N76 12474

LOW-COST SILICON SOLAR ARRAY PROJECT

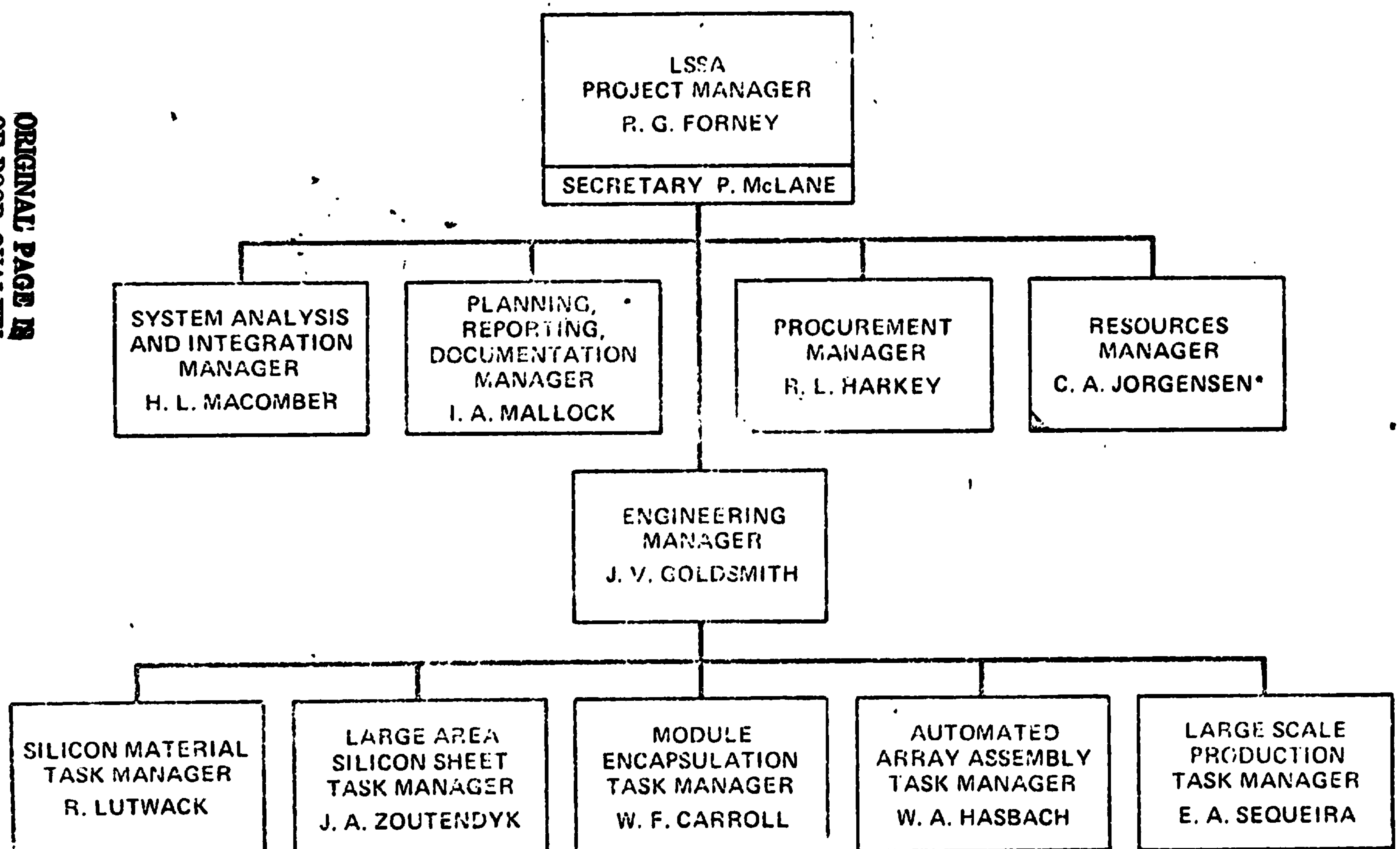
John V. Goldsmith
Jet Propulsion Laboratory
California Institute of Technology

ABSTRACT

The responsibility to conduct ERDA's Low-cost Silicon Solar Array Project, which is a part of the overall Solar Photovoltaics Program, has been delegated to the California Institute of Technology's Jet Propulsion Laboratory (JPL). An Industry Briefing formally announcing this Project was conducted February 5, 1975. The objectives of the Project include a 1985 goal to reduce silicon solar array prices to less than $500/KW. These low-cost arrays further shall have lifetimes greater than 20 years, conversion efficiencies greater than 10% and a national rate of units manufactured greater than 500MW per year. A Project team, led by Robert Forney, has been organized at JPL. This team is divided presently into five major Task areas: Silicon Material, Large Area Silicon Sheet, Module Encapsulation, Automated Array, and Large Scale Production. The Tasks are all part of one integrated effort dedicated to reaching the Project's 1985 objectives. Specifically, the Silicon Material Task is to concentrate on reducing the basic solar cell quality silicon material price to less than $30/Kg with a goal of less than $10/Kg. The Large Area Silicon Sheet Task is to convert the low-cost material into large areas of silicon with the required properties and dimensional thicknesses that will permit their conversion into high efficiency solar cells. The added price goal of this process is less than $1.60/sq. ft. The Encapsulation Task is to produce low-cost, long-life, greater than 20-year lifetime encapsulation materials and techniques. The Automated Array Task is to convert the sheets of silicon into solar arrays utilizing facilities, designs and processes that will result in the less than $500/KW objective. The Large Scale Production Process Task has as its primary objective the supply of silicon solar array modules to ERDA's Photovoltaic Program Demonstration and System Test and Analysis Projects. Approximately 10 megawatts of these modules are presently planned to be procured from Industry with gradually increasing annual buys over the next eight years. It is anticipated these buys will stimulate the market and assist Industry in developing better modules at lower cost. This Large Scale Production Task will benefit from the technology advancement achieved in the previously described four Tasks and could serve as a practical test of improved designs and production techniques. It is a goal that hardware procured through the Large Scale Production Task will be bought for less than $5 per watt by 1979 and $2 per watt by 1983.

This Low-cost Silicon Solar Array Project is to be a National effort involving the best talents in Industry and Universities. Requests for Proposals in the first four Task areas were solicited during April, and proposals are now under evaluation. A Request for Proposals for the first 40 kilowatts of solar array modules required in the Large Scale Production Task will be released in the near future.

LOW COST SILICON SOLAR ARRAY PROJECT
ORGANIZATION

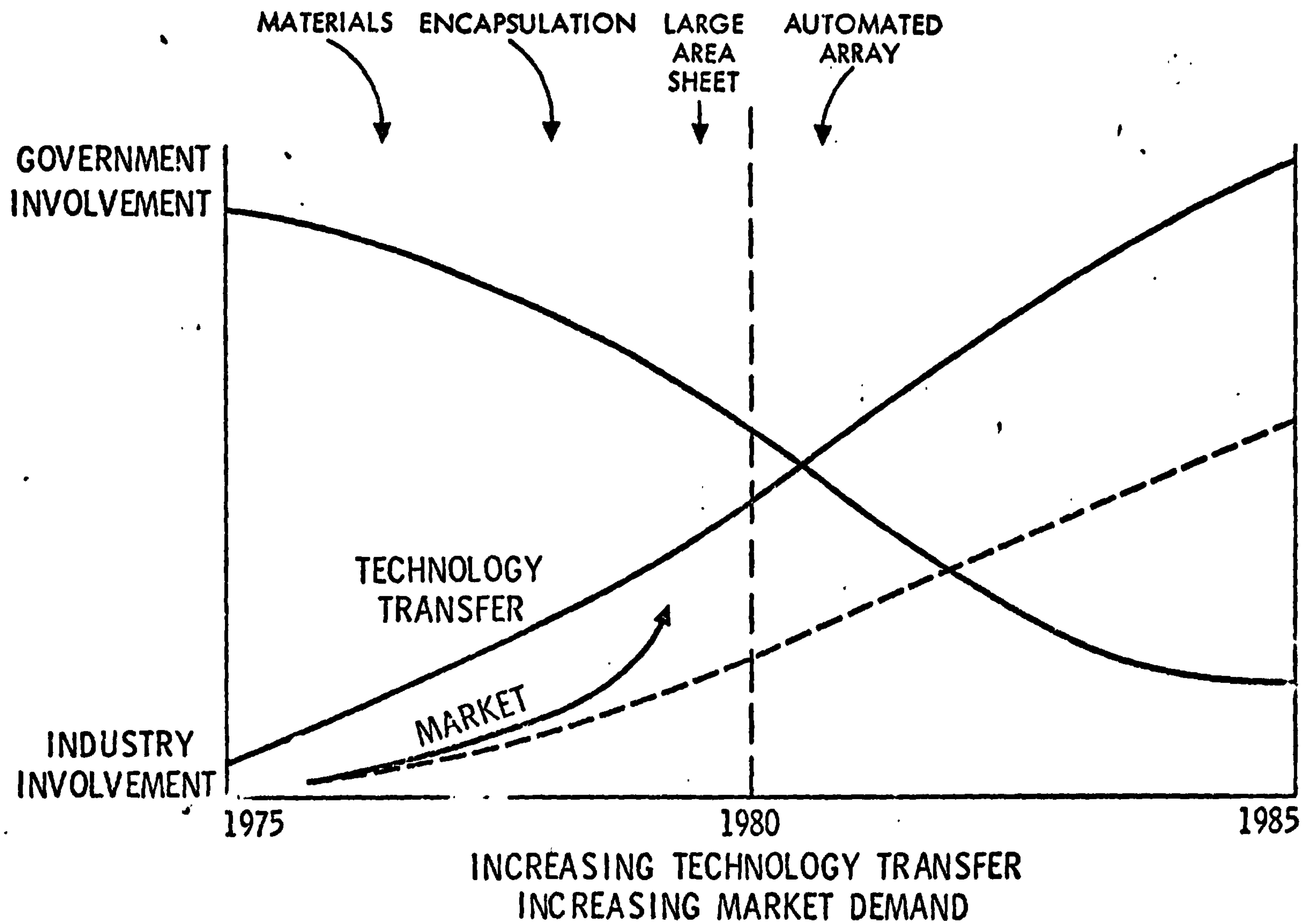


*PART-TIME

◣ INDIRECT

LOW-COST SILICON SOLAR ARRAY PROJECT

RELATIVE ROLES OF GOVERNMENT AND INDUSTRY



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LOW-COST SILICON SOLAR ARRAY PROJECT

1985 PROJECT TECHNICAL REQUIREMENTS

1985 PROJECT TECHNICAL REQUIREMENTS

- EFFICIENCY > 10% Array
- LIFETIME > 20 years
- COST < $500/KW
- PRODUCTION RATE ≥ 500 MW/yr

KEY NEEDS:

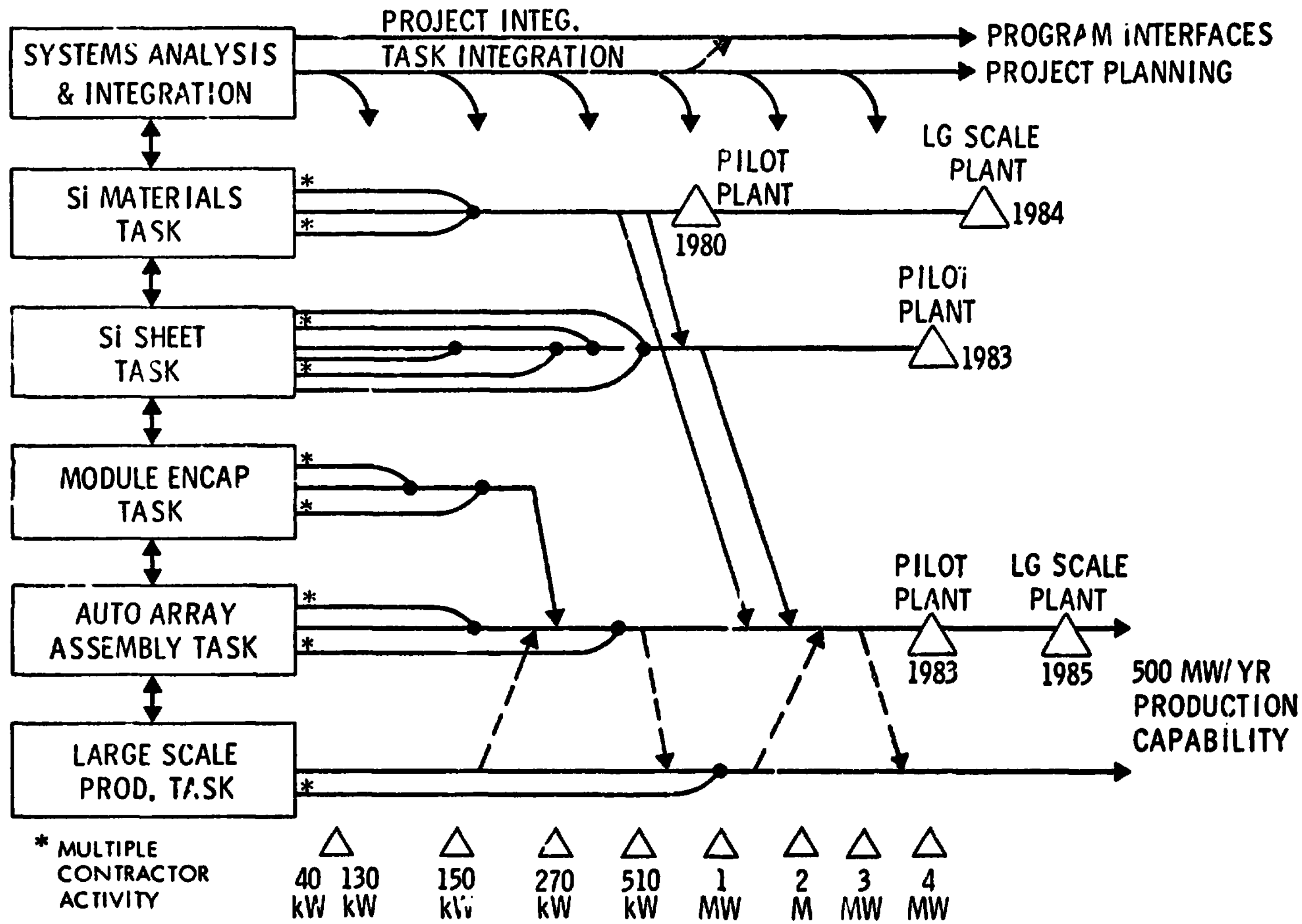
- LOW COST SOLAR CELL QUALITY SILICON MATERIAL
- LOW COST, HIGH EFFICIENCY SILICON SHEET DEVICES
- LONG LIFE, PRACTICAL SOLAR ARRAY ENCAPSULANTS
- INTEGRATED, VALUE ENGINEERED, AUTOMATED ARRAY FABIRCATION

LOW-COST SILICON SOLAR ARRAY PROJECT

SUMMARY IMPROVEMENTS REQUIRED

	1975	1985
SILICON MATERIAL	$ 60/kg	< $30/kg
SILICON WAFER	$ 28/sq ft	< 1.60/sq ft
ARRAY FABRICATION	$140/sq ft	< 1.60/sq ft
	(~30,000/kW)	(< 500/kW)

LOW COST SILICON SOLAR ARRAY PROJECT
TASK INTERACTIONS



PHOTOVOLTAIC CONVERSION OF SOLAR ENERGY

Contract #W7405-eng-26

OAK RIDGE NATIONAL LABORATORY

March 75 - July 76

$180,000

J. W. Cleland, R. D. Westbrook

H. L. Davis and R. F. Wood

1) Objective

The first and most immediate objective of the photovoltaic conversion work at ORNL is the development of a thorough understanding of and techniques for controlling certain factors which are known to degrade the electrical characteristics of p-n junctions in silicon semiconductor devices. The most important of these factors is the nonuniform distribution of phosphorus which is introduced by conventional doping techniques. As a possible means of circumventing this problem a thorough study of nuclear doping is currently being emphasized. The second objective of the program is the identification and control of point, line and surface imperfections which act as recombination centers to degrade the minority carrier lifetime in both single and polycrystalline silicon, and in other III-V and II-VI semiconductors. A third objective of the program is the identification and study of new solar cell materials and growth methods.

2) Past Activity

This project, though recently initiated, is closely related to other research at ORNL, e.g., the work on ultra-pure germanium, nuclear doping, crystal growth, optical and electrical properties of solids, pure materials research, chemical vapor deposition, electron microscopy, semiconductor device modeling and testing, and organic semiconductors.

3) Current Effort

The first phase of this work is being devoted to the applicability of "nuclear doped" silicon to the silicon solar cell. All methods presently used in the preparation of silicon for semiconductor devices introduce a nonuniform distribution of any chemical dopant. It has been demonstrated that the distribution of phosphorus, the standard n-type dopant, takes the form of striations which intersect and degrade the characteristics of a p-n junction. These striations can be greatly reduced by nuclear doping, in which the ^{30}Si of normally available silicon transmutes to ^{31}P after thermal neutron capture with a half-life of 2.6 hours. Also, no other impurities are introduced by the nuclear doping process in contrast to the possibility of inadvertant contamination of the melt with copper, gold, etc. during normal doping procedures. The performance of high power silicon diodes, thyristors and avalanche detectors is significantly improved for nuclear-doped Si over that for conventionally doped material, and a similar improvement may be attainable in the efficiency of silicon solar cells.

We have irradiated wafers and ingot sections of both single crystal and polycrystalline silicon in various reactor locales with a thermal to epithermal neutron ratio from unity to 2,000, and have introduced 10^{13} to 10^{16} phosphorus cm^{-3}. The times and temperatures required to remove (n,γ) and fast neutron lattice damage are being studied, and electrical property measurements are in use to determine the carrier concentration, mobility, and minority carrier lifetime as a function of the total flux, thermal/epithermal ratio, and annealing requirements. Electron microscope and microscopic spreading resistance measurements are in progress, and test specimens are also being evaluated at other laboratories as regards their performance as avalanche detectors, high voltage power rectifiers and thyristors, and solar cells.

4) Future Plans

After the first stage of the research program is well advanced, and definitive results on the role played by the nonuniform distribution of dopants have been obtained, the emphasis will shift toward studies of electron-hole recombination processes. This part of the program will rely heavily on a close interplay between experimental and theoretical research. Advanced optical techniques and spin-resonance (where applicable) will be used to determine the lattice sites, concentration, energy levels and lifetimes associated with those impurities and point imperfections which introduce deep traps and act as recombination centers. The role played by dislocations, grain boundaries, and surfaces in promoting recombination and thus reducing the minority carrier lifetime will be thoroughly studied by optical, Auger electron, LEED and electron microscopy techniques. The theoretical work will be directed toward a determination of the energy levels, wave functions and lifetimes of electrons and holes at deep traps and in the vicinity of line and surface imperfections. These are particularly important studies because the ultimate success of photovoltaic conversion as an alternative source of energy is likely to depend on the possibility of using polycrystalline, amorphous or highly impure silicon or other materials.

Single crystal ingots of silicon will be grown by float zone refining and Czochralski pulling and a systematic study will be made of the requirements for control of point defects, defect clusters, dislocations, twins, stacking faults and unwanted chemical impurities. Crystals with varying concentrations of those impurities most frequently found in silicon will be grown for use in lifetime studies. Samples of silicon from newer growth processes such as edge-defined, film-fed growth and internal zone growth will be procured and prepared for testing. Studies of growth methods for III-V, II-VI, polycrystalline, amorphous and organic semiconductors will be surveyed. The possible use of Shottky barriers instead of p-n junctions will be explored because such an approach may lead to simplified fabrication procedures and hence reduced costs.

5) Survey of Key Results to Date

The most serious problem that was anticipated with the nuclear doping technique was the removal of radiation damage that is introduced as a consequence of (n,γ) recoils following thermal neutron absorption, and as a consequence of all other damage mechanisms activated by the reactor irradiation. We have now produced phosphorus concentrations in silicon from 10^{13} to 10^{16} cm^{-3} by neutron doping, and in all cases have been able to recover the carrier mobility and a substantial percentage of the carrier lifetime by suitable annealing schedules. We find that generally the mobility returns to normal at lower temperatures than the lifetime, but as the annealing study is incomplete at this time we do not know the upper limit, if any, of lifetime recovery.

DEVELOPMENT OF A 20% EFFICIENT SOLAR CELL

Grant No. GI-43090

15 Months

Initiated 1 June 1974

$119,400

Principal Investigator:

Dr. Joseph Lindmayer

SOLAREX CORPORATION

1335 Piccard Drive

Rockville, Maryland

Presented At

National Solar Photovoltaic Program Review Meeting

Los Angeles, California

July 22-25, 1975

ABSTRACT

The efficiency of silicon solar cells has been increased significantly in the last few years, particularly after the introduction of the violet cell. With the onset of the terrestrial photovoltaic program, it became apparent that techniques should be found for high efficiency inexpensive solar cells. This Grant was given just for such a purpose. The actual work has proceeded along the lines which are basic to inexpensive technologies, such as the use of CZ crystals, chemical surface preparation, short junction formation in quantity, back junction formation by simple alloying, no clean room operation, etc.

Progress in efficiency during the grant period was continuous and the 20% efficiency has been just about reached by this time as is indicated in the attached figures. The reason for the gradual improvement is that nature resists the idea of large jumps; improvement in one parameter usually results in degradation of another and this continuous cross talk is the reason for graduality.

Much of the efficiency of silicon solar cells was limited by the generation of three types of defect states: bulk states, surface induced states, and surface states. The magnitude and distribution of these defects affect the three basic parameters, photocurrent, photovoltage and fill factor.

A. Current

The quantum yield of the cells have been improved continuously. The short wavelength response is controlled by defect states near the front junction while the red response is controlled by bulk states and by defects generated near the back surface. The total collection efficiency is approximately 78% at the moment for flat surfaces but can be increased by some 5-6% with textured surfaces. There is clearly room for continued improvement in the current collection efficiency.

B. Photovoltage

The complex matter of photovoltage has been attached heavily both theoretically and experimentally. A general mathematical treatment indicates that the practical limit of a room temperature photovoltage of about 600 mV is controlled by surface thermal generation current. We believe that the problem has been theoretically identified with this work and, therefore, gives an important guideline for the experimental approaches. We believe that with sufficient experimental effort, the photovoltage could be raised much above 600 mV.

C. Fill Factor

Great improvements have been accomplished in the control of the fill factor and it can now be held very close to the ideal value; namely in the range of 78-80%. These excellent results indicate the potential return that can be obtained by minimization of defect states.

The combined theoretical and experimental effort which went in many directions during the grant could not encompass detailed studies of all the related phenomena but has been instrumental in establishing a range of parameters that can provide consistently high conversion efficiencies.

DEVELOPMENT OF A 20% EFFICIENT SOLAR CELL

GRANT No. GI-43090

15 MONTHS, INITIATED 1 JUNE 1974

$119,400

PRINCIPAL INVESTIGATOR:
JOSEPH LINDMAYER
SOLAREX CORPORATION

OBJECTIVES

INCREASE TERRESTRIAL EFFICIENCY OF SILICON SOLAR CELLS TO 20%

UTILIZE POTENTIALLY INEXPENSIVE TECHNOLOGIES

APPROACH

IMPROVE OPTICAL COUPLING W. AR COATING AND TEXTURING

IMPROVE SHORT AND LONG WAVELENGTH RESPONSE

IMPROVE FILL FACTOR TOWARD THEORETICAL VALUES

STUDY PHOTOVOLTAGE LIMITATIONS

LAST 6 MONTHS ACTIVITY

CONTINUED STUDIES FOR BETTER FRONT JUNCTION FORMATION

MAPPING ELEMENTS AND COMPOUNDS FOR REAR HIGH-LOW JUNCTION FORMATION

CHARACTERIZATION OF LOW TEMPERATURE DIFFUSION

DEFECT GENERATION STUDIES

IMPROVE AND SIMPLIFY TANTALUM OXIDE COATING

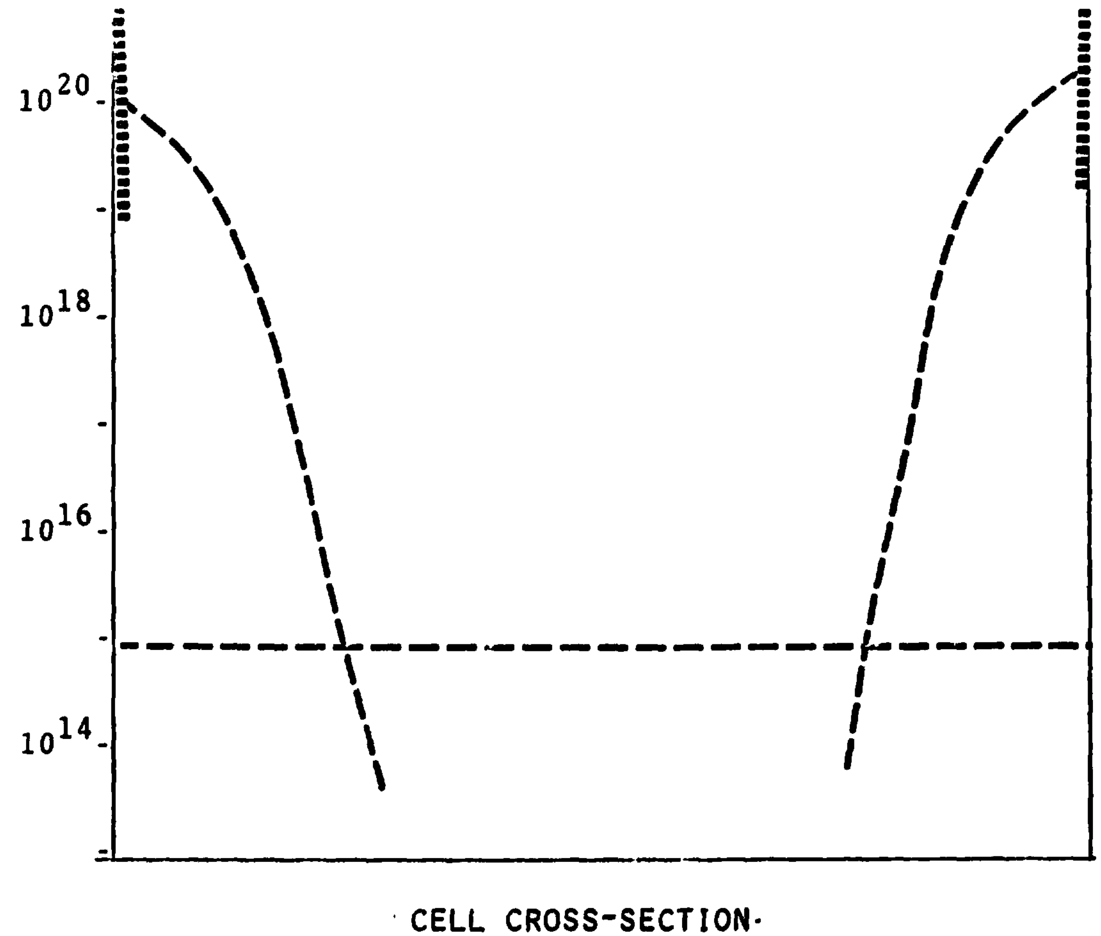
STUDY TEXTURING

COMPARE P-ON-N AND N-ON-P

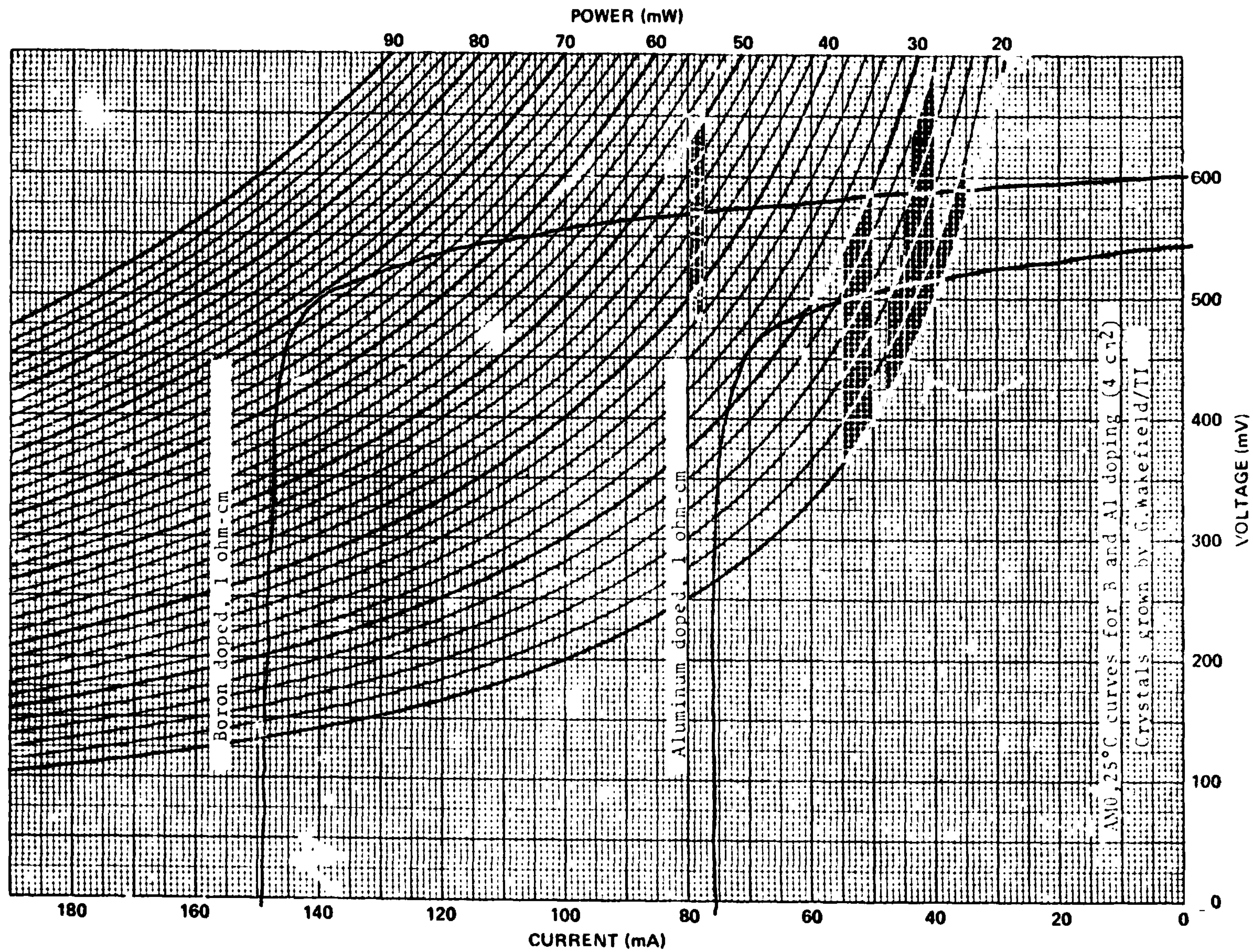
IMPROVE MEASUREMENT TECHNIQUES

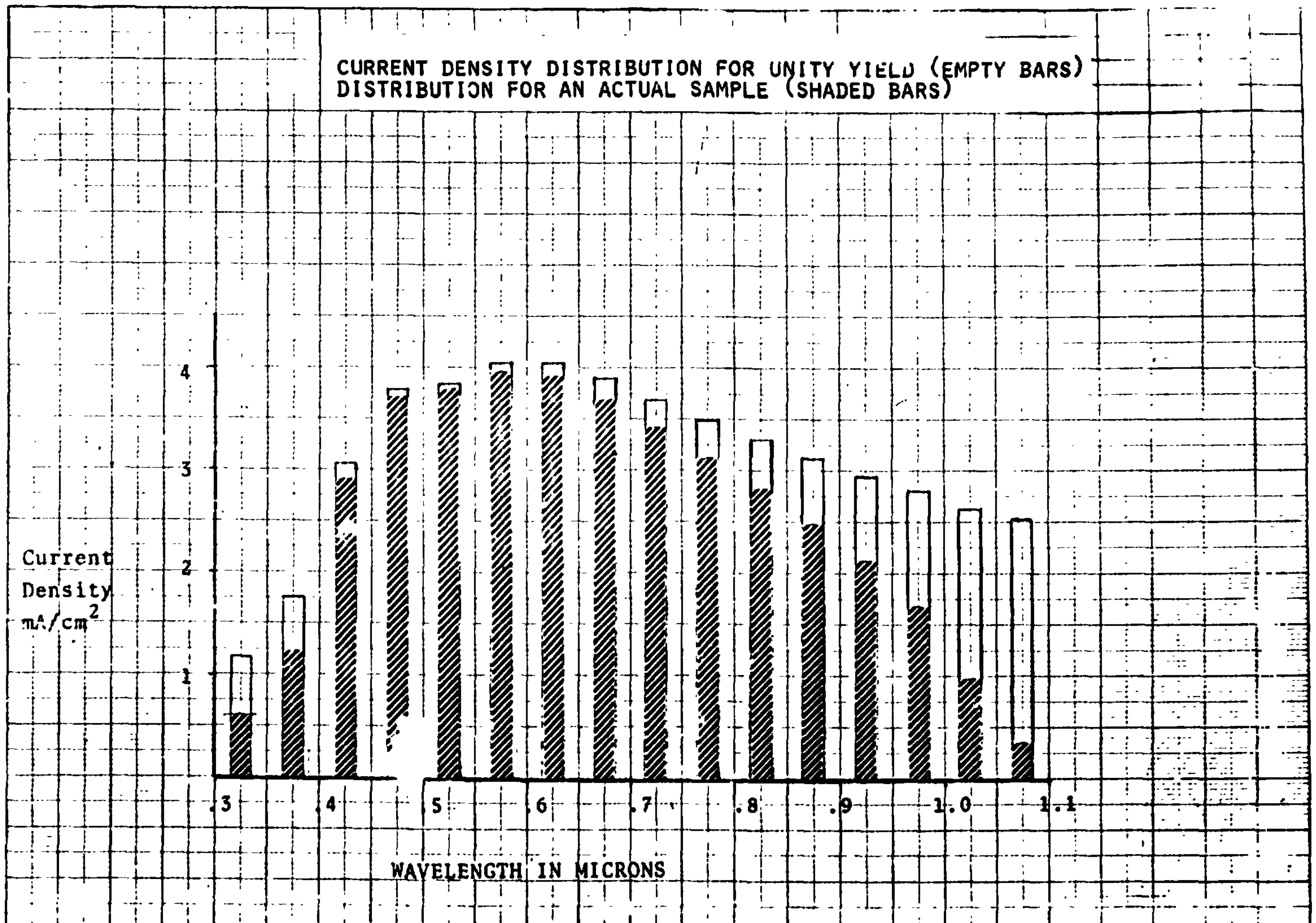
DEFECT STATES (cm^{-3})

1. BULK STATES ARISING FROM CRYSTALLOGRAPHIC DISORDER
2. DEFECTS PROPAGATING FROM SURFACE DURING JUNCTION FORMATION
3. SURFACE OR INTERFACE STATES

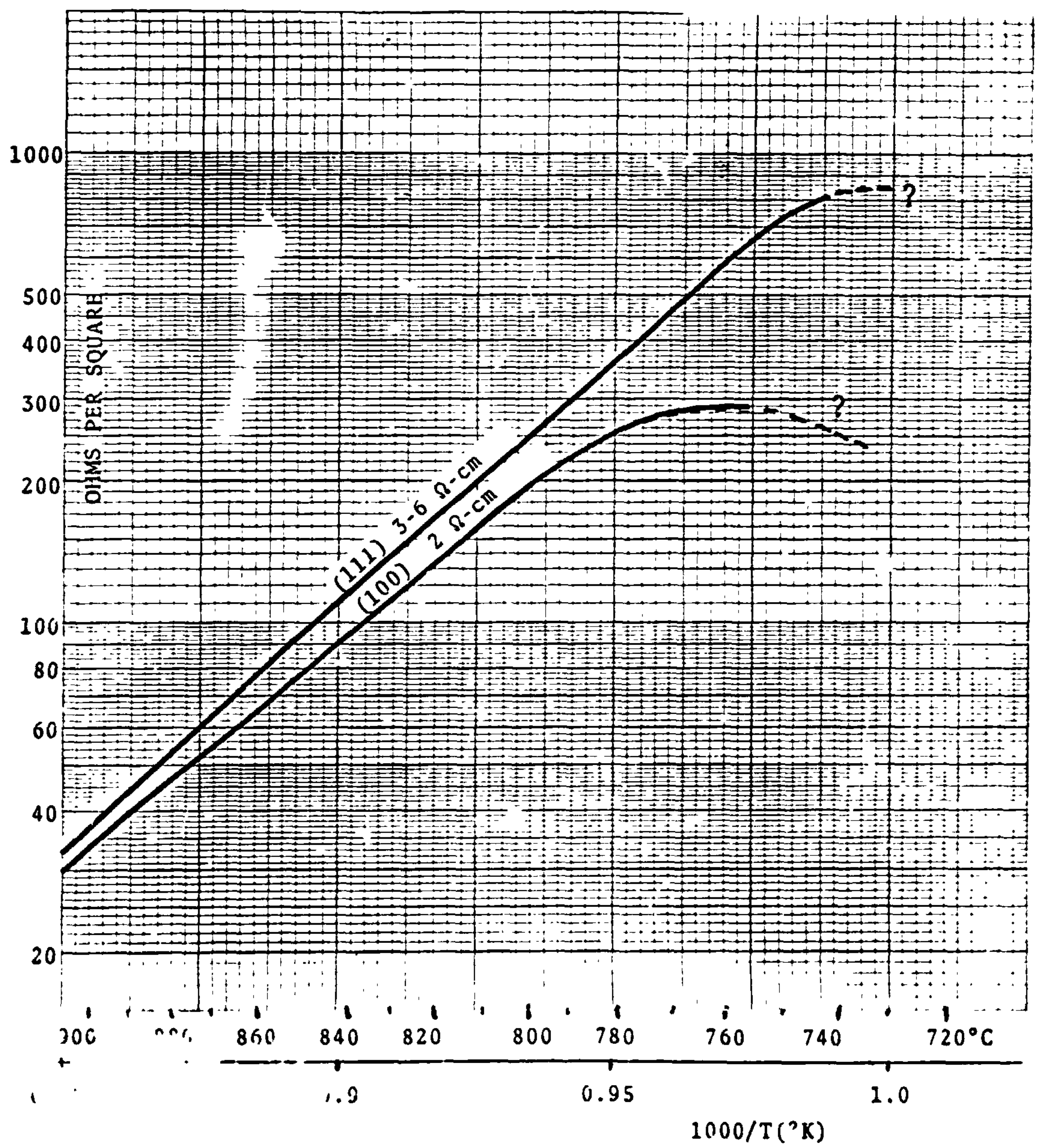


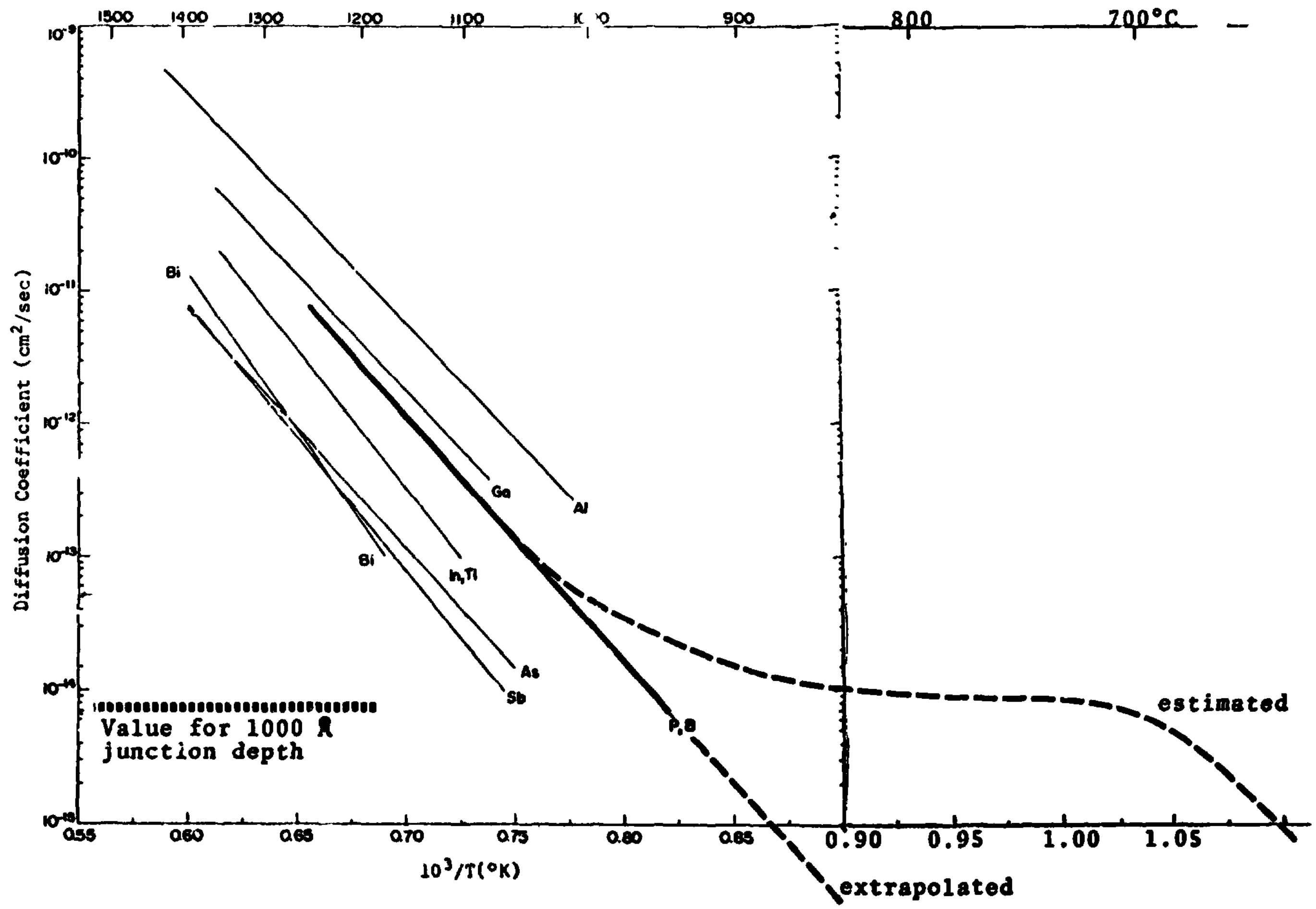
THREE BASIC TYPES OF DEFECTS IN SILICON CELLS


POWER (mW)
90
80
70
60
50
40
30
20
VOLTAGE (mV)
600
500
400
300
200
100
0
CURRENT (mA)
180
160
140
120
100
80
60
40
20
0
Boron doped, 1 ohm-cm
Aluminum doped, 1 ohm-cm
AM0,25°C curves for B and Al doping (4 cm2)
Crystals grown by G.Wakefield/TI


CURRENT DENSITY DISTRIBUTION FOR UNITY YIELD (EMPTY BARS)
DISTRIBUTION FOR AN ACTUAL SAMPLE (SHADED BARS)
Current Density mA/cm²
4
3
2
1
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
WAVELENGTH IN MICRONS

SHEET RESISTANCE OF DIFFUSED PHOSPHORUS LAYER AS A FUNCTION OF TEMPERATURE (10 MIN.)

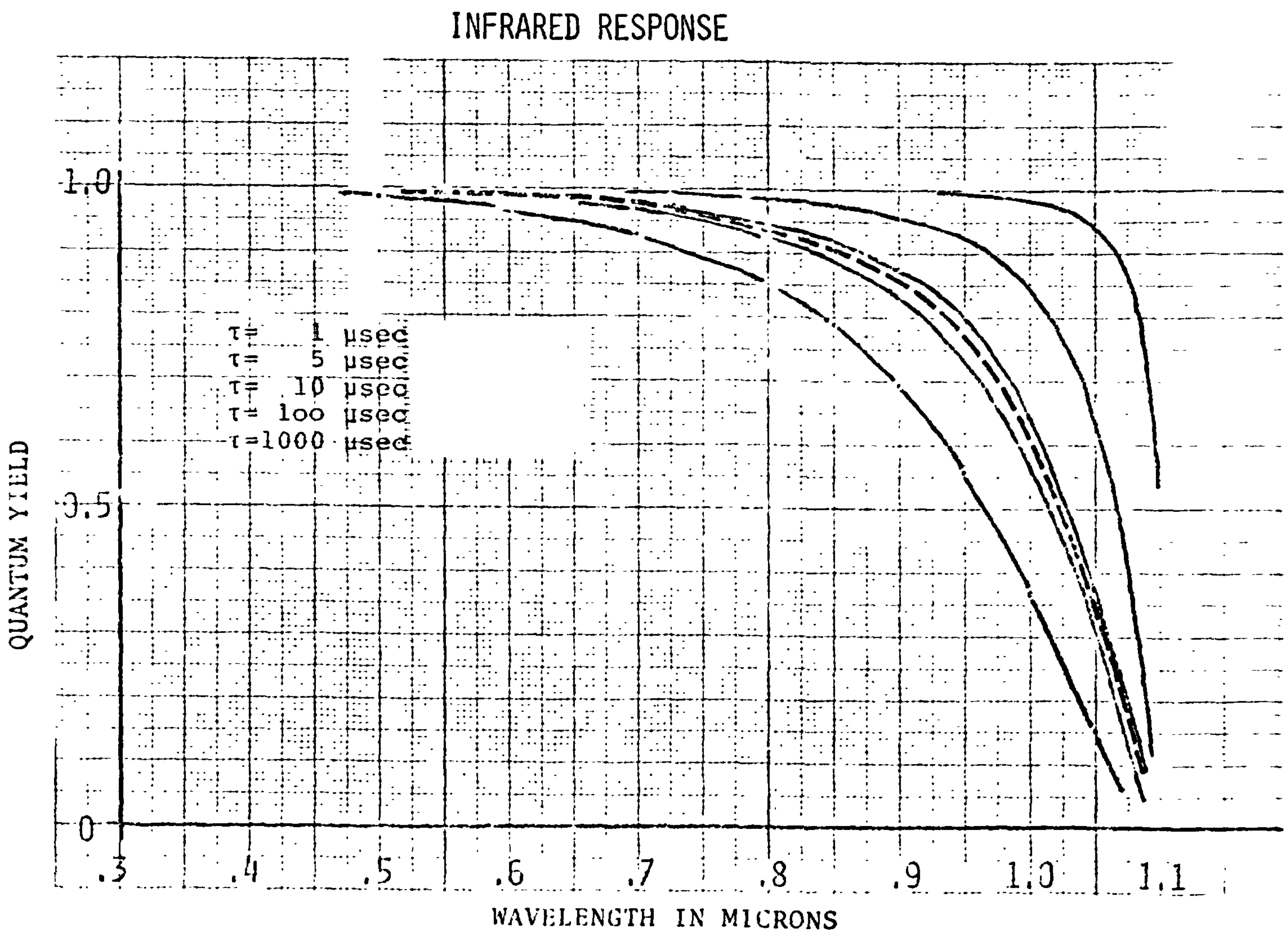




ESTIMATED PHOSPHORUS DIFFUSION CONSTANT AS COMPARED TO PUBLISHED VALUES

TABLE FOR DIFFERENT BACK LAYERS

Compound	Character	Remarks
B glass	p-type	spin-on
Ga glass	n-type	spin-on
CeO_2	n-type	electron beam
Cr	p-type	filament
Si (p-type)	n-type	electron beam
Ti	p-type	filament
Ta_2O_5	p-type	electron beam
Ni	n-type	electron beam
SiO	n-type	electron beam
Si (metallurgical)	p-type	electron beam
Ge	n-type	electron beam
MoO_3	n-type	electron beam
Mn	n-type	electron beam
Mo	?	electron beam
V	?	electron beam
Sn	n-type	electron beam
Al_2O_3	p-type	electron beam
AlP	n-type	electron beam
B_2O_3	?	electron beam



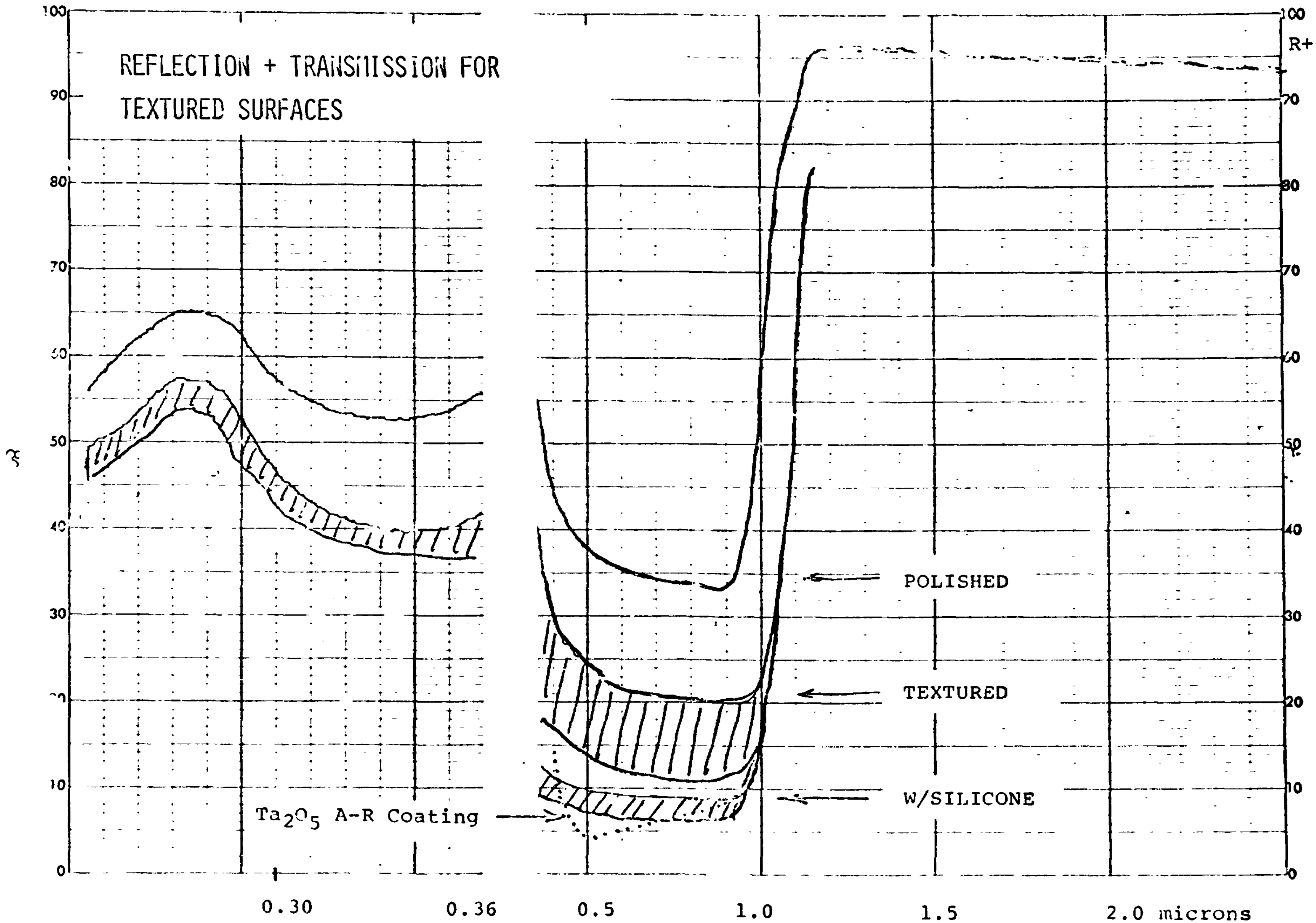
Quantum curves (precalculated) help to determine lifetime in the neighborhood of the back contact (dashed line)

TEXTURING FOR LIGHT TRAPPING

ALKALINE ETCHES | ACID ETCHES

PREFERENTIAL ETCHING WITH AND WITHOUT MASKING

1) BARE CELL REFLECTION MAY BE REDUCED FROM 35% TO 12%
2) COATED WITH ORGANIC MATTER, BELOW 10% REFLECTION
3) TEXTURING OFFERS ONLY 6-7% GAIN IF AR COATING IS USED
4) DIFFICULT TO HOLD FILL FACTOR WITH TEXTURED SURFACE
5) SOME SLOW DEGRADATION MAY OCCUR WITH (100) PLANE


REFLECTION + TRANSMISSION FOR
TEXTURED SURFACES
R+
%
POLISHED
TEXTURED
W/SILICONE
Ta_2O_5 A-R Coating
0.30
0.36
0.5
1.0
1.5
2.0 microns
0
10
20
30
40
50
60
70
80
90
100

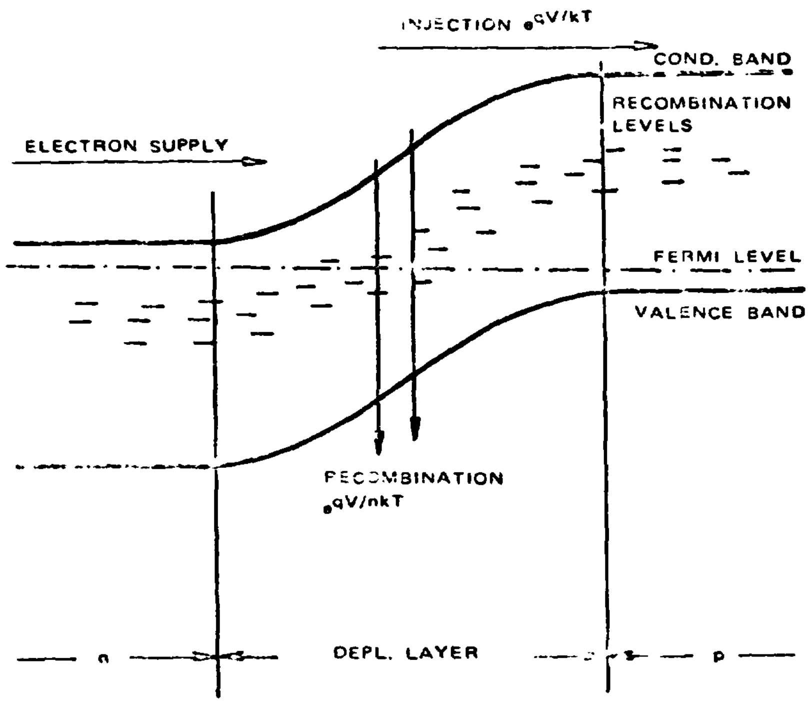
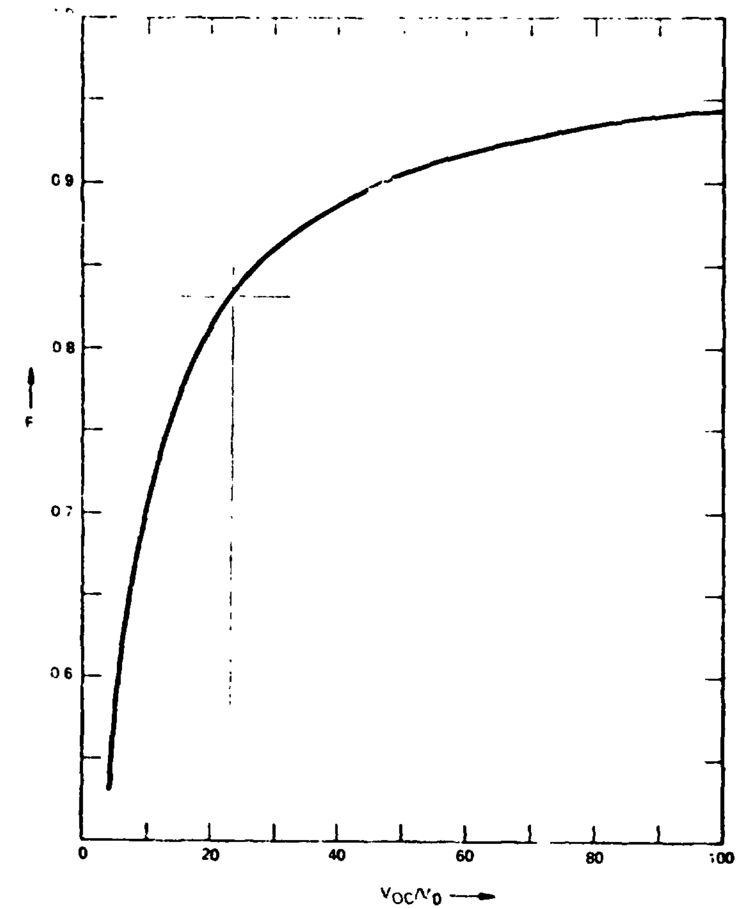


Figure 3. Energy barrier at an n-p junction. Space charge recombination current through recombination centers in the middle of the barrier is the first current component that flows as a forward bias is applied in a p-n junction. True injection will start at higher voltages.



J. LINDMAYER, COMSAT TECHNICAL REVIEW VOLUME 2 NUMBER 1, SPRING 1972

The fill factor could bė as high as 83% at V_{oc}=600 mV and V_0=26 mV
Actual values reached 80% with 4 cm^2; harder to maintain for large areas.

$$J_0 = \frac{q n_i^2}{N} \frac{D}{W}$$

REVERSE CURRENT DENSITY WITH HIGH REAR CONTACT RECOMBINATION

$$J_0 = \frac{q\, n_i^2}{N + \frac{J_{sc}}{qW}} \frac{D}{L} \tanh W/L \Bigg|_{s=0}$$

LEADING TO VOLTAGE INCREMENT OF BOTH KIND

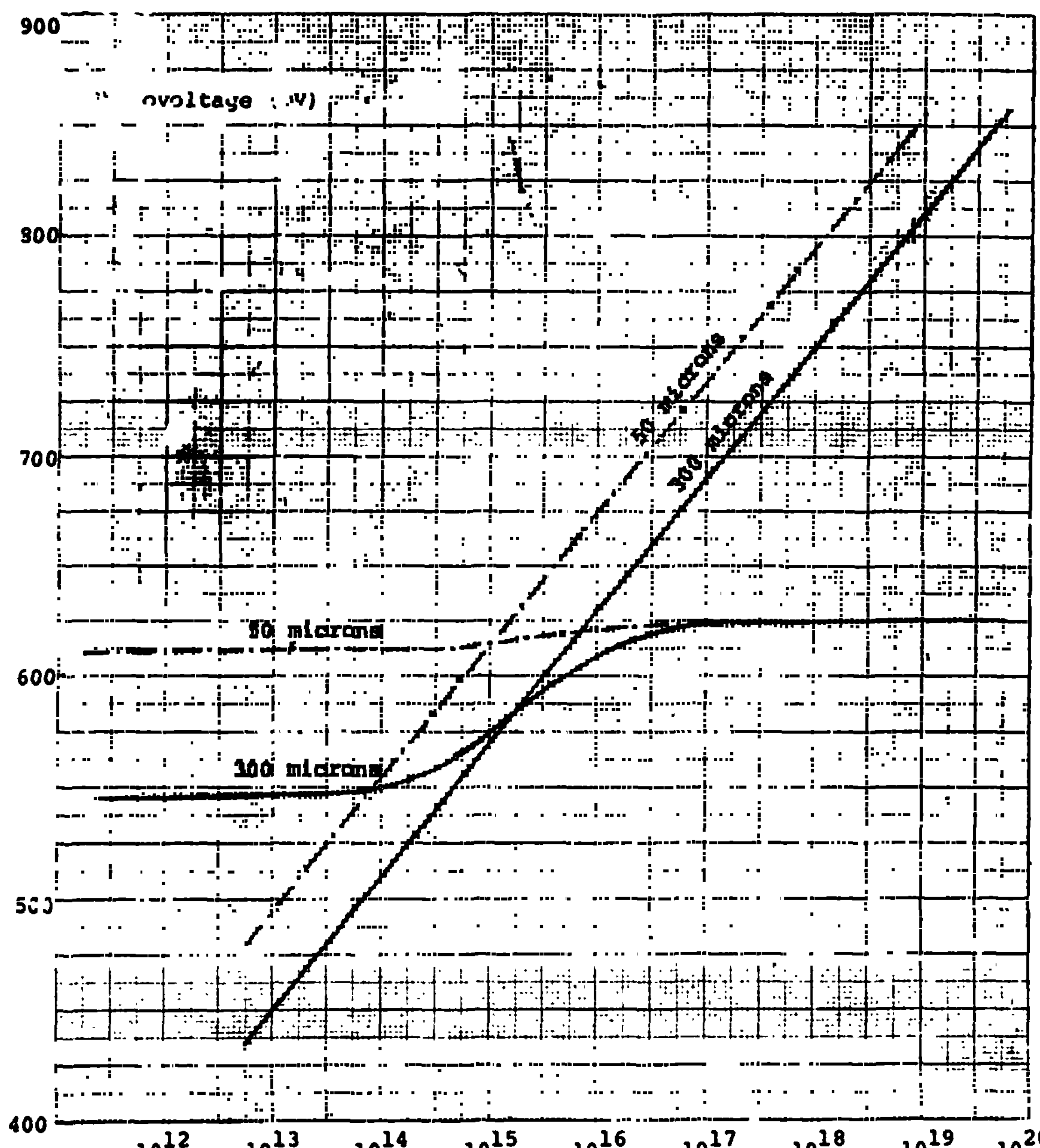
BULK REVERSE CURRENT DENSITY WITH LOW REAR CONTACT RECOMBINATION (s=0), CONTRIBUTING TO INCREASED PHOTOVOLTAGE

$$J_F = \frac{q n_i^2 D}{\int_0^{x_J} N\, dx}$$

LEADING TO VOLTAGE LIMITATION

REVERSE CURRENT FROM TOP LAYER LIMITS PHOTOVOLTAGE WHEN THE BULK CURRENT IS MINIMIZED

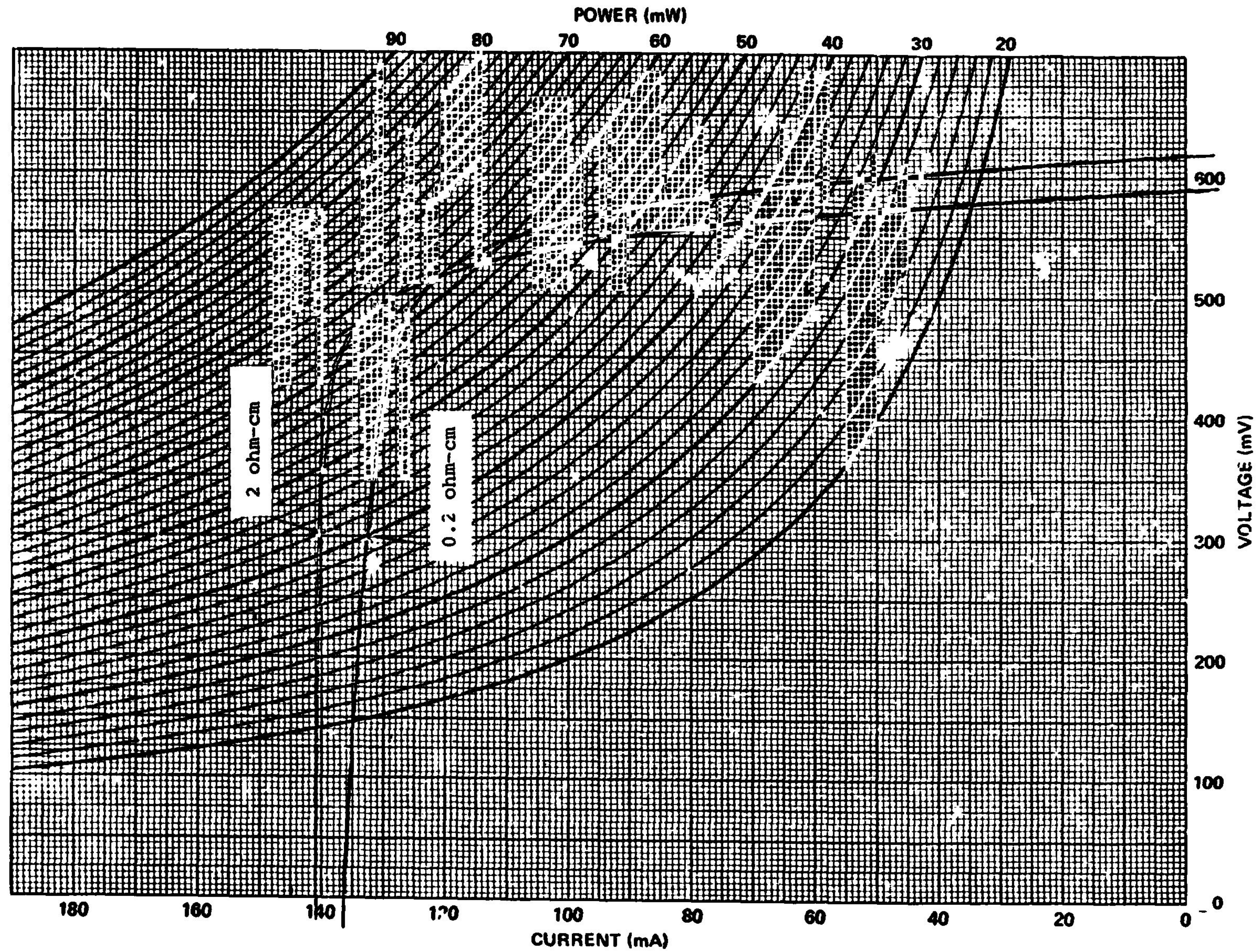
DETAILED CALCULATION MAY BE FOUND IN LAST QUARTERLY REPORT

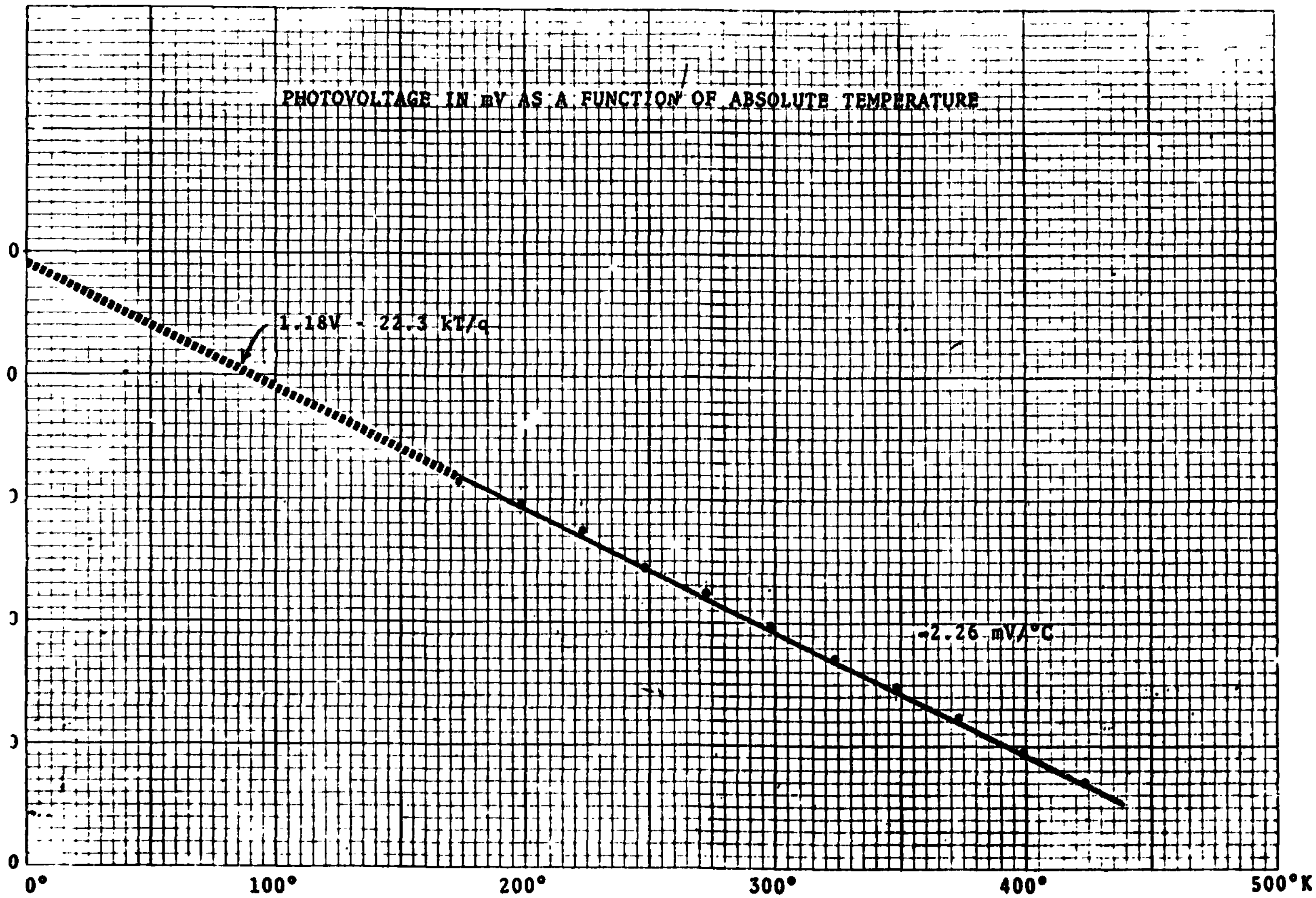


CALCULATED PHOTOVOLTAGE FOR TWO CELL THICKNESSES. THE PARALLEL LINES ARE FROM THE BULK CONTRIBUTION ALONE (CONVENTIONAL), AT LOW DOPING LEVELS IMPROVEMENTS ARE SEEN FROM REDUCED REAR RECOMBINATION, AT HIGH DOPING REVERSE CURRENT OF TOP LAYER LIMITS PHOTOVOLTAGE.

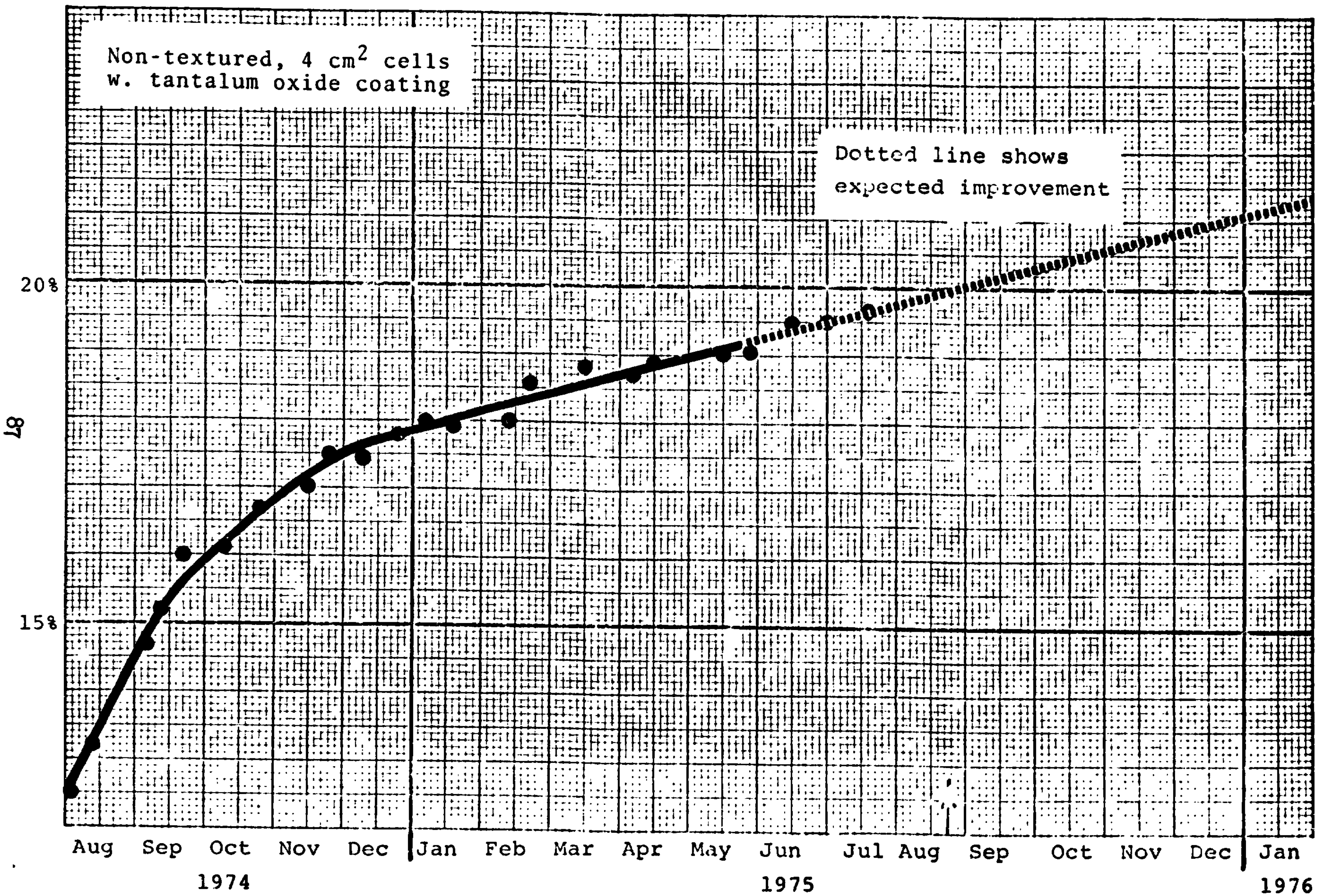
ORIGINAL PAGE IS
OF POOR QUALITY

C.2


POWER (mW)
90
80
70
60
50
40
30
20
2 ohm-cm
0.2 ohm-cm
VOLTAGE (mV)
600
500
400
300
200
100
0
180
160
140
120
100
80
60
40
20
0
CURRENT (mA)


PHOTOVOLTAGE IN mV AS A FUNCTION OF ABSOLUTE TEMPERATURE
1.18V - 22.3 kT/q
-2.26 mV/°C
0°
100°
200°
300°
400°
500°K

PROGRESS IN TERRESTRIAL EFFICIENCY



SUMMARY OF KEY RESULTS

IMPROVED TANTALUM OXIDE COATINGS

TEXTURING MAY LEAD TO LONG TERM DEGRADATION

HIGH FILL FACTORS AROUND 80%

BETTER UNDERSTANDING OF PHOTOVOLTAGE PROBLEMS

HIGHER PHOTOVOLTAGE, ABOVE 600 mV

BETTER RESPONSE

EFFICIENCY NEAR OR AT 20%

EFFICIENCY IMPROVES WITH CONCENTRATION

PLANNED ACTIVITY FOR NEXT 6 MONTHS

GRANT ENDS IN AUG. 1975; RENEWAL REQUESTED

IF RENEWED, THE EFFICIENCY RANGE ABOVE 20% WOULD BE EXAMINED, INCLUDING BASIC RESEARCH ON EFFECTS OBSERVED BUT NOT WELL UNDERSTOOD

SOLAR SILICON DEFINITION GRANT

AER 75 - 03972

PRINCIPAL INVESTIGATOR - DR. G. F. WAKEFIELD

TEXAS INSTRUMENTS INCORPORATED
DALLAS, TEXAS 75222

This project is being conducted to define a preliminary chemical purity specification for solar grade silicon. The specification should permit the utilization of less pure (than semiconductor grade) silicon to manufacture solar cells having efficiencies of at least 10% AMO. Lower purity solar silicon should be obtainable for significantly reduced cost than semiconductor silicon, since lower cost processing approaches could be utilized. The criticality of this goal is easily appreciated from the fact that silicon presently contributes 20% to cost of solar panels. Reduction of the panel cost to one tenth present cost is obviously material limited. Economies of scale and learning do not forecast the required cost reduction since semiconductor silicon is already an established, relatively large scale industry. This program was thus conducted on a compressed time scale to allow earliest consideration of the reduced purity requirements.

The approach on this project was to prepare crystals from high purity silicon doped to known level with many common impurities. This impure silicon was fabricated into small area diodes and solar cells to evaluate the effect of the impurities on device performance. Measurements were made of the I-V characteristics (with emphasis on the slope of the recombination and injection influenced curves), the photoresponse behavior and lifetime measurement by photoconductive decay technique. Following selection of the maximum levels of impurities tolerable within the performance criteria, samples of impure silicon were fabricated into solar cells by several solar cell manufacturers. The performance of these cells was compared to performance of cells fabricated simultaneously from semiconductor silicon by the same manufacturer to eliminate processing variables. The results of the diode evaluation showed that up to several ppm of most common impurities were tolerable in the raw material silicon used for crystal growth. The impure silicon provided for solar cell manufacturers tests was grown from silicon containing 10 ppm of each of the impurities being studied, for a total impurity level of 120 ppm in the melt.

The solar cells made from the impure silicon were consistently lower in performance by .5 to 1% absolute from all sources. The V_{OC} and I_{SC} were reduced .5750 to .565 V and 31 to 20 ma/cm^2 for 2" diameter cells semiconductor grade silicon and the impure silicon respectively. Cells from the impure silicon thus performed 90% as well as cells made from silicon having 10^4 - 10^5 higher purity level. The consistency of data from several sources of fabrication and the normal distribution shape of the yield curve tend to support the validity of the data.

A preliminary specification was drafted, reviewed with government and producers, and included in the grant final report.

SOLAR SILICON DEFINITION

SOLAR SILICON DEFINITION GRANT

NSF GRANT NO: AER75-03972

PERIOD: 15 OCTOBER 1974
TO
31 OCTOBER 1975

PRINCIPAL INVESTIGATOR:
DR. GENE WAKEFIELD

PERFORMED AT:
TEXAS INSTRUMENTS

GRANT AMOUNT: $172,400

SOLAR SILICON DEFINITION

TEXAS INSTRUMENTS/SOUTHERN METHODIST UNIVERSITY

GOAL:

- ESTABLISH A SPECIFICATION FOR SOLAR GRADE SILICON RAW MATERIAL WHICH CAN BE USED TO OPTIMIZE PERFORMANCE VS. MATERIAL COST FOR SOLAR CELLS TO PROVIDE A REALISTIC TARGET FOR LOW COST SILICON MANUFACTURING METHODS.

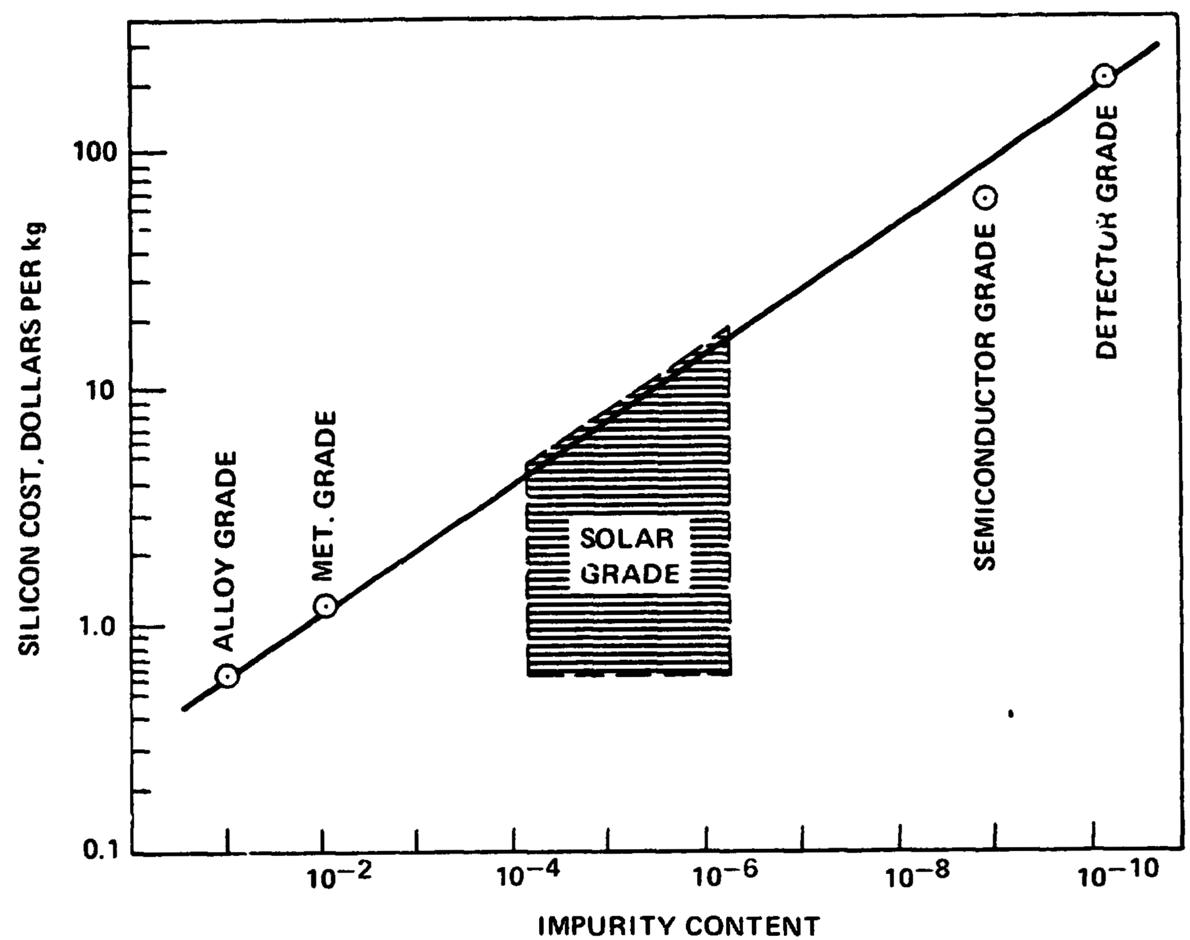
APPROACH:

- DEFINE AN IMPURITY PROPERTY VS. PERFORMANCE MATRIX WHICH WILL ALLOW DETERMINATION OF IMPURITY TOLERANCE LEVEL. EVALUATE MATERIAL AS P-N DIODE TO SELECT MATERIAL FOR FABRICATION OF SOLAR CELLS BY SOLAR CELL MANUFACTURERS. EVALUATE SOLAR CELLS.

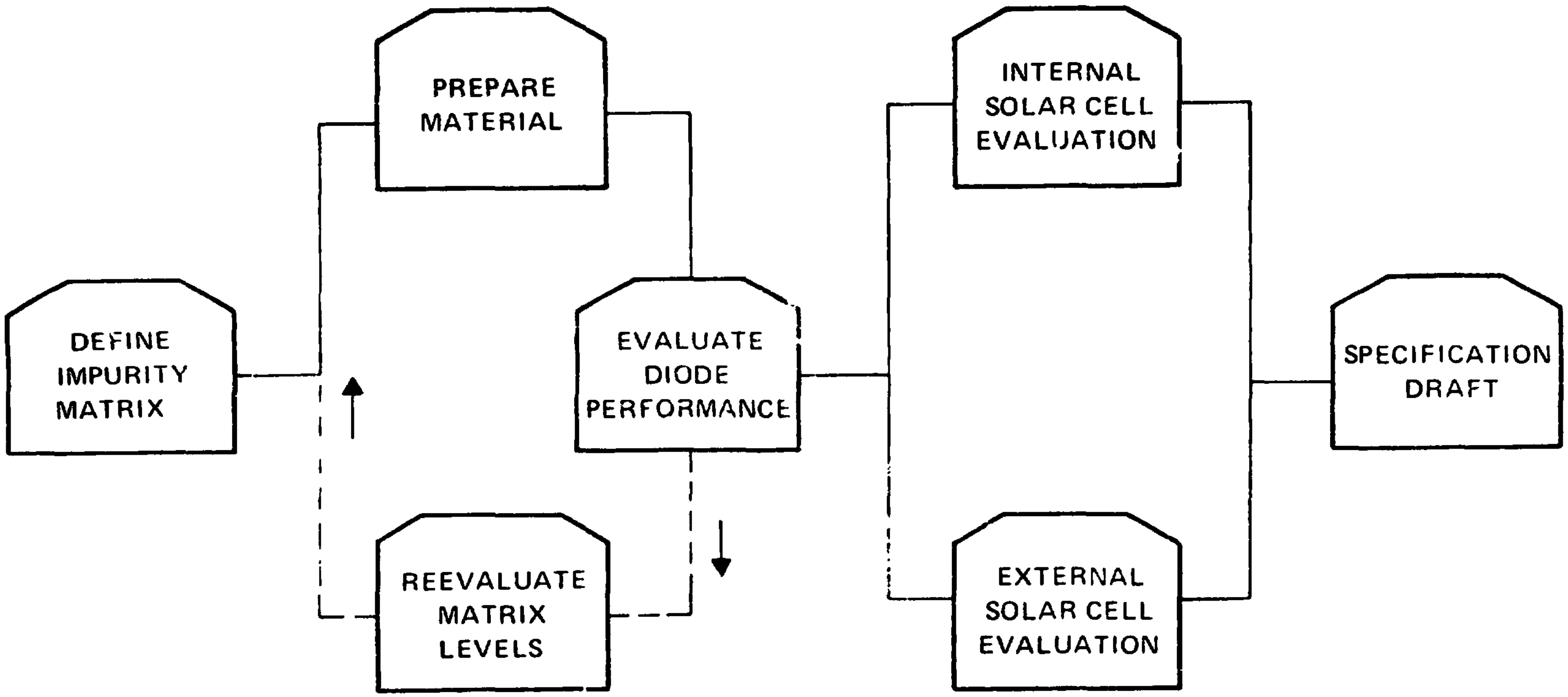
- SYNTHESIZE SOLAR GRADE SPECIFICATION AND PUBLISH AFTER REVIEW WITH INDUSTRY AND NSF.

JULY 1975 AER75-03972

SOLAR SILICON DEFINITION



SOLAR SILICON DEFINITION
EXPERIMENTAL APPROACH



JULY 1975 AER75-03972

SOLAR SILICON DEFINITION GRANT

PLANNED ACTIVITY	RESULT
• COMPLETE DIODE FABRICATION AND EVALUATION	• COMPLETED
• FABRICATE AND EVALUATE SOLAR CELLS	• SOLAR SILICON WITH 100 ppm IMPURITIES YIELDED 90% OF PERFORMANCE OF SEMICONDUCTOR SILICON
• PREPARE SPECIFICATION FOR IMPURITY CONTENT OF SILICON	• PRELIMINARY SPECIFICATION FOR SOLAR SILICON WRITTEN
• REVIEW AND PUBLISH SPECIFICATION	• SPECIFICATION REVIEWED AND PUBLISHED.

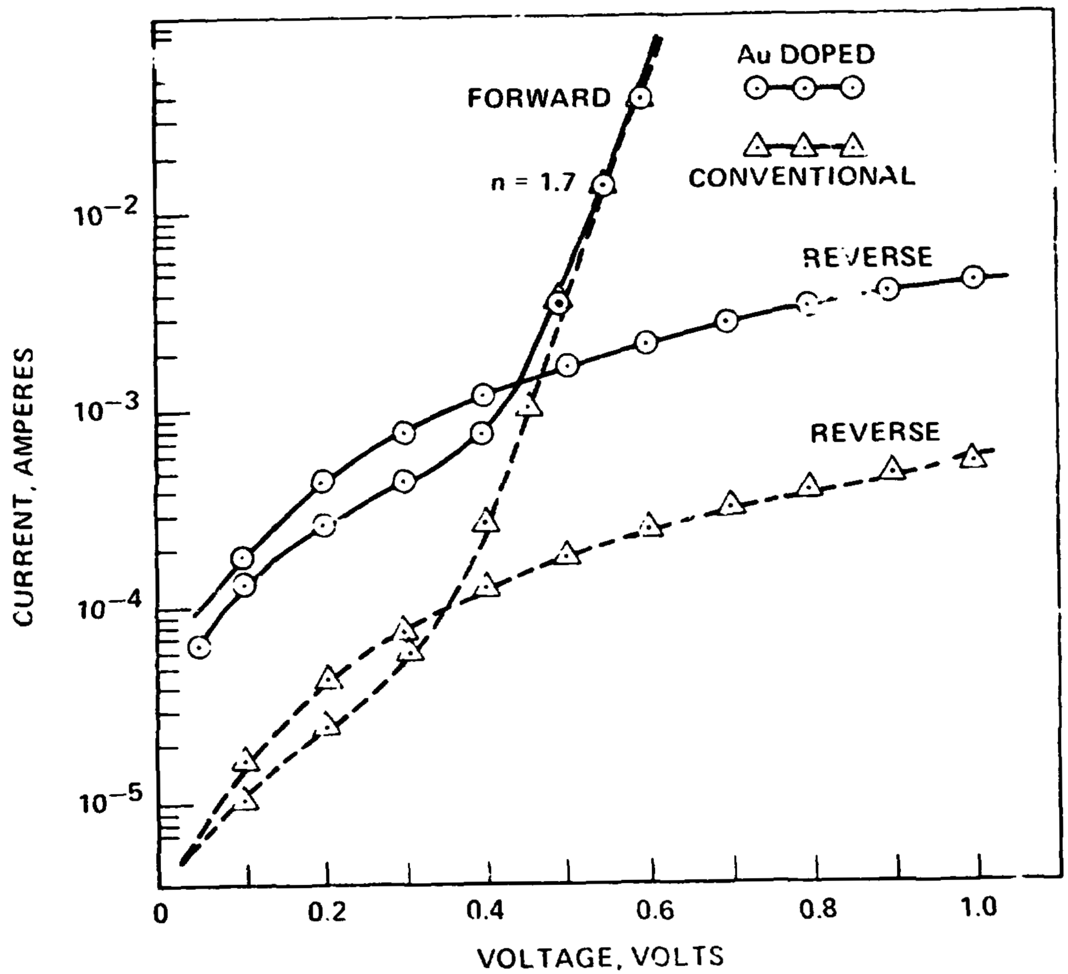
JULY 1975 AER75-03972

SOLAR SILICON DEFINITION

IMPURITY MATRIX FOR SOLAR SILICON DEFINITION

IMPURITY	GROUP	CONCENTRATION LEVELS LOG N, ATOMS/CC			SOLID SOLUBILITY
SODIUM	IA	15	17		9×10^{18}
MAGNESIUM	IIA	14	15	16	5×10^{18}
ALUMINUM	IIIA	14	15	16	2×10^{19}
COPPER	IB	13	14	15	1×10^{18}
GOLD	IB	14	15	16	1×10^{17}
ZINC	IIB	14	15	16	6×10^{16}
TITANIUM	IVB	13	14	15	1×10^{15}
VANADIUM	VB	13	14	15	5×10^{15}
CHROMIUM	VIB	13	14	15	5×10^{15}
MANGANESE	VIIB	13	14	15	4×10^{16}
IRON	VIII	14	15	16	3×10^{16}
NICKEL	VIII	14	15	16	1×10^{17}

INFLUENCE OF IMPURITIES ON SILICON SOLAR CELLS

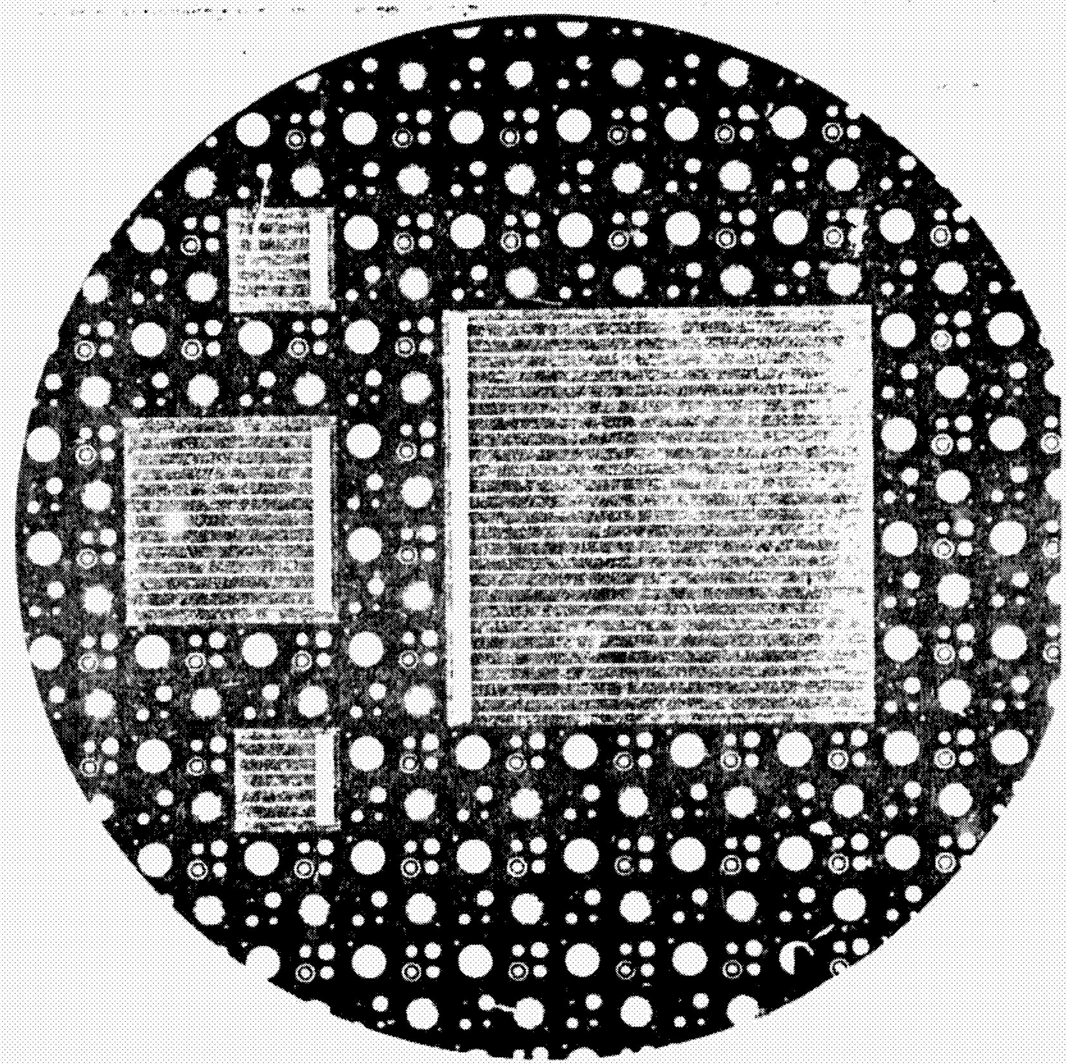


GOLD IMPURITY:
BEFORE PROCESSING
1×10^{16} a/cc;
AFTER PROCESSING .
7×10^{14} a/cc.

SOLAR SILICON DEFINITION

INFLUENCE OF IMPURITIES ON SILICON SOLAR CELLS

JUNCTION AREAS FROM 2×10^{-4} TO 4 cm^2



TEST PATTERN FOR DIODES AND SOLAR CELLS

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INFLUENCE OF IMPURITIES ON SILICON SOLAR CELLS

SUMMARY OF PHOTORESPONSE FROM DOPED SILICON SOLAR CELLS

IMPURITY	CONCENTRATION, a/cc X 10^{15}	PERFORMANCE*
COPPER	.3–2	.95
CHROMIUM	.1	.96
TITANIUM	.01–1	.88
MANGANESE	.01–.1	.94
VANADIUM	.01–.1	1
MAGNESIUM	.1–1	1
NICKEL	.01+.1	.97
IRON	.01–.7	.98
ALUMINUM	20	.7
GOLD	.7	.9

*RATIO OF SEMICONDUCTOR SILICON CELLS.

SOLAR SILICON DEFINITION

SILICON SOLAR CELL EVALUATION

CRYSTAL NUMBER	MELT COMPOSITION* ppm	RESISTIVITY OHM-CM, TYPE	FABRICATOR	RATIO TO "PURE" SILICON PERFORMANCE**
N	0.35 P	1, n	ALL	1 (AM1)
18	10 EA Ni, Cu, Cr, Mg, Mn, Ti, V 50 Fe; 0.35 P	0.8, n	TI	.88
			MOBIL TYCO	.95
			SOLAREX	.94 (.85)***
			SOLAR POWER CO.	.92
P	0.35 B	1, p	ALL	1 (AM0)
19	100 Al	0.9, p	TI	.6
			CENTRALAB	.66
			SOLAREX	.47
			MOBIL TYCO	.4

*BALANCE SEMICONDUCTOR GRADE SILICON
**BY SAME FABRICATOR
***RATIO TO WACKER SILICON, RESTIVITY ~ 8 OHM-CM

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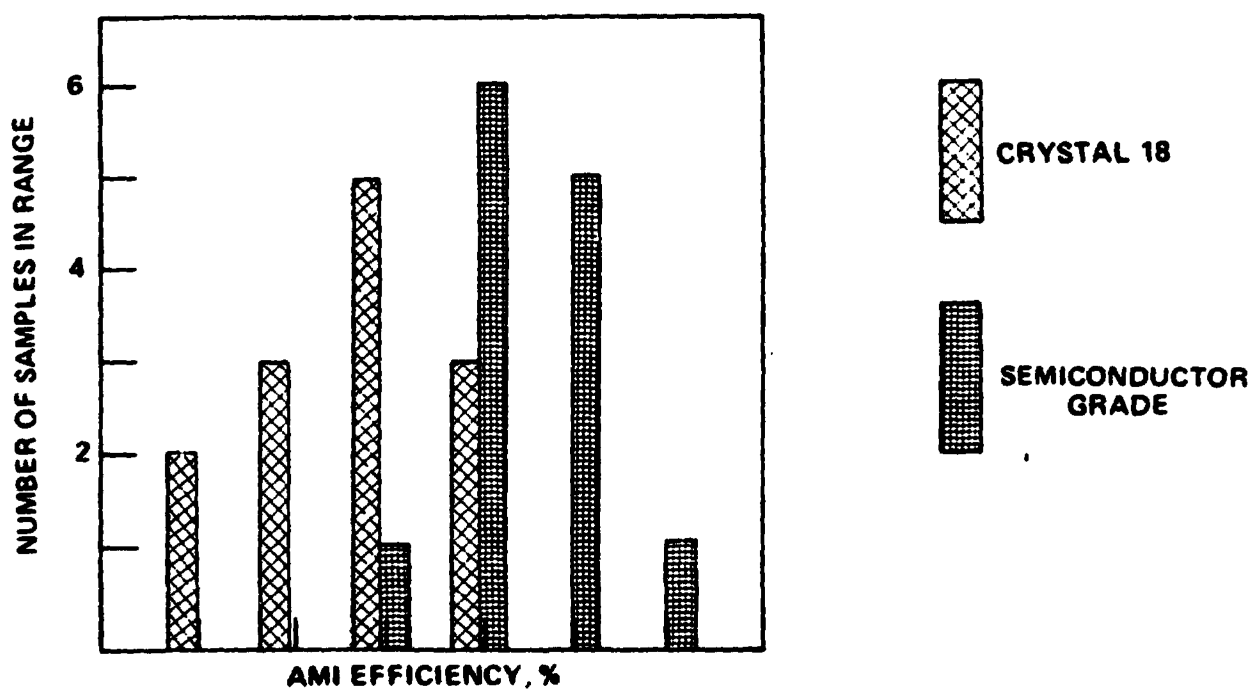
SOLAR SILICON DEFINITION

DISTRIBUTION OF SOLAR CELL CONVERSION EFFICIENCY



FABRICATED BY SOLAR POWER CORPORATION

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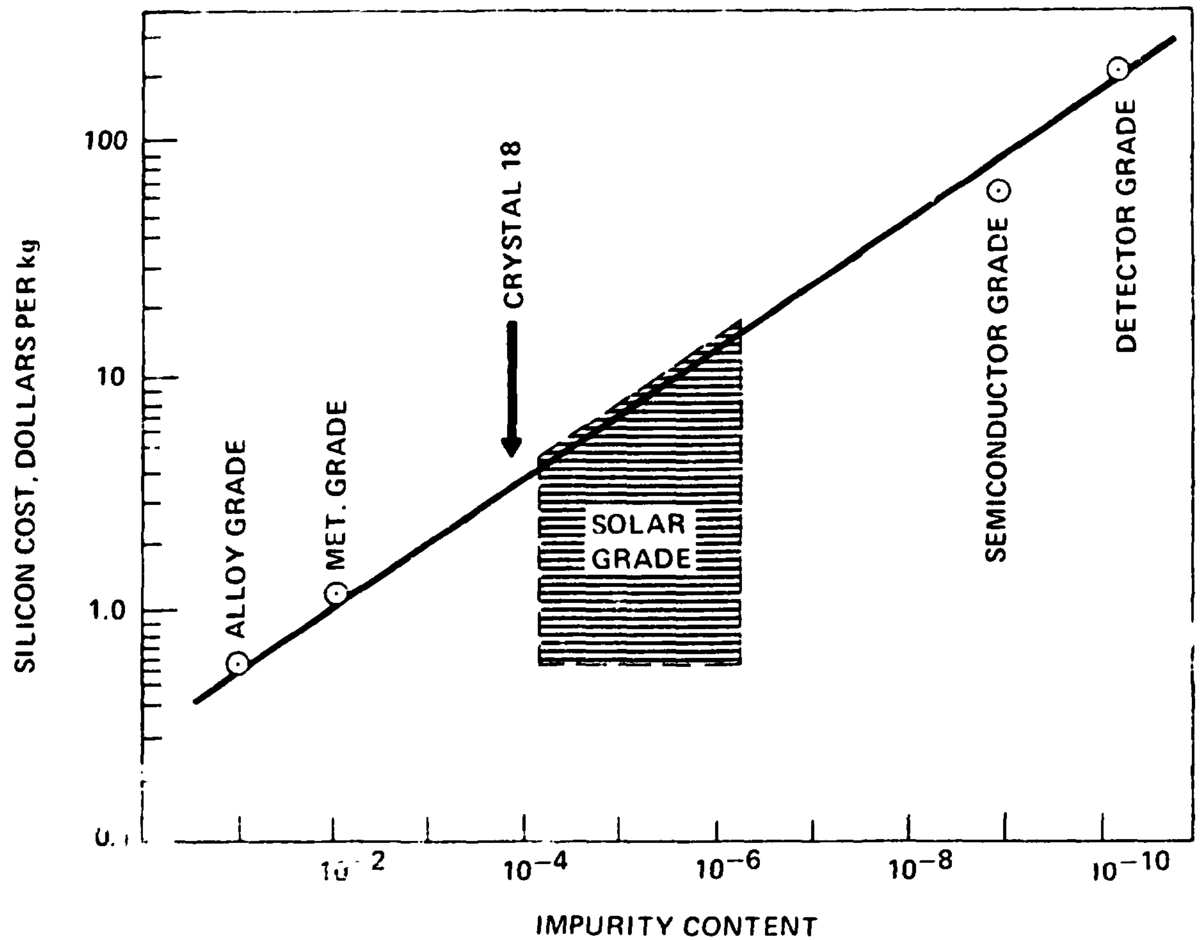
SOLAR SILICON DEFINITION



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SOLAR SILICON DEFINITION

PRELIMINARY SPECIFICATION FOR SOLAR SILICON

RAW MATERIAL:

MAXIMUM IMPURITIES (ppm)

IRON	25	VANADIUM	5
NICKEL	5	COPPER	5
CHROMIUM	5	OXYGEN	5
MAGNESIUM	5	CARBON	5
MANGANESE	5	ALUMINUM	1
TITANIUM	5	BORON	.01
PHOSPHORUS	.01		

CRYSTAL SHEET:

SOLAR SILICON SHEET (FROM ANY METHOD) SHOULD BE DISLOCATION FREE MATERIAL EQUIVALENT TO CZOCHRALSKI CRYSTAL PULLED FROM ABOVE RAW MATERIAL.

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SOLAR SILICON DEFINITION

SUMMARY OF KEY RESULTS

- DIODE AND SOLAR CELL PREFORMANCE OF DEVICES FABRICATED FROM SOLAR SILICON SHOWED EFFICIENCY (AM0) $>$ 10%.
- INFLUENCE OF IMPURITIES ON CZOCHRALSKI CRYSTAL GROWTH MINIMAL.
- PRELIMINARY SPECIFICATION FOR SOLAR SILICON WAS PREPARED ALLOWING PPM AMOUNTS OF COMMON METALS.
- LOW COST SILICON MANUFACTURING METHODS FOR SOLAR SILICON ARE LIKELY.

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