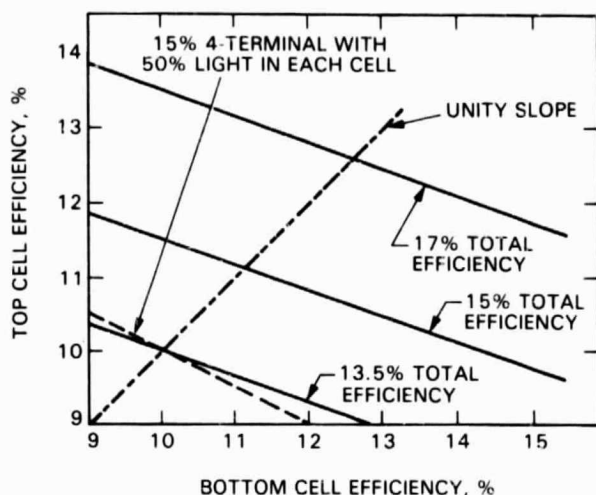


Figure 17. Estimate of Expected Efficiencies of Four-Terminal CdS/CdTe on CdS/CuInSe₂ Optically Stacked Cells for Various Separate Cell Efficiencies, Assuming that 35% of the Sunlight is Reaching the Bottom Cell

something less than 50% might be appropriate. Even the simplest calculations for expected efficiencies from two-terminal devices are complex in that they depend on the actual quantum efficiencies and physical properties of the separate cells. However, some simple projections can be made for the CdTe/CuInSe₂ device. A two-terminal version with V_{oc} about 1.25 V, J_{sc} about 16 mA/cm², and FF of about 0.75 would be 15% efficient. All of these parameters seem possible for cascade cells: 0.8 V and 0.45 V have been achieved individually for CdTe and CuInSe₂ cells; at a 40% spectral fraction, at least 16 mA/cm² should be available from CuInSe₂; and FF rises in CuInSe₂ devices for lower cell currents.³

In practice, initial cells are likely to be limited by light losses in the top cell. Sub-band-gap light that should theoretically pass through the top cell may still be absorbed, scattered, or reflected. These losses occur because of below-band-gap absorption in gap states near the band edge, scattering by impurities and grain boundaries, and interfacial reflections. Another required research task is the optimization of a transparent back contact for use in top-cell devices, especially for p-CdTe. Further optimization of the individual cells for use in cascade devices should provide opportunities for performance enhancements.

3. New Window Materials

Cadmium sulfide has been the most frequently used heterojunction partner with thin-film polycrystalline absorbers. Zinc has been alloyed with CdS to make Cd_{1-x}Zn_xS, raising the band gap. However, resistivity rises rapidly as Zn is added, and materials have not been made with Zn/Cd ratio

³Preliminary outdoor test measurements at SERI on (Cd, Zn)S/CuInSe₂ cells show an increase in fill factor at lower light intensities.

greater than 0.2 and band gap over 2.5 eV. There are substantial reasons for developing new n-type heterojunction partners (window materials):

- (1) To optimize single-junction top cells by letting the maximum number of solar photons reach the junction, and to better match various absorbers in terms of interface properties. Figure 18 shows several selected highly conductive, highly transparent window materials currently under investigation. Note the substantial fraction of photons lost by using CdS as the heterojunction partner.
- (2) To allow the maximum amount of light to reach the high-band-gap top cell of a cascade device, especially where the top cell is the one limiting the current.
- (3) To match new windows to bottom cells in cascade designs, where bandgaps can be as low as that of the top-cell absorber. For instance, n-CdSe or n-CdTe might be potential bottom-cell windows for p-CuInSe₂ beneath a CdTe top cell.

In addition, it is important to develop p-type windows to match n-type absorbers in four-terminal devices, where the polarity of top and bottom cells do not have to be the same, or for single-junction cells, to match with several alternative n-type absorbers that have not yet been optimized.

The p-type window materials would be useful in a number of specific cell designs where n-type absorbers may be advantageous, because they are frequently easier to contact. For example, n-CdSe might be usable as a good top-cell absorber at 1.7 eV if a high-conductivity, high-band-gap p-type window could be developed. Also, a substantial number of n-type absorbers (n-CdTe, n-CuInSe₂) exist and have not been exploited because of a lack of a p-type window.

4. III-V Thin Films

In addition, the family of III-V semiconductor has been selected as the basis of study for thin-film cells for the Advanced High-Efficiency Concepts Task based on the combination of high performance, controllability of physical properties, and well-developed research efforts. The research can be broken up into three broad overlapping areas. These are thin films, III-V films on silicon, and multijunction thin-film cells. In the first area, several concepts are under study for preparing polycrystalline films primarily for single-junction cells, as described above.

The second area includes heteroepitaxial growth of III-V's on silicon and offers the potential of building upon the mature silicon photovoltaic technology. Higher efficiencies could be obtained from the modules by adding a III-V layer to the silicon and a dramatic increase in performance could be achieved by using a high-band-gap alloy with an active silicon cell to form a two-junction cascade cell. The existing crystalline silicon module technology would remain largely unchanged for this multijunction flat-plate cell and module approach.

It is quite possible that the goals of 20% efficient multijunction thin-film cells can be achieved through continued improvements in the active semiconductor layers. The current program structure is directed toward obtaining these improvements. To push efficiencies significantly above present levels, solar-cell structures must be improved. Looking at recent improvements in efficiency in single-crystal silicon cells, it can be seen that the cell structures are much different from those of five years ago. The new crystalline silicon cells take advantage of effective surface passivation techniques, reduced recombination velocity near contacts, improved antireflection coatings and optical trapping. Conversely, for GaAs cells, the basic designs of planar, single-junction cells are largely unchanged over the last five years. New structures cannot be implemented without continuing III-V materials research to develop the necessary components of the structure. As was and is being done in silicon, the III-V photovoltaic researchers can benefit from participation with the non-PV community in establishing better understanding and control of all aspects of the materials.

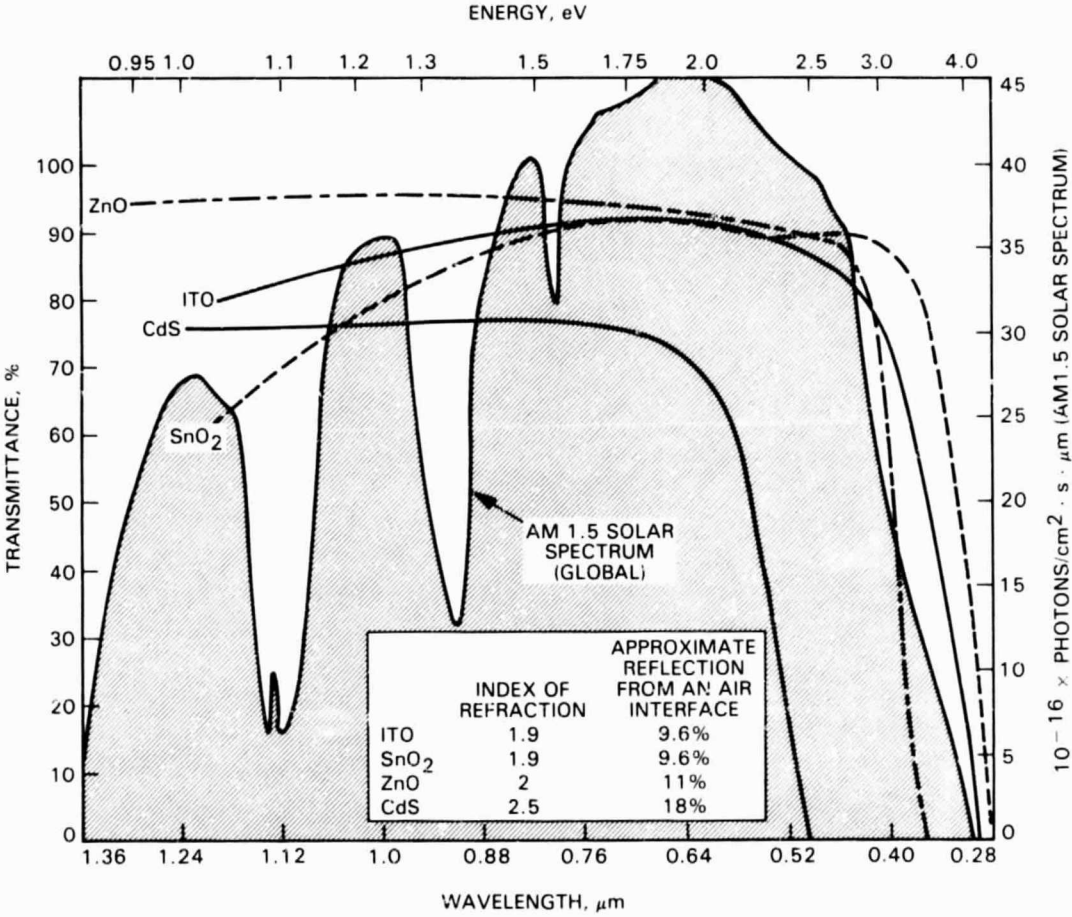


Figure 18. Window Materials: Transmittance of Selected High-Band-Gap Heterojunction Partners (Left Vertical Axis Applies to Materials; Right Vertical Axis Applies to Spectrum)

SECTION VI

MODULE TECHNOLOGIES

A. RIBBON-MODULE TECHNOLOGY

The ribbon technology chosen for this investigation is based on the dendritic-web growth process being developed by Westinghouse (see Section III). The processes that were analyzed are essentially those used by Westinghouse for the Module Experimental Process System Development Unit (MEPSDU) contract (1980). Since there is continuing process development, the results shown here are conservative; however, these module results can be considered typical for use with all ribbon technologies. The module packaging (encapsulation) technologies considered here are similar to those used at present by a number of crystalline-silicon module manufacturers. EVA is the module laminant with glass superstrate. No further design discussion is necessary here because of the similarity to today's commercial practice. Rather, the advancements or changes from present practice will occur principally in module assembly automation as annual module manufacturing volumes increase.

The projected advanced web growing process is considered an early 1990's technology. The advanced web grower will be capable of producing 16.3% encapsulated-cell-efficiency ribbon (15% module efficiency) at a rate of 30 cm²/min. For this projected process, the cost of the silicon feedstock material is assumed to be \$14/kg (1980 \$) by 1990. This commercially scaled plant will be capable of producing 27 MW/yr of 60 x 120 cm modules. A more complete description of the processes can be found in Reference 13.

Recent cost analyses for manufacture of silicon web modules have shown a projected cost of \$76/m² (1980 \$). The two most expensive module manufacturing process steps completely dominate the cost: advanced web growth and module lamination. The web-growing process is nearly one third of the total technology cost, with nearly half of the web-growing process cost being the materials cost. Similarly, the laminating process is approximately one fifth of the total technology cost, with nearly 70% of that cost being the materials and more than half of the materials cost being the cost of the glass superstrate.

For a 15% efficient module, the module cost-per-watt rating is 50.5¢/W. The highest-efficiency web modules manufactured to date (30 x 120 cm) are 13.2%, with 12.5% modules being typical. These are among the highest flat-plate module efficiencies attained using current technology.

B. AMORPHOUS-SILICON MODULE TECHNOLOGY

Amorphous-silicon module design and cost assessment is in progress at SERI, and preliminary results are contained in a report (Reference 14) that includes the leading module design being investigated, and the requirements and assumptions for the module design. A separate discussion on bypass-diode protection that offers a design consideration to protect against cell failure resulting from reverse bias (negative voltage) is also included.

1. Design Requirements

Previous studies of solar-cell modules have served to define the technical requirements for durability, performance and safety. Technical requirements that an amorphous-silicon module will have to meet for general commercial applications are discussed here.

The outdoor environment under which any PV modules, including amorphous-silicon modules, must operate places important structural requirements on design. The modules can be expected to encounter various physical or environmental loads in their lifetimes, including the effects of wind, seismic activity, and snow and ice buildup. Amorphous-silicon modules must withstand physical shock from hail, thermal shock from changes in air temperature and solar heating, and abrasion and soiling from environmental contaminants such as dust and smog. The solar cells and interconnect layers within the modules must be protected against moisture. Other environmental factors limit the choices of materials used in module construction.

Several design requirements relate to the modules' electrical operation. Electrical isolation must be considered within the solar-cell structure, the module, and the array, for abnormal conditions of current surges and excessive voltages that could occur for various off-nominal operation and/or failure modes. Electrical failures should not result in fire, safety hazards, or failure propagation beyond the initial point of failure. If a failure has occurred, the module design should allow for easy fault detection and replacement.

Safety requirements set specific limitations for operating voltages, materials, and physical characteristics. The solar cells and electrical connections should be insulated so that they do not pose an unnecessary hazard to persons from electric shocks. Materials used in construction should not endanger the environment or operating personnel, even if the module is accidentally damaged. The need to be able to handle the modules safely during installation and replacement limits the size and weight of acceptable module designs.

Technical design characteristics generally must be traded off against the need for low production costs. Similarly, trade-offs exist between module efficiency, size, and production costs. All of these must be considered in the design of amorphous-silicon modules. The only aspect of module design that will be dealt with explicitly in this section is the optimization of module output given certain cell characteristics, voltage requirements, and diode protection requirements. Module dimensions and materials are given conditions for the analysis.

2. Module Concept

Monolithic series-connected cells within a module differ significantly from those in a module based on the current crystalline silicon technology. The solar cells are a thin film of amorphous silicon material deposited on a substrate, rather than slices of crystalline silicon ingot. Cell interconnections are made with films of aluminum and transparent conductive oxide material rather than with grids of metal sintered to the

cell's surface. Because the cells are made by the deposition of films, their design characteristics are governed by the nature of the materials and the desired output from the module.

The design of the module has the advantages of potentially low fabrication costs, low and uniform current density and high voltage in a single module. Individual solar cells considered here are thin strips running the entire width of the module. The narrow width of the solar cells is governed by the sheet resistance of the transparent conductive oxide. The long solar cells provide an internal parallel connection redundancy, thereby adding to the module's reliability. The large-area module is assumed to be 4 x 4 ft., approximately 120 x 120 cm.

3. Assumptions for Module Design

Characteristics of the solar-cell material are based on the research work performed at RCA under SERI contract. The assumption is that large-area commercially produced cells in 1995 will be able to match the performance of today's small-area cells produced under laboratory conditions.

The cells' current, voltage, and associated electrical parameters taken from the RCA work and additional assumptions used in the module design are listed below:

Open-circuit voltage (V_{oc})	= 0.84 volts
Short-circuit current density (J_{sc})	= 17.8mA/cm ²
Fill factor (FF)	= 0.676
Efficiency (Eff)	= 10.1%
Cell area	= 1.09 cm ²
Reverse-bias voltage of the cell (V_{RMAX})	= -6.7 volts
Diode forward voltage drop (V_{FD})	= 0.7 volts
Sheet resistance of transparent conductive oxide, (P_{TCO})	= 5 Ω/\square
Gap width between cells (w)	= 100 μ m

4. Module Design Analysis

Key parameters of module design, cell width, and the maximum number of cells in a bypass group, depend on the characteristics of the amorphous-silicon solar cells and the TCO.

The optimum cell width (W_{OPT}) is calculated as $W_{OPT} = 0.49$ cm. The maximum number of cells in a bypass group (N_{MAX}) is calculated, on the basis

of allowable reverse bias of the cells (V_{RMAX}), as $N_{MAX} = 8$. These results in combination with the assumptions made about the solar cells allow us to calculate the following module characteristics:

Cell width + cell gap width = $0.49 + 0.01 = 0.5$ cm

Number of series connected cells in module = $120/0.5 = 240$ cells

Module operating voltage = $240 \times 0.63 = 151$ 150 volts

Module open-circuit voltage = $151 \times 0.84/0.63 = 201$ 200 volts

Module short-circuit current = $120 \times 0.5 \times 17.8/1000 = 1.07$ amps

Module operating current = $120 \times 0.5 \times 16/1000 = 0.96$ amps

Module power = $150 \times 0.96 = 144$ watts

Module packing fraction = $0.49/0.5 = 0.98$

5. Module Configuration

A possible configuration of a 120 x 120 cm module without a built-in diode is shown in Figure 19. However, it can still contain one discrete bypass diode placed at the end of the module.

The cell interconnection is shown in Figure 7. If further evaluation indicates a need for protective diodes within the module, the configuration shown in Figure 20 may be a solution.

Calculations indicate that a bypass diode should be installed in the module across every eight cells. Since each cell in the module will generate about 1 ampere, the bypass diode should be rated to carry at least 1 ampere.

In this configuration, the aluminum metallization of every eighth cell is extended toward the end of the module for bypass diode connections. This extended aluminum will be thicker so it can carry 1 ampere.

To have room on the module for the bypass diodes, a 1.5-cm space is provided along one side of the module. This is a loss of approximately 1% of active cell area. This module schematic is shown in Figure 21.

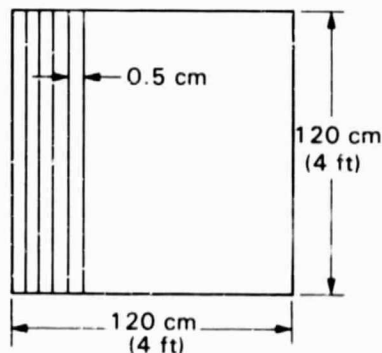


Figure 19. Monolithic Amorphous-Silicon Module

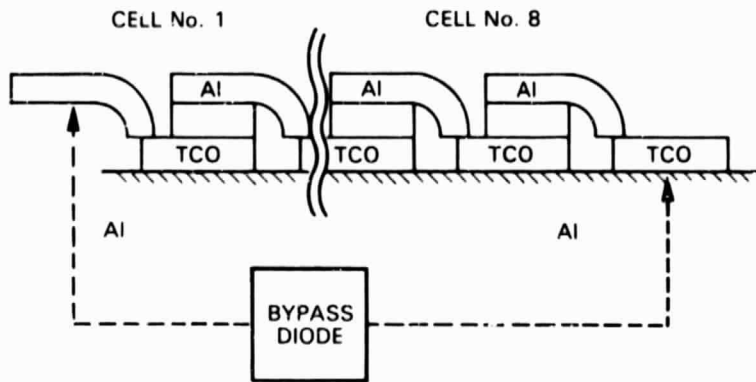


Figure 20. Bypass Diode Connection Schematic

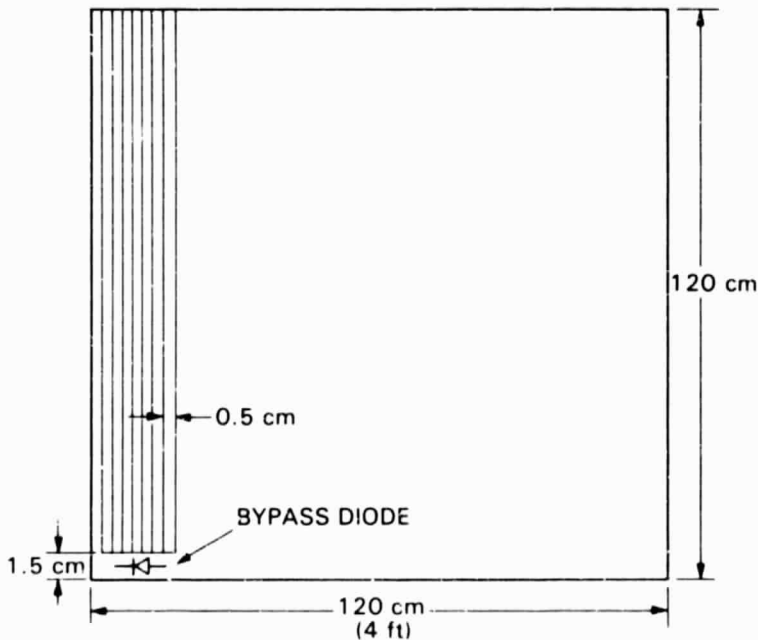


Figure 21. Module with Bypass Diode Across Every Eighth Cell

6. Cost Assessment

Amorphous-silicon module cost estimates are being developed by SERI, based on conceptual designs. The preliminary data indicate that those costs per unit area may be about a factor of 2 lower than those of the silicon ribbon module. These estimates assume large-scale production in the 1995 period and must be considered preliminary, as the amorphous-silicon module is in the early stages of development. A description of the conceptual module production process steps and cost breakdown is contained in Reference 14.

C. THIN-FILM POLYCRYSTALLINE MODULE TECHNOLOGY

The thin-film polycrystalline module design is taken from a SERI Research Report (Reference 15).

In this report two module concepts are reviewed. The major difference between the two is that one uses metal grid current-collection fingers for the front contact and the other uses a transparent conductive oxide. The cell design is basically similar to that described in the discussion on amorphous silicon, i.e., monolithic deposition, scribed cell divisions, and series-connected module design. The design requirements described in the section of amorphous-silicon module are also appropriate here. The use of bypass diodes also is considered.

1. Module Concept

As with the amorphous-silicon module, the thin-film polycrystalline module consisted of a large area of monolithic series-connected cells. The solar cell used in the module design is the Boeing (CdZn)S/CuInSe₂ cell shown in Figure 22. The Al grid contact is shown in the cross sectional view of the metal grid fingers mentioned above.

Parameters representing the material properties and cell characteristics were projected on the basis of current technology and future expectations based on achievement of the goals set forth in the National Photovoltaics Program Five-Year Research Plan. A list of important cell and module parameters used in the design of the modules is given below:

Cell and Module Parameters

Cell efficiency	15%
Cell open-circuit voltage	0.570 V
Cell short-circuit current density	0.035 A/cm ²
Cell operating voltage	0.456 V
Cell operating current density	0.03281 A/cm ²
Module dimension	4 x 4-ft.
Transparent conductive oxide sheet resistance	5 Ω/\square

For a monolithic module design, calculations can be made to find the cell width and contact design that will optimize module performance. The calculations are based on the information in the list of cell and module parameters given above, along with process constraints such as the minimum possible gap between cells and other practical considerations in module construction. The subject is well covered in Reference 16.

The module's design must begin with the selection of its basic structure. Two factors tend to dominate the selection of a structure. The

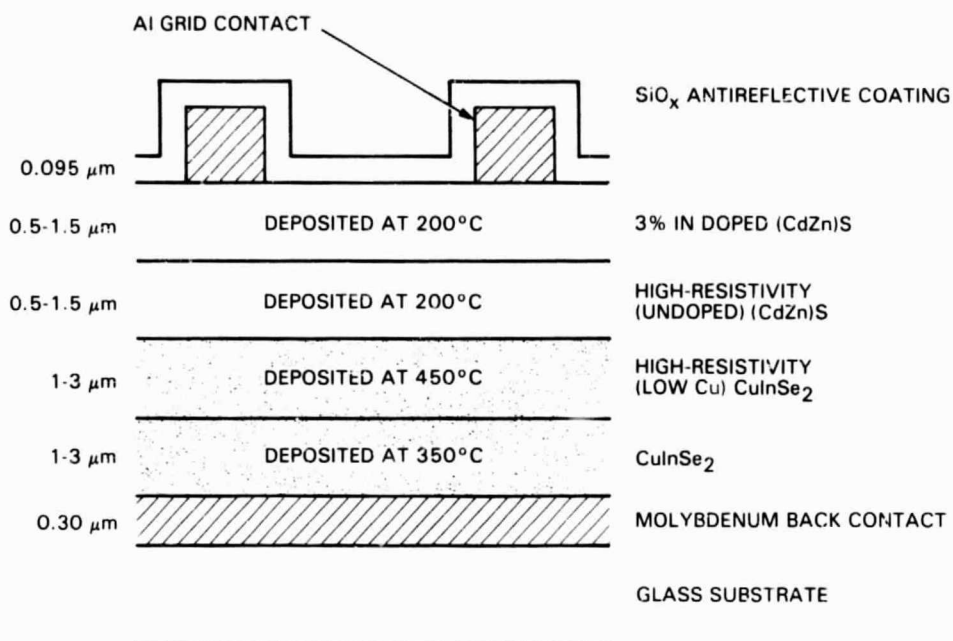


Figure 22. Cell Structure Showing Deposition Temperatures and Material Composition

first is the relatively high sheet resistivity of the window side of the solar cells. The typical approach to overcoming this problem is a metallic grid on the surface to collect the photocurrent. For moderate-sized solar cells, the grid shades about 10% of the active area, resulting in a corresponding loss in power output. For a large-area module as proposed in this study, the shading losses would be even larger. The second factor entering into the selection of the structure for the modules is the potential for low manufacturing costs. The structure must be simple enough that processing steps and handling are held to a minimum. Furthermore, fabrication requirements should be consistent with relatively low-cost high-volume manufacturing techniques.

To use the monolithic module structure design for (CdZn)S/CuInSe₂, a few changes are necessary and desirable because of the difference in material from amorphous silicon. The most important change is in the way the solar cells are made. Fabrication of the amorphous-silicon module begins with the deposition of the antireflection coating and the top contact on what will be the front cover glass. The solar cells are constructed from the top down. For (CdZn)S/CuInSe₂ solar cells, the proposed fabrication order is reversed. The heterojunction between (CdZn)S and CuInSe₂ probably cannot tolerate the 450°C temperature at which the CuInSe₂ is deposited. Therefore, modules would be constructed on a supporting substrate with the back contact, antireflection coating and glass cover being the last steps in module production.

Another module structure change is to replace the TCO front contacts with metallic grid fingers, as shown in Figure 23. The contacts are tapered fingers of metal that extend over one edge of a solar cell, forming a series connection with the back metallization of the adjacent solar cell. A TCO

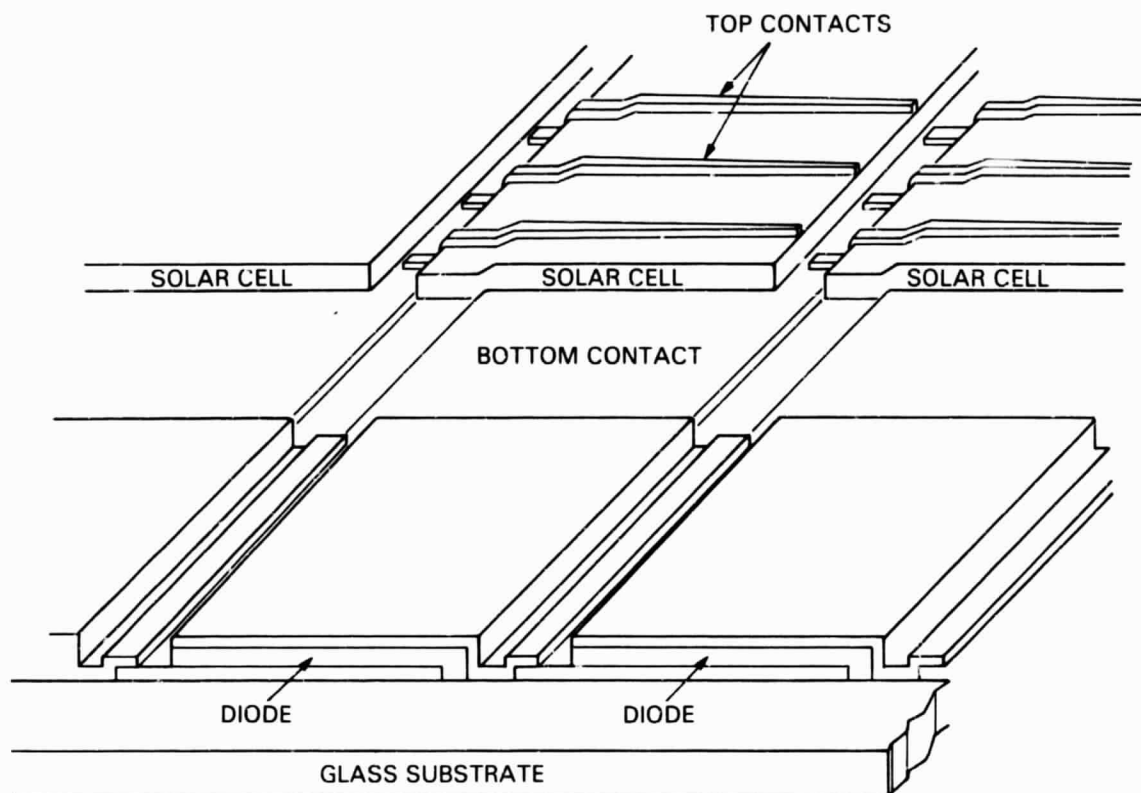


Figure 23. Monolithic Module Design for $\text{CuInSe}_2/\text{Cd(Zn)S}$ Solar Cells

contact is considered as an alternative design structure because there has not been enough research work done on this type of module to establish which is the most effective contact design. A complete discussion of each process step can be found in Reference 16.

After completion of the module design effort, a sequence of manufacturing steps was developed to produce the modules on a commercial scale. Cost estimates were developed for each manufacturing step. Some of the manufacturing process descriptions and cost information were taken from SERI's Advanced Photovoltaic Module Costing Manual. The Jet Propulsion Laboratory Solar Array Manufacturing Industry Costing Standards (SAMICS) methodology was used for the preparation of the remaining cost estimates. Format A process descriptions were developed for the manufacturing steps and cost estimates were calculated using the SAMICS Improved Price Estimation Guidelines (IPEG) equation.

2. Module Cost Assessment

At present, polycrystalline thin-film cost estimates are being developed by SERI, based on conceptual designs and on module technology that is still in the early stages of development. Preliminary cost estimates indicate that the polycrystalline thin-film module cost is about the same as that of the amorphous-silicon module. These estimates assume large-scale production in the 1995 period, and the confidence level is similar to that for

the amorphous-silicon module. A description of the conceptual module production process steps and cost breakdown are contained in Reference 14.

D. MODULE TECHNOLOGY ISSUES

A number of important issues relevant to cost projections and their implications for future research and development of thin-film cells and modules were uncovered during the analysis:

- (1) The overall module cost estimate is sensitive to material thickness and deposition rates for individual processing steps. The most important example is the CuInSe_2 deposition step, where very little is known about deposition rate limitations or required material thickness. If the deposition rate for this processing step were doubled, total module costs would be reduced. Processing cost estimates for the $(\text{CdZn})\text{S}$ solar cell layer, front and back cell contacts, and the antireflection coating display similar sensitivities to these assumed parameters.
- (2) The heterojunction between $(\text{CdZn})\text{S}$ and CuInSe_2 cannot tolerate temperatures as high as those at which the CuInSe_2 is deposited, making it necessary to construct the cells on a substrate rather than on the back of a glass front cover.
- (3) The module design work indicated that metal grid contacts have a distinct advantage over TCOs for the front cell contact, except possibly in the area of contact degradation (corrosion due to moisture, etc.). Transparent conductive oxide films have not been developed with properties as good as those assumed in the module design analysis (95% light transmittance and sheet resistance of 5% or less). The light transmittance might be further reduced by increased material thickness. It may be necessary to deposit extra contact material to ensure adequate thickness at the edge of each cell where the TCO goes over a corner on its way to making contact with the back metallization of the next cell. Another problem stems from the poor conductivity of the TCO. Cells must be made narrower in width to lower the resistance losses in the top contact, but the packing efficiency drops because the gap between cells is fixed. Finally, the gap between cells is actually larger for the TCO module design because an additional scribing step is required to isolate the top contact after deposition. The last two problems reduce the active cell material area by around 3%, compared with the module design using metal finger grid contacts.
- (4) Questions remain about the deposition methods selected for the CuInSe_2 solar-cell layer. Two different methods were considered: evaporation and reactive sputtering. The evaporation method relies on a new technique to control material evaporation rates, using Knudsen cells. Controlling the evaporation rate and composition of the deposited cell material may still be a problem using this approach. Copper is the most difficult to control because of the high temperature required (1400°C). Unfortunately,

even less is known about the potential of the alternative method, i.e., reactive sputtering. Preliminary work has been promising, but cell efficiencies are well below those produced by evaporation. The process descriptions in the referenced SERI report are for considerably higher deposition rates and larger deposition areas than have been demonstrated.

- (5) Bypass diode protection was included in the module design using metal-grid front contacts and also in the design using TCO front contacts. No additional manufacturing process steps were required to construct the bypass diodes in the module with metal grid contacts. The diodes and interconnects were constructed of the same materials as the solar cells and the back and front contacts. For the module design employing TCO front contacts, an additional masking step and metal deposition step were required to complete the interconnection of the bypass diodes.
- (6) Although material costs are important in the final module cost, the cost of the semiconductor materials is not significant. Materials used to encapsulate the module are the principal material costs. Glass for the back substrate and for the front cover and the materials used in the edge seal raise the encapsulation system's share of total module cost. A more significant finding was the small contribution made by the solar-cell deposition steps to the total cost of materials used. Indium and selenium are expensive materials and might have been expected to influence the final module cost estimate heavily.

E. THIN-FILM MODULE RELIABILITY

A key area of concern with thin-film module design is developing a technology base to integrate the emerging thin-film cells and materials into reliable 30-year-life modules. This section reports on the JPL thin-film reliability and engineering activity to accelerate the development of this technology base.

The research areas associated with achieving reliable thin-film power modules can be divided into two general groups: those associated with achieving long-term reliability, and those associated with achieving needed module electrical performance (cell integration and module engineering research).

1. Reliability Research

Achieving 30-year-life thin-film modules requires solutions to the same generic problems as those facing crystalline-silicon modules. These include galvanic and electrochemical corrosion of cell metallizations, photothermal degradation of encapsulants, voltage breakdown of electrically insulating encapsulants, delamination of encapsulants, hot-spot damage to cells and encapsulants, front-surface soiling and glass breakage. Because of the thin metallization layers inherent in thin-film cells, they are likely to

be much more sensitive to damage due to corrosion mechanisms. Similarly, hot-spot heating of cells is likely to be affected by the low cell shunt resistances from point defects and the greater susceptibility to junction shunting due to cell overheating. Glass breakage is substantially complicated by the common application of an electrically-conductive tin oxide layer, which requires a 400°C processing temperature that tends to remove glass temper.

In addition to these module-level failure mechanisms, there are a number of issues relative to the intrinsic reliability of the thin-film cells themselves. Light-induced degradation of cell efficiency and point defects (junction shorts) are areas of active research at SERI and elsewhere in the cell-physics community.

2. Cell Integration and Module Engineering Research

The second major challenge to achieving application-ready thin-film power modules is electrically integrating the cells in a way that avoids major performance losses due to the high series resistance, variable efficiency, and numerous point defects (junction shorts) generally encountered in thin-film cells. Research topics include developing analytical methods for calculating the performance impact of the abovementioned loss mechanisms and arriving at cell geometry and interconnection circuits that control losses to tolerable levels. Reliable attachment of leads to thin-film cells is a major problem, as typical crystalline-Si methods such as soldering and ultrasonic bonding lead to extensive cell performance degradation. Measurement methods for quantifying electrical performance of thin-film cells and modules are poorly defined at present, due to the lack of stable cells to serve as reference cells, to the highly varied spectral response characteristic of different cells, and to the absence of solar simulators that have accurate spectral irradiance distributions. The industry now relies on outdoor sunlight measurements, a technique that is not suitable for large-scale production.

SECTION VII

CONCLUSIONS

The PA&I Center study team, with the assistance of SERI and JPL team members, have studied the collected data on silicon sheet and thin-film cell and module technologies and, based on their judgment and on the opinions and comments of the researchers interviewed, have arrived at the following summary statements:

A. GENERAL

- (1) Unlike the wafered-silicon cell technologies, which are limited by the sawing process, both the silicon-ribbon and the thin-film cell and module technologies have the potential to achieve the long-range goals for flat-plate modules if the Government continues vigorous support of its National Photovoltaics Program by funding as planned (in the DOE Five-Year Research Plan) or proposed by the responsible task managers at SERI and JPL. Funding at or less than the current level will jeopardize the timely achievement of the long-range goal. Continued strong support of the Program by the industry is also a key need to maintain progress momentum and to ensure the success of the program.
- (2) Among the silicon-ribbon cell and module technologies, the web-process and EFG-process cells and modules are most promising. Their highest cell efficiencies achieved to date are 16.7% and 14% respectively.
- (3) Amorphous-silicon cells have already been commercialized, at least in consumer electronics applications that do not demand competitiveness with utility-level energy production. The reported highest single-junction cell efficiency is 11.5% with 1 cm^2 cells. The efficiency goal of 12% efficiency with 100 cm^2 cells appears to be achievable in 1988 (SERI Amorphous Silicon Research Schedule) without depending on any breakthroughs. However, the achievement of module efficiencies in the 15% range is unlikely with single-junction amorphous silicon cells.
- (4) Some degree ($\approx 5\%$) of photon-induced degradation may be unavoidable with a-Si cells.
- (5) Polycrystalline thin-film technologies have made remarkable progress, especially during the past few years, despite the relatively limited research effort. Although the small-area cell efficiencies at 10% to 11% with both CuInSe_2 and CdTe cells remained unchanged during the last year or two, large-area ($>10 \text{ cm}^2$) cells have begun to show efficiencies in the 6% range. Cell modeling and cell characterization are also making good progress.

- (6) The achievement of 15% efficiency small-grain polycrystalline thin-film and amorphous-silicon modules requires considerable research effort, and almost certainly requires multijunction devices. Successful future thin-film multijunction cells might consist of a CuInSe_2 or Ge bottom cell or possibly one of the innovative chalcopyrite materials with a band gap of 1 eV or less combined with a thin-film GaAs or GaAlAs high-efficiency top cell, or CdTe if high enough conversion efficiency is achieved to enable its use as the top cell. Other combinations may utilize amorphous and polycrystalline thin films or even an amorphous or polycrystalline thin film, each on top of a silicon-ribbon bottom cell.
- (7) Industry opinions were that extensive research efforts are still required in the areas of materials and materials property theory and analysis, as well as measurement techniques and standardization for reliable evaluation of cell and module performance.

B. SILICON RIBBONS

- (1) The web ribbon process has extremely high module performance potential; 13.4% efficient 30 x 120 cm modules have been made, and 16% modules are possible without research breakthroughs.
- (2) The web process is limited by growth throughput. Ribbon growth throughput must be improved by a factor of 2 to 4 and the process must demonstrate steady-state closed-loop ribbon growth for long periods of time for successful large-scale production.
- (3) If the above growth improvements for web are not achieved by 1986, industry will probably lose interest in further process development.
- (4) The buried twin planes found in web may be beneficial to cell performance in that they can function as gettering sites for impurities and crystalline defects during cell thermal processing.
- (5) The EFG process has made great progress, especially in the past year or two. The nonagon growth process now produces adequate sheet growth rates and still has the potential for improvement by a further factor of 2 to 4.
- (6) Efficiencies of EFG cells now average 11%, with some cells over 14%.
- (7) The only ribbon process now in commercial module production is EFG. The experience factor gained from this production and field experience feedback is extremely valuable in guiding future process research and development.
- (8) Solavolt expects the RTR process to become available in modules early in 1985.

- (9) The ESR process is being developed by Arthur D. Little, Inc. However, the level of experience is very low compared with those of EFG and web.
- (10) Continued low-angle silicon sheet ribbon research over the next two years should allow evaluation of the potential for growth of thin, flat-surface ribbon.
- (11) There may be some potential for eventual growth of single-crystal ribbon by the LASS process.
- (12) All ribbon processes continue to be limited in growth rate by stresses and potential buckling. Stress-related modeling and research should continue and should be closely coupled with experimental growth research work.
- (13) Several cell-performance enhancement approaches such as Kaufmann hydrogen ion engine passivation and the small-area MIS contact techniques developed by Martin Green can potentially be applied to the several ribbon technologies. These techniques have the potential for efficiency improvement by several percentage points over those cell efficiencies currently achieved on ribbon silicon.

C. AMORPHOUS-ALLOY CELLS

- (1) Amorphous-silicon cells are now considered a commercial product for small consumer goods such as watches, radios, calculators, and small battery chargers. These cells are generally not packaged to withstand an outdoor environment and do not have high enough efficiencies for bulk power-generation applications.
- (2) Analyses show that amorphous-alloy power modules can be made in large-quantity production for about \$34/m². Current efficiency of a 100 cm² submodule is about 8%. Efficiencies for large modules must achieve 12% or higher to be economic in U.S. grid-connected applications.
- (3) Single-junction large-area amorphous modules are not likely to achieve greater than about 10% efficiency, as small-area cell efficiency is expected to be limited to about 13% to 14%.
- (4) Multijunction amorphous-alloy or amorphous-polycrystalline cells and modules must be developed to achieve large-area module efficiencies greater than 12%.
- (5) Amorphous-silicon alloys with high band gap as well as amorphous alloys with low band gap require continued research for eventual integration into high-efficiency tandem cells and modules.
- (6) Transparent conducting oxide materials require increased attention to improve optical and electrical properties. The interaction between TCO and amorphous silicon should be examined carefully to project device durability.

- (7) Early operation of clean cell fabrication systems and establishment of standardized baseline film deposition parameters are important to interchange of R&D results. The cell-performance aspects related to fabrication processes can be readily assessed once a repeatable baseline process is established. The directions for future advancement can also be better projected using such a baseline.
- (8) Analytical efforts for cell modeling must be continued to achieve understanding of cell performance and to identify areas for improvements. Photon-induced degradation is one such area.
- (9) Experimental work in multijunction amorphous silicon cells should be increased. The work can be done in parallel with single-junction cell research, since synergism can be expected to accelerate the progress.
- (10) Module-related research must be increased steadily with strong joint funding by industry. The timing should be such that the amorphous silicon technology industrialization can be achieved smoothly in the early 1990's.
- (11) Total industry funding of amorphous-silicon-related R&D is of the order of 10 times the R&D effort sponsored by the National Photovoltaics Program.
- (12) There are now eight significant industrial amorphous silicon R&D groups in the United States. One or two more large R&D efforts are likely to emerge in 1985.

D. POLYCRYSTALLINE THIN FILMS

- (1) Small-area-cell efficiencies are in the 10% to 11% range with both CuInSe_2 and CdTe cells. Large-area ($\approx 100 \text{ cm}^2$) cells have begun to show efficiencies in the 6% range.
- (2) Excellent work is now being done in the thin-film polycrystalline R&D area. Results of research efforts are beginning to be very significant. If the present rate of progress continues, a basic understanding of the materials and cell technologies should come together over the next two to three years for at least CuInSe_2 and CdTe technologies. This could lead to a spurt in cell-performance progress in 1987-1988.
- (3) Carrier-collection mechanisms in CuInSe_2 cells must be resolved early. Are these cells really heterojunctions or homojunctions?
- (4) Much of the present behavior of CuInSe_2 cells is probably influenced, or even controlled, by grain-boundary effects. It has been postulated that multiple grains are series-connected electrically by tunnel junctions. Much of the observed behavior of CuInSe_2 cells, including low V_{OC} , might be explained by such a mechanism. More cell modeling work is required.

- (5) Research toward high-efficiency tandem polycrystalline thin-film cells requires strengthening, since tandem cells are almost certainly needed to achieve high module efficiency with polycrystalline thin films. Combinations of differing polycrystalline cell technologies as well as polycrystalline and amorphous combinations should be researched.
- (6) To increase the rate of development of understanding, it appears appropriate to focus any possible additional near-term R&D funding on basic polycrystalline materials research.
- (7) A realistic Polycrystalline Thin-Film Project research plan should be written instead of the existing draft plan.
- (8) Module-related R&D has a secondary priority at this time. However, some module-related research, including materials' compatibility in modules, fabrication process scalability and module-cost estimates should be strengthened.

E. SUMMARY STATEMENT

The conclusions presented in VII A, VII B, VII C, and VII D on the status and perspective of silicon sheet and thin-film cell and module technologies have been drafted by the PA&I Center study-team members with the concurrence of the SERI and FSA study team members. To summarize these conclusions, the PA&I Center study team members prepared the following summary statements. These summary statements are personal opinions and recommendations formulated by the PA&I Center team and do not reflect managerial views of PA&I Center, SERI and FSA. Therefore, they should be carefully judged by DOE management for use in directing the DOE PV Program; consultation with the respective research centers is recommended.

- (1) Considerable progress has been made with wafered silicon sheet technologies to improve efficiency, improve reliability, and reduce cost. However, the wafer technologies will have great difficulty in meeting DOE PV Program goals for flat-plate collectors, primarily because of limitations in sawing technology. Continued support of float-zone research will improve the present state of the art of wafered-technology cell performance and is recommended.
- (2) Silicon-ribbon technology, especially web ribbon, continues to show great promise for achievement of higher module efficiency and reduction of flat-plate module cost to \$75/m² in the early 1990's. Continued support is highly recommended toward solving the problems of high-speed ribbon growth. Strong industry participation and cost sharing is essential for continued progress.

- (3) Module efficiencies near 12% using single-junction thin-film module technology, or amorphous-silicon or polycrystalline thin-film technologies, could be achieved in the late 1990's. Module cost in the range of \$40/m² may be achieved when large-scale thin film depositions and module facilities are developed.
- (4) Thin-film amorphous and polycrystalline cell and module technologies have the potential of meeting the DOE PV flat-plate module program goals only if cells are formed into multijunction monolithic structures. Therefore, increased emphasis should be placed on multijunction cell research.
- (5) It is clear that it is too early to pick a winner from among the various technologies. A winner may not emerge for several years. There is also a strong possibility that both silicon ribbon and thin-film single-junction or multijunction modules will have long-term commercial power generation applications in 1995 and beyond.

SECTION VIII

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APPENDIX A

INDUSTRY INTERVIEWS

This appendix contains summary statements collected during interviews with selected industry representatives who are involved in research on silicon ribbon, amorphous and polycrystalline thin-film technologies. The information addresses level of research effort conducted, objectives and status of research, corporate-sponsored research tasks, and comments regarding U.S. Department of Energy (DOE) objectives, DOE program direction, needed research to be funded by DOE in support of industry, corporate plans, and PV industry needs and expectations.

Interviews were also held with Electric Power Research Institute (EPRI) representatives on general research issues of interest to the electric utility industry.

The data sheets are collated as follows:

Ribbon Technology

Westinghouse Electric Corp.
Mobil Solar Energy Corp.
Soliavolt International
Energy Materials Corp.
Arthur D. Little, Inc.

Amorphous Silicon

Spire Corp.
Chronar Corp.
Energy Conversion Devices, Inc., with Standard Oil Co. of Ohio
(Sovonics Solar Systems)
Solarex Corp.
ARCO Solar, Inc.
Minnesota Mining and Manufacturing Co.
Institute of Energy Conversion (also included in polycrystalline group)
Exxon Research and Engineering Co.

Polycrystalline Thin Film

Ametek, Inc.
Eastman Kodak Co.
Institute of Energy Conversion
Boeing Co. (Sovolco)
Southern Methodist University
Monogram Industrials Research Laboratory (Monosolar) with
Standard Oil Co. of Ohio
University of Illinois

Utility Industry Issues

Electric Power Research Institute

RIBBON TECHNOLOGY SURVEY

ORGANIZATION: Westinghouse Electric Corp.
Pittsburgh, Pennsylvania

INTERVIEW: Site visit on August 16, 1984, with Don Roberts, Bob Campbell, Stu Duncan.

1. Technology category, key words:

Low-cost silicon sheet, silicon ribbon, dendritic web.

2. Level of effort:

Ribbon-growth-related contracts from the Flat-Plate Solar Array Project (FSA) \$1.1M in 1984.

Utility partner and Electric Power Research Institute (EPRI) support \$1.7M in 1984.

Westinghouse Corp. support \$1.3M in 1984.

3. Objectives:

To develop the silicon dendritic-web crystal-pulling technology to meet steady-state throughput goals of 30 cm²/min using continuous melt replenishment and closed-loop growth control. A module pilot plant is to be set up with a capability of about 1 MW/year. CY84 objective is 10 cm²/min rate for 10 meters pull to be achieved routinely and repeatably.

4. Status:

Current peak module efficiency is 13.3%.

Current peak web growth speed is ≈ 3 cm/min for ribbon 5 to 6 cm wide and 150 μ m thick; 1.5 cm/min is a more typical linear growth rate.

The oxide flaking problem in the growth furnace is nearly solved.

Molybdenum contamination from the susceptor is apparently not a problem. Moly concentration in the ribbon is $<10^{12}$ /cc.

Melt replenishment is now in use in R&D furnaces.

Dynamic shields allow relatively high pull rates after start of growth.

5. Plans:

Automatic closed-loop control of growth process.

Improve thermal management in growth region for high-speed, low-stress growth.

Build 1 MW semi-automated pilot line in 1986.

TiPdCu cell metallization may be changed to PdNiCu in the future.

6. Comments:

Photovoltaics presentations were made to Westinghouse top management (T. Murrin, D. Danforth). Stronger corporate commitment is hoped for.

Key ribbon-growth R&D issues: growth speed, ribbon stress, oxide flaking, melt replenishment, boat construction, ribbon-growth and temperature-profile sensing, closed-loop growth control.

Low-frequency induction heating is used.

Multiple heat shields above, below, and around the boat control temperature profiles.

Continuous replenishment not yet in use in production furnaces.

Present sources of silicon shot for replenishment appear adequate.

Westinghouse production cost analyses have indicated that 12%-efficient modules made with ribbon grown at 20 cm²/min. in a 25 MW/year plant can achieve \$0.50 to \$0.70 per watt (1980 \$). This manufacturing plant could be in place by 1989.

A 10 cm²/min. growth rate in a 1 MW/year pilot plant should yield modules equal in cost to those made with Cz material.

Westinghouse market studies have shown that Westinghouse could capture a \$425M business share of the PV market in the 1990-2010 period if Westinghouse project goals are met over the next few years.

Ribbon width is not limited to present widths of 5 to 6 cm.

RIBBON TECHNOLOGY SURVEY

ORGANIZATION: Mobil Solar Energy Corp.
Waltham, Massachusetts

INTERVIEW: Telecon with K. Ravi on September 13, 1984.

1. Technology category, key words:

Silicon ribbon, low-cost silicon sheet, edge-defined film-fed growth (EFG), nonagon silicon sheet growth.

2. Level of effort:

Flat-Plate Solar Array Project (FSA) contract: \$367,000.

Mobil nonagon development done entirely with Mobil funds.

3. Objectives:

Low-cost, high-speed quality ribbon sheet and module production using EFG process.

4. Status:

Mobil now grows nonagons 2 in. on a side; typical thickness is 13 mils with 100 cm²/min growth rate; 14% cells can now be made; average is about 11% using current process. Hydrogen passivation also increases cell efficiency by 15% to 30%, but is not a part of current process sequences.

5. Comments:

Module production near 200 kW/year.

Nonagon facets are now cut to make cell blanks by two methods, laser and diamond saw. The diamond saw gives best yields so far.

Potential 16% to 17% cell efficiency appears realizable in the future.

Present EFG sheet is grown from non-symmetric dies so that the carbon inclusions (SiC) are concentrated near the rear surface of the sheet.

Mobil will deliver 37 kW of EFG modules for the Sacramento Municipal Utility District (SMUD) Phase II installation.

Approximately 480 ft. of ribbon can be grown from a given quartz crucible setup before change-out of crucible assembly is required.

Growth rate of EFG can be tripled in the future by going to 4-in. facets and by increasing linear growth speed by 50%.

RIBBON TECHNOLOGY SURVEY

ORGANIZATION: Solavolt, Inc.
(Motorola Inc. and Shell Oil Co., are parent organizations)
Phoenix, Arizona

INTERVIEW: Phone conversation with Arnie Lesk on September 12, 1984
Phone conversation with Bill O'Connor, President, on
September 18, 1984.

1. Technology category, key words:

Low-cost silicon sheet, silicon ribbon, chemical vapor deposition (CVD)-deposited silicon sheet, laser or electron-beam recrystallization, ribbon-to-ribbon (RTR).

2. Level of Effort:

No government support since 1981.

Process development done on corporate funds (level unknown).

3. Objectives:

Maintain a position in the module market while developing RTR process.

Introduce limited RTR process product to market in 1985.

Produce RTR module products at cost lower than competing module processes.

4. Status:

Solavolt is producing on the order of 200 kW per year of polycrystalline Si modules.

Crystal Systems, Inc., heat-exchange method (HEM) ingots provide about 60% of present production sheet supply; the remainder is Wacker Silso. The HEM material is wafered at Solavolt International.

The RTR process is producing better-quality cells than was expected at this time.

Cell and module initial production processes are now being implemented.

5. Comments:

Solavolt expects to scale up production with RTR when product can undersell sliced polycrystalline-silicon wafer technologies.

Wafered polycrystalline silicon is today's low-cost PV module technology.

The RTR process is expected to achieve efficiencies equal to those achieved with sliced polysilicon processes and within 1% of that achievable with Czochralski wafers by about 1986.

RIBBON TECHNOLOGY SURVEY

ORGANIZATION: Energy Materials Corp. (EMC)
South Lancaster, Massachusetts

INTERVIEW: Telecon interview with Dave Jewett, President, on September 13, 1984.

1. Technology category, key words:

Silicon ribbon sheet, low-cost silicon sheet, low-angle silicon sheet growth (LASS).

2. Level of effort:

FSA/DOE PV funding level in 1984 \approx \$296,000.

Venture investor support also of same order of magnitude as Federal funding.

Also has FSA contract for low-cost copper-silicon alloy matrix solar-grade silicon refining process.

3. Objectives:

Low-cost, very high-growth-rate silicon-sheet process.

Achieve flat or nearly flat sheet surface.

Reduce sheet thickness to 15 mils or less.

Achieve single-crystal or nearly single-crystal growth.

4. Status:

Ribbon that has planar surface regions of several cm^2 can be pulled.

Recently completed clean facility for better growth environment control.

5. Comments:

Limited partnership exists between EMC and funding partners.

RIBBON TECHNOLOGY SURVEY

ORGANIZATION: Arthur D. Little, Inc.
Cambridge, Mass.

INTERVIEW: Telecon interview with E. Sachs on September 13, 1984.

1. Technology category, key words:

Low-cost silicon sheet, edge-supported ribbon (ESR).

2. Level of effort:

No current National Photovoltaics Program support.

Corporate support continues at relatively low level.

3. Objectives:

Develop a low-cost ribbon-sheet process capable of producing cost-effective, high-efficiency PV cells and modules.

4. Status:

Customers have fabricated 12.5% cells on ESR.

Ribbon growth is stable.

Ribbon 6 cm wide, 2.5 cm/min growth rate, 10-12 mils thickness.

Minority carrier diffusion length is 70 μm .

5. Plans:

Commercialize ESR process.

6. Comments:

Ribbon stress remains a critical issue. Federal funding of stress studies is wasted; the actual ribbon growers should receive all R&D funding.

Process has no die problems.

Process does not require critical temperature control.

Federal thin-film goals are very optimistic.

The whole thin-film module technology area is way off and is highly overfunded.

AMORPHOUS-SILICON TECHNOLOGY SURVEY

ORGANIZATION: Spire Corp.
Bedford, Massachusetts

INTERVIEW: Telecon with Vic Dalal on September 10, 1984.

1. Technology category, key words:

Multijunction amorphous cell, glow-discharge deposition, SiGe low-band-gap cell alloy.

2. Level of effort:

\$530K in FY84 from the Solar Energy Research Institute (SERI) and an equivalent amount from Spire and Spire's venture partner, Polaroid Corp.

Sandia National Laboratories now funds Spire for developing III-V-based multijunction cells for concentrators.

3. Objective:

Develop a glow-discharge deposition system and to produce 16% efficient two-junction or three-junction cells in three years.

4. Status:

A single-chamber glow-discharge deposition system has been constructed and is in operation. The chamber wall is plasma-cleaned to avoid contamination.

A six-chamber deposition system has been constructed one year ahead of schedule.

Several a-Si:H cells exhibited 6% to 6.5% efficiency, according to the measurements made by the University of Delaware.

P-type, a-SiGe:H alloy films having 1.5-eV band gap have been successfully deposited. Such a film is an excellent window for an a-SiGe:H bottom cell ($E_g \approx 1.45$ eV).

A proof-of-concept multijunction cell, p,a-SiC:H/i,n,a-Si:H/p,SiC:H/i,n,a-Si:H, has been fabricated. The two subcells were series-connected by a n,a-Si:H/p,a-SiC:H tunnel junction. Although the cell efficiency was low ($\approx 3.2\%$), the tunnel junction did function to cascade the open-circuit voltage.

5. Plans:

Cells 1 cm^2 of 12% to 15% efficiency within two years.

Development of a 1.45 eV low-band-gap a-SiGe bottom cell.

Operation of seven-sector multichamber reactor for stacked-cell fabrication, to begin in October 1984.

Maximize efficiencies of single-junction cells using a-Si, a-SiGe, a-SiC or a-Si(Hg) as subcell candidates.

Continue theoretical and experimental studies of multijunction cells to improve efficiencies and reduce cell degradation.

6. Comments:

Achievement of 15% multijunction cell efficiency in two years should be straightforward.

Large-area submodule efficiency should be 12%.

Cell degradation can be reduced to less than 5% with multijunction cells because contributing mechanisms, i.e., surface and volume effects, can be decoupled.

For the low-band-gap cell, a-SiGe:H is crystallographically and electronically better than a-SiSn:H.

Optimum band gaps of two-junction cells are 1.8 eV and 1.45 eV for top and bottom cells. Cells p,a-SiC:H/i,n,a-Si:H (1.78 eV), and a-SiGe cells with 20% Ge having 1.5 eV band-gap energy, are being fabricated and tested individually.

Fully functional modules, 12% to 15%, will be tested in 1989-1990. Similar modules will be available commercially in 1991. It will take \$30M research and development funds at Spire through 1990 to accomplish this.

A multijunction device is superior to a single-junction device because of wider selection of cell materials and smaller photon-induced degradation.

Cell material research should be emphasized over module research while the technology is still in an early stage of development.

Crystalline superlattice structures may be an alternative to all amorphous structures.

There is only one multijunction contract with SERI, in comparison with a multiplicity (redundant) of single-junction contracts.

Promoting of synergisms and increased communications between research organizations is in order.

AMORPHOUS-SILICON TECHNOLOGY SURVEY

ORGANIZATION: Chronar Corp.
Trenton, New Jersey

INTERVIEW: Site visit, Alan Delahoy and George D. Self on August 17, 1984.

1. Technology category, key words:

Single-junction amorphous-silicon, glow-discharge deposition (new), CVD (old but continuing), six-pack deposition machine.

2. Level of effort:

Three-year \$6.2M SERI contract (30% cost-shared), single-junction amorphous-silicon cell and module development with glow discharge.

Continuation of CVD research contract with SERI at \$300K level.

About \$200K National Science Foundation grant for high-purity silane production.

About 12 people are involved in a-Si R&D (out of 90 total at Chronar).

3. Objectives:

Achievement of 12%, 1 cm² cell and 8%, 30 cm² module in 1986.

4. Status:

A single-chamber glow-discharge deposition machine that is capable of fabricating two six-packs (six 30 x 30 cm submodules) in two hours has been constructed. Six such interconnected deposition chambers are installed at the Trenton plant site, and are producing 30 x 30 cm submodules.

Small (10 x 10 cm) battery chargers with an active area efficiency of approximately 4% are now in the market. Subcells are series-connected using laser patterning.

Submodules 30 cm² are also under development for trickle charging of batteries in Caterpillar Co.'s construction machinery.

Submodules with areas 107 ± 2 cm² achieved 6% efficiency (1984 SERI Program milestone).

A 1 MW/year plant is under construction in the New York area.

A glass/SnO₂/p-i-n, a-Si:H/Al cell having 0.07 cm² area has achieved an AMI efficiency of 6% using p,a-SiC:H with E_g = 2.1 eV.

Research has been initiated on low-band-gap (0.9 eV to 1.4 eV) alloys for tandem cells.

5. Plans

Chronar's target is to have an automated 1 MW/yr pilot plant of operating in Princeton in 1988 or 1989, and commercial production starting in 1990.

Construction is planned or under way for 10 1 MW plants (five in North America, five abroad) in 1985. These plants will operate in a batch-process mode similar to the present process sequence at Princeton.

6. Comments

Stability problems are similar to those of everyone else ($\approx 10\%$ degradation in 30 h). The thermal cycle tests as well as outdoor tests are in progress (total of approximately 100 W of modules exposed at Princeton for four months).

Tandem cells are yet to come but don't know how soon.

Cell efficiency improvement expected at a rate of 1% per year; 8% in eight years is possible.

Module cost could be \$1.00/W in late 1980's, and possibly \$0.50/W with a continuous production process. Current cost is \$3.50 to \$4.00/W including \$2.00/W for labor, \$0.17/W for glass, \$0.20/W for silicon, \$0.80/W for aluminum, plus other consumables.

The a-Si market at 1 MW plant size with 5% module is satisfactory for the time being. A large potential remote market already exists in Australia and Saudi Arabia.

The cell efficiency goals that have been widely publicized by DOE have slowed a-Si market growth. The bottom line, which is of consumers' concern, is the system energy cost.

AMORPHOUS-SILICON TECHNOLOGY SURVEY

ORGANIZATION: Energy Conversion Devices, Inc. (ECD) with Standard Oil Co. of Ohio (Sohio) (Sovonics Solar Systems)
Troy, Michigan

INTERVIEW: Site visit on August 14, 1984; ECD participants, Masat P. Izu, Vice President, Photovoltaics; Joseph J. Hanak, Director, Photovoltaic Processes and Products; Wally Czubyj, Advanced Device Research; Mike Hack, Theory; Steve Hudgens, Vice President Research, and Richard Bleiden.

1. Technology category, key words:

Multijunction amorphous silicon, glow-discharge deposition, Roll-to-roll (R-T-R), Ovonic photovoltaic processor.

2. Level of effort:

No government funding.

\$22M has been provided to date by Sohio to Sovonics Solar Systems, the joint venture with ECD.

Sharp Ltd., ECD Solar Inc. was formed in June 1982 to manufacture and market a-Si solar cell modules using a 3 MW/yr, six-chamber Ovonic PV cell processor.

A total of 150 people including Sohio employees and staff are involved in PV R&D in support of Sovonics.

3. Objectives:

Establish multimegawatt roll-to-roll, a-Si cell and module production capability.

Near-term (three to five years) efficiency goal of 15% and far-term target of 30% with tandem cells.

4. Status:

A 3 MW/year Ovonic PV processor has been installed at the Sharp PV plant in Nara, Japan. It is manufacturing tandem cells on 30 cm-wide stainless steel (SS) sheet (6 to 8 mils thick), and pocket-calculator-size modules are marketed at an unknown volume.

Single-junction, small-area a-Si laboratory cell achieved $\approx 10\%$ efficiency.

Multijunction a-Si cells (a-Si/a-SiGe) have achieved efficiencies better than those of Mitsubishi.

An ECD plant in the Detroit area is about to begin production of a-Si cells on 40 cm-wide SS sheet at an undisclosed rate using its Ovonic processor. The cells are shipped to the Sohio (Sovonics) module plant in the Cleveland area where they are assembled into modules.

Theoretical and experimental research on a-Si cell materials and cells is making good progress. Low-band-gap bottom-cell research and research to minimize the Staebler-Wronski effect are also in progress.

A 1.72 eV/1.4 eV cell band-gap combination is found most desirable for tandem a-Si cells, according to ECD analysis.

5. Plans

Bring ECD-Sohio a-Si module plants to full production.

Achieve 12% cell efficiency in three years, 15% in three to five years.

Develop a good low band gap cell material (1.2 to 1.4 eV).

Install an in-line inspection system in the Ovonic processor.

6. Comments

Continuous roll-to-roll process is the key to cost reduction.

Roll-to-roll process eliminates two-dimensional non-uniformity of deposited film that occurs otherwise. The non-uniformity in the film is limited to within 5% of roll edges with R-T-R process.

Silane gas impurity does not pose any problem.

Cell stability is better with multijunction cells. Subcells can be thin, and thin cells are basically more stable.

Achievement of 15% module efficiency is expected to be very difficult.

Good morphology of the SS substrate is important to achieve high efficiency cells. Steel surface defects having a μm dimension propagate into deposited film. Certain suppliers' steel cannot be used to make good cells.

For commercialization of a-Si modules on a large scale, government help is needed: i.e., sponsor a few large a-Si array experiments (such as SMUD).

AMORPHOUS-SILICON TECHNOLOGY SURVEY

ORGANIZATION: Solarex Corp.
Rockville, Maryland

INTERVIEW: Site visit on August 17, 1984 with John Corsi, President.

1. Technology category, key words

Single-junction amorphous silicon, glow-discharge deposition.

2. Level of effort:

\$1,000K in 1984 from SERI; unknown amount of corporate funding.

The Thin-Film Division has approximately 70 persons, including a few people in production, which is increasing now.

3. Objectives

The project goals for amorphous-silicon R&D are same as SERI's, but the internal Solarex goals are more aggressive.

4. Status

Pilot production of a-Si modules started in January 1984 at the suburban Philadelphia facility.

Modules having various sizes up to 20 x 20 cm have been fabricated.

An unknown quantity of calculator modules have been shipped to Hong Kong and Taiwan.

Battery chargers (12 x 13 cm) have been built.

An in-line production machine has been assembled and is being debugged.

5. Plans:

Increase a-Si module production.

6. Comments:

A 10% efficient, \$0.50/W large-volume production, low-cost module is possible in 1990.

A 15% module is desirable but difficult to achieve.

A 6% to 7% efficient module is highly probable in 1990.

Early a-Si modules will have 5% to 6% efficiencies, good enough for battery chargers. As efficiency improves, a-Si modules will begin to take over some (~50%) of the crystalline silicon market in the 1990's. If the DOE goals are met by then, a-Si could do better.

The a-Si market for the next few years will be production-limited rather than market-limited.

No specific research is conducted on multijunction cells at this time.

Long-term government funding, as in many foreign countries, is more desirable. Current DOE funds are spread too thin and multiyear continuity is not assured.

Crystalline-silicon product cost is limited by the cost of polycrystalline silicon. True low-cost production success of the Union Carbide Corp. refining process is questionable unless the fluidized-bed reactor (FBR) succeeds.

Ribbon silicon can be a viable technology if ribbon-growth problems are solved.

Leave the technology development to industry. Government should help develop the market.

Solarex has cancelled plans for a one-shot utility PV demonstration deal such as the 1 MW PV power plant that had been planned, mainly due to probable discontinuation of the Federal PV tax credit.

AMORPHOUS-SILICON TECHNOLOGY SURVEY

ORGANIZATION: ARCO Solar, Inc.
Woodland Hills, California

INTERVIEW: Site visit on September 18, 1984 with Don L. Morel,
Director, Advanced Research.

1. Technology category, key words:

Single-junction and multijunction amorphous silicon,
glow-discharge deposition, CuInSe_2 .

2. Level of effort:

All corporate funding.

One hundred persons in PV R&D including supporting staff. Eighty are scientists and engineers. Approximately 20 are in crystalline silicon, 40 in amorphous silicon and 20 in polycrystalline thin films. Analytical and QA-related staffers service all areas.

Manufacturing capability for crystalline-silicon modules and systems has been demonstrated with Hesperia, California, 1 MW and Carissa Plains, California, 4.75 MW systems.

Recent reorganization that reduced major ARCO Solar divisions to three divisions caused PV activities to move under the Metals Division for a short time. The PV activities have recently been shifted back under the same vice president in the Chemicals Division as before.

3. Status:

Single-junction, laboratory-size ($\approx 1\text{cm}^2$) a-Si cells have 10% to 11% efficiency.

A single-junction, 30 x 30 cm module has shown 7.9% module efficiency and 9% active area efficiency, according to SERI measurements in October, 1984. A large module, 30 x 120 cm, was 5% efficient.

Single-junction, a-SiGe cells with $\approx 5\%$ efficiency fabricated.

Addition of Ge in Si matrix causes rapid decrease of E_g . Ge percentages up to 40% appear to be practical.

A multijunction a-Si/a-Si cell 4 cm² achieved a conversion efficiency of 7%. Top cell thickness is approximately 200 Å. With such a thin cell, sub-band-gap absorption is not a problem.

There is no difficulty in fabricating an a-Si tunnel junction.

Amorphous materials including SiC, SiGe and others that are candidates for cells, are being systematically investigated.

Research on TCO materials is not limited to ITO; ARCO has not made any a priori choice for the TCO material.

4. Plans:

Improve laboratory cell efficiency to 13% to 15%.

Develop a-Si modules with 10% efficiency at a cost that customers are willing to pay.

Improve the module efficiency--cell efficiency ratio, from 2/3 up to 3/4.

5. Comments:

The utility market is well defined by the utility sector in terms of required efficiency and cost in \$/m².

Other a-Si markets, which are international, are difficult to deal with.

A 10% module efficiency at a satisfactory cost (to the customer) is a realistic target.

The thin-film market will start to develop for remote applications, which are more sensitive to cost than efficiency. However, when thin-film efficiency exceeds crystalline and thin-film cost becomes comparable with crystalline cost, the crystalline modules will be out of the marketplace. This could occur in five to 10 years, more like five years than 10 years. The market-penetration time element is crucial for the thin-film technology's survival.

An E_g of 1.85 eV for the top cell and 1.2 eV for the bottom cell is a theoretical optimum.

To make a TCO with less than 15 Ω/□ is not easy. Optical transmission and the yield both begin to suffer.

Not enough attention has been paid among the a-Si community to TCO development.

Similarly, more work is required in the superstrate-substrate area. Glass and stainless steel may not necessarily be the best choices.

The ARCO Solar CuInSe₂ cells are similar to those of Boeing. CdTe work has been put "on the back burner" for now.

Development of measurement standards for proper calibration of spectrum-sensitive amorphous-silicon cells should be funded by the government.

Current government support in advanced materials and devices has been spread too thin.

Any serious (and large) PV organizations will do the production scale-up development by themselves. Results coming out of the government-sponsored research on the above subject are of marginal value to large PV companies, since they already have the needed R&D results. Only the small companies will benefit from such work.

AMORPHOUS-SILICON TECHNOLOGY SURVEY

ORGANIZATION: Minnesota Mining and Manufacturing Co. (3M)
St. Paul, Minnesota

INTERVIEW: Telecon with Frank Jeffrey on September 6, 1984.

1. Technology category, key words:

Single-junction amorphous silicon, glow-discharge deposition, polyimide substrates, integrated subcells, roll-to-roll process.

2. Level of effort:

In 1984, \$765K from SERI equivalent funding from 3M.

About 16 persons (five investigators, two managers and nine supporting staff).

3. Objective:

Construction of a three-chamber deposition system for substrates up to 15 x 15 cm.

Demonstration of 12%-efficient, 2.5 cm² cells. Subsequent demonstration of 8% submodules, 100 cm².

Uniform i, n and p a-Si film deposition over areas up to 1000 cm².

4. Status:

An open-zone roll-to-roll deposition system (single chamber) capable of handling 10 cm-wide substrates is in operation.

Cells 5 mm² having a microcrystalline n-type top layer have been fabricated on a polyimide film and tested. An efficiency of 6.0% has been achieved.

Deposition rates up to 6 Å/s have been achieved using monosilane.

Depth profiling showed four orders of magnitude reduction of the boron concentration within 200 to 400 Å in the i-layer using the current open-zone deposition system.

5. Plans:

Construction of a three-chamber deposition system.

Achievement of 7% cell efficiency by the end of 1984.

Continuation of cell fabrication and cell degradation research.

Long-range development of the roll-to-roll module fabrication system.

6. Comments:

Company management is strongly supportive of the effort.

Remote stand-alone applications would be the near-term market.

Low level of government funding to educational institutions for basic PV research is causing shortage of graduates for hire in PV research.

Development of suitable high-temperature polymer substrates is a generic problem, but various companies are making reasonable progress -- not an insurmountable problem.

Good substrate morphology is very important.

AMORPHOUS-SILICON TECHNOLOGY SURVEY

ORGANIZATION: Exxon Research and Engineering Co.
Annadale, New Jersey

INTERVIEW: Telecon on October 11, 1984, with T.D. Moustakas, Corporate
Research Laboratory.

1. Technology category, key words:

Amorphous materials, sputtering, glow-discharge deposition, molecular beam epitaxy (MBE).

2. Level of Effort:

Corporate funding provided for fundamental research on amorphous materials, including amorphous silicon.

Seven to eight persons are involved in the thin-film materials research.

3. Objective:

Advance understanding of amorphous material properties and superlattice structures.

4. Status

A single-chamber sputtering system is in operation for deposition of a-Si films.

A SS/n-i-p, a-Si:H/ITO cell (1 cm^2) having microcrystalline n and p layers achieved an efficiency of 5.5% in 1983; $J_{sc} = 13 \text{ mA/cm}^2$, $V_{oc} = 0.86 \text{ V}$, $FF = 0.5$. The deposition required removal of the specimen from the chamber after each layer deposition for system cleaning.

Currently, Exxon is only pursuing fundamental research on amorphous materials and not on solar cells.

5. Plans:

Terminate the sputter deposition work, and initiate MBE research for superlattice fabrication involving crystalline III-V compounds.

6. Comments:

Amorphous-silicon cells could potentially achieve cell efficiencies closer to theoretical values than is the case with crystalline-silicon cells. For example, 12% practical efficiency and 15% theoretical efficiency with a-Si versus 15% practical (19%, M. Green) and 30% theoretical efficiency with crystalline cells.

Single-junction a-Si cell efficiency of 15% can be achieved in three to five years.

V_{oc} and FF are key areas for improvement.

Resistivity of TCO can be reduced from $10 \Omega/\square$ by doping ITO with Sb or F.

Research is needed on wide-band-gap materials; 1.9 eV a-Si:H has already been obtained by sputtering. Other materials such as silicon nitride and silicon oxide are also candidates.

Photon-induced degradation problem can be solved, and multijunction cells would have less degradation than single-junction cells.

POLYCRYSTALLINE THIN-FILM TECHNOLOGY SURVEY

ORGANIZATION: Ametek, Inc.
 Paoli, Pennsylvania

INTERVIEW: Telecon on September 11, 1984, with P. Meyers and followup
 with Frank Schmidt, Vice President, Research

1. Technology category, key words:

CdTe, Schottky barrier cell, MIS structure, electrodeposition.

2. Level of effort:

No government funding in FY84.

Commercial production for Ametek instrumentation applications.

3. Objective:

Technology development for commercial production of specialty CdTe PV devices; Schottky barrier cell using electrodeposition method.

4. Status:

Ametek CdTe cells have achieved efficiencies of 8.6% with a 2-mm-dia-dot cell and 6.2% with a 10 cm² cell respectively. The cell structure is substrate/electrodeposited Cd (1 to 2000 Å thick)/electrodeposited CdTe (2 μm thick)/oxide film insulator/Ni Schottky barrier (2 to 300 Å thick)

N-type CdTe has 0.5 μm crystal grain size and 1.45 eV band gap.

5. Plans:

Fabricate small-area cell assemblies (30 to 100 cm²) at 70% production yield for flat-plate arrays for use in Ametek-manufactured instrument products. The efficiency goal for the production modules is 5%.

6. Comments:

The current Schottky barrier cell configuration is not suitable for 10% to 12% cells.

Tandem cells are not in Ametek's activity plans at present.

Cancellation between photogenerated majority carriers, which diffuse against the electric field, and the minority carriers, which drift along the field, tend to limit the open-circuit cell voltage.

Government funding should be for materials research, tax credits to stimulate PV consumer purchases, and market development.

POLYCRYSTALLINE THIN-FILM TECHNOLOGY SURVEY

ORGANIZATION: Eastman Kodak Co.
Rochester, New York

INTERVIEW: Telecon on September 11, 1984, with Y. S. Tyan on 9/11/84.

1. Technology category, key words:

CdTe, close-spaced sublimation (CSS).

2. Level of effort:

Kodak discontinued most research on CdTe solar cells in FY84.

Kodak's research laboratory is keeping the PV activity in the standby position with a minimum number of personnel.

3. Objective:

The objective was to achieve 12% efficiency with CdS/CdTe cells.

4. Status:

A 10.5% efficient, thin-film CdS ($0.1\ \mu\text{m}$ thick)/CdTe ($4\ \mu\text{m}$ thick) cell was fabricated by CSS in 1982. The film was deposited on a Nesatron (soda-lime glass coated with doped In_2O_3) substrate.

SnO_x deposition by CVD was experimented with in order to reduce high film resistivity encountered with In_2O_3 . The new cell using SnO achieved 10.9% efficiency ($0.1\ \text{cm}^2$).

PV research is continuing at a minimum level.

5. Plans:

If the PV market outlook improves, Kodak would probably come back into the PV R&D arena.

6. Comments:

A 12% efficient CdS/CdTe cell is achievable without much difficulty.

Kodak will not be interested in PV unless there is a sizable market. Therefore the research work had been directed toward process scale-up by making use of a "simple, monolithically integrated thin-film solar-cell array" (16th IEEE PV Specialists Conference, 1982).

Multijunction cell work was considered but not done at Kodak.

Advanced materials such as CdTe have not been fully developed and therefore a demonstration experiment involving thin-film modules is not recommended for government funding at this time. However, Kodak will not enter into the PV market unless a successful experimental system demonstration has already been made. Potential PV market exists in developing countries such as Communist China and India where electricity is not available in many parts of the country and is badly needed, especially in remote areas.

POLYCRYSTALLINE THIN-FILM TECHNOLOGY SURVEY

ORGANIZATION: Institute for Energy Conversion (IEC)
University of Delaware
Newark, Delaware

INTERVIEW: Telecon with John Meakin on September 12, 1984.

1. Technology category, key words:

CuInSe₂, CdTe, heterojunction, multijunction, amorphous silicon, CVD.

2. Level of effort

Funding of \$613K in FY84 from SERI for CuInSe₂-based tandem-cell research.

Seeking private funding for Cu₂S cell development

Thirty-five persons total: 15 in polycrystalline thin-film, 10 in a-Si, 10 supporting both areas.

3. Objective:

Achieve 15% submodule efficiency with a tandem cell, i.e. CdTe/CuInSe₂, in FY90.

4. Status:

A small-area (0.09 cm²) CuInSe₂/CdS cell achieved 9.5% ELH-lamp efficiency.

A small-area (0.09 cm²), CuInSe₂/CdS-CdTe/CdS tandem heterojunction cell achieved 3.0% ELH-lamp efficiency. The practical efficiency limit is 21%, according to a calculation.

A scalable deposition system for CuInSe₂ using feedback-controlled resistance heaters with Knudsen sources is in operation.

A program is being developed for module engineering.

5. Plans

Achievement of highest possible subcell efficiencies. This is required for a 15% efficient tandem cell.

Continue development of scalable film deposition schemes.

6. Comments:

Many people are not aware of the progress in, and underestimate the potential of, polycrystalline thin-film cells for both single-junction and multijunction cells.

A broad range of subcell combinations is available for tandem structures, e.g. CdTe/CuInSe₂ and polycrystalline thin-film plus amorphous thin film.

Module efficiencies larger than 12% are still 10 years away.

Reproducibility of desired characteristics of the production-scale cells depends upon uniformity of the source material quality and deposition uniformity. This requires appropriate engineering analysis and experimentation.

Ten-percent-efficient a-Si modules are achievable, but there are stability problems.

Thin-film semiconductor fabrication has been based largely upon empirical results. Better understanding of the physics and chemistry involved in thin-film fabrication is required.

POLYCRYSTALLINE THIN-FILM TECHNOLOGY SURVEY

ORGANIZATION: Boeing Aerospace Co. (Sovolco)
Seattle, Washington

INTERVIEW: Site visit on August 9, 1984, with Roger Gillette, Solar Systems.

1. Technology category, key words:

CuInSe₂, CdZnS, heterojunctions, multijunction devices.

2. Level of effort:

Funding of \$260K in FY84 from SERI.

Ten persons, including technicians, and other supporting staff are involved in thin-film research.

Boeing bought out the Reading & Bates, Inc., interest in the Sovolco venture in May 1984. Thereafter Boeing continued module commercialization, thin-film cell and cell-assembly research and development. The commercialization will probably be done by a Boeing licensee.

3. Objective:

Boeing's internal objective is to achieve 12% efficiency in 1984 and 13% in 1985 with a CdZnS/CuInSe₂ cell.

4. Status:

After the achievement of 11%-efficient CuInSe₂/CdZnS in 1983, large-area (10 x 10 cm) submodules have been fabricated and tested. The submodule consists of four 2.5 x 10 cm cells producing 1.6 V_{OC} output. An effective area efficiency is 6.1% under ELH lamp illumination without AR coating. The submodule structure is glass/Al grid/nZnCdS/pCuInSe₂/Mo/Ta/glass with the thin-film cell thickness between 0.3 and 0.4 mil.

Four of the 10 x 10 cm experimental submodules were made into a square module using ultrasonic bonding for interconnection.

5. Plans:

Fabrication of 60 x 120 cm modules, each consisting of eight 30 x 30 cm submodules. The submodule contains 12 30.5 x 2.5 cm cells, and the design output voltage and current are 15.6 V and 4.1 A at P_{\max} (64 W). The module efficiency target is 9%.

6. Comments:

EVA laminate's reactions with moisture and with CuInSe_2 require further research.

The stability of CuInSe_2 cells appears good. The material is already known to be stable at high temperatures, and Boeing experimental cells have been durability-tested during the past year.

Boeing will start multijunction cell research in the near future.

A reliable measurement standard is needed. The current standard cell is a silicon cell.

Boeing strongly desires government funding for research on in-line deposition process development, cell patterning development, and process scaleup.

According to Strategies Unlimited, the module sales price targets are \$2.16/W at 5.5 MW/year volume in 1990 and \$1.64/ W_p at 20 MW/year volume in 1993, including marketing and profit. The Boeing (Sovolco) target module cost in 1990 is \$1.05/W at 5.5 MW/year volume; 98% yield is expected after initial cell burn-in.

POLYCRYSTALLINE THIN-FILM TECHNOLOGY SURVEY

ORGANIZATION: Southern Methodist University (SMU)
Dallas, Texas

INTERVIEW: Telecon with T. L. Chu on September 13, 1984.

1. Technology category, key words:

CdTe, heterojunction, CVD.

2. Level of effort:

Funding of \$271K in FY84 from SERI

Funding from SERI in other related areas is \$135K in FY84 for Close-Spaced Vapor Transport of CuInSe₂ to Poly Solar, with Chu of SMU as the principal investigator.

3. Objective:

The objective of the CdTe research is to demonstrate the fabrication of CdTe heterojunction cells using a CVD technique.

Cell efficiency goals are 10% in 1984, 11% in 1985 and 12% in approximately three years with lab-fabricated large-area cells.

4. Status:

A 1 cm² ITO/p-CdTe heterojunction cell achieved an AM1 efficiency of 7.2%. The substrate is Sb/W/graphite.

The CVD-fabricated CdS/p-CdTe cells had poor characteristics, possibly due to chemical reactions at the interface.

5. Plans:

Attainment of improved resistivity uniformity with p-CdTe films. Desirable resistivity range is 20 to 50 ohm-cm. The current value is in the 100 ohm-cm range.

Formation of good ohmic contact with p-CdTe using an antimony interlayer.

Development of steel substrates to replace graphite.

6. Comments:

None.

POLYCRYSTALLINE THIN-FILM TECHNOLOGY SURVEY

ORGANIZATION: Monogram Industries Research Laboratory (Monosolar)
with Standard Oil Co. of Ohio (Sohio)
Inglewood, California

INTERVIEW: Telecon with Bulent M. Basol on September 11, 1984.

1. Technology Category, key words:

CdTe, heterojunction, electrodeposition.

2. Level of effort:

British Petroleum and Sohio, Cleveland, purchased Monosolar in July 1984; Current CdTe R&D is conducted under Sohio funding at the Monosolar Research Laboratory site in Inglewood, California, with B.M. Basol as a consultant through the end of 1984.

3. Objective:

Commercialization of thin-film cell and module by Sohio.

4. Status:

Achieved 9.35%, AM1.5 efficiency with CdS/CdTe thin-film cell with an area of 0.02cm².

Achieved 8.7% active area efficiency with a large-area (2.1 x 2.1 cm) cell.

The above cells were fabricated by the electro-deposition process.

5. Plans:

Transfer of Monosolar activity to Sohio.

Improve cell efficiencies to 10% or higher.

6. Comments:

Require more data on cell stability.

POLYCRYSTALLINE THIN-FILM TECHNOLOGY SURVEY

ORGANIZATION: University of Illinois
Urbana, Illinois

INTERVIEWED: Telecon with John Thornton, formerly with Telic Co., on
October 18, 1984.

1. Technology category, key words:

CuInSe₂, magnetron reactive sputtering, multijunction thin-film cells.

2. Level of effort:

Subcontract with SERI under negotiation.

Contract with EPRI under negotiation, ≈\$100K.

Total contract value through 1983 at Telic is \$962K.

Currently, three post-doctorate researchers plus five students are involved in PV work at the University of Illinois. Two persons were in PV research at Telic in 1983.

3. Objective:

Advance understanding of magnetron sputtering technology for its scalability and deposited-film quality.

4. Status:

Demonstrated reactive sputtering of Cu+In in H₂Se.

A reactively sputtered CuInSe₂ cell achieved an efficiency of 4% (3 x 3 mm cell) with $J_{sc} = 35 \text{ mA/cm}^2$.

Ten-foot-long in-line deposition system for fabricating four 2.5 x 2.5 cm (CdZn)S/CuInSe₂ cells, which was built at Telic, has been transferred to University of Illinois.

Module cost study at Telic, done jointly with SRI, indicated that a module cost of \$0.30/W_p at 25 to 50 MW/year is possible using the magnetron sputtering technology.

Assumed cell and module efficiencies were 10% and 8%, respectively. Systems would cost \$2/W_p installed at the utility site.

5. Plans:

Start subcontract-funded research at the University of Illinois.

Conduct ion-assisted deposition for SERI to improve cell morphology and performance.

Investigate a-Si film fabrication using both sputtering and glow-discharge deposition methods.

Conduct tandem-cell research for a-Si (1.7 eV) + CuInSe₂ (1.0 eV) cell structure in four-terminal configuration.

6. Comments:

Reactive sputtering using a magnetron is a scalable process, as has been demonstrated by the sheet-glass industry.

Reactive sputtering is better suited than boat evaporation for fabricating higher-order compounds such as ternaries and quaternaries.

C. ELECTRIC POWER RESEARCH INSTITUTE

The Electric Power Research Institute (EPRI) has interest in photovoltaics as a potential power generation source for utilities. Over the past years EPRI has funded a number of studies and workshops to review the photovoltaics technology research status, and to focus research objectives on utility needs in addition to funding modest research tasks to advance the state of the art. On August 10, 1984, a visit was made to EPRI to interview Ed DeMeo and Roger Taylor on utility objectives and prospects and on EPRI opinions about the potentials for ribbon and thin-film technologies. Highlights of their comments:

- The 15% average efficiency goal for flat-plate modules is considered essential for utility penetration. For thin-film devices, 15% module efficiency can only be achieved with multijunction cells. Multijunction cell modules may be constructed with a low-band-gap cell using CuInSe_2 or crystalline silicon and with a high-band-gap cell using CdTe or amorphous silicon.
- Polycrystalline thin-film single-junction modules are not expected to achieve efficiencies higher than 12% and cannot become competitive with higher-efficiency silicon devices, although they are potentially of lower cost per watt or per unit area.
- At present, amorphous-silicon research has a critical-mass effort compared with the other thin films. Four issues must be resolved:
 - (1) Efficiency
 - (2) Stability and degradation
 - (3) Low-band-gap alloys (a key area in the EPRI program)
 - (4) Deposition, scale-up
- Basic materials research is still needed to enhance the understanding of cell performance and of the limitations of thin-film devices.
- For silicon-ribbon technology, web (the only single-crystal-material ribbon) is the front runner and has the best chance of meeting the DOE long-range goal. Presently the web program is asking the right questions, is receiving the support of the Technical Advisory Committee, has the right management support, and hence is expected to make rapid progress.
- The Electric Power Research Institute is a partner in the web-ribbon research project jointly with DOE, Westinghouse, Southern California Edison Co. and Pacific Gas and Electric Co.
- The estimated commercial-applications time scale for ribbon and thin-film technologies is as listed below:

Ribbon-Silicon Power Modules

Research: one to two years
Pilot line: two to three years
25 MW production line: 5 to 7 years

Thin-film Power Modules

Research: five years
Pilot line: two to four years
Commercial production: 10 years

- The future of the photovoltaics industry will depend on corporate staying power. The next one to three years will determine the long-term winners. Cost-shared programs with industry are critical over the next few years.

A report of an ad hoc photovoltaics advisory committee on Photovoltaic Power System Research Evaluation was recently published by EPRI. Highlights of that report are worth noting:

- The ad hoc PV advisory committee members represent a wide spectrum of the PV community, including managers of PV companies; university, industrial and Government researchers; electric utility industry representatives, and Government R&D program managers. The review took place in the context of carefully examined criteria for energy-significant use. (In this context, energy significance implies aggregate installed capacity of at least 10 GW_p). Cost and performance criteria for flat-plate panels are: efficiency target of 14% to 17% (25°C) and cost target of \$100 to \$125/m², based on providing utility-quality power at a current-dollar levelized bus-bar energy cost of \$0.15/kWh. The cost is based midway between projected energy costs for new power plants burning oil and coal. The review also included an examination of the outlook for PV industry development as self-sustaining businesses. The EPRI conclusions regarding the R&D posture appropriate for the crystalline silicon sheet, amorphous-silicon and polycrystalline thin-film technologies are shown in Table A-1. The major concern for the silicon sheet technology was whether it can meet the cost targets for utility application. The concerns for the amorphous-silicon and other thin-film technologies were whether they can meet the efficiency goals and demonstrate long-term module reliability.

The EPRI-sponsored amorphous-silicon research is aimed at an improved fundamental understanding of amorphous materials and devices. Three areas of investigation are currently being pursued:

- (1) Research to develop low-band-gap amorphous-silicon alloys that possess both good optical and electronic properties.
- (2) Studies of the kinetics of amorphous film deposition processes.
- (3) Development and application of physical and device models for amorphous-silicon alloy materials and cells.

Table A-1. Development Characteristics of Photovoltaic Technologies as Projected by EPRI

Development Characteristic	Tandem Amorphous Silicon	Crystalline Silicon Sheet	Polycrystalline Thin Films
Probability of Meeting Cost Targets	high	medium	high
Probability of Meeting Efficiency Targets	medium	high	low
Technical			
Probability of Meeting Reliability Targets	medium	high	medium
Margin for Meeting Targets	high	low	low
Time to Resolve Technical Uncertainties	10 years	10 years	20 years
Management			
Level of Complementary Development Efforts	high	high	low
Degree of Private R&D Investment	high	medium	low
Availability of Near-Term Markets	high	high	medium

The EPRI thin-film cell research is all aimed at the development of high-efficiency tandem-junction cells with a goal of greater than 15% module efficiency. The work is pursued through contracts with industry and academic institutions (no in-house research) and is structured to provide development guidance through improved theoretical understanding. Present (1984-1985) funding is about one million dollars per year.

APPENDIX B

EXCERPT FROM THE SERI AMORPHOUS SILICON FIVE-YEAR RESEARCH PLAN

III. THE TECHNICAL PLAN

The ASRP project is organized into two primary and five secondary research activities (see Table 2), not to be confused with the five major categories of Materials Research, Cell R&D, Submodule R&D, Process Development, and Module R&D. The two primary research activities are (1) single-junction solar cells, and (2) multijunction, stacked solar cells. The five secondary research activities are (1) material deposition rate; (2) alternative material deposition methods, such as chemical vapor deposition (CVD); (3) light-induced effects; (4) device testing and reliability; and (5) supporting research, such as theory, plasma kinetics, and transparent conductors. The two primary research activities involve strong government/industry partnerships made up of multidisciplinary teams whose objective is to achieve improved photovoltaic device efficiencies. Such multidisciplinary research is required because the various parts of thin film photovoltaic devices are strongly interdependent and cannot be pursued effectively in isolated projects. This is a consequence of the thin film nature of the technology, whereby surfaces/interfaces play a major role in the properties of the device. Research in single-junction solar cells will lead to meeting the near-term DOE goals for thin film photovoltaic modules and will also provide the basis for the longer-term development of multijunction, stacked solar cells. These multijunction devices are needed to meet the longer-term efficiency goals, above 20%, of the DOE program. The five secondary activities relate to specific tasks in support of the two primary activities and provide a mechanism for investigating newer options.

Table 2. Amorphous Silicon Research Project Activities

Primary Activities	
o	Single-junction solar cells
o	Multijunction, stacked solar cells
Secondary Activities	
o	Light-induced effects
o	Material deposition rate
o	Alternative deposition methods
o	Device testing and reliability
o	Supporting research: theory, plasma kinetics, etc.

Single-Junction Solar Cells

The objectives of this activity are to improve the understanding and efficiency of single-junction amorphous silicon solar cells and to bring the U.S. technology base to a position where U.S. industry can remain competitive in the international arena. This is to be accomplished by strong government-industry partnerships, including federal program support for at least three multidisciplinary industrial teams to improve the conversion efficiency of single-junction solar cells, address stability and reliability questions, and perform the research required for making proof-of-concept, intraconnected, single-junction solar cells (submodules). University and DOE research center research projects will be supported by the federal program to augment industrial contract efforts. The multidisciplinary teams will be selected by competition from the private sector; multi-year contracts will be awarded, pending availability of funds, to achieve time-phased goals. The success of the research program and the essential deployment of the technology by industry will be enhanced by (1) requiring a serious commitment from the participating organizations, as evidenced by substantial cost-sharing (at least 30%) of the total program costs; and (2) strengthening the supporting government research program, which addresses specific technical problems and newer, high-risk options that the private sector cannot reasonably be expected to undertake.

Government-sponsored research has identified the glow-discharge method as the best technique yet discovered for growing amorphous material for a-Si thin film solar cells. Consequently, the deposition method to be used by the selected multidisciplinary teams is currently restricted to this glow-discharge method. Multichamber deposition systems will also be developed for growing individual amorphous silicon layers (p-type, i-type, and n-type). Multichamber deposition systems permit control over the material properties of the individual layers and reduce cross-contamination of the layers considerably. Research results from the secondary research activities will be incorporated into the project as necessary.

Multijunction Solar Cells

Theoretical calculations show that single-junction amorphous silicon solar cells using today's amorphous materials have a theoretical conversion efficiency limit of 18%-20%. The practically achievable conversion efficiency of single-junction solar cells is estimated to be 13%-15%. The federal long-term technical goal (Table 1) for flat-plate photovoltaic systems is a module efficiency/cost combination of 13% at \$40/m² to 17% at \$75/m². To increase the probability of meeting the long-term technical goals, solar cell devices such as stacked cells, which consist of two or three single-junction solar cells in a vertical stack, offer potentially much higher conversion efficiencies. The theoretical limit of the multijunction stacked solar cell is almost 30%. However, several effects reduce this theoretical limit to a practical limiting efficiency of 20%-25%. In addition to the higher efficiencies possible with stacked cells, these devices may be inherently more stable than a single-junction "thick" p-i-n cell because of the thinner layers of active, or intrinsic, material in each of the individual p-i-n cells that make up the stacked device. Stacked-cell efficiencies are currently limited by the quality of the alloy material, which in turn limits the current from devices utilizing this material.

In addition to the conventional stacked solar cell concept, an advanced research concept, "amorphous semiconductor superlattices," was recently introduced. The amorphous semiconductor superlattice consists of alternating layers 8 Å to 1200 Å thick of hydrogenated amorphous semiconductors such as silicon, germanium, silicon nitride, or silicon carbide. The material composition is controlled by periodically changing the composition of the reactive gases in a plasma reactor without interrupting film growth. Using this thin film technology, a solar cell could be fabricated that has improved properties and higher conversion efficiencies.

The objective of the research activity in this area is to perform research both in specific areas of amorphous silicon alloy materials and deposition techniques, and in the structure of stacked cells, to achieve solar cell efficiencies of greater than 20% in the long term. This will be accomplished by government/industry/university partnerships that include federal program support for at least two multidisciplinary teams with multiyear contract awards, pending availability of funds, having time-phased research goals. Cost-sharing of at least 20% is required to enhance the probability of success and to achieve an effective technology transfer to the private sector. This project will be supported by the secondary research activities. High-efficiency, multijunction solar devices offer conversion efficiencies potentially above 20% in the long term. However, it must be recognized that some significant research successes are required to achieve the technical goals; thus, this activity involves greater risk than the single-junction, but lower efficiency, approach.

Milestones

Goals and milestones for the federal amorphous silicon program were selected after extensive analysis that involved current U.S. and foreign technology, U.S. industries, DOE laboratories, universities, and other research-oriented institutions. Principal milestones (see Figure 6 for program schedule) are as follows:

FY 1984

- o Single-junction submodule efficiency of 6% achieved for an area of 50 cm².
- o Design completed of multichamber deposition systems for preparing single- and multijunction solar cells.

FY 1985

- o Single-junction submodule efficiency of 7% achieved for an area of 100 cm².
- o Multichamber deposition systems operational.
- o Multijunction solar cell efficiency of 12% achieved for an area of 1 cm².

Project Milestone ▲ Project Decision Point △						
		1984	1985	1986	1987	1988
Activity		FY84	FY85	FY86	FY87	FY88
Single-Junction Solar Cells						
1. Materials Research						
Deposition Method				▲ (Select)		
Stability (light-induced)				▲ (Assess)		
Deposition Rate				▲ (Select Method)		
2. Cell R & D						
Achieve Efficiency with Deposition Rate Goals				12% (1 cm ²) ▲	10% (1 cm ²)(20 Å/s) ▲	13% (1 cm ²) ▲
3. Submodule R & D						
Achieve Efficiency and Size Goals		6% (50 cm ²) ▲	7% (100 cm ²) ▲	8% (1000 cm ²) ▲		12% (100 cm ²) ▲
4. Process Dev. & Module R&D						
Multichamber Deposition System		▲ (Design)	▲ (Operational)	▲ (Assess)		
Achieve Efficiency and Size Goals				▲ (Assess R & D)		9% (10,000 cm ²) ▲*
Multijunction Solar Cells						
1. Materials Research						
Preparation and Evaluation		▲ (Initiate E _g < 1.5 eV)	▲ (Initiate E _g > 1.7 eV)		▲ (Assess/Select)	
Deposition Method					▲ Select	
Stability (light-induced)					▲ (Assess)	
Deposition Rate					▲ (Assess)	
2. Cell R & D						
Achieve Efficiency Goals			12% (1 cm ²) ▲			18% (1 cm ²) ▲
Research Multichamber Deposition System		▲ (Design)	▲ (Operational)		▲ (Assess)	
3. Submodule R & D						
Achieve Efficiency and Size Goals						13% (100 cm ²) ▲
4. Process Dev. & Module R&D						
Deposition System					▲ (Evaluate)	
Achieve Efficiency and Size Goals					▲ (Assess R & D)	
*Efficiency and size milestones for module require substantial industry participation Note: Efficiencies are measured at 28° C and AM 1.5						

Figure 6. Amorphous Silicon Research Project Schedule and Decision Points