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SANDIA REPORT

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1989 DOE/Sandia Crystalline Photovoltaic Technology Project Review Meeting

P. A. Basore, Editor

Prepared by
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1989 DOE/SANDIA CRYSTALLINE PHOTOVOLTAIC TECHNOLOGY PROJECT REVIEW MEETING

July 11-13, 1989

SAND--89-1543

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Marriott Hotel
Albuquerque, New Mexico

P. A. Basore, Editor
Photovoltaic Cell Research Division, 6224
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

This document serves as the proceedings for the annual project review meeting held by Sandia's Photovoltaic Cell Research Division and Photovoltaic Technology Division. It contains information supplied by each organization making a presentation at the meeting, which was held 11-13 July 1989 at the Marriott Hotel in Albuquerque, NM. Information supplied by other Sandia contractors and single-page data sheets generated by the cognizant Sandia Technical Liaison for each contract are also included. Sessions were held to discuss national and international photovoltaic programs, one-sun crystalline silicon cell research, concentrator silicon cell research, concentrator III-V cell research, and concentrating collector development.

TABLE OF CONTENTS

1989 DOE/SANDIA CRYSTALLINE PHOTOVOLTAIC TECHNOLOGY PROJECT REVIEW MEETING AGENDA

	Tuesday, July 11	Wednesday, July 12	Thursday, July 13
8:30a	**PROGRAM OVERVIEW** Session Chair - Paul Basore, Sandia DOE/HQ - Andy Krantz Sandia - Eldon Boes Japan - Hideki Hasegawa PVUSA - Steve Hester	**CONCENTRATOR SILICON CELLS** Session Chair - David King, Sandia Stanford - Ron Sinton Purdue - Dick Schwartz AstroPower - Jerry Culik Solarex - Jerry Silver	**CONCENTRATOR WORKSHOP** Session Chair - Beth Richards, Sandia Panel: Sandia - Clement Chiang Alpha Solarco - Ed Schmidt ENTECH - Mark O'Neill JPL - Ron Ross PVUSA - Walter Stolte
10:00a	Break	Break	Break
10:30a	**ONE-SUN UNIVERSITY INITIATIVE** Session Chair - John McBrayer, Sandia ASU - Dieter Schroder Cornell - Sandra Hyland Duke - Ulrich Goesele NCSU - George Rozgonyi SUNY/A - James Corbett	**CONCENTRATING COLLECTORS** Session Chair - Alex Maish, Sandia EPRI - Frank Dostalek ENTECH - Mark O'Neill Alpha Solarco - Edward Schmidt Black & Veatch - Sheldon Levy	**SANDIA IN-HOUSE RESEARCH** Session Chair - Paul Basore, Sandia Oxide Interface - Carl Seager PDFL - John McBrayer Array Tracker - Alex Maish SBM3 - Beth Richards 20% Module - Clement Chiang
12:00n	Lunch	Lunch	Lunch
1:30p	**ONE-SUN SILICON CELL RESEARCH** Session Chair - John McBrayer, Sandia AstroPower - Bob Hall UNSW - Dave King, Sandia Stanford - Rich King GIT - Ajeet Rohatgi	**CONCENTRATING COLLECTORS** Session Chair - Jay Chamberlin, Sandia SAIC/TFI - Kelly Beninga, SAIC Wattsun - Ron Corio 3M - Al Zderad SEACorp - Don Curchod	**SANDIA PV LAB TOURS** PASTF - Jay Chamberlin PDML - James Gee PDFL - John McBrayer
3:00p	Break	Break	
3:30p	**ONE-SUN WORKSHOP** Session Chair - John McBrayer, Sandia Panel: SERI - Bhushan Sopori ARCO - Kim Mitchell AstroPower - Bob Hall Mobil - Fritz Wald Solarex - John Wohlgemuth Westinghouse - Dick Hopkins	**III-V CELL RESEARCH** Session Chair - James Gee, Sandia Spire - TBD Varian - Gary Virshup Boeing - Lewis Fraas Michigan - Tim Drummond Sandia - James Gee	
5:00p	Reception - Hotel	Barbecue - Dan Arvizu	

Sandia National Laboratories
Albuquerque, New Mexico 87185

Welcome to the 1989 DOE/Sandia Crystalline Photovoltaic Technology Project Review Meeting

For as long as Sandia National Laboratories has been involved in the DOE Photovoltaic Energy Technology Program, we have been hosting periodic meetings to bring together our research and development contractors with the Sandia staff and other interested parties. The first Project Integration Meetings (PIM) were held every six months. This was relaxed to nine months as the project matured and the roles of the various players became better defined. Declining budgets in recent years led to a further relaxation to once-a-year and a corresponding change in title to Project Review Meeting (PRM). While this year's meeting is still a PRM (whimsically pronounced "prom"), I chose to change the first part of the name to emphasize the similarity between concentrator and one-sun photovoltaic technologies based on crystalline (and large-grain polycrystalline) materials. Crystalline materials, especially silicon, have established an enviable record for reliability and longevity unlikely to be surpassed by competing photovoltaic technologies in the next decade. The task of supplying the near-term growth in demand for photovoltaics therefore lies primarily with the attendees at this meeting.

The history of crystalline photovoltaic technology has been marked by compromise between efficiency and cost. The challenge is to produce innovative solutions that both increase efficiency **and** reduce cost. Several such innovations will be described at this meeting. In that same spirit, I have attempted to make these proceedings more useful while at the same time requiring less effort on everyone's part. Rather than reproduce overhead transparencies, which have a low information density and are often modified prior to the meeting, each presentation is accompanied by a maximum of five pages of relevant printed information in these proceedings. Contractors not making a presentation were invited to supply up to three pages of information. There were no restrictions on format, to allow contractors to utilize as much previously-prepared material as possible. In addition, a contract data sheet prepared by the cognizant Sandia Technical Liaison is included for every contract, adjacent to the submitted material, so that each contractor's activities can be directly compared with their stated contract objectives. This approach certainly reduced the preparation time required here at Sandia. I hope that it similarly improved the productivity of our contractors, while producing a document that contains even more information than in the past.

Paul Basore

Dr. Paul A. Basore
Conference Chairman,
Photovoltaic Cell
Research Division, 6224

Program Overview

The DOE National Photovoltaic Program: Overview
Andrew D. Krantz, DOE

(This page provided for your notes)

OVERVIEW OF THE CRYSTALLINE CELL AND CONCENTRATOR COLLECTOR PROJECTS

Eldon C. Boes
Sandia National Laboratories

This presentation will discuss the Crystalline Cell and Concentrator Collector Projects in the broad context of photovoltaics power technology now and in the future.

Opportunities for Photovoltaics

The potential of photovoltaics as a very broadly applicable power source is just now becoming recognized outside the photovoltaics community. For a few applications, such as light buoys and communications, PV is already recognized as the best power source. That PV is also the best power source for many other applications, including many remote residential systems, water pumping systems, and village power systems, is not yet widely known, but that information is spreading rapidly. These applications represent very large markets for PV technology. Thus, for the first time we can confidently project steadily growing markets for photovoltaics. These markets represent a very real opportunity for photovoltaics technology to develop and expand.

One Sun Crystalline Si Technology

Approximately 60% of the 1988 PV module sales were for single or poly Si (X-Si) modules. Much of the market growth expected in the next several years is likely to have a definite preference for X-Si modules. This is because many of these applications will be individually too small for concentrator systems, and they may prefer the more established performance and durability of X-Si technology over the newer, less proven thin film technologies. Thus, I predict a steadily growing market for X-Si technology over the next several years.

This represents a major opportunity for the X-Si industry. The timing appears ripe for the design and development of new and larger production facilities. Of course, that also represents an opportunity to develop next-generation, higher efficiency products as well as more automated, more cost-effective production facilities.

Concentrator Technology

The steadily expanding deployment and application of PV power technology also represents an opportunity for PV concentrators. PV module and system prices are still a major hindrance for installation of larger systems. Achievement of lower PV module prices will result in competitive advantages, so the development of PV concentrator modules which can be sold for about $1/Wp represents the basis for a successful commercial venture. The opportunity for concentrators is that they still look like one of the best technological routes to $1/Wp modules.

There are additional reasons for optimism and excitement about PV concentrator technology today.

1. There is a broad technology base. Over the past several years, we have learned a great deal about all of the PV concentrator technology issues, including

   - Cost-effective collector designs
   - Lens materials and designs
   - Concentration ratios
   - Cell assemblies
   - Reliability

2. DOE support for technology development is available. The Concentrator Initiative Program will begin in early FY90 with multiyear, cost-shared support for both concentrator cell and collector technology development. Preliminary module development contracts are already underway.

3. Investment capital is available. It is my observation that more entrepreneurs are stepping forward with both technology development plans and investment sources that will support the development and production facilities needed to make concentrators a commercial success.

The challenge for the PV concentrator industry is to successfully bring this technology to the marketplace in 3 to 5 years at attractive system prices. More specifically, the industry needs to offer durable and reliable PV power systems in the range of $2 to $4/Wp. This requires both the development of the collector technology and the development of manufacturing facilities. It also requires the development of concentrator cell technologies and manufacturing facilities to make these available at acceptable prices.

The payoff to successful firms will be sales of about 10 MW per year starting in about 5 years and growing steadily beyond that.

Recent Accomplishments

One of the most rewarding aspects of working in photovoltaics R&D is that progress has been both quite rapid and continuous. Figure 1 illustrates that progress for the past decade in terms of the best laboratory cell efficiencies, for concentrator, crystalline Si, and thin film technologies. This chart contains several important and interesting points:

1. Very substantial progress has occurred in all three photovoltaic technologies.

2. That progress shows no sign of slowing or reaching "upper limits".

3. Considerable improvements in commercial products are possible through technology development utilizing the latest research results.

This last point requires some explanation. At present, commercial PV modules have efficiencies which reflect the best laboratory cell efficiencies of 10 years ago. In other words, adoption of cell research results of the past 10 years will result in modules of much higher efficiencies than those of current commercial modules.

There have been many significant accomplishments in photovoltaics R&D in the past year. Those of most relevance to the Sandia Crystalline Cell and Concentrator Projects are summarized in Table 1.

Sandia's Role

Over the next several years Sandia plans to place more of its emphasis on technology development and technology transfer in the Crystalline Cell and Concentrator Projects. This is in order to support industry in competing for the significantly larger markets that we project for the mid 1990's. However, we will continue to conduct some research aimed at longer term, higher efficiency photovoltaic technologies.

In both the 1-sun X-Si and concentrator cell areas we will emphasize support to industry in adopting the research results of the past several years. The Concentrator Initiative will support this technology transfer of high efficiency concentrator cell concepts, both Si and GaAs, to industry with multiyear, cost-shared contracts. We also hope to place industrial contracts in FY90 for the development of higher efficiency commercial 1-sun X-Si cells. Sandia's new Photovoltaic Device Fabrication Laboratory will be used as a vehicle for characterizing high efficiency Si cell processes and for transfering these into industrial settings.

In the concentrator collector area we will emphasize direct technical assistance to firms involved in the development of commercial PV concentrators under the Concentrator Initiative. This support will include design analysis, consultation on materials, components, and processes, and evaluation of prototype components and collectors. While we will continue some module development in-house, we truly view the focus to have shifted into the industrial arena, and so we plan to devote most of our efforts to supporting industry.

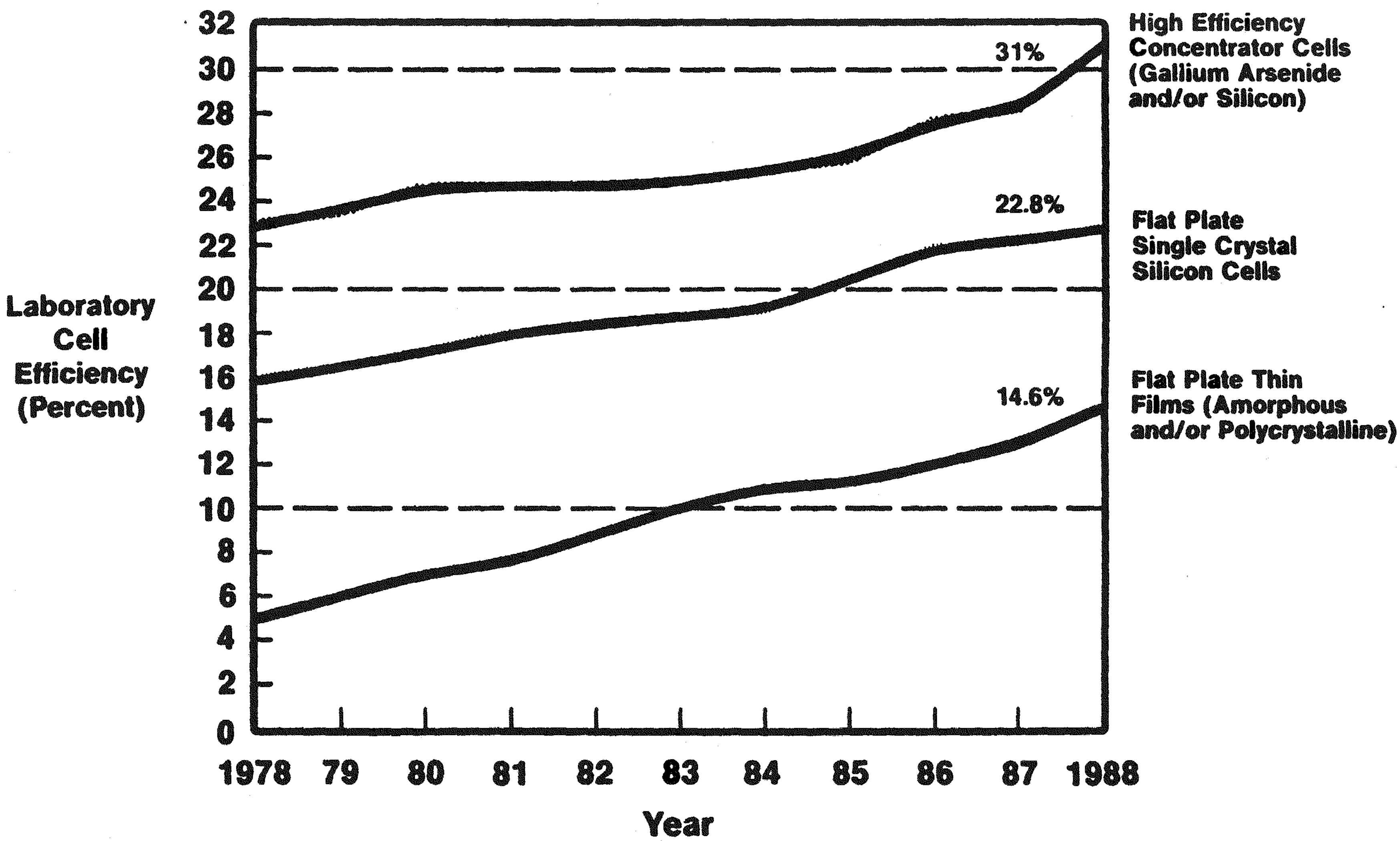


Figure 1. Laboratory PV Cell Efficiencies

Research Area	Result	Remarks
1-Sun X-Si	UNSW has achieved 17% efficiency on four different poly-Si materials. (Best efficiency was 17.8%.)	This result suggests that efficiencies for poly-Si cells can be about as high as efficiencies for CZ cells.
	AstroPower has achieved 15.7% efficiency with a Si-film-on-ceramic cell.	This is the best "thin-film" cell efficiency reported.
	The PDFL at Sandia is beginning operation.	This facility will conduct Si cell optimization and technology transfer for both 1-sun and concentrator cell technologies.
Concentrator Cells	Sandia, Varian, and Stanford achieved 31% efficiency for a mechanically stacked MJ cell.	First demonstration of a photovoltaic conversion efficiency above 30%.
	Stanford reports major progress on the UV degradation problem with their point-contact cell.	This problem appears solvable.
	UNSW delivered a batch (~500) of Si cells with (prism-covered) efficiencies of 24%.	High yields of high-efficiency Si cells are possible.
	Stanford reports high efficiencies using magnetic CZ material.	Magnetic CZ material may be a cost-effective alternative to the relatively scarce FZ material.
	Spire and AESI have achieved 24% efficiency with a GaAs cell grown on Ge.	This may be an attractive concentrator cell technology in the near future.
	Varian has achieved 27% with a monolithic MJ AlGaAs/GaAs cell at 1-sun.	This could become a very attractive concentrator cell technology in the future.
Concentrator Collectors	Sandia has achieved a peak module efficiency of 20% with a 12-lens, Si-cell experimental module.	Most features of this module are ready for commercialization.
	Prism covers have been successfully used in a 200X point-focus design.	Use of prism covers result in approximately a 10% efficiency gain.
	Prototypes of the Sandia microprocessor-based array tracking controller have been provided to industry.	This technology represents an economical and practical solution to the array control problem.

Table 1. Recent Accomplishments

CRYSTALLINE Si PHOTOVOLTAIC R & D PROGRAM UNDER THE SUNSHINE PROJECT

Hideki Hasegawa
Department of Electrical Engineering, Hokkaido University, Sapporo, 060 Japan, and

Tetsuro Kobayashi
Sunshine Project Promotion H.Q.
Agency of Industrial Science and Technology
Ministry of International Trade and Industry
Kasumigaseki, Chiyoda-ku, Tokyo, 100 Japan

Abstract

Present status and future of research and development on crystalline Si solar cells in Japan under the Sunshine Project are briefly reviewed. Remarkable efficiency improvements have been achieved in poly-Si cells. A new cost estimation has been made. Future plan is dedicated to fabrication of thin-substrate cells for both efficiency enhacement and cost reduction.

Sunshine Project

The purpose of the present paper is to review briefly the present status and future plan of crystalline Si photovoltaic R & D efforts in Japan which have been pursued under the Sunshine Project of Ministry of International Trade and Industry(MITI). This Project was initiated in July, 1974, aiming at a long-term goal of establishing technological capabilities of supplying adequate new and clean energy as a major proportion of the energy demand after several decades from then. In 1980, "New Energy Development Organization (NEDO)" was established jointly by MITI and the private sector for accelerated promotion of the Project. This organization has been serving as the contracting agency for R & D activities concerning various new energy technologies under the Sunshine Project. The budgetary trend for solar energy program under the Sunshine Project is summarized in Fig.1 where the shaded portion shows that for the photovoltaic program including photovoltaic system development.

Role of Photovoltaics

As seen in Fig.1, major portion of the Sunshine Project is dedicated to photovoltaics including both crystalline and amorphous Si solar cells. The budget for solar cell module development is briefly shown in Table 1. Although the total budget shown in Fig.1 has been decreasing slightly in recent years due primarily to availability of low-cost oil, one notes that the fraction occupied by photovoltaics is steadily increasing, being more than 90 % for 1989. The ultimate aim for photovoltaics is practical exploitation of photovoltaic energy in supplying 2-3 % of the total electricity demand in Japan in the year of 2000 (according to the latest forecast published in October 1987, the energy consumption in Japan in the year 2000 is

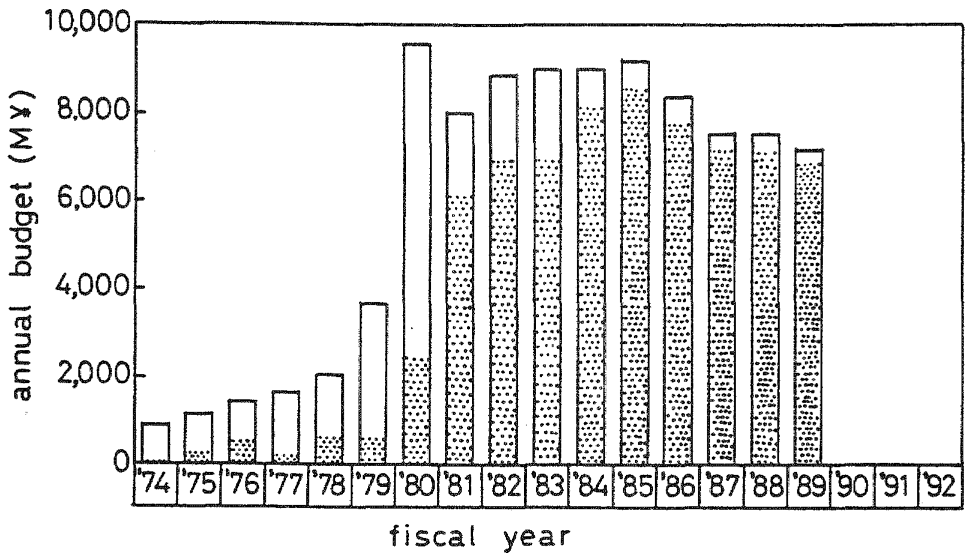


Figure 1 Budget for solar energy program under Sunshine Project

Table 1 Budget for Solar Cell Modules under Sunshine Project
(unit: million yen)

fiscal year	1983	1984	1985	1986	1987	1988	1989
poly-Si cell	1,662	1,764	1,835	2,235	1,807	1,325	1,987(*)
a-Si cell	1,260	1,741	2,172	2,205	2,145	2,790	1,929(*)

(*)for development of new-type cells for the term '89-'92

estimated to be equivalent to a total of 540 million kilolitres of oil). In terms of the PV module cost, 100-200 yen/W with reasonable efficiencies for lowering BOS cost is set to be the final target.

Present Status of Crystalline Si Photovoltaics in Japan

The Sunshine Project has been pursued on 3-4 year periods with subsequent interim assessment which in turn modifies the targets and contracts in the subsequent term. Last year (1988), the third assessment was made, following those in 1982 and 1985, and a new 4-year plan (FY1989-1992) was set out. The research items on the crystalline Si solar cell for the term of FY 1986-1988 included (1)low-cost production of Si, (2)substrate fabrication technology (cast ingots and sheets) and (3)cell fabrication technology.

Sufficient supply of low-cost high quality material is essential for successful development of crystalline Si photovoltaics in large scale. Low-cost production of Si by various approaches were investigated, including SOG-Si production by carbothermic reduction of high purity silica. Preparation technology for square substrates by casting has been established where large ingots with reduced oxygen and carbon contents were prepared by a semi-continuous casting furnace with reduced solidification speed and lower cooling rate, followed by highly efficient wafering with a multi-wire saw. The maximum life time of 35 µS (p-type, 39 ohm-cm) and cell efficiency of 15.7 % were achieved. Direct Si sheet formation by the spin cast process was also investigated, resulting in life time of 6 µs(p-type, 50 ohm-cm) and cell efficiency of 12.3%.

Various efforts were made to improve the efficiency of the crystalline Si solar cells, including hydrogen passivation of polycrystalline bulk, surface passivation by silicon dioxide and silicon nitride, improvement in device structure and design, two-dimensional CAD tool development for device simulation and design, development of maskless formation process of fine electrode patterns and optical loss reduction by double-layer AR coating. The project targets, annual improvements and present achievements concerning cell efficiency under the Sunshine Project are compared in Table 2 and Fig.2 for the crystalline and amorphous Si solar cells.

On the basis of the present technological achievements and those expected in future, a realistic cost estimation was carried out, and the key result is shown in Fig.3.

A New 4-Year Plan for Crystalline Si Photovoltaics

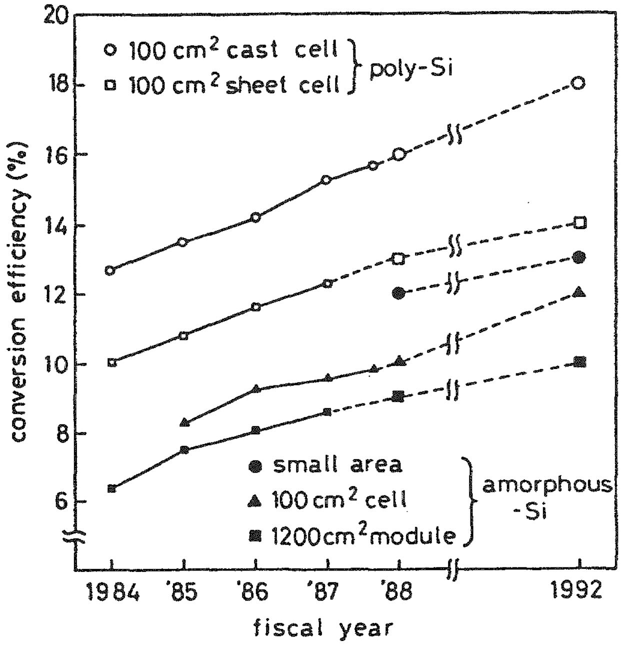
Photovoltaic R & D programs for the new term (1989-1992) include (1) thin-substrate crystalline Si solar cells, (2) multi-layered (tandem) solar cells and (3) production technology of

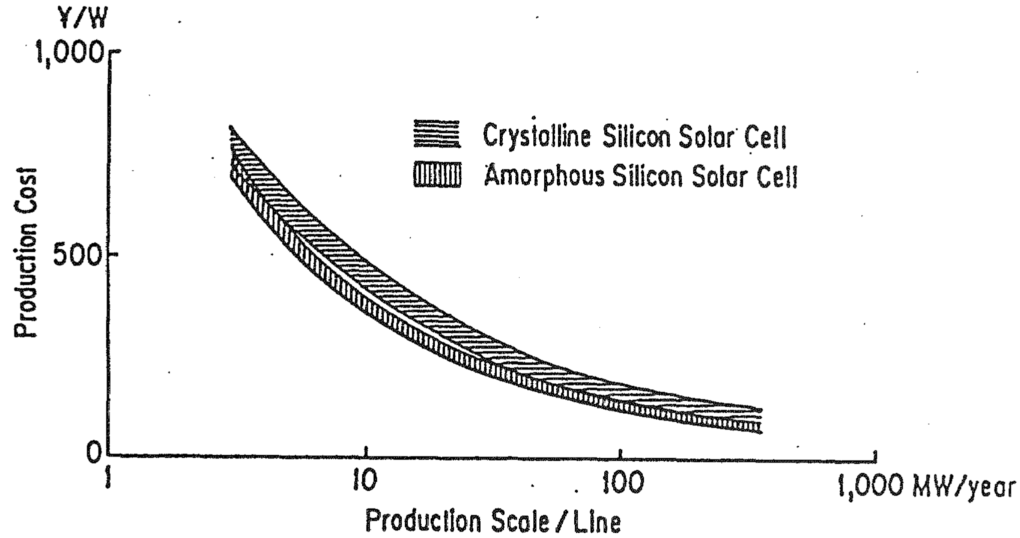
Table 2 Summary of the Project target and achievement

	Targets		Achieved (Mar,1989)
	FY1988	FY1992	
Poly Crystal (sheet, $100cm^2$)	11%	14%*)	12.3%
Poly Crystal (cast, $100cm^2$)	15%	18%*)	15.7%
Single Crys.($4cm^2$)	18%	23%*)	20 %
Amorphous ($100cm^2$)	10%	12% DR:10%/yr	9.6% (single) 10.1% (tandem)
Amorphous ($1200cm^2$)	8%	10% DR:15%/yr	9.0%
Stacked (a-Si/ i/poly-Si,$100cm^2$	-	14%	-
Stacked (a-Si/CdTe or C.I.S.$1200cm^2$)	-	13%	-

*)thin substrate cells DR = degradation rate

Figure 2 Trends of solar cell conversion efficiencies under the Sunshine project for poly Si and a-Si cells





Production Scale	10 MW/year	100MW/year
Crystalline Silicon Solar Cell	440~490 Y/W	140~190 Y/W
Amorphous Silicon Solar Cell	350~390 Y/W	130~150 Y/W

Figure 3 Results of future cost estimation plotted against production scale per line

amorphous Si solar cells. An outline of the new R & D program on the thin-substrate crystalline Si solar cell is given in Table 3. The basic recognition is that use of thin crystalline substrates is effective to realize both lower material cost and higher efficiency. The program is dedicated to development of (a) high-purity substrate fabrication technology, (b) high-speed fabrication technology of substrates and (c) new cell-design and fabrication technologies of thin-substrate solar cells.

Acknowledgment: The authors are grateful to Dr. Y. Hayashi, Electrotechnical Laboratory for his useful discussion.

Table 3 Outline of New 4-year Plan (1989-1992) on Thin Substrate Crystalline Si Solar Cells

(a) High-purity substrate fabrication technology	
aim	improvements in the quality of solar grade silicon materials and improvements in the productivity, quality and thin slicing of substrates.
target	impurity O:below $2x10^{17}cm^{-3}$, C:below $5x10^{16}cm^{-3}$ diffusion length above 150 μm ingot size 20cmx20cm substrate thickness below 200 μm
approach	impurity reduction, establishment of electromagnetic casting, establishment of slicing technology
(b)High-speed fabrication technology of substrates	
aim	development of very high-speed fabrication technology of thin and large-area substrates. Manufacturing of low-cost solar cells with improved efficiency.
target	substrate size 20cmx20cmx0.1mm fabrication speed above 1 sheet/min efficiency(10cmx10cm) above 14%
approach	temperature control in material growth material and design improvement in the mold module
(c) New cell-design and fabrication technologies	
aim	development of design and fabrication technologies of high efficiency thin-substrate crystalline Si cells
target	poly-crystal cell;cell conversion efficiency of above 18% for 10cmx10cm and above 17% for 15cmx15cm single crystal cell; cell conversion efficiency of above 23 % for 2cmx2cm
approach	the following key technologies will be developed. (1)stress reduction in thin-substrate-cell fabrication (2) new device structure and design method (3) optical confinement (4) surface passivation (5) printed fine electrode fabrication (6) large-area-cell technology

PVUSA: Overview and Status

Steve Hester
Pacific Gas and Electric

PHOTOVOLTAICS FOR UTILITY SCALE APPLICATIONS

PROJECT DESCRIPTION:

* Phase 1...1986-1990 , Phase 2...1990-1993
* Cooperative, National, Utility, PV Demonstration
* 3.5 MW of various-sized Buy American PV systems
* Multiple U.S. Utility involvement & sites

CONCEPT:

* Gain needed knowledge on Utility PV system operation, maintenance, and impacts

OBJECTIVES:

* Compare and evaluate PV systems (both modules and BOS) for performance and reliability
* Assess O & M costs within a utility setting
* Evaluate PV systems in various geographic areas
* Provide utilities with hands-on experience
* Document and disseminate the data

PVUSA PROJECT ORGANIZATION

STEERING COMMITTEE

DOE
EPRI
CEC
PG&E
Virginia Power/Virginia
Hawaii/Maui Electric

PROJECT TEAM

Management
Engineering
Procurement
Construction
Data & Analysis

TECHNICAL REVIEW COMMITTEE

DOE/EPRI/CEC/SANDIA/SERI
JPL/PG&E/VIRGINIA POWER/
SAN DIEGO GAS & ELECTRIC/
SALT RIVER PROJECT/
HAWAII/MAUI ELECTRIC

Also interested in participation:

City of Austin
Central and Southwest
Lower Colorado River Authority
New York State E.R.D.A.
New York State Electric and Gas
Public Service Co. of Colorado

BENEFITS OF PARTICIPATION

* Knowledge of PV technology
* Hands-On experience
* Involvement with:
  - TRC (PV experts)
  - Other installations
  - National data base
* Leverage

U.S. HOSTING OVERVIEW

* 25 kW or 50 kW system
* Similar to larger Davis
* 50/50 PVUSA cost sharing
* S.C. Contribution credit

EMERGING MODULE TECHNOLOGIES (EMT)

Promising, but unproven, PV collector technologies which will be evaluated for inclusion in future PVUSA Utility Scalable segments.

- o 2 EMT Procurements
- o 20 kW PV Arrays
- o Project supplied structures & PCU

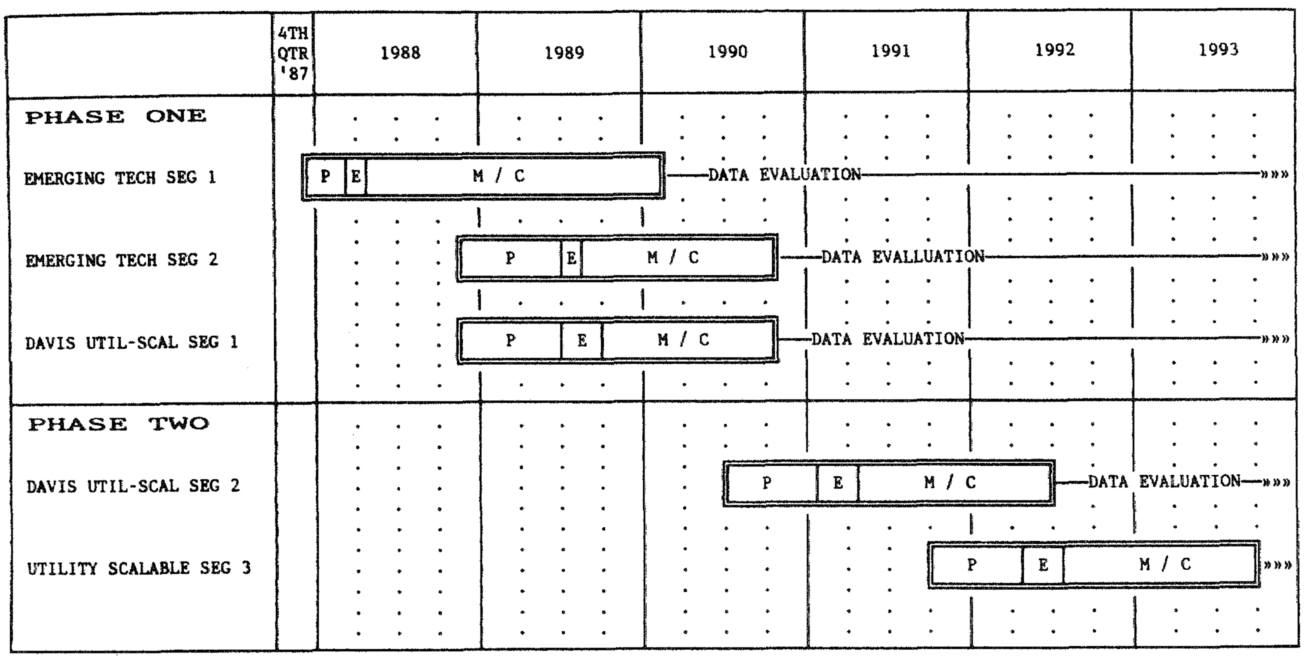
UTILITY SCALABLE SEGMENTS (U.S.)

Optimized complete turnkey PV systems which will provide realistic evidence of O&M costs, reliability, system performance, and grid interaction.

- o 3 U.S. Procurements
- o 200-400 kW Turnkey systems
- o Other utilities 25 kW, 50 kW, (100 kW)

PVUSA SCHEDULE

06/07/89



Subject to Availability of Funds

LEGEND: P - Procurement
E - Engineering by Vendors
M - Material Manufacturing
C - Construction of Segments

PROJECT ACCOMPLISHMENTS

* PROJECT ORGANIZATION ESTABLISHED
  - Responsibilities defined
  - Funding in place for Phase 1

* DAVIS SITE COMPLETE
  - I&C Building and DAS in place
  - EMT-1 & EMT-2 & US-1 areas developed
  - Future expansion areas available

* ARCO & SOVONICS ARRAYS GRID CONNECTED
  - ARCO, Highest efficiency 20kW array
  - Sovonics, Largest tandem a-Si array

* UPG ARRAY INSTALLATION STARTED

* DATA ACQUISITION SYSTEM
  - State-of-the-art
  - In operation

* PVUSA STANDARDS & SPECIFICATIONS INITIATED

* US-1 AND EMT-2 SELECTIONS MADE

PVUSA PV SELECTIONS

EMT-1

VENDOR	MODULE TECHNOLOGY
ARCO Solar	Microgridded Crystalline Silicon
Solarex	Bifacial Poly-Silicon
Sovonics	Tandem Junction Amorphous Silicon
UPG	Tandem Junction Amorphous Silicon
Entech	Linear Concentrator, Silicon Cells

EMT-2

VENDOR	MODULE TECHNOLOGY
ARCO Solar	Copper Indium Diselenide (CIS)
AstroPower	Polycrystalline Silicon film on ceramic substrate
Photon Energy	Cadmium Sulfide/Cadmium Telluride (CdS/CdTe)

All EMT PCU's (Inverters) From DECC/HELIONETICS

US-1

VENDOR	SYSTEM TECHNOLOGY
ARCO Solar	Flat-plate, 1-Axis Tracking, Crystalline Silicon, Dickerson PCU
Chronar	Flat-plate at fixed 30, Amorphous Silicon, Magna Power PCU
Integrated Power Corp (IPC)	Flat-plate, 1-Axis Tracking, Mobil Solar EFG Silicon, Omnion PCU

DO NOT MICROFILM
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One-Sun University Initiative

LIFETIME AND DEFECT STUDIES IN POLYSILICON SOLAR CELLS

J.B. Mohr, S.H. Park, I.G. Hwang, D.K. Schroder and C.E. Backus

Department of Electrical and Computer Engineering
Arizona State University
Tempe, AZ 85287-5706

Two limitations in polycrystalline silicon solar cells are the low lifetime and the reduction of lifetime with increased doping concentration. The low lifetime is generally attributed to recombination at bulk impurities, grain boundaries, twin planes, and dislocations. In this program we are trying to understand the causes and mechanisms of this reduced lifetime. The first year tasks are:

- Obtain poly-Si materials and solar cells from Mobil Solar Energy Corp. and Solarex Corp.
- Verify cell I-V and efficiency; characterize the diffusion length by surface photovoltage, the lifetime by open-circuit voltage decay, and defects by deep-level transient spectroscopy.
- Map the diffusion length; choose appropriate sections of virgin material and cells for further microscopic studies.
- Fabricate Schottky barrier devices on material with appropriate grain boundaries and other defects for electron beam-induced current measurements.
- Based on EBIC characterization choose samples for transmission electron microscopy.

As-grown material and completed cells were supplied by Mobil Solar Energy Corp. (edge-defined film-fed growth (EFG) Si) and by Solarex Corp. (cast Si) for this program. The major effort so far has been devoted to Mobil's EFG material with only few measurements made on Solarex material. Solarex cast poly-Si will be studied more intensely during the next phase.

Our approach is to proceed from global to detailed measurements. By global measurements we mean measurements that give us spatial information of certain material characteristics such as diffusion length, generation lifetime, defects and impurities from EBIC and from SIMS plots. Based on these plots, we use more detailed methods (e.g. DLTS, TEM) to study the microscopic properties of certain defects or certain regions of the samples.

We are using a variety of characterization techniques to determine the recombination properties of structural and point defects in poly-Si material and solar cells. The techniques are:

- Surface photovoltage for minority carrier diffusion lengths
- Open-circuit voltage decay for minority carrier lifetimes
- Electron beam induced current for defect mapping
- Pulsed MOS capacitor for generation lifetimes
- Deep level transient spectroscopy for defect identification
- Current-voltage measurements for junction quality
- Secondary ion mass spectrometry for point defect mapping
- Transmission electron microscopy for microscopic structural information
- Electron channeling for grain orientation
- Optical microscopy
- Defect etching for defect delineation

Surface Photovoltage (SPV):
We use SPV to determine the minority carrier diffusion length and have utilized the mapping capabilities of the technique, as illustrated in Fig.1, where a diffusion length map is compared with a sketch of the optically observable defects of the sample. We use a computer-controlled SPV apparatus in one of several sample configurations. For flat sample surfaces we use a capacitive probe pressed against the sample. This technique does not work for unpolished surfaces of starting material where we form optically transparent Schottky barrier contacts using 200 Å thick Al. For completed cells we etch small mesa diodes and use them for SPV measurements.

It is quite obvious from Fig.1 that of the many linear defects, only certain ones are electrically active. This is further corroborated by EBIC plots of such samples. We have not yet found a correlation of diffusion length with defects observed optically, but correlation with EBIC plots is quite good. The diffusion lengths before processing are in the 50 to 60 μm range increasing to 70-100 μm after cell processing. Occasionally they exceed 100 μm after processing.

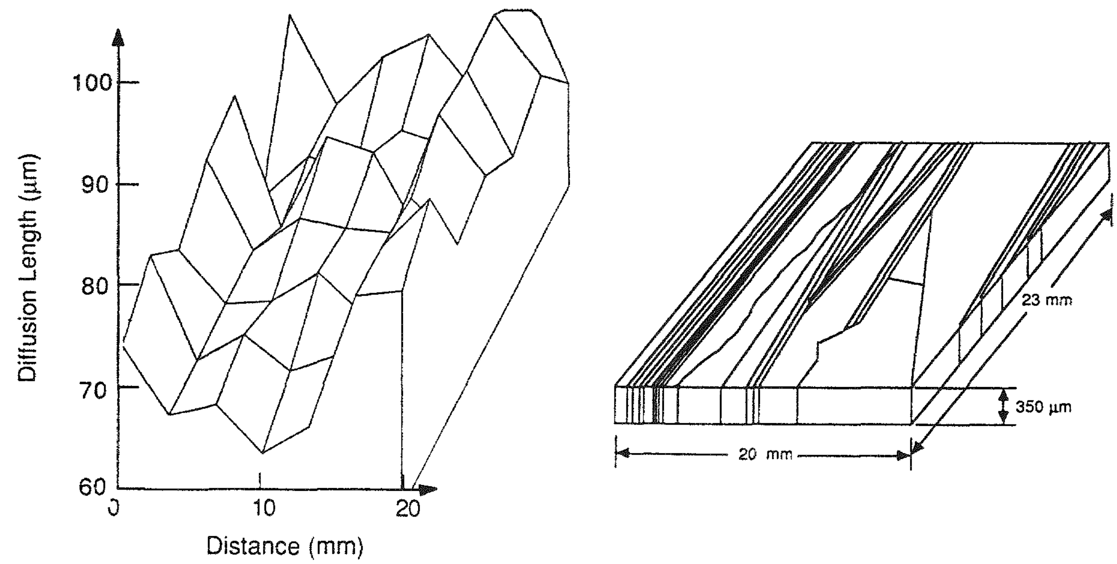

Fig.1 Spatial distribution of diffusion lengths and defects of EFG sample 490811 after cell processing.

Deep Level Transient Spectroscopy (DLTS):
We expected no difficulties in measuring DLTS signals in poly-Si materials since EBIC measurements showed very distinctive dark line defects, associated with grain boundaries, twins and other defects. To our surprise we have not been able to observe majority carrier DLTS peaks in p-type EFG material provided with Schottky contacts. This may be due to one of several reasons: (i) the material contains such low defect concentrations that we do not detect them. This is unlikely as our DLTS system, based on the lock-in amplifier approach, is able to detect concentrations at the $10^{-4}N_A$ level. We can detect deep-level concentrations in the 10^{11} to 10^{12} cm^{-3} range in single-crystal Si and in deliberately contaminated poly-Si. (ii) The defects are located in that portion of the band gap where they are not accessible to majority carrier DLTS probing. This may be, since we are only able to probe approximately the lower half of the band gap using Schottky contacts. (iii) EFG material behaves differently from single-crystal Si as far as DLTS measurements are

concerned. This may well be since the defect structure in poly-Si is quite different from the usual point defects in single crystal materials.

To check whether EFG material gives DLTS peaks at all, we have diffused gold into both single-crystal Cz and into EFG materials and measured the energy levels and gold concentrations by DLTS. Gold was chosen since its behavior in Si is well known. We find very distinctive peaks for both materials whose energy levels correspond with the well-known gold levels at 0.35 eV and at 0.56 eV above the valence band edge as shown in Fig.2. For comparison we show on the same figure the DLTS plot for a non gold-diffused EFG sample which shows no peak whatsoever. The height of the gold peaks is not indicative of the gold concentration, since the doping concentration of the two samples differ from one other. We find the gold concentration to be higher in the EFG sample by about a factor of ten and attribute this to gold precipitation at the boundaries. This in spite of the fact that the boundary volume is much smaller than the total Schottky volume. The gold precipitation is discussed further in the EBIC section.

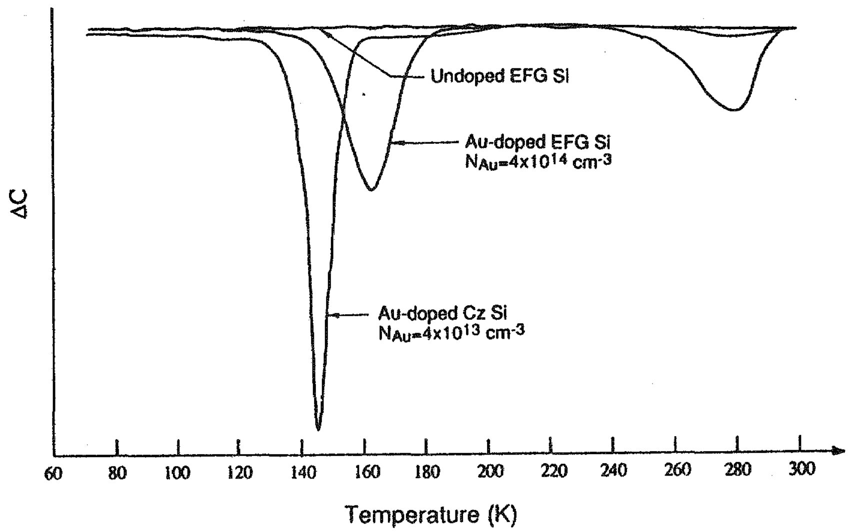

Fig.2 DLTS plots of gold-doped Cz, gold-doped EFG, and non gold-doped EFG.

Electron Beam Induced Current (EBIC):

EBIC has proven to be very useful for spatial recombination mapping by showing electrically active structural and point defects. We generally see many fewer electrically active defects in EBIC plots than in optical micrographs. Obviously many line and area structural defects are not electrically active. We show in Fig.3 two EBIC plots; one for a conventional EFG sample and one for a gold-diffused EFG sample. Two significant differences are observed: (i) the general Au-diffused sample current is reduced, and (ii) the current in the "valleys" at the boundaries is significantly reduced. These "valleys" are indicated by arrows. Other nonuniformities in the EBIC signal are due to scratches on the Schottky metal contact.

The overall reduction of the EBIC signal is due to diffusion length reduction in the non-boundary regions of the sample. Typically the diffusion lengths for samples diffused with gold at 930°C for 90 min are around 25 μm - significantly below the 50 to 75 μm of undiffused material. The reduction of the EBIC signal in the high recombination boundaries, indicated by the letters A and B in Fig.3, indicates significant gold precipitation or segregation at the boundaries. This is to be compared with the much smaller "dip" C of the non-gold EFG sample compared to A and B.

We believe it is the segregated gold at the boundaries that accounts for the increased gold concentration in the EFG sample as measured with DLTS.

Secondary Ion Mass Spectrometry (SIMS):

We have made some preliminary SIMS measurements on EFG material using the imaging mode of SIMS and have found carbon segregation at boundaries and also at what appear to be dislocations. The measurements have so far been confined to the upper 300 Å from the surface. We are extending the measurements by "looking" deeper into the sample beyond 300 Å. In addition, we are attempting to lap and polish laterally to within a few microns of a grain boundary that had preciously been shown to contain significant carbon concentrations. This involves lapping the wafer from the side not from the top, having previously marked the location of the boundary determined by "planar" SIMS and by EBIC. By lapping to within SIMS sputtering distance we expect to be able to determine the lateral carbon distribution within a boundary.

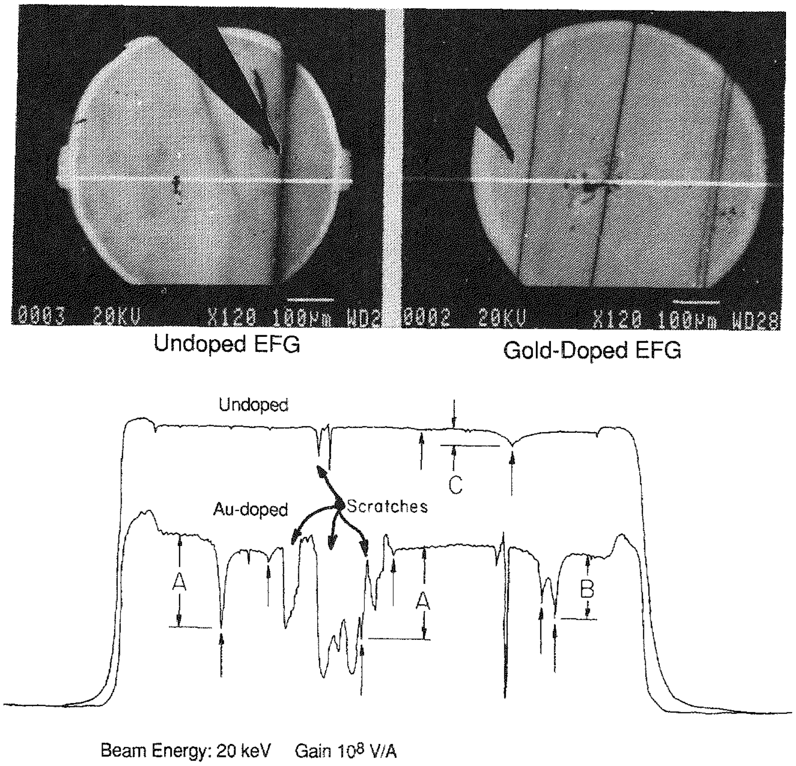

Fig.3 EBIC plots before and after gold diffusion in EFG.

Pulsed MOS Lifetime:

Lifetimes in solar cell materials are generally measured by surface photovoltage, photoconductive decay or other *recombination* lifetime characterization techniques. The recombination lifetime τ_r, of course, governs solar cell behavior. However, the depth resolution of τ_r measurements is poor being determined by the minority carrier diffusion length, which may be tens or even hundreds of microns. For higher resolution lifetime mapping, it is advantageous to measure the generation lifetime τ_g by the pulsed MOS capacitor method. The measurement depth is determined by the gate voltage induced space-charge region width that is typically on the order of 1 to 5 microns allowing smaller volumes to be probed. The technique also allows lateral mapping and depth-dependent lifetime determination. The method's weakness is the necessity to grow an oxide layer for the MOS capacitor formation. Virgin material is difficult to measure since room-temperature oxides are generally of poor quality.

Generation lifetimes of EFG material, shown in Fig.4, are in the 5 to 10 µs range prior to hydrogen passivation. This sample has undergone a conventional 450°C - 45 min. hydrogen anneal to reduce interface states at the Si-SiO_2 interface, but such anneals do not appear to passivate boundaries and other bulk defects significantly. The τ_g/τ_r ratio depends on the location of the energy level of the dominant generation/recombination (G-R) centers in the band gap and it is typically 50 to 100 for single crystal Si. For the EFG sample it is only about 5 to 10 which may be due to the distributed energy nature of the G-R centers associated with planar and volume defects like grain boundaries and precipitates. When profiling the lifetime to a depth of about 6 µm from the surface, we find the lifetime to be relatively constant with depth in some samples, but in others it increases into the wafer. We have not yet observed generation lifetimes that decrease with depth.

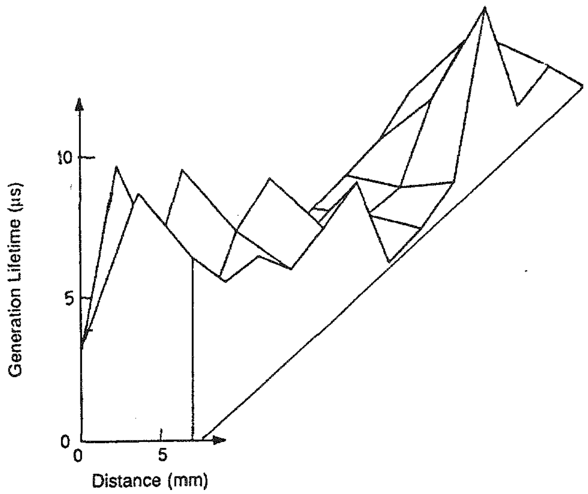

Fig.4 Generation lifetime before hydrogen passivation.

Transmission Electron Microscopy (TEM):

Selected portions of some samples have been chosen for detailed TEM analysis. So far we have not found any significant features in TEM images that correlate with other measurements. However, we have not yet made TEM measurements on the gold-diffused samples.

Title: One-Sun Crystalline Solar Cell Research

Contractor:
Arizona State University
Tempe, Arizona 85287

Principal Investigator:
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Current Contract Number:
55-0702A
Current Contract Period:
From:7/88 **To:**7/89
Project/Area/Task:
Crystalline Cell Research
Task 3 One-Sun Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
John D. McBrayer
Telephone:
(505) 844-7327
Contract History:

Number	FY	Level	Source
55-0702A	1988	$126,400	DOE

Objective:
To investigate defects, their causes and their effects on solar cell performance microscopically and macroscopically, including identification of defects and their spatial distributions.

Approach/Present Tasks:
To carry out this work successfully it is necessary to characterize defects in starting materials and follow through in defect characterization of completed cells. Both low and high efficiency cells and the materials from which these cells were made will be evaluated to aid in effectively carrying out this research.

Status/FY 1989 Accomplishments:
Detail characterization of both polycrystalline cast material and EFG material is on going.

FY 1989 Milestones:
Obtain starting material and completed cells from FZ, CZ and other one-sun silicon crystals. Verify the cell current-voltage and efficiency measurements and characterize the diffusion length. Map the diffusion length and choose sections of both virgin material and completed cells for microscopic studies. Fabricate Schottky barrier devices on wafers and cell surfaces for electron beam induced current measurements. Choose samples for transmission electron microscopy evaluation

FY 1990 Milestones:
Continue material and cell evaluations. Correlate composition and electronic structure of microdefects in Si with technological processes. Initiate gettering studies. Investigate passivation techniques.

Summary Date
June 1989

High Temperature Deformation of Silicon

S. L. Hyland and D.G. Ast
Contract # 55-0702B

June, 1989

Solarex semicrystalline silicon grown under three different crystal growth conditions was investigated to determine correlations between electrical properties and mechanical properties. The samples consisted of:

	good solar cells	bad solar cells
Material	standard Solarex	overstressed Solarex
	Wacker	low yield stress (τ_c) Solarex

Samples were mechanically tested using four-point bending, and hardness was measured using a Tukon hardness tester with a pyramidal diamond indenter. Electron beam induced current measurements were used to determine the electrical properties of these materials.

Figure 1 shows the four-point bending rig used for the mechanical tests. The sample is loaded into the furnace by placing it between the two top rollers and the two bottom rollers, as shown in the figure. As the weight is applied, the bottom two rollers move up against the sample, applying a pure bending moment to the sample between the two inner rollers. As the sample deforms under this applied stress, the deflection of the sample center is measured by the deflection probe resting on the sample surface.

The mechanical tests consisted of heating the samples to $1100°C$and applying a weight equivalent to the application of a surface stress of 1.5 MPa. Every three minutes the applied stress was increased by 0.5 MPa. The stress is simply related to the time through the initial applied stress, the stress increment, and its duration (in this case, multiples of 3 minutes). When the applied stress exceeded the (surface) yield stress, plastic deformation begun and the measured deflection began to increase. Figure 2 shows the deflection vs. time curves for the four different samples tested. The Wacker material and the standard Solarex material , which have similar electrical properties in terms of solar cell behavior, also look remarkably alike mechanically. The applied stress at which they begin to yield is about the same, and the increase in plastic strain for each increment in stress is also similar. These materials, then, look the same as far as mechanical properties are concerned, but they are quite different from the two materials which make poor solar cells. These two materials, overstressed Solarex material and low τ_c Solarex material , are again mutually similar in their mechanical properties. They resist bending much more than the Wacker material and the standard Solarex material , indicating that these materials have a higher yeild and flow stress than the two materials that make good devices.

Initially, it was thought that the electronically better materials would resist defor-

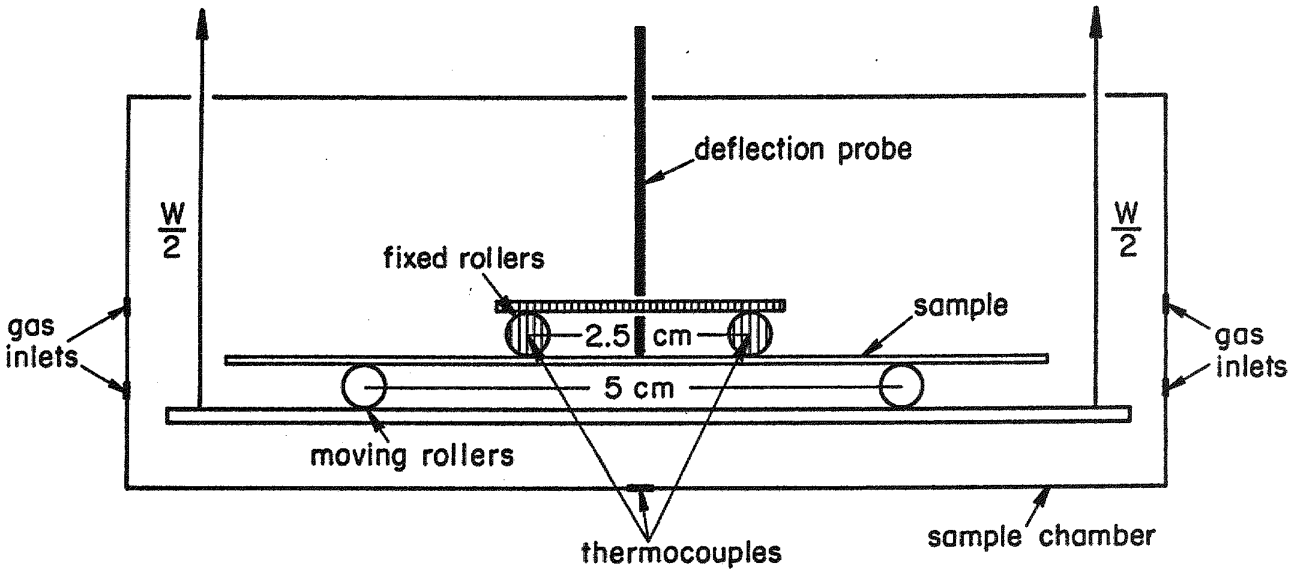

Figure 1: The four-point bending rig used to deform silicon samples.

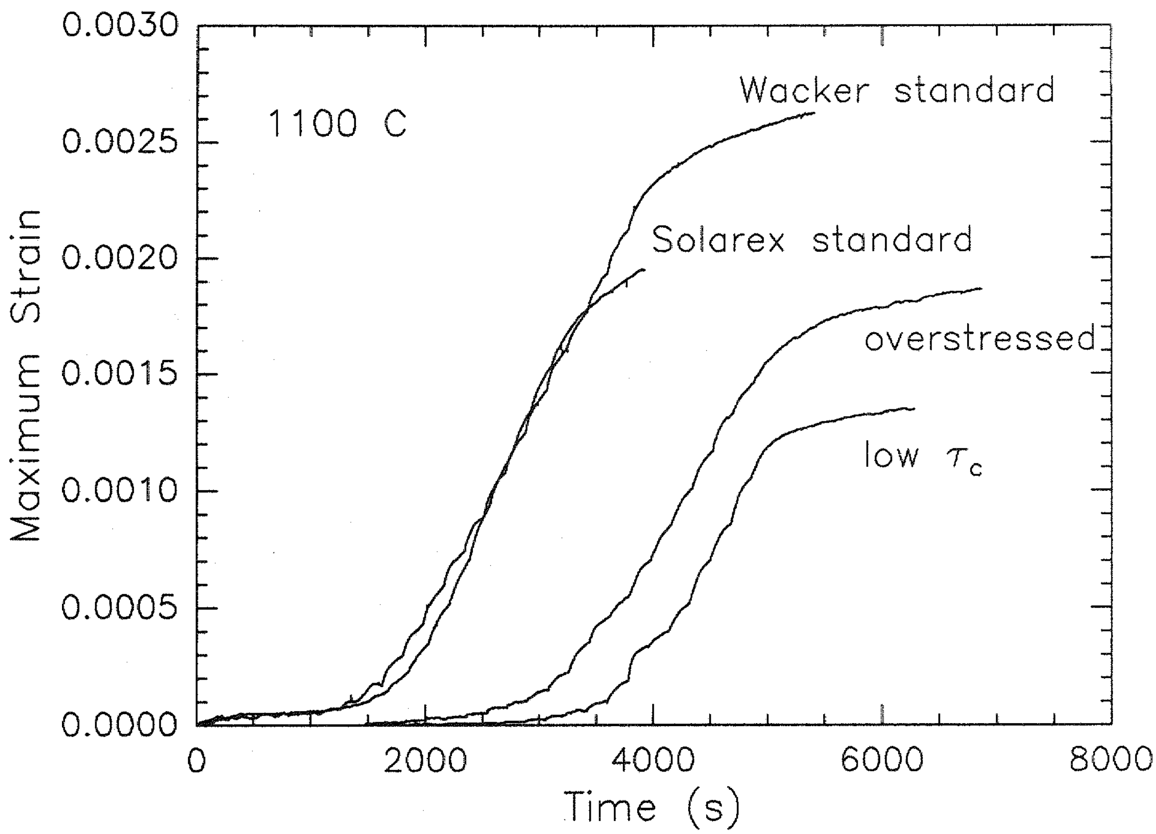

Figure 2: Four-point bending of the three Solarex materials and Wacker silicon.

mation more than the overstressed Solarex material and low τ_c Solarex material , since the better materials have a lower dislocation density. However, it is clear from Figure 2 that this was not the case. Since the better materials began to creep at a relatively low applied stress, it seems that even these materials contain sufficient numbers of dislocations to initiate plastic deformation. All these materials must have been stressed beyond the yield stress during crystal growth. The overstressed Solarex material and the low τ_c Solarex material were stressed far more than the Wacker material and the standard Solarex material , generating a far more developed dislocation structure in the as-grown material. Upon re-loading during four-point testing, these more highly stressed materials required higher applied stresses to make these entangled dislocations move, or to generate new dislocations capable of responding to the applied stress. Initial measurements of the material hardness seem to correlate the four-point bending tests, that is, the materials that make poor solar cells are harder than the materials making better devices.

The electron-beam induced current (EBIC) measurements also support the theory of a more highly developed dislocation structure in the overstressed Solarex material and the low τ_c Solarex material . Figure 3 shows a comparison of the three Solarex materials. Figure 3a, the standard Solarex material , can be compared to Figure 3b, the low τ_c Solarex material , and Figure 3c, the overstressed Solarex material , where the dislocation densities of the two types of materials are obviously different. In the standard Solarex material , there are dislocations homogeneously distributed throughout the grains, while in the two other materials, there are both homogeneously distributed dislocations and areas of intense dislocation interaction. These defect clusters may make plastic deformation more difficult in these materials, corroborating the four-point bending results.

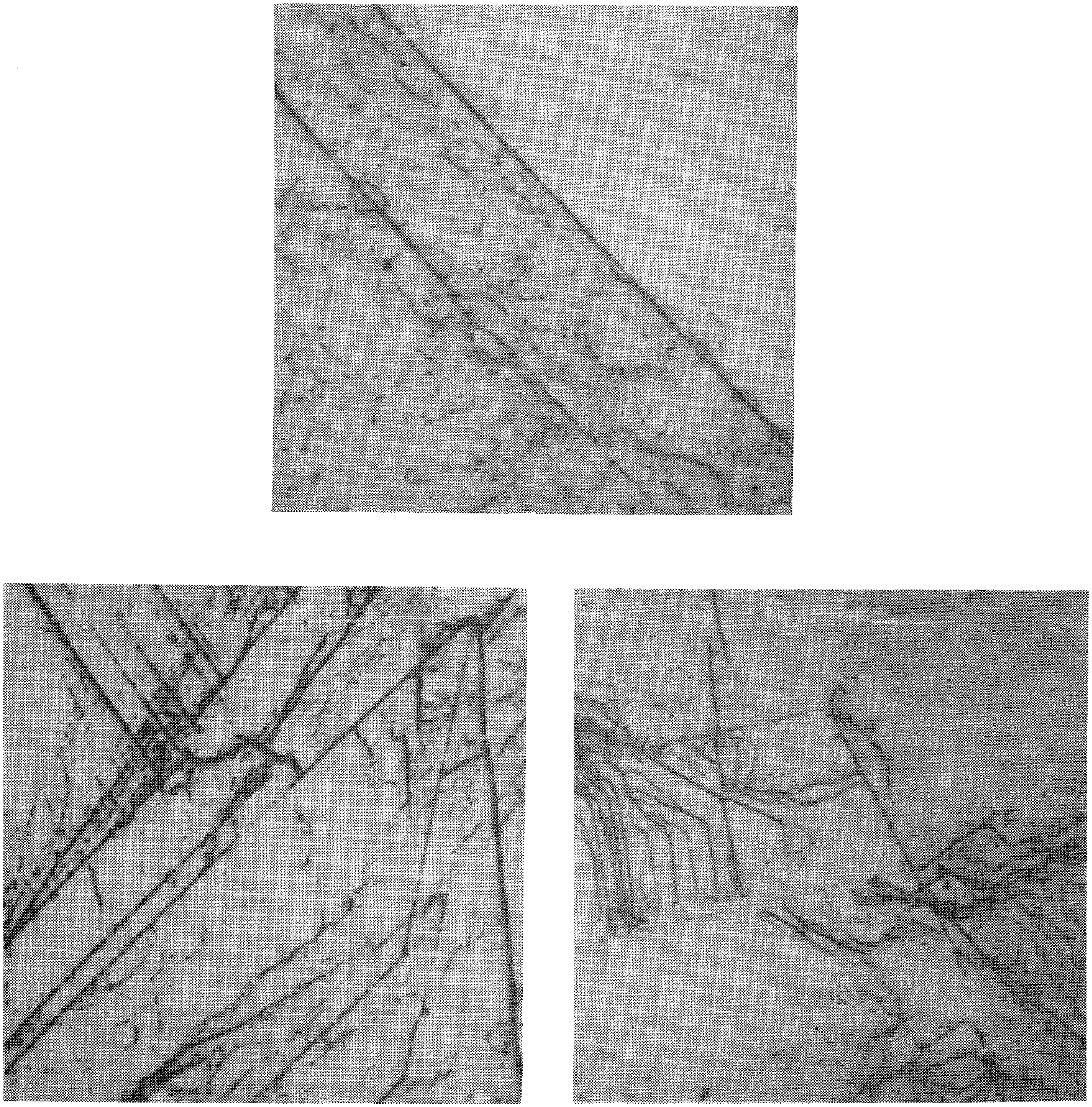

Figure 3: Electron-beam induced current images of (a)standard Solarex material, (b)low τ_c Solarex material, and (c)overstressed Solarex material.

Title: Mechanical Deformation of One-Sun Crystalline Silicon

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Principal Investigator:
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Current Contract Number:
55-0702B
Current Contract Period:
From: 9/88 **To:** 9/89
Project/Area/Task:
Crystalline Cell Research
Task 3 One-Sun Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
John D. McBrayer
Telephone:
(505) 844-7327
Contract History:

Number	FY	Level	Source
55-0702B	1988	$116,000	DOE

Objective:
To study the high temperature deformation of Si, and in particular investigate the effects of plastic deformation at temperatures near the crystal growth temperature and the extent to which this plastic deformation is reversible.

Approach/Present Tasks:
The approach to investigate the high temperature behavior of silicon is to create dislocations in FZ, CZ, and other one-sun silicon crystals by four-point bending, and analyze the deformation both macroscopically and microscopically at temperatures above and below the critical temperature of 1200C, and to analyze the effect of planar defects on the reversibility of plastic deformation at high temperaturés. To characterize the electrical activity of the defects introduced by the plastic deformation and passivated by hydrogen we will use EBIC and LBIC.

Status/FY 1989 Accomplishments:
Contract is on going. Preliminary indications reveal the possibility of using a simple stress test to indicate "good" starting material from "bad".

FY 1990 Milestones:
Selection and preparation of FZ, CZ and other one-sun silicon crystals for high temperature deformation studies at 900 to 1300C. Complete material and electrical evaluation of all deformation experiments.

FY 1991 Milestones:
Provide recommendations for improved crystal growth. Re-evaluate new crystals. Improve crystal growth computer models.

Major Project Reports:
None

Summary Date
June 1989

INTERACTION OF INTRINSIC POINT DEFECTS WITH DISLOCATIONS IN POLY-CRYSTALLINE SILICON

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Duke University
Durham, NC 27706

Introduction

Agglomerates of oxygen, carbon, and intrinsic point defects together with dislocations are suspected to limit the minority carrier diffusion length in solar-grade crystalline silicon. The agglomeration of oxygen and carbon is associated with volume changes which may partly be accomodated by intrinsic point defects. In order to formulate a quantitative model of precipitation and agglomeration during crystal growth the thermal equilibrium concentration and the diffusivity of self-interstitials as well as the source/sink efficiency of dislocations for point defects have to be measured. The present report concentrates on preliminary gold diffusion experiments designed to investigate the sink efficiency of dislocations for silicon self-interstitials.

Background Information on the Diffusion of Gold in Silicon

Gold in silicon is mainly dissolved on substitutional sites (Au_s) but diffuses almost exclusively in its interstitial form, Au_i. The change-over from interstitial to substitutional site is accomplished by the kick-out mechanism [1]

$$Au_i \rightleftarrows Au_s + I \ , \tag{1}$$

which involves silicon self-interstitials, denoted by I. The incorporation of substitutional gold requires the generation of self-interstitials and their subsequent annihilation at appropriate sinks such as surfaces or dislocations. Measurements of the concentration profiles of Au_s, diffusing from a gold layer on the surface into dislocated silicon, can therefore be conveniently be used to determine the sink efficiency of dislocations.

For extremely high dislocation densities (e.g. 10^9 cm^{-2}) the dislocations keep the self-interstitial concentration always close to its equilibrium value C_I^{eq}. Under these circumstances the concentration profile of indiffusing Au_s reflects a constant effective diffusivity

$$D_{eff}^{(i)} = D_i C_i^{eq} / C_s^{eq} \tag{2}$$

which is well-known from measurements in deformed single-crystalline silicon [2]. In (2) D_i denotes the Au_i diffusivity, C_i^{eq} the solubility of Au_i, and C_s^{eq} the solubility of Au_s.

Conclusions

Gold diffusion into solar-grade polycrystalline silicon shows that the effectiveness of dislocations for absorbing silicon self-interstitials is much lower than expected. Therefore, contrary to common knowledge, it is essential to take into account non-equilibrium effects of intrinsic point defects even in highly dislocated solar cell material. This work is supported by SERI subcontract XL-8-18097-1.

References

1. W. Frank, U. Gösele, A. Mehrer, and A. Seeger, in: Diffusion in Crystalline Solids, G.E. Murch and A.S. Nowick, eds. (Academic Press, New York, 1984) p. 64.

2. N.A. Stolwijk, J. Hötzl, W. Frank, E.R. Weber, and H. Mehrer, Appl. Phys. A. 39, 37 (1986).

3. W. Jüngling, P. Pickler, S. Selberherr, E. Guerrero, and H. Pâtzl, IEEE-Trans. ED-32, 156 (1985).

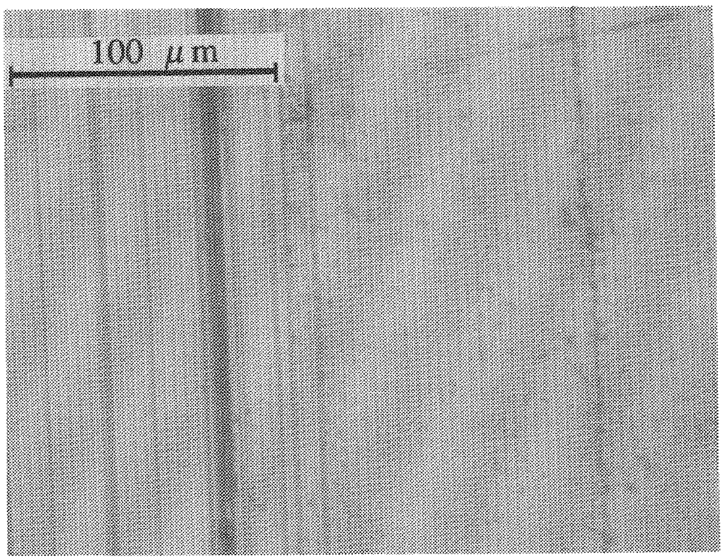

Figure 1. Optical micrograph of typical area of solar-grade poly-crystalline silicon showing twin boundaries and etch pits corresponding to dislocations.

Oh the other hand, if dilsocations would not act as sinks, typical U-shaped profiles should be observed which are characterized by a strongly concentration dependent effective diffusivity [2]

$$D_{eff}^{(I)} = \frac{D_I C_I^{eq}}{C_s^{eq}} \left(\frac{C_s^{eq}}{C_s} \right)^2 \quad , \qquad (3)$$

where D_I is the diffusivity of self-interstitials. Such profiles are typical for gold diffusion into dislocation-free silicon [1]. The limiting cases (2) and (3) can easily be distinguished experimentally. Solar-grade, poly-crystalline silicon shows typically dislocation densities in the order of 10^7 cm^{-2} (see e.g. Fig. 1). Therefore, we expect an appreciable influence of these dislocations on the gold diffusion profile, which should also reflect the inhomogeneous distribution of dislocations.

Experimental Approach and Preliminary Results

A thin layer of gold is evaporated on one side of solar-grade p-type crystalline silicon (EFG ribbons from Mobil Solar Energy Corporation). The samples are then encapsulated in quartz and annealed for various times and temperatures, typically between 900 and 1100°C. After the samples have been bevelled, spreading resistance profiles, indicative of the Au_s concentration, are measured across the samples. Because of some resistivity fluctuations in the starting silicon and because of large fluctuations in the dislocation density in different grains of the material, a fairly large variation in the profiles can be found even for the same annealing conditions. Expamples of spreading resistance profiles taken perpendicular (Fig. 2b) to the inevitable twin boundaries show larger fluctuations of the incorporated gold concentraton that those taken parallel to the twin boundaries (Fig. 2a).

Representative spreading resistance profiles for gold diffusion at 950°C for 300 seconds, 30 minutes and 3 hours are shown in Figure 3 and compared to the starting profile without gold diffusion. It is clearly seen that the spreading resistance (and therefore also the gold concentration) increases with diffusion time. An analysis requires the dislocation density, which has been determined by an appropriate Wright etch (see, e.g., Fig. 1), and a comparison to the expected gold diffusion profiles obtained by computer simulation.

Computer Simulations of Gold Diffusion

The partial differential equations describing the diffusion of gold in silicon including the influence of dislocations have been incorporated in the partial differential equation simulator ZOMBIE obtained from the University of Vienna [3]. Non-uniform dislocation densities can be handled by the program, but because of space limitations only results for constant dislocation densities are shown in this report. The simulation results as shown in Fig. 4 for gold diffusion from one side at 950°C for 30 minutes and for various dislocation densities, indicate that a dislocation density of about 10^7 cm^{-2} should have resulted in an erfc-type behavior, which is not consistent with the experimental results.

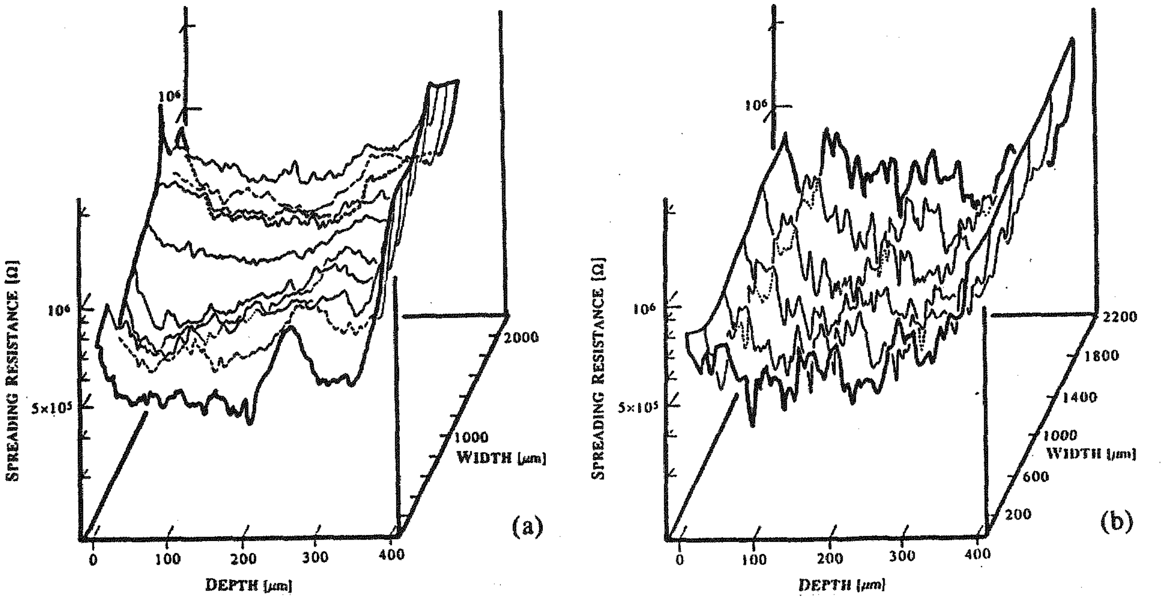

Figure 2. Spreading resistance profiles of poly-crystalline silicon diffused with gold from left hand side at 950°C for 30 minutes taken a) parallel and b) perpendicular to twin boundaries.

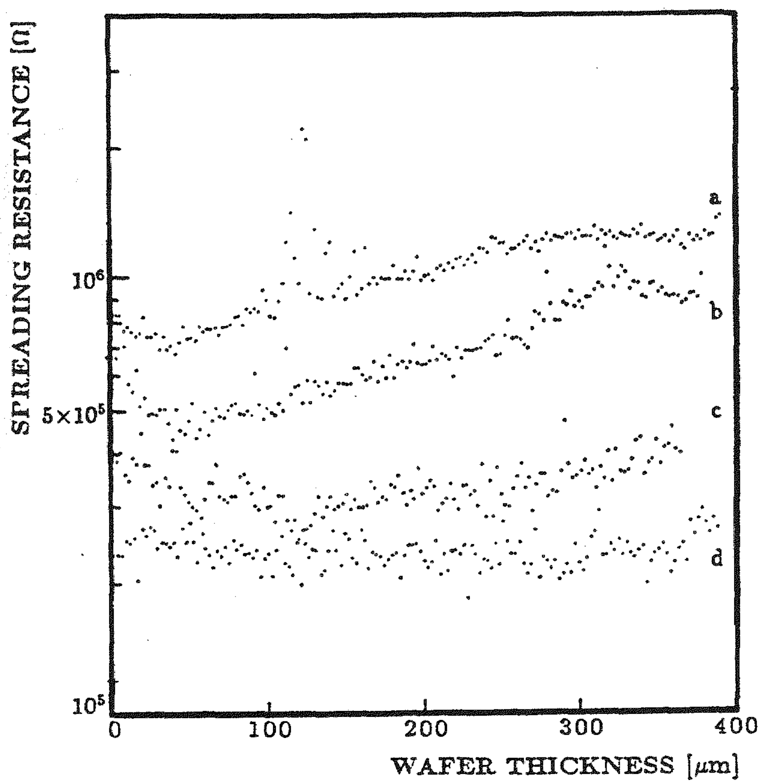

Figure 3. Spreading resistance profiles of solar-grade crystalline silicon after gold diffusion from the left-hand side at 950°C for 3 hours (a), 30 min. (b), 300 sec. (c), and without gold diffusion (d).

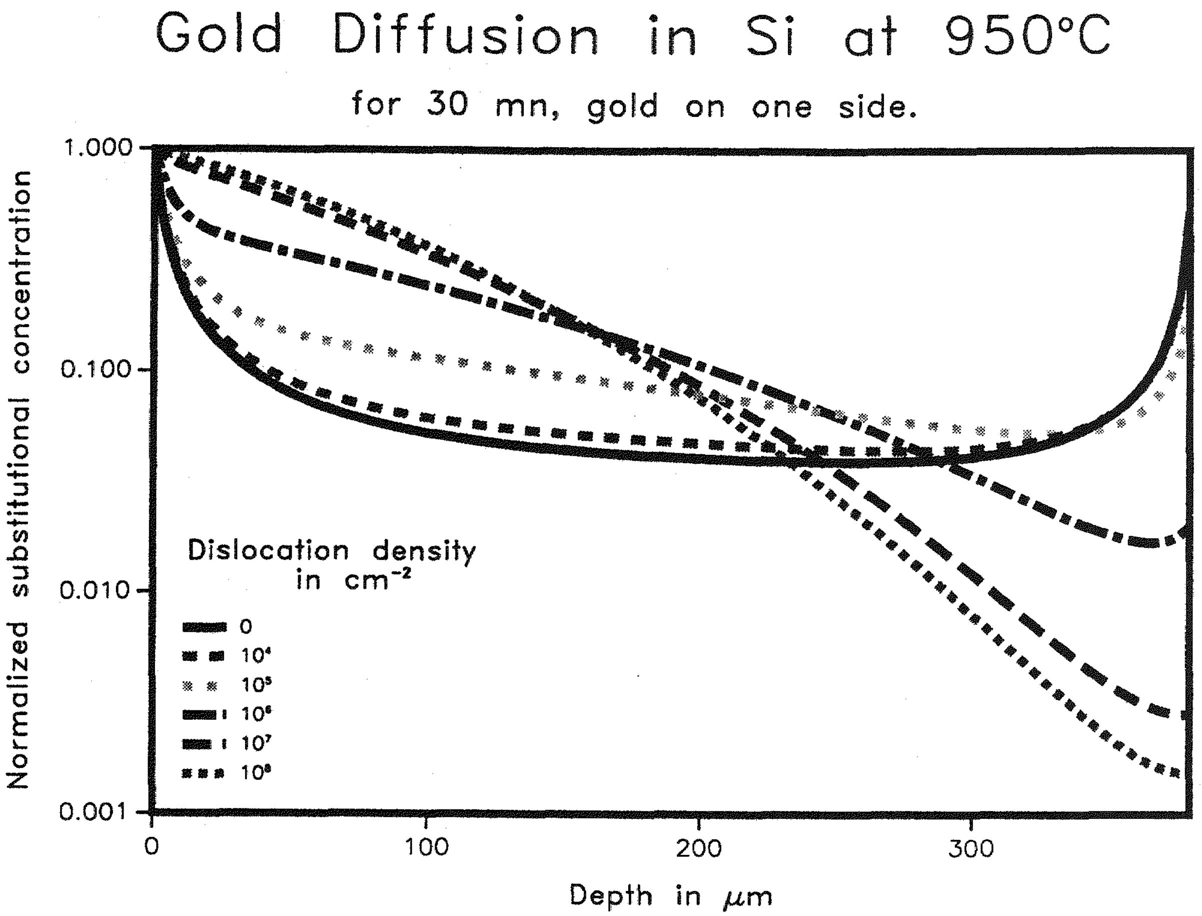

Figure 4. Simulated gold concentration profiles for 30 minutes 950°C diffusion from left hand for different uniform densities of dislocations ranging from 0 to 10^8 cm^{-2}.

Basic Studies of Point Defects and Their Influence on Solar Cell Related Electronic Properties in Crystalline Silicon

Project/Area/Task:
Crystalline Silicon

Contractor:
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Department of Mechanical Engineering
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Durham, NC 27706

Principal Investigator: U.M. Goesele

Telephone: (919) 684-2832

Contract Number: 18097-1

Current Contract Period From: 06/01/88 **To:** 08/31/89

Directing Organization:
Solar Energy Research Institute

Project Engineer: B.L. Sopori

Telephone: (303) 231-1383

Contract Funding:		**Source:**
FY 1988	$99,000	SERI

Objectives:

To understand the influence of impurities and defects in crystalline silicon solar cell materials.

Approach/Present Tasks:

Carry out experiments and theoretical analyses to determine parameters which control defect-impurity interaction, and evaluate their effect on minority carrier diffusion length.

Status/FY 1988 Accomplishments:

None.

FY 1989 Milestones:

Submit Quarterly Report.

Major Project Reports:

None.

Summary Date: November 1988

The Effectiveness and Stability of Impurity/Defect Interaction and Their Impact on Minority Carrier Time

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The project is based on the chemical and electrical behavior of defect interfaces in crystalline silicon wafers, dendridic web and EFG ribbons as photovoltaic materials. Of particular interest at these interfaces is the practical issue of how stable a particular gettered element will be during subsequent thermal processing or device operation. We believe the fundamental aspects of gettering processes and the local improvement range of gettered material, or hydrogen deactivation, can be readily determined using a model epi/misfit dislocation system. This information will then be extended to EFG and web materials. The emphasis in this initial study has been on the hydrogen passivation of defects in silicon, particularly at pure or metal decorated dislocations. The p-type epitaxial silicon wafers used in this study contained two buried interfaces which had a controlled number of deliberately introduced misfit dislocations[1]. The silicon layers were grown with an addition of approximately 2% GeH_4 to a $SiCl_2H_2$ Chemical Vapor Deposition reactor. The samples were then anisotropically etched, as schematically shown in Fig.1, so that misfit dislocation end points were exposed along the (111) side walls of the etched trench. The top (100) surface was masked by a 600Å oxide to reduce hydrogen exposure to the top surface. An unetched (111) oriented silicon wafer was also plasma treated. Hydrogen passivation was carried out using a Kaufman Ion Beam System at the SERI. Secondary ion mass spectroscopy (SIMS), transmission electron microscopy (TEM) and scanning electron microscopy in electron beam induced current mode (EBIC/SEM). SIMS was used to determine the hydrogen profile, TEM to reveal the hydrogen induced defects and surface radiation damage due to the hydrogen plasma process, while EBIC/SEM provided an image of the electrical activities of individual crystal defects.

A two dimensional SIMS hydrogen-distribution image which has an area of 150-μm diameter was obtained on a beveled surface as shown in Fig.2. Note that the hydrogen intensity on the directly exposed (001) surface and along the trenches is much higher than that in the bulk. Also a hydrogen-depth profile was obtained by sputtering the sample from the (001) surface down to about 1 mm deep and showed that most of hydrogen was accumulated on the surface within the range of 2500 Å.

Figure 3 shows EBIC/SEM images before and after the hydrogen plasma process. In Fig.3a, a clear EBIC image was obtained only on the Schottky diode area, whereas a similar image (Fig. 3b) taken on the beveled surface of the hydrogenated sample exhibits contrast all over the top surface area. Note that on the beveled area only the Schottky diode is in contrast. This is interpreted as revealing as inversion layer on the surface associated with the hydrogen and reflects an initial treatment with hydrogen far in excess of a practical passivation treatment.

Structural degradation of the surface regions is generally observed when samples are exposed to the high flux hydrogen plasma. Figure 4(a) and (b) show cross-section TEM bright field images of a sample before and after hydrogenation. The heavily damaged surface region extended to a depth of approximately 2500 Å. Individual defects such as gas bubbles and extended planar defects lying on {111} habit planes are evident. A plan view TEM bright field image of the near surface region of a <111> silicon wafer after hydrogenation is shown in Fig.4(c). Planar defects are evident with a density from 10^8-10^{10}cm^{-2} that are similar to defects reported by Ponce[2] who identified them as H-stabilized platelets. Similar extended defects were found along the misfit dislocations after hydrogenation, as shown in Fig. 5(b). In Fig.5(a), cross-section TEM image shows a clear two dimensional dislocation network, where lines indicate the dislocations paralell to the image plane and end points indicate the dislocation perpendicular to the plane. Gas bubbles and hydrogen stabilized (111) platelets are present in Fig.5(b) along the dislocations indicating a strong interaction with misfit dislocations after the hydrogen plasma process.

Comparing SIMS and TEM, we found that hydrogen was concentrated in the near surface 2500Å region and its density decreased gradually with distance into the bulk. In this hydrogen concentrated region, the surface was heavily damaged and many microdefects were formed. Hydrogen diffused into the crystal to form Si-H bonds to stabilize these microdefects, as mentioned by Ponce[2]. Therefore, this surface layer containing hydrogen decorated defects or hydrogen stabilized defects has different energy state with bulk crystal. The difference of the energy state between surface and bulk can form a junction and results in an unusual EBIC/SEM image. On the other hand, hydrogen can neutralize the dopant, B in this case[3,4]. On the hydrogen-rich surface, the effective concentration of acceptors can be greatly reduced. The surface can form intrinsic silicon or even n^- silicon, thereby forming a junction between the surface layer and the p type bulk. Because of both above reasons, hydrogen plasma process can result an inversion layer on the surface. The inversion layer builds up an internal electrical field to give the EBIC image in the SEM.

The study will be continue using the model epitaxial silicon wafer system for different exposure dose in the coming year. Under suitable exposure dose, we will focus on the study of the hydrogen diffusion mechanism and improvement of minority carrier lifetime. Deuterium plasma source is expected to be used for high sensitivity SIMS measurement to profile the hydrogen from surface to bulk as well as along the misfit dislocations. Furthermore, the interaction of hydrogen with some metal, which are carrier lifetime killers, will be studied by using the same model system gettered metal and hydrogen.

REFERENCE

1. G. A. Rozgonyi et al. J. Cryst. Growth 85,300(1987)
2. F. A. Ponce et al.,Inst. Phys. Conf. Ser. 87(1), 49(1987)
3. N. M. Johnson and M. D. Moyer, Appl. Phys. Lett. 46(8), 787(1985)
4. N. M. Johnson, Appl. Phys. Lett. 48(11), 709 (1986)

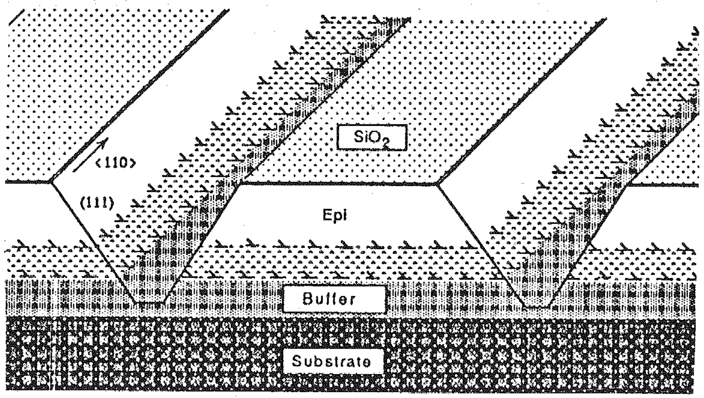

Fig. 1 Schmatic diagram of anisotrpically etched Grooves in oxidized epitaxial layer with misfit dislocation

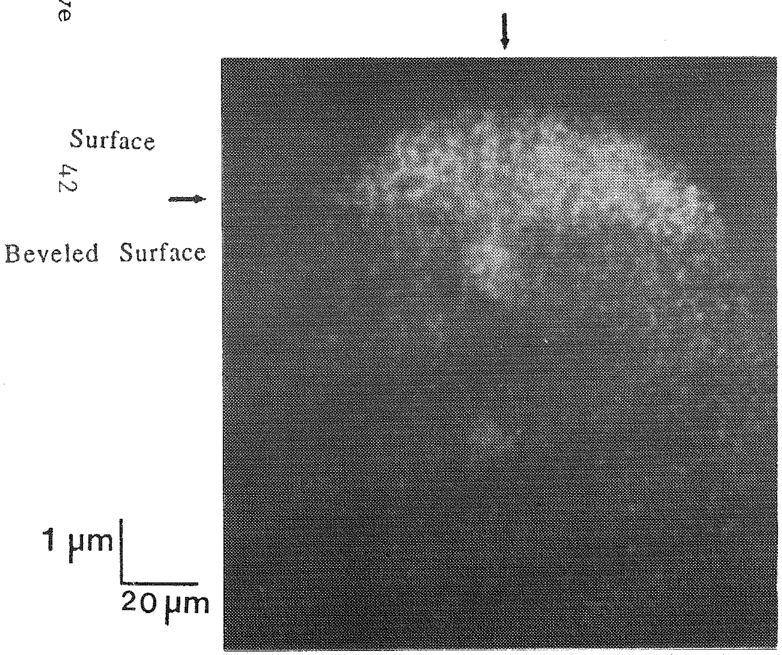

Fig. 2 Two dimension SIMS image of (100) epitaxial silicon wafer on bevel surface.

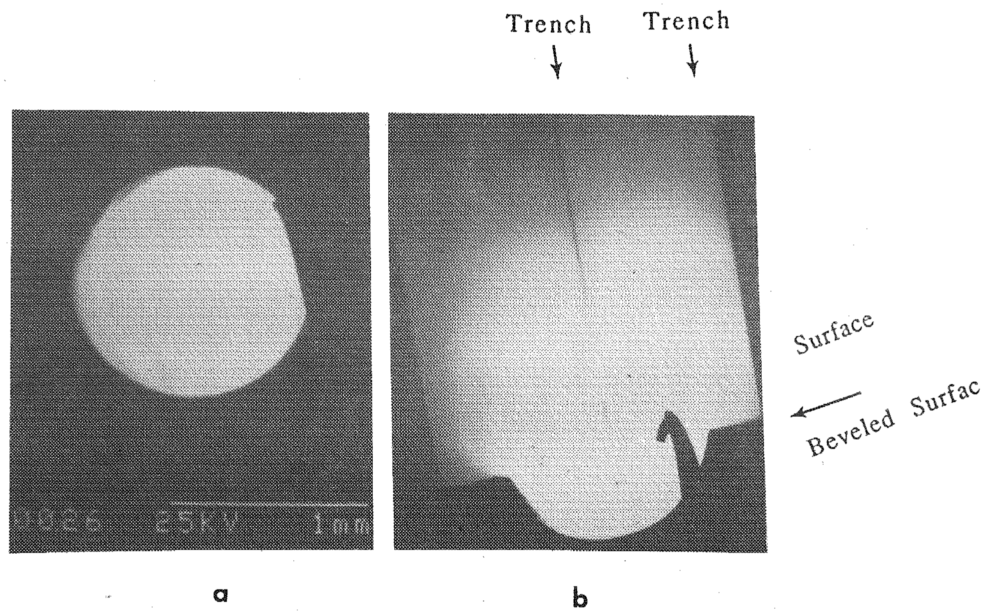

Fig.3 EBIC/SEM image of epitaxial silicon wafer (a) Before hydrogenation, EBIC image on ϕ1.2 mm Schottky diode on the surface of wafer. (b) After hydrogenation, EBIC image of Schottky diode on beveled surface and of all the surface where sample was directly exposed to hydrogen plasma.

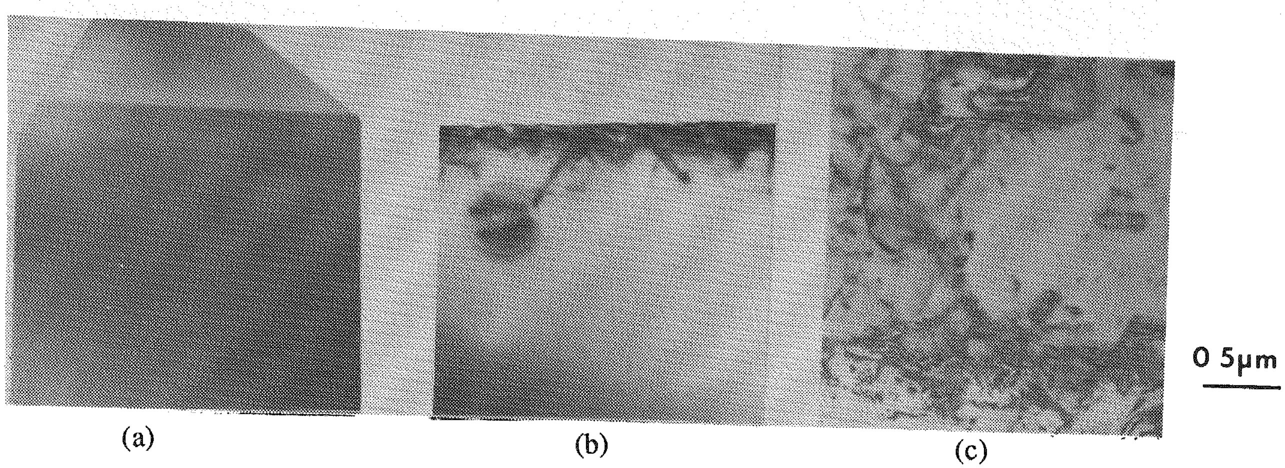

Fig. 4 Bright field image of TEM (a) Cross-section TEM image of (100) silicon wafer before hydrogenation (b) As (a), after hydrogenation (c) Plane-view TEM image of (111) silicon wafer after hydrogenation.

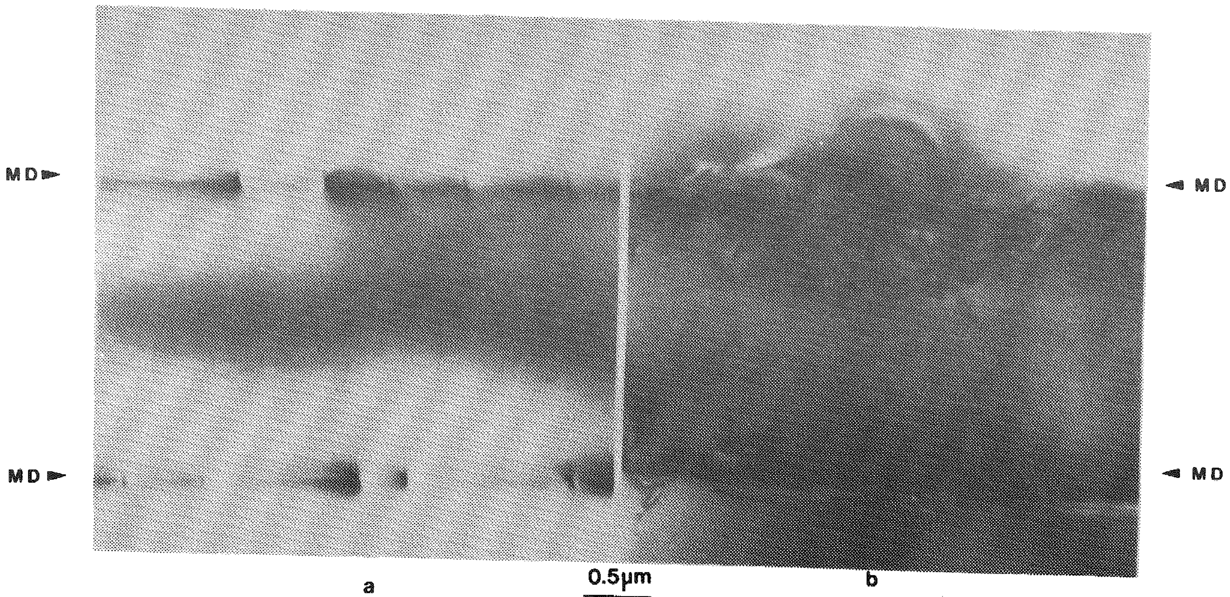

Fig. 5 Bright field image of cross-section TEM of <100> silicon wafer with two misfit dislocation (MD) interfaces. **a.** before hydrogen plasma process, **b.** after hydrogen plasma process, MD decorated with hydrogen-induced defects.

The Effectiveness and Stability of Impurity/Defect Interactions and Their Impact on Minority Carrier Lifetime

Project/Area/Task:
Crystalline Silicon

Contractor:
North Carolina State University
Office of Contracts and Grants
Box 7214
Raleigh, NC 27695-7214

Principal Investigator: G. Rozgonyi

Telephone: (919) 737-2934

Contract Number: 18097-2

Current Contract Period From: 06/01/88 **To:** 08/31/89

Directing Organization:
Solar Energy Research Institute

Project Engineer: B.L. Sopori

Telephone: (303) 231-1383

Contract Funding:		**Source:**
FY 1988	$140,000	SERI

Objectives:

To establish effectiveness of gettering as a viable technique to improve the quality of low-cost silicon substrates.

Approach/Present Tasks:

- Use specially designed structures to study basic properties such as characteristics of impurity (metallic) diffusions in the presence of defects and impurity trapping at the defects.
- Study de-activation of defects by impurities such as hydrogen and/or oxygen.
- Design gettering/annealing procedures for web dendritic and EFG ribbons.

Status/FY 1988 Accomplishments:

None.

FY 1989 Milestones:

Submit Quarterly Report.

Major Project Reports:

None.

Summary Date: November 1988

PASSIVATION AND GETTERING IN SOLAR CELL SILICON

by

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I. INTRODUCTION.

Passivation of solar cell silicon means a mechanism by which an agent prevents the deleterious defects in the material from having an impact on the electrical performance of the device, even though the defects may essentially still be present in the material. It is well known that hydrogen can passivate defects in semiconductors; part of program is then to study the means by which hydrogen is introduced in to silicon, the way in which it interacts with defects, and the way in which it diffuses; an account of this work is given in Sect. II. Fluorine is also proposed to passivat defects in silicon, and we have begun some work on that as well, as will also be discussed in the next section. Gettering means a mechanism which essentially removes the deleterious defects from the material so that they will no longer have an impact on the electrical behavior of the material; typically gettering is used to remove the fast diffusers, such as Cu, Fe, Cr, Ni, Au. As we will discuss in Sect. III, we have begun gettering studies using radio-active tracers, specifically ^{64}Cu; we will also discuss gettering in liquid mercury.

II. PASSIVATION STUDIES.

As we have discussed[1], hydrogen can be introduced into silicon during growth or by heat-treatment in a hydrogen atmosphere, by implantation, by various forms of plasma-treatment, by wet-etching and electrolysis, by boiling in water, and during polishing, the latter being a topic we will return to in the next section. Part of our studies deal with the systematics of such introduction, i. e., establishing the temperature and doping dependences of the introduction; companion theoretical studies[2] are also being carried out. The presence of Si-H vibrational IR bands indicate that hydrogen clearly interact with dangling bond defects in silicon; there are a great many such distinct defects which will result eventually in a well-identified family of defects; although we have proposed models[3] for these defects, and there have been corroborative studies[4], further studies experimental and theoretical studies remain to be done. As shown by the pioneering work of Sah, of Pankove, of Johnson, and of Stavola and their co-workers we now know that hydrogen deactivates shallow acceptors and shallow donors. There are models for these configurations and the associated IR bands, but further work remains to be done; for example, we have found[5] for reactive-ion etched silicon that there are two stages of deactivation of boron and excess mobile hydrogen in the material as well, points we will return to below. Related theoretical[6], x-ray-standing-wave and channeling studies have been and are being carried out to further the understanding of the mechanisms of the interaction of hydrogen with impurities in silicon.

In the space permitted here we will only discuss our studies about the diffusion of hydrogen in silicon, which as we have reviewed[1] has a complex history. From normal diffusion one would expect to get a complementary error function profile vs depth (X): $H = H_o \, \mathrm{erfc}(Z)$, with $Z = X/(4 \cdot D \cdot t)^{1/2}$' with H - the hydrogen concentration, H_o - the surface concentration, D - the diffusion coefficient, and t - the diffusion time. Many workers have assumed this to be the observed profile AND the correct scaling, and typically both assumptions are mistaken for hydrogen diffusion in silicon. We have shown[1] for hydrogen diffusing through traps that normal Fickian diffusion occurs and *for the steady-state case*, an exponential profile obtains: $H = H_o \exp(-Z)$, where here $Z = X/(D/\cdot K \cdot d)^{1/2}$, with K - the rate constant for the trapping, and d - the concentration of the traps; *NOTE*: *the scaling is different*. We have been unable to prove this scaling for the non-steady-state case, but our numerical solutions to the equations of this system do exhibit an exponential profile with a dependence on the density of traps. We have also shown[1] that the diffusion equation when molecule formation is occuring is NON-Fickian, contrary to the assumtions in the literature, and that in the steady-state case the profile will be as follows: $H = H_o / (1 + X \cdot Z)^2$, with here $Z^2 = (6 \cdot D)/(H^\circ \cdot K)$, with K here being the rate constant for molecule formation; note again a quite different scaling factor that that of the erfc. function. Our numerical solutions to the diffusion equation for the molecule formation case have this shape, and we are endeavoring to establish the scaling dependences.

We have published[7-9] systematic diffusion profiles and have evolved a semi-quantitative model for the profiles, which we will describe next; our numerical solutions of the diffusion equations are endeavoring to achieve a quantitative fit to the profiles and unambiguously establish the parameters of the equations. In both p- and n-type crystalline silicon there can be a very large concentration of hydrogen (e.g., $19/cm^3$) with an exponential profile; it is in this region that <100> platelets of hydrogen are observe[10-13]--we argue[14] that these platelets nucleate and grow during the diffusion process, and are responsible for the embrittlement of silicon by hydrogen. In low resistivity (0.1 and 1 Ωcm) p-type (boron-doped) silicon hydrogen trapping occurs with a plateau corresponding to the saturation of the boron with one hydrogen and an exponential profile beyond the plateau with the slope varying with impurity concentration, more steep for higher concentration of boron. Such a profile characteristic of impurity trapping occurs deep in the silicon; between that profile and the shallow exponential profile is a "bump" in the total profile which appears to be due to the accumulation of additional hydrogen at the boron, perhaps by the impurity-mediated molecule formation process we call a "pick-off" reaction. The diffusion profiles for 10 and 100 Ωcm p-type (boron-doped) silicon are essentially identical and appear to be that associated with molecule formation; it is this change in the nature of the diffusion profile that has led us to suggest that the donor level associated with the isolated hydrogen occurs at $E_v + 0.3$ (± 0.1) eV. The diffusion profile for 100 Ωcm n-type (P-doped) silicon is essentially identical to the p-type molecule-formation profiles. The profiles for lower resistivity samples of this n-type material also exhibit a molecule-formation like tail penetrating the sample, but the slope depends on the doping concentration, the higher the phosphorus concentration the steeper the slope and the shallower the penetration; in addition a "bump" appears between this tail and the shallow exponential platelet-profile, the magnitude of the bump increasing with dopant concentration; again we attribute these features to impurity-mediated molecule formation and the accumulation of hydrogen (perhaps molecular) at the dopant site. Our numerical solutions are directed at probing these models quantitatively, and understanding the profiles for different temperatures.

III. GETTERING STUDIES.

There are a number of elements known as the "fast diffusers" in silicon: Fe, Cr, Ni, Cu, Au, etc. Typically these are common contaminants in silicon solar materials and in micro-electronic material, and often act as recombination centers, although they may precipitate or be trapped and be, at least temporarily, "removed" electrically from the sample. The art of gettering has arisen to deal with these elements, and various approaches developed to physically remove the elements from the eltrically active area of the material; examples are gettering with HCl, "internal gettering" at oxide precipitates, gettering at back-side damage, etc. We describe this work as still an "art," because in no case that we know of is the binding energy of the element to the gettering site known, i.e., one cannot assess the effectiveness of the getterer for all possible processing steps. Since many techniques to detect these elements require that they be in an appropriate charge state, we have begun gettering studies using radio-active tracers which may be detected independently of the bonding of the element. Those studies were diverted, however, by the results which indicate that copper enters silicon during polishing of the wafer. We therefore have attempted to introduce ^{64}Cu into crystalline and ribbon silicon at room temperature by polishing, or from an HF, HNO_3, HCl, or ammonia solution. The first attempts were unsuccessful, i.e., we could not detect an radio-active copper of more than $10^{16}/cm^3$ in concentration. Since our wafer had only $10^{15}/cm^3$ boron, and since we expect the copper to be trapped at the boron, that result is not conclusive concerning copper entry in to wafer silicon; we are repeating the measurements in samples with $10^{19}/cm^3$ boron, and a higher sensitivity to the copper.

It is not generally realized but in the preparation of some of the ultra-high purity germanium used for nuclear detectors liquid bismuth was used as a getter for the fast diffusers. That motivated us to try a liquid mercury bath as a gettering medium; the gettering studies are not complete, although we have established that the mercury will remove iron at or near the surface of the silicon. We have been diverted, however, by the recognition that contact of silicon with mercury, *as occurs in the wide-spread use of the mercury probe*, leaves some mercury on the surface of the silicon. The mercury quickly forms islands and spread on greater immersion. We have carried out channeling, x-ray-standing-wave, scanning electron microscopy, and C-V measurements on such samples, and these results are being published. In particular the mercury can alter the Schottky barrier height and electrical properties of the material. We have found that HNO_3 removes the mercury, but it oxidizes the surface as well. Further studies are in progress.

IV. REFERENCES.

1. "Hydrogen In Crystalline Semiconductors," S. J. Pearton, J. W. Corbett, and T.S. Shi, Appl. Phys. A 43 (1987) 153-195.
2. "Etching Silicon Surfaces with Hydrogen Atoms," F. Lu, J.W. Corbett, and L.C. Snyder, Phys. Lett. *133* (1988) 249.
3. "Models for the Hydrogen-Related Defect-Impurity Complexes and Si-H Infrared Bands in Crystalline Silicon," T.S. Shi, S.N. Sahu, G.S. Oehrlein, A. Hiraki and J.W. Corbett, *Phys. Stat. Sol.* (a) *74*, 329-341 (1982).
4. "Oxygen-dependent Si-H IR bands in c-Si," T.S. Shi, L.M. Xie, G.R. Bai, and M. W. Qi, Phys. Stat. Sol. (b) 131 (1985) 511.
5. "Effects of Deuterium Plasmas on Silicon Near-Surface Properties," J.L. Lindström, G.S. Oehrlein, G.J. Scilla, A.S. Yapsir, and J.W. Corbett, J. Appl. Phys., in press.
6. "Hydrogen Passivation of a Substitutional Sulphur Defect in Silicon," A.S. Yapsir, P. Deák, R.K. Singh, L.C. Snyder, J. W. Corbett, and T.M. Lu, Phys. Rev. B *38* (1988) 9936-9940.
7. "Passivation in Silicon," J. W. Corbett, J. L. Lindström, S.J. Pearton and A.J. Tavendale, Solar Cells, 24 (1988) 127-133.
8. "Hydrogen in Silicon," J. W. Corbett, J. L. Lindström, L. C. Snyder, and S. J. Pearton in *Defects in Electronic Materials*, eds., M. Stavola, S. J. Pearton, and G. Davies, (MRS, Pittsburgh, 1988) pp. 229-239.
9. "Configuration and Properties of Hydrogen in Crystalline Semiconductors," S.J. Pearton. M. Stavola, and J.W. Corbett in *Defects in Semiconductors 15*, ed. G. Ferenczi (Trans Tech, Switzerland, 1989) 25-37.
10. N.M. Johnson, F.A. Ponce, R.A. Street, and R.J. Nemanich, Phys. REv. B 35 (1987-1) 4166.
11. F.A. Ponce, N.M. Johnson, J.C. Tramontana, and J. Walker in *Microscopy of Semiconducting Materials*, ed., A.G. Cullis (Inst. Phys. Bristol, 1987) p. 49.
12. H.P. Strunk, H. Cervga, and E.G. Mohr in *Microscopy of Semiconducting Materials*, ed., A.G. Cullis (Inst. Phys. Bristol, 1987) p. 457.
13. S.J. Jeng, G.S. Oehrlein, and G.J. Scilla, Appl. Phys. lett. 53 (1988) 1755.
14. "Embrittlement of Materials: Si(H) as a Model System," J. W. Corbett, P. Deák, C. Ortiz-Rodriguez, and L.C. Snyder, J. Nucl. Materials, (1989) in press.

Passivation/Gettering in Solar Cell Silicon

Project/Area/Task:
Crystalline Silicon

Contractor:
The Research Foundation of
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P.O. Box 9
Albany, NY 12201

Principal Investigator: J.W. Corbett

Telephone: (518) 442-4518

Contract Number: 18097-3

Current Contract Period From: 06/01/88 **To:** 08/31/88

Directing Organization:
Solar Energy Research Institute

Project Engineer: B.L. Sopori

Telephone: (303) 231-1383

Contract Funding:		**Source:**
FY 1988	$126,000	SERI

Objectives:

To study passivation of defects and impurity gettering in silicon.

Approach/Present Tasks:

- Carry out theoretical and experimental investigations on the defect passivation by hydrogenation.
- Establish diffusivity of hydrogen in silicon.
- Use radioactive tracers to study diffusion and removal of metallic impurities.

Status/FY 1988 Accomplishments:

None.

FY 1989 Milestones:

- Submit Quarterly Report.

Major Project Reports:

None.

Summary Date: November 1988

One-Sun Silicon Cell Research

SILICON-FILM ON CERAMIC SOLAR CELL RESEARCH

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AstroPower, Inc.
30 Lovett Avenue, Newark, DE 19711

Abstract

To reach its maximum potential the Silicon-Film process requires the development of a light-trapping structure. Factors affecting the surface recombination at the back silicon surface have been identified, and the layers are being tailored to minimize deleterious effects at this interface. Light-trapping designs have been calculated for several back surface layers, and several test structures have been employed to evaluate light-trapping effectiveness. Initial results indicate the required electrical properties of the barrier layer are being achieved. Conceptual module designs incorporating an integrated Si-Film structure have been developed.

1. INTRODUCTION

The Silicon-Film process is being developed with the objective of achieving a high performance, low cost solar cell for terrestrial power applications. The approach is being guided by device modeling to achieve a high performance solar cell structure based on imperfect materials. The specific technical approach involves the deposition of thin silicon layers on a rigid ceramic substrate. The commercial feasibility of this approach has been demonstrated by the recent achievement of a 78 cm^2, 8.5% commercial size solar cell. The potential of this approach is further established by the achievement of a 1 cm^2, 15.7% Si-Film solar cell.

The solar cell design guiding the development of the Si-Film process evolved from a set of design rules. It has been shown that application of these design rules leads to solar cell structures capable of conversion efficiencies in excess of 19%. Crucial to the achievement of these performance levels is the utilization of thin (20 to 50 micron) layers coupled with the utilization of light-trapping. The use of thin layers of silicon leads to enhanced performance for the Si-Film solar cell structure as compared to the conventional thick crystalline silicon solar cells, and a significant reduction in the quality requirements for the silicon.

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2. SILICON-FILM SOLAR CELL WITH LIGHT-TRAPPING

2.1 Design

The Silicon-Film device structure has been designed to utilize light-trapping to optimize performance. The use of light-trapping leads to increased performance for the thin Silicon-Film solar cell, when compared to conventional thick solar cell designs. The standard thick device contains a significant amount of photogenerated minority carriers deep in the base region. These can only be effectively recovered if the minority carrier diffusion length is at least two times the thickness. Standard cast wafers, as well as most CZ grown wafers, fall far short of this diffusion length requirement. Therefore, the great majority of the silicon in the bulk of the device is of limited use in terms of device performance and significant numbers of carriers go uncollected.

For the light trapped structure the minority carriers are all generated close to the surface and are, therefore, relatively easy to collect. Long diffusion lengths are not required, allowing the use of higher doping levels which lead to higher Voc.

The efficiencies of a 35 micron thick Silicon-Film light- trapping device is compared to a standard 400 micron thick device in Figure 1. It can be seen that with an optical path length 10 times the thickness of the device (Z=10), the efficiency of the light-trapping structure exceeds that of a standard thick device at all diffusion lengths of interest. Diffusion length changes are modeled with corresponding changes in doping level. It is also worthy to note that the light-trapping device reaches its peak efficiency at a modest diffusion length of 70 microns and is somewhat insensitive to changes in diffusion lengths over a threshold of 45 microns.

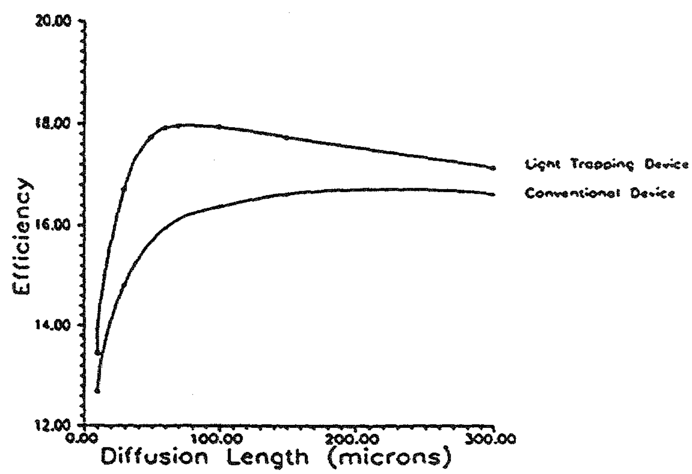

Figure 1.

Efficiency of a 35 um light-trapping device compared to a conventional 400 um thick device.

2.2 Light-Trapping Structures

For complete analysis of the absorption in an optically confining thin silicon solar cell, crystalline silicon has been utilized as a test structure. Work has focused on the use of (110) silicon and back surface texturing. The accounting for all photons in a textured thin structure is severely complicated when that device is supported on a non-transparent substrate. For those reasons, free standing thin silicon was chosen as the initial test structure.

Work that has been completed includes an analysis of a back surface textured (110) wafer. The experimental absorption data for such a sample is shown in Figure 2. Also shown are data for a similar sample (both are 100 microns thick) with a polished back surface. Both samples have double layer anti-reflection coatings on the front and back surfaces. These coatings insure that light not totally internally reflected is transmitted out, simulating worst case conditions. The coatings have been tailored to minimize reflection in the 600 to 1200 nm range.

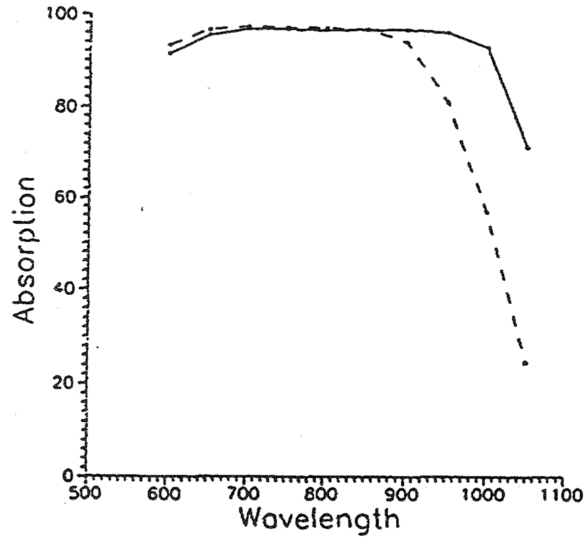

Figure 2. Absorption of thin (110) Silicon AR coating front and back: solid line, textured back; dashed line, polished back.

An analysis of the absorption expected from a back surface textured (110) device has been completed. This analysis predicts the percent of light remaining in the device as a function of path length (given in terms of Z, the nominal device thickness).

The experimental data in Figure 2 can be modeled to determine the effective Z due to the light trapping. That analysis generated a Z of approximately 7 for the experimental sample.

Samples of polycrystalline silicon have been thinned for a similar analysis. Results show that random texturing of a polycrystalline sample generate a Z of approximately 2.

3. PROCESS DEVELOPMENT

A set of processes are presently under development to generate Si-Film wafers for solar cells. There are two solar cell products which emerge, and these are illustrated in Figure 3. From a process standpoint, Product II differs from Product I only by the addition of the metallurgical barrier. However, as has been indicated, there are performance gains realized when the light-trapping feature of the metallurgical barrier is employed. Additionally, there are two factors that lead to a material cost reduction in the production of Product II Si-Film wafers. First, the optically trapped device employs a reduced amount of silicon (i.e. thinner) in the deposited silicon layer. Second, lower purity (i.e., even lower cost) ceramic materials can be employed in the ceramic substrate as a consequence of the chemical barrier feature of the metallurgical layer.

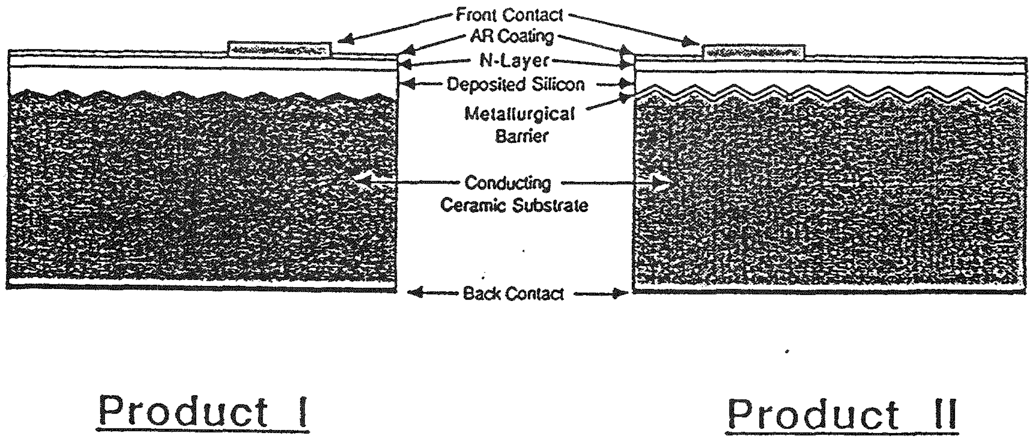

Figure 3. Si-Film Device Structures.

Several candidate barrier layers were selected based on their ability to prevent impurity transmission, to serve as a suitable wetting surface for the deposited silicon, to introduce minimum mechanical stress, and to assist in the light-trapping. A successful candidate barrier layer has been identified, and a deposition method is being employed to coat 100-cm^2 ceramic substrates with the selected barrier layer.

4. INTEGRATED SI-FILM MODULES

An initial analysis has been undertaken to identify ways in which cells fabricated using the silicon-film approach can be connected in series in a single substrate, using a potentially low cost process. The analysis indicates that a monolithically integrated polycrystalline silicon solar cell will reduce module costs by a factor of two through decreased device and assembly costs.

The present technology of silicon module assembly involves stringing together 36 individual elements. The proposed work will lead to the reduction of assembly costs in two areas: first, there will be fewer elements, each one being larger and more efficient, and second, all contacting will be limited to the two opposing backs (or edges) of each element. The length of these elements will coincide with one dimension of the module, therefore limiting device contacts to two edges of the module. The contacting of the illuminated side of the device will be completely eliminated from the new design. Assembly will be reduced to contacting the backs (or edges) of 9 or less elements.

The Si-Film process presently under development will be utilized in the fabrication of the monolithically integrated Product III. With the exception of the isolating and contacting step, the process sequence is the same for the Product II device already under development.

A key feature of this new module design is the ability to isolate areas of the element (i.e., Si-Film wafer) into segments. This device is pictured in

Figure 4. The fact that the active device is only 20 to 50 microns thick and is supported by an insulating substrate allows this to occur. A contacting scheme has been developed to retrieve the generated power in any I-V configuration required. All electrical contacts are applied on the top of the device. All interconnections to the module will be made on the edges or backs of the elements. The metallization trenches can be formed by etching, laser scribing, or sawing. The interconnect metal can be applied by a screen printing squeegee method or by electroplating. Electrically, the element pictured represents 36 diodes in series. This interconnection occurs on a rigid ceramic substrate (i.e., monolithically). Figure 4 shows a complete module. In this case the module is formed from 8 individual elements. Electrical contacts need only be made at the edges of each element. The contacting metal can be wrapped around to the back of the insulating ceramic for back contact.

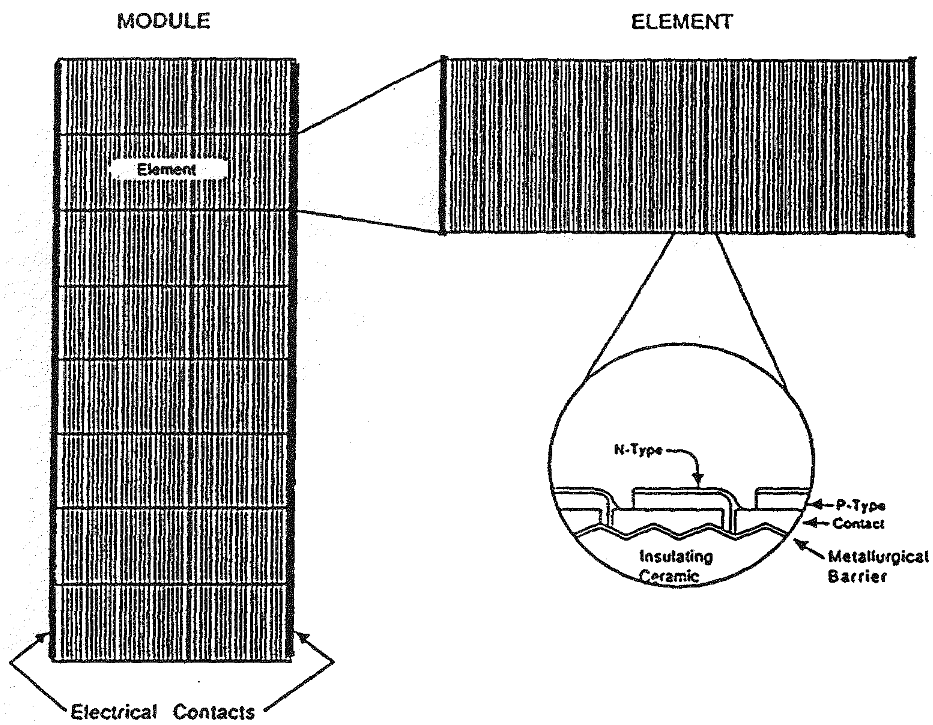

Figure 4. Silicon-Film Product III module, element, and cross-selection.

The Voc of a module is determined by the number of segments on an element. The Jsc of a module is determined by the area of the segment and the number of elements. Each of the elements are wired in parallel in the module requiring only electrical connections along the sides of the module.

The example shown was configured to deliver I-V characteristics similar to the existing industry standard module. The isolation and contact scheme, however, allows for virtually any configuration that maybe required. If a higher voltage, lower current configuration is required, the number of segments per element can be increased. This can be done without effecting the process by which the Si-Film wafer is fabricated, all that need be altered is the isolation and metallization steps.

Title: Polycrystalline Silicon-Film Solar Cells

Contractor:
Astrosystems, Inc.
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30 Lovett Ave.
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Principal Investigator:
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(302) 366-0400
Current Contract Number:
05-7828B
Current Contract Period:
From: 4/89 **To:** 11/89
Project/Area/Task:
Crystalline Cell Research
Task 3 One-Sun Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
Paul A. Basore
Telephone:
(505) 846-4516
Contract History:

Number	FY	Level	Source
33-5518	1987	$238,670	DOE
33-5518	1988	259,980	DOE
05-7828A	1989	311,000	DOE
05-7828B	1989	377,811	DOE

Objective: The objective of this research is to demonstrate that the high efficiency and stability of crystalline silicon can be coupled with an inexpensive growth process that lends itself to continuous, large-scale production of solar cells.

Approach/Present Tasks: The approach is one that involves development of a technique for growing a thin (50-μm) film of crystalline silicon on an inexpensive ceramic-based substrate coated with a barrier layer. The barrier layer must simultaneously serve to shield the silicon from substrate contaminants, passivate the rear silicon surface, provide a path for current flow to the substrate, and provide the reflectance and texturing necessary to obtain light trapping. Separate tasks are defined in the contract to demonstrate surface passivation, light trapping, conductivity, spatial uniformity, and efficiency. An additional task requires the investigation of methods for producing monolithic submodules using this process.

Status/FY 1989 Accomplishments: In previous work with 100-μm thick silicon layers and no barrier layer, cell efficiencies of 15.7% on 1 cm^2 and 8.5% on 84 cm^2 were demonstrated. A new silicon deposition technique in conjunction with a candidate barrier layer has demonstrated uniform large-area grains over a 100-cm^2 ceramic substrate. Preliminary results with this barrier material look promising for passivation, conductance, and light trapping.

FY 1989 Milestones: Produce 1-cm^2 cells with a silicon thickness of less than 50 μm which have a 25°C efficiency of at least 14%, and three 10-cm^2 cells from a single 100-cm^2 substrate which all have an efficiency exceeding 10%.

Major Project Reports:
- A.M. Barnett, et al., "14% Efficient Thin Crystalline Silicon-Film Solar Cells," Proc. of 20th IEEE PVSC, Las Vegas, NV, Sept. 1988.

Summary Date
June 1989

ONE SUN SILICON SOLAR CELL RESEARCH

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Principal Investigator: Martin A. Green

1. Objectives

This project seeks to improve the efficiency of both crystalline and polycrystalline silicon solar cells. The most spectacular recent progress has been obtained with a new solar cell structure, the passivated emitter and rear cell (PERC cell), which has increased silicon cell efficiency to close to 23%. Good progress has also been obtained in implementing a laser textured, laser grooved cell sequence on cast polycrystalline substrates with efficiencies approaching 17% demonstrated for 10 cm^2 cells.

2. PERC Cells

The PERC cell structure is shown in Figure 1. The most distinctive structural feature is the way rear contact is made directly to the moderately doped substrate through small area contact holes in a passivating rear oxide. A major processing difference is extensive use of chlorine based processing giving rise to superior oxide passivation and post-processing bulk lifetimes.

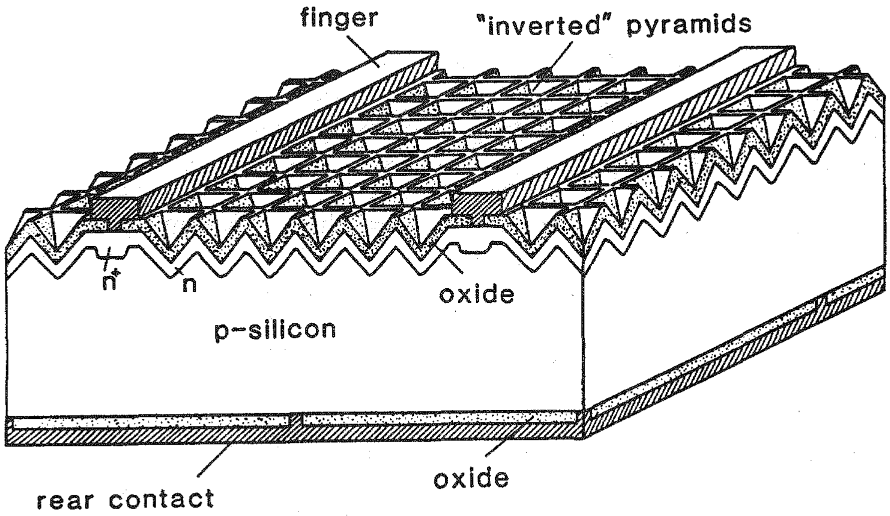

Figure 1: PERC cell (passivated emitter and rear solar cell)

Table 1 compares recent high efficiency silicon cell results. Compared to our group's earlier generation PESC cells (passivated emitter solar cell), the PERC cells display much higher V_{OC} and J_{SC} due to the better surface passivation, particularly along the rear surface, and better post-processing bulk lifetimes. The effective light-trapping scheme formed by the inverted pyramids on the top surface and the dielectrically isolated rear reflector contribute to an exceptionally high infrared response and hence J_{SC}. The lower fill factor arises primarily from the additional base resistance arising from lateral current flows through the base from the contact points typically spaced more than a millimetre apart.

Table 1: Comparison of recent high performance silicon solar cells (independently confirmed in all cases under the Global AM1.5 spectrum at 25°C)

Cell Type	Voc (mV)	Jsc (mA/cm2)	FF (%)	Effic. (%)
0.2 Ω cm p-type PESC	669	38.6	82.9	21.4
200 Ω cm n-type Stanford	703	40.6	77.9	22.3
0.2 Ω cm p-type PERC	696	40.3	81.4	22.8

Compared to Stanford University cells, V_{OC} and J_{SC} are remarkably similar given the difference in cell structure, dopant type and dopant density. The PERC cells, however, have a much higher fill factor due to their operation in a low injection mode with an ideality factor close to unity. In the Auger limit, the ideality factor of cells operating in a high injection mode approaches the value of 2/3 which gives them a theoretical advantage in this area (M.A. Green, IEEE Trans. Electron Devices, Vol. ED-31, 1984, p. 671). However, for high injection cells with defect determined recombination, the ideality factor is much higher, approaching 2 as in the case of the present Stanford cells.

3. Polycrystalline Cells

There has been recent quite marked progress with polycrystalline silicon cell efficiency using the passivated emitter solar cell structure (PESC structure) of Figure 2.

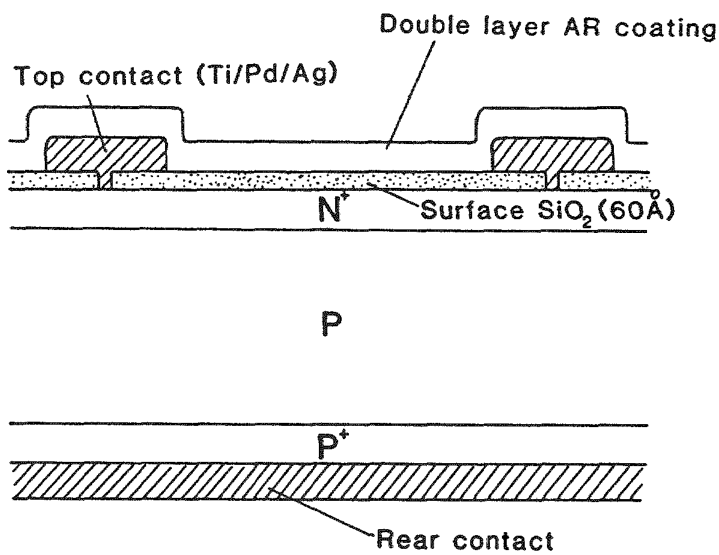

Figure 2: PESC cell

By combining a phosphorus pretreatment step with rear Al alloying treatments, exceptionally high efficiencies have been obtained for a range of polycrystalline material as shown in Table 2. Of particular interest is the fact that the best polycrystalline silicon material (supplied by Osaka Titanium) gives efficiencies very similar to the CS controls.

Table 2: Summary of the best efficiencies to date on polycrystalline cells from 4 suppliers compared to CZ controls (Sandia measurements, Global AM1.5, 25°C, all cells nominally 1 Ω cm resistivity, 2 cm x 2 cm).

Supplier	Voc (mV)	Jsc (mA/cm2)	FF (%)	Effic. (%)
A	605	35.2	78.2	16.6
B	603	35.6	78.4	16.8
C	618	35.6	78.0	17.1
D	623	36.0	79.4	17.8
CZ controls	620	36.8	80.0	18.2

These cells employ photolithographic processing and double layer AR coatings which are not generally considered low cost processing options. However, our earlier work with crystalline PESC cells has shown the large increases resulting from surface texturing (or grooving). Such texturing would increase the efficiency of the CZ control of Table 2 to beyond 19%.

More importantly, our work with crystalline cells has shown that such efficiencies above 19% with 1 Ω cm CZ material can also be obtained with much lower cost laser grooved cell structure of Figure 3. This technology has been licensed to some of the largest present manufacturers of silicon cells. The feedback received from corresponding costing studies is that the cost of producing cells with such a sequence is no higher than with the silver screen printing sequence which forms the basis of present commercial practice. However, power output from processed cells is 30-50% higher.

It follows from Figure 3 and the results of Table 2 that low cost polycrystalline silicon solar cells of efficiencies approaching 19% should be feasible, if a low cost way can be found for texturing the top surface of the cell (the anisotropic etches used for CZ substrates are not effective in this regard).

Accordingly, one objective of the present work is to demonstrate polycrystalline silicon solar cell efficiency in the 18.5-19.0% range by combining laser texturing of the cell surface with the laser grooved cell processing sequence.

Good progress has been made to date. A variety of laser texturing strategies have been demonstrated to result in reflection loss comparable to, or smaller than, that obtained with anisotropically etched, textured CZ controls. The increased flexibility afforded by laser texturing means that schemes utilizing "triple bounces" of reflected light are feasible, although not necessarily the best economic choice.

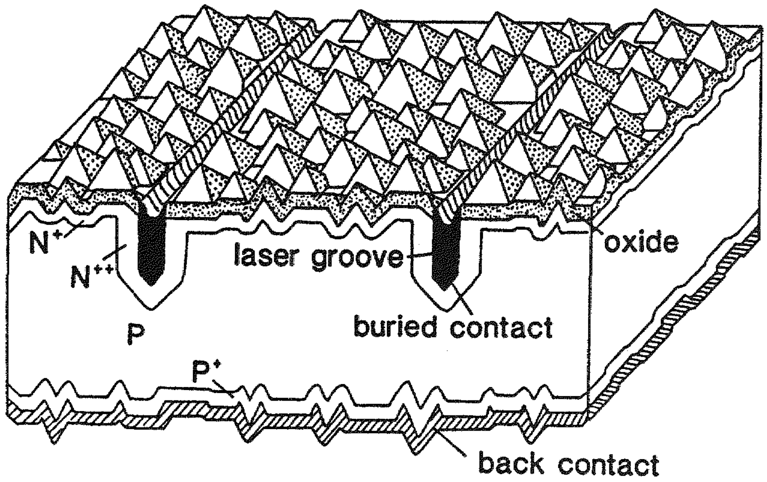

Figure 3: Laser grooved, buried contact solar cell.

A good start has been made on integrating the laser texturing step into the laser grooved cell processing sequence as indicated by the results of Table 3. This compares the performance of the best cells to date fabricated from 1 Ω cm polycrystalline wafers supplied by "Manufacturer C" of Table 2 using both the PESC sequence and the "laser textured, laser grooved" sequence.

Table 3: Comparison of results from 1 Ω cm polycrystalline wafers (Manufacturer C) using two different processing sequences (Global AM1.5, 25°C).

Sequence	Area (cm^2)	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF (%)	Effic. (%)
PESC	4	618	35.6	78.0	17.1
Laser text. & grooved	10.5	595	36.4	76.5	16.6

Although the laser based sequence is presently down a little on V_{OC} and fill factor, it has already established a clear advantage in J_{SC}. Reflection measurements indicate similar reflection loss in both cells ("double bounce" oxide coated texturing versus planar DLAR coating). This indicates the improved J_{SC} arises from the benefits of oblique coupling of light into the cell. Increasing V_{OC} and fill factor to the expected levels combined with implementation of a "triple bounce" texturing scheme is expected to result in marked improvements in the laser based approach beyond the very creditable level of 16.6% efficiency already established.

5. Conclusion

Although this report has concentrated upon progress in two areas of our current activity, considerable progress has been obtained across the whole spectrum of our activities since the last Project Review Meeting in July, 1988, as summarized below.

In the non-concentrating crystalline cell area, efficiencies up to 19.6% have been demonstrated for 7 cm x 7 cm FZ cells using the laser grooved sequence of Figure 3. Sixteen such cells have been encapsulated into a nominally 30 cm x 30 cm module which has given 17.0% total area efficiency (including frame) in measurements at Sandia. Using the PERC structure of Figure 1, efficiencies up to 22.8% have been demonstrated as reported in the text. Such efficiencies are consistent with module efficiencies above 20%.

As reported, polycrystalline cell efficiency of 17.8% has been demonstrated with the PESC cell structure of Figure 2. This figure is expected to be surpassed by laser textured, laser grooved polycrystalline cells during the present project.

In the concentrator area, "module ready" PESC cells have demonstrated efficiencies up to 25.2% above 100 suns concentration, when combined with Entech prismatic covers. Outdoor lens/cell testing at both Sandia and Entech have given efficiencies in the 20-21% range using other such cells of about 24% efficiency. Twelve such cells have been combined into an experimental concentrator module at Sandia which has displayed 20.4% efficiency. This is believed to be the first photovoltaic module to display an efficiency above 20%, significantly higher than the figure of 17.2% which was previously the highest.

Acknowledgements

The PERC cells described in the report were developed by a team at UNSW led by Andrew Blakers with significant contributions from Zhao Jianhua, Aihua Wang and Adele Milne. The laser textured, laser grooved cells resulted primarily from the efforts of John Zolper, Mohan Narayanan and Stuart Wenham. The contributions of Sandia Technical Monitor, David King, and colleagues at Sandia in the area of cell and module characterization are also gratefully acknowledged.

Title: One-Sun Silicon Solar Cell Research

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Principal Investigator:
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Current Contract Number:
75-0282

Current Contract Period:
From: 9/88 **To:** 3/90

Project/Area/Task:
Crystalline Cell Research
Task 3 One-Sun Silicon

Directing Organization:
Sandia National Laboratories

Project Engineer:
David L. King

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(505) 844-8220

Contract History:

Number	FY	Level	Source
06-2755	1987	$114,582	DOE
06-2755	1988	$51,000	DOE
75-0282	1988	$299,000	DOE

Objective: The objective of this activity is to continue the development and improvement of three separate one-sun silicon solar cell technologies.

Approach/Present Tasks: (1) Improve passivated emitter (PESC) cell processing for both p-type and n-type silicon and incorporate optimized light trapping schemes. Improvement of the back surface passivation is a primary effort. Goal is 23% efficiency. (2) Improve laser-grooved, buried-contact cell technology for both one-sun and low concentration applications. Goals is 20% at one-sun for 50 cm^2 Cz silicon and 20.5% at 20 suns using Cz silicon. (3) Improve one-sun polycrystalline silicon cell processing technology and cell design using thin substrates and reduced front surface reflection losses. Goal is to demonstrate 18% efficient, 12 cm^2 polysilicon cell.

Status/FY 1989 Accomplishments: (1) A PESC cell with an improved rear surface design (called the PERC cell) has been developed. Efficiencies over 22% have been achieved with 4.0 cm^2 FZ PERC cells. (2) Laser-grooved, 46 cm^2 FZ cells have been assembled into a 16 cell module that achieved 17.0% efficiency. (3) Polycrystalline material from four suppliers (Silso, Semix, HEM, Osaka Titanium) achieved 17% with 4 cm^2 cells. The best poly cell achieved 17.8%.

Major Project Reports:

- M.A. Green, et al, "Laser Grooved and Polycrystalline Silicon Solar Cell Research," Sandia Contractor Report to be published.
- P. Campbell, et al, "Light Trapping with Tilted Pyramids and Grooves," Proc. of 20th IEEE PVSC, Las Vegas, NV, Sept. 1988.
- S.R. Wenham, et al, "High Efficiency Laser Grooved Buried Contact Solar Cells," Proc. of 4th Intl. PVSEC, Sydney, February 1989.
- S. Narayanan, et al, "High Efficiency Polycrystalline Solar Cells," Proc. of 4th Intl. PVSEC, Sydney, February 1989.
- A.W. Blakers, et al, "22.6% Efficient Silicon Solar Cells," Proc. of 4th Intl. PVSEC, Sydney, February 1989.

Summary Date
June 1989

One-Sun, Backside-Contact Solar Cells

R. R. King, R. A. Sinton, and R. M. Swanson
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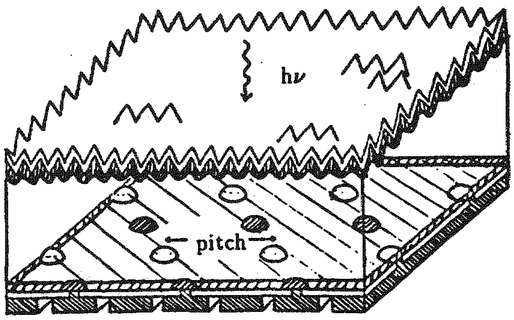
Stanford, CA 94305

Cell Design

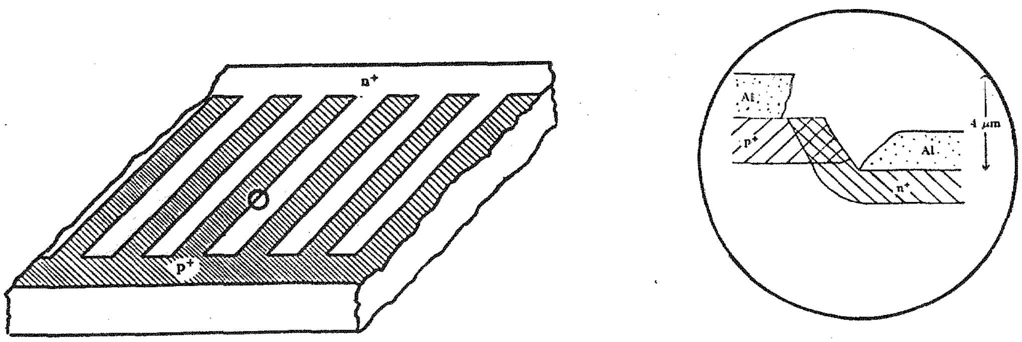
- Point Diffusions *

  $\eta = 22.3\%$ at 0.100 W/cm^2, 25°C (measured at SERI)



- Trench/Mesa †

  $\eta = 21.9\%$ at 0.100 W/cm^2, 25°C (measured at Sandia)



Both of these cell types have the zero grid obscuration and very low metal series resistance inherent in backside-contact designs. These features make it possible to increase the cell area for one-sun applications, with very little loss in performance. 37.5 cm^2 cells of both types have been fabricated.

* R. R. King et al, *Proc. of the 20th IEEE PVSC*, Sep. 1988.

† Sinton and Swanson, Manuscript submitted for publication.

Perimeter Recombination

- Proportional to ratio of sawcut area to illuminated area

  ⇒ perimeter recombination can be reduced by increasing cell area or by decreasing cell thickness

- Increases with increasing minority carrier density in the region covered with emitters

  ⇒ low-resistivity substrates will suppress perimeter recombination

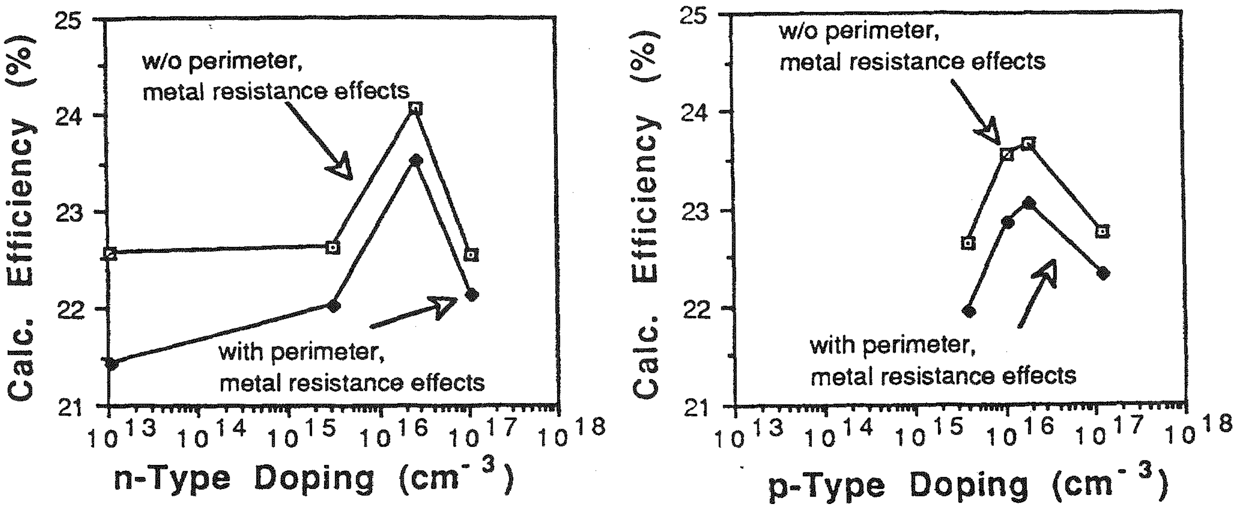
- Can be minimized by optimizing the distance between the sawcut and the region covered with emitters

Responsivity has been experimentally observed to be low on n-type, low-resistivity, backside-contact cells, resulting in a loss in absolute efficiency of about 3% *. Therefore, most cells were fabricated on high-resistivity substrates.

* R. R. King et al, Appl. Phys. Lett., Vol. 54, No. 15., 10 April 1989, pp. 1460-1462.

Dependence of Point-Contact Cell Efficiency on Substrate Doping

Recombination in uniformly-doped, float-zoned, thermally-oxidized wafers was measured by contactless photoconductivity decay. The effective lifetime, τ_{eff} , found in this way includes the effects of both surface and bulk recombination.

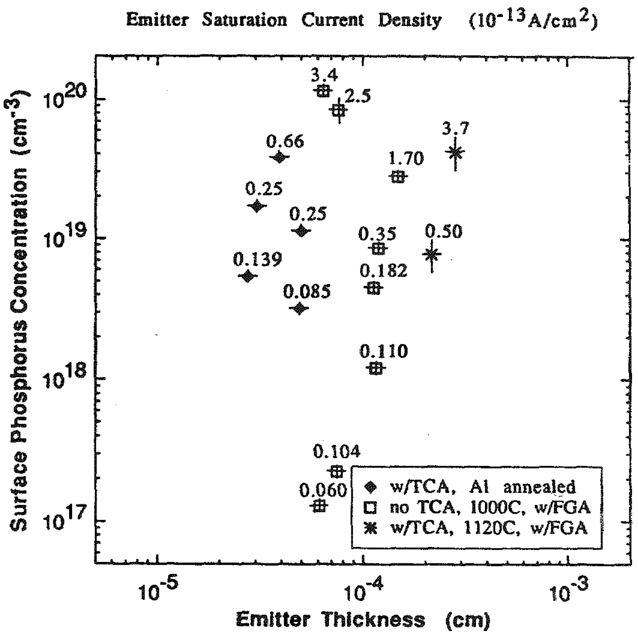


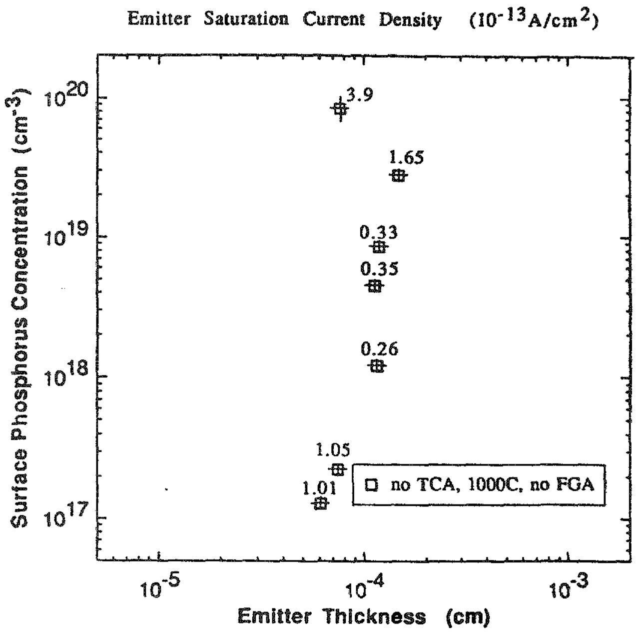
The figures above show the calculated efficiency of 100 μm thick point-contact solar cells built on doped substrates in low-level injection, based on measured values of τ_{eff} *. The perimeter recombination was calculated by optimizing the distance between the sawcut and the nearest point emitter for each doping concentration, assuming a sawn cell size of 4 cm × 5 cm. Metal series resistance was also calculated assuming this cell size. Note that perimeter recombination accounts for a loss in absolute efficiency of ~1% for high-resistivity substrates, compared to ~0.5% for low-resistivity substrates.

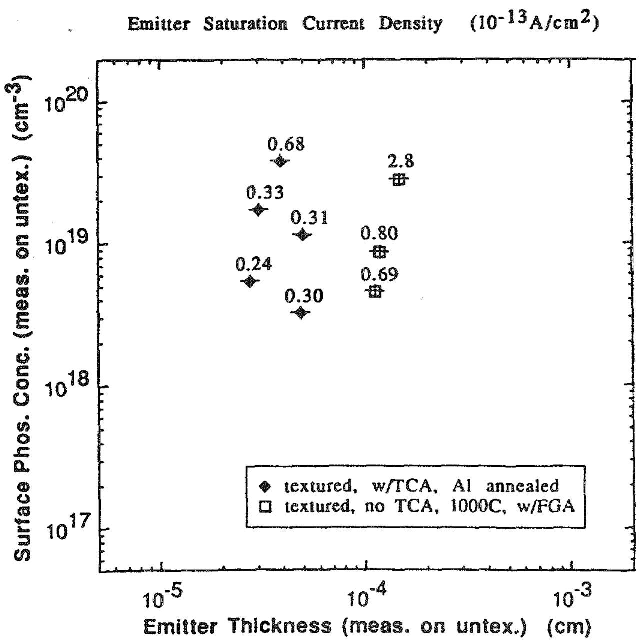
* R. R. King et al, *Proc. of the 4th IREE PVSEC*, Feb. 1989.

Recombination at the Oxidized, n-Type, Silicon Surface *

The emitter saturation current density, J_o , of n-type diffusions at the oxidized silicon surface was measured for a variety of oxidation, anneal, and surface conditions, using contactless photoconductivity decay.

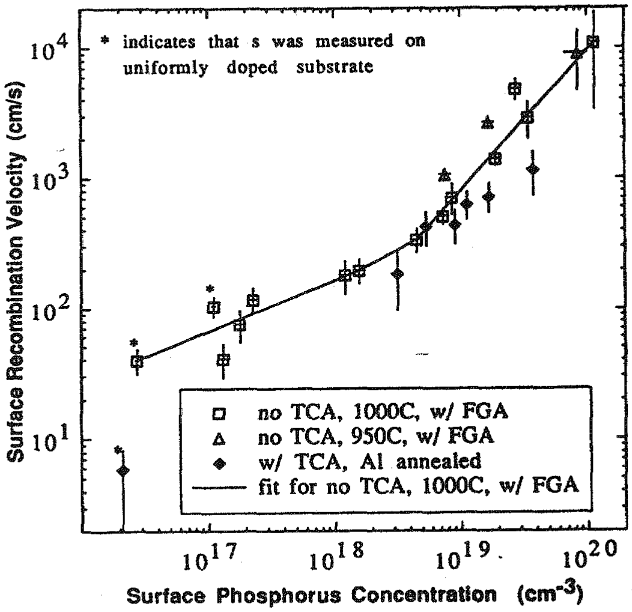




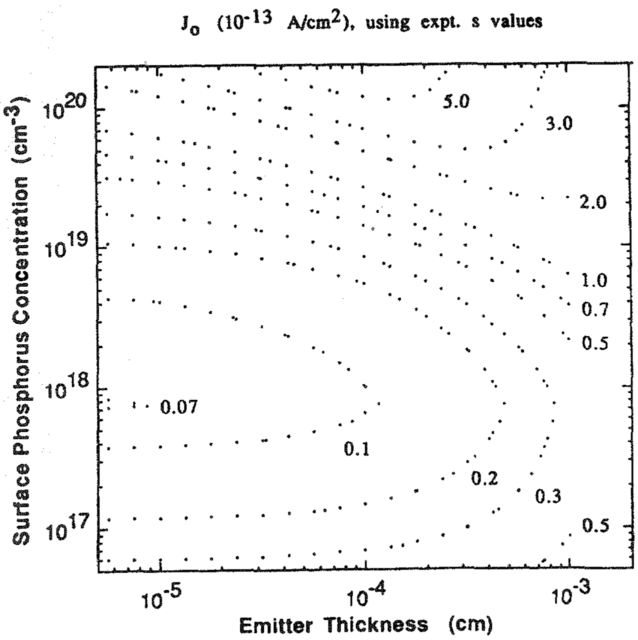


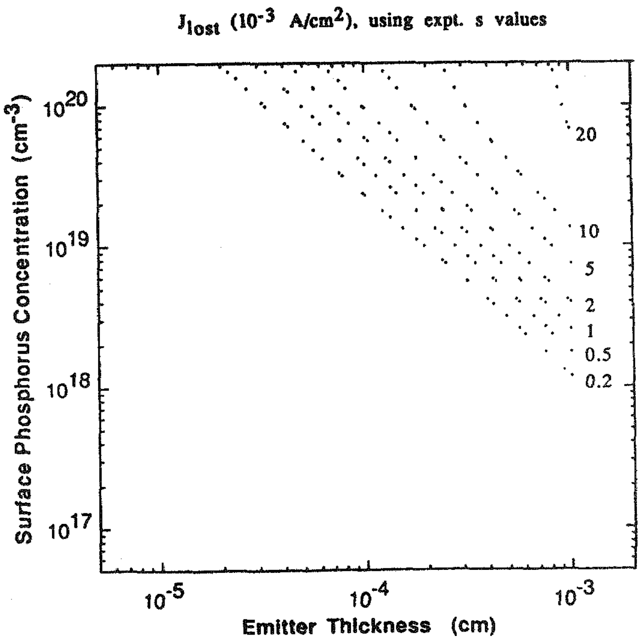
* R. R. King et al, manuscript submitted for publication.

From the these J_o measurements, and SIMS measurements of the phosphorus profiles, the surface recombination velocity, as a function of surface phosphorus concentration was extracted.



This new data was used to generate contour plots of J_o and J_{lost} for oxidized, n-type diffusions, where J_{lost} is defined to be the current density photogenerated within the volume of an emitter on the sunward surface of a solar cell, minus the current density flowing out of the emitter into the substrate.





Title: One-Sun Crystalline Solar Cell Research

Contractor:
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Current Contract Number:
63-3886
Current Contract Period:
From:7/88 **To:**7/89
Project/Area/Task:
Crystalline Cell Research
Task 3 One-Sun Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
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Contract History:

Number	FY	Level	Source
63-3886	1988	$115,584	DOE

Objective:
The objective of this contract is to provide high efficiency one-sun single crystal silicon solar cells. These cells will be used to establish the reliability and present performance limits of larger area one-sun silicon solar cells operating in sub-module configurations.

Approach/Present Tasks:
On a best effort bases a minimum of 200, 2x6cm, single crystal silicon solar cells will be delivered to Sandia National Laboratories. The efficiency goal for each cell is 21%.

Status/FY 1989 Accomplishments:
Cell and process design are completed. Module assemble design and tooling are completed.

FY 1989 Milestones:
The 200 solar cells will be delivered in the form of two sub-modules with the remaining cells delivered in cell carriers:

a. One sub-module of approximately - 30x30cm.
b. One sub-module of approximately - 12x12cm.
c. Cells in cell carriers should be easily solderable without AR coat on busbar metal.

FY 1990 Milestones:
Evaluation of the performance and reliability of the solar cells and the sub-modules will be completed.

Major Project Reports:

- King, R.R., et al, "Doped surfaces in one sun, point-contact solar cells," Appl. Phys. Lett. 54(15) 10April 1989.

Summary Date
June 1989

EFFECTS OF DEEP LEVELS, INJECTION LEVEL, AND LIGHT TRAPPING ON DESIGN AND PERFORMANCE OF HIGH EFFICIENCY SOLAR CELLS

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In spite of recent improvements in cell performance, a considerable gap still remains between the theoretically possible and experimentally achieved efficiencies of one sun silicon and GaAs solar cells. Unlike some concentrator cells, best one sun cell performance today is limited by SRH recombination and not by the intrinsic Auger recombination. The right combination of material quality, cell design and light trapping can raise the injection level in the cell to a point where Voc becomes limited by Auger recombination. Model calculations in this paper reveal how to approach the efficiency limits in a practical manner by knowing the deep level position and understanding the interplay between trap location, base resistivity, lifetime, and light trapping.

1. Silicon Solar Cells

Figure 1 shows that optimum doping for a low starting (undoped) quality material (τ~10μs) is ~$10^{17}cm^{-3}$, regardless of the deep level position. However, optimum resistivity for a very high quality starting material (τ~10ms) will shift from 0.2 ohm-cm to $\geq$200 ohm-cm if the lifetime limiting trap location shifts from Ev+0.20 to Ev+0.56eV. Cell design used in these calculations is shown in Table 1. Figure 2 shows that the knowledge of deep level is important because a relatively higher starting (undoped) lifetime material (τ=1ms) with shallow trap can actually result in lower efficiency compared to a 100μs starting lifetime material with midgap trap when both materials are doped to 0.2 ohm-cm for cell fabrication. This is because shallow traps show much stronger doping dependence than the midgap trap.

Figure 3 shows that if the trap density increases with doping density then the optimum resistivity shifts from 0.2 ohm-cm to 1-5 ohm-cm.

Figure 4 shows that in the case of a very high quality starting material (τ~10ms) with midgap trap, the cell operates under high enough injection level at all resistivities so that its lifetime and performance is limited by intrinsic Auger recombination. However, in the shallow trap level case, Figure 5, the injection level and cell performance decreases and becomes limited by material quality or SRH recombination. This is primarily because, unlike the midgap trap material, lifetime in the shallow trap material decreases with the increase in injection level prior to the Auger limit.

Finally, Figure 6 shows that for a low starting lifetime silicon ($\tau \sim 10 \mu s$), Voc and cell performance is always dictated by SRH recombination with midgap trap cells showing higher performance than Ev+0.2ev trap cells for all resistivities.

2. Program Development for Light Trapping

Currently there is no public domain or commercially available ray tracing program for the solar cell community. In accessing the direction of high efficiency one sun cells, it was observed that such a program might have a strategic use. The following list of attributes was compiled to guide the direction of development of a ray tracing program for general use.

1) Applicable to any computer system with Fortran 77 and ANSI
2) Compatibility with current and future modeling programs
3) New structures easily incorporated due to modular nature of program
4) No simplification of structures, a 3 dimensional analysis in all modes of operation
5) Different modes of operation to provide different information as a compromise to speed.
6) 1,2, and 3 dimensional profiles should be available
7) Variable angle of incidence
8) Surface structures should be independent of each other
9) Different material systems should be easily modeled
10) Cover glass treated as fully as the semiconductor
11) Grid lines modeled as fully as possible
12) Loss in flux due to sides, back, grids, cover glass, and reflection should be provided
13) Average increase in surface area to be output
14) Various spectra and intensities accounted for

Improvement in cell performance for various textured surfaces will be presented, Figure 7 shows textured surfaces modeled.

3. GaAs Solar Cells

In most n-type GaAs grown today, Shockley-Read-Hall recombination controls the minority carrier lifetime at doping levels below $\sim 1 \times 10^{18} cm^{-3}$ and is commonly assumed to be independent of trap characteristics and doping concentration. It is shown here that various realistic combinations of deep level location, cross section, and trap density can result in orders of magnitude fluctuations in lifetime values. In addition, deep levels which reside within 0.4 eV from the valence band edge and 0.3 eV from the conduction band edge can make the lifetime a strong function of doping concentration in the material resulting in large variations in lifetime values, Figure 8. This has important ramifications for GaAs devices such as solar cells where optimized design and performance depends on assumed lifetime behavior. An alternative design is proposed which utilizes a thin base, thin buffer, and back surface passivation and makes the cell performance relatively insensitive to the trap characteristics, Figure 9. Furthermore, this modified cell design can also result in one sun efficiencies over 25% for moderate lifetime values (20 ns) reducing the need for very high quality GaAs for high efficiency devices, Table 2.

TABLE 1. Configuration of N^+-P-P^+ Cells Used in Numerical Simulations

1. Cell area of 1 cm^2
2. Series resistance of 0.2 ohm
3. Uniform emitter doping of 2.0×10^{19} cm^{-3}
4. Emitter thickness of 0.2 microns
5. Cell thickness of 254 microns
6. Uniform BSF doping of 2.0×10^{18}
7. BSF thickness of 2 microns
8. 5% shadow and reflective loss
9. 98% effective back surface reflector
10. FSRV and BSRV of 0 cm/sec

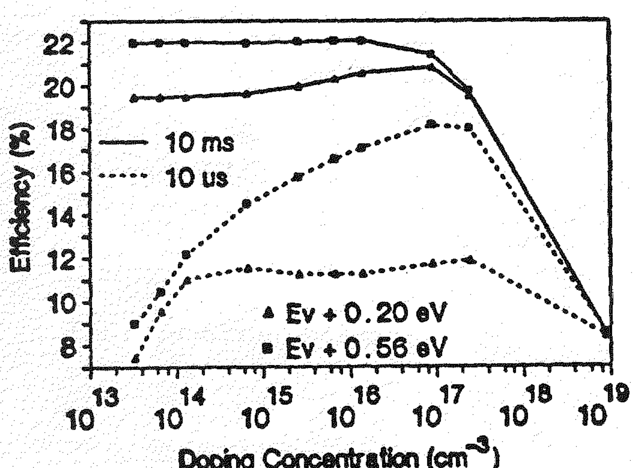


Figure 1. Effect of base quality (τ=10μs and 10ms), base doping, and trap location on cell performance.

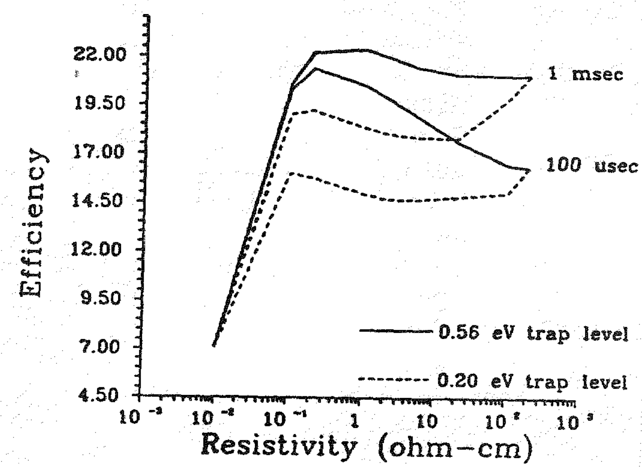


Figure 2. Comparison of cell performance for higher lifetime material (τ=1ms) with shallow trap and lower lifetime (τ=100μs) with midgap trap.

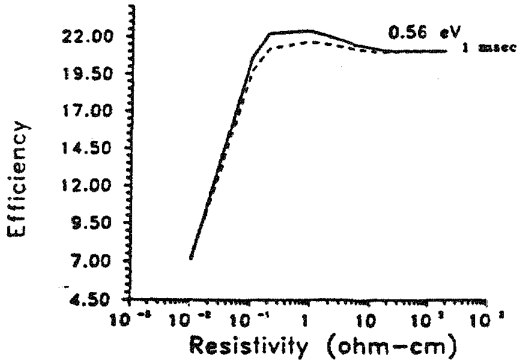


Figure 3. **Effect of trap density as a function of doping density for higher lifetime material (τ=1ms) and midgap trap.**

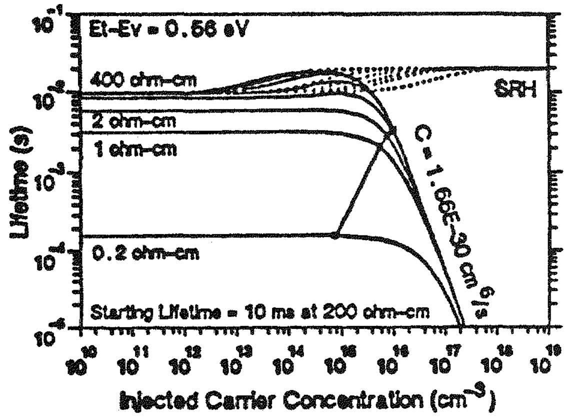


Figure 4. **Net lifetime (solid lines) and SRH lifetime (dotted lines) as a function of injection level, base doping and trap location in a high quality silicon (τ=10ms at 200Ω-cm) with a midgap trap. Points designate lifetime and injection level at V_{oc}.**

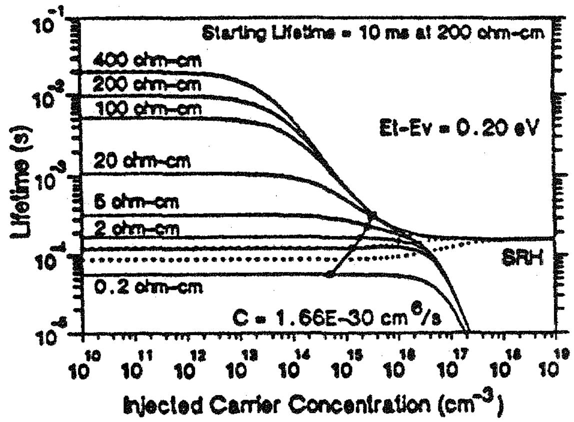


Figure 5. **Net lifetime and SRH lifetime in a high quality silicon (τ=10ms at 200Ω-cm) with a shallow (0.20eV) trap.**

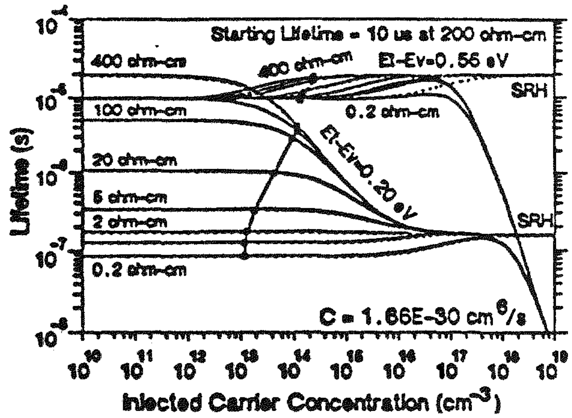


Figure 6. **Net lifetime and SRH lifetime in a low quality silicon (τ=10μs at 200Ω-cm) with a midgap trap as well as E_v+0.20eV trap.**

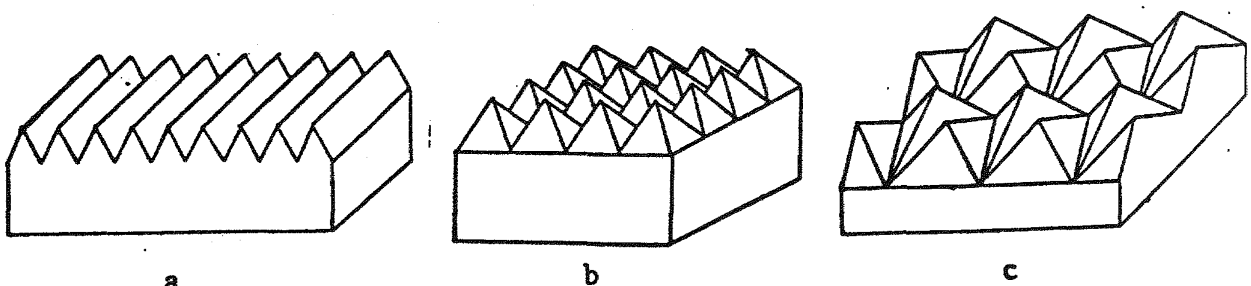


Figure 7. **Various surface designs modeled by ray tracing program a) slats b) pyramids c) tetrahedrons.**

Table 2. Cell data calculated using PC-1D for the device structures listed. A 5% surface loss, AM1.5 conditions and an 0.5 um emitter with $N_A = 2x10^{18}cm^{-3}$ was used in each calculation.

width (um) base	width (um) buffer	Doping (cm^{-3}) base	Doping (cm^{-3}) buffer	FSRV (cm/s)	BSRV (cm/s)	T_o (ns)	V_{oc} (volts)	J_{sc} (mA/cm^2)	Eff (%)
				Actual					
2.0	2.0	$2.0x10^{17}$	$2.0x10^{18}$				1.013	24.5	21.2
				Match					
2.0	2.0	$2.0x10^{17}$	$2.0x10^{18}$	$1.25x10^5$	$1.0x10^6$	8	1.01	24.56	21.39
				Material and interface optimization					
2.0	2.0	$2.0x10^{17}$	$2.0x10^{18}$	$1.0x10^4$	$1.0x10^6$	8	1.016	24.59	23.02
2.0	2.0	$2.0x10^{17}$	$2.0x10^{18}$	$1.0x10^4$	$1.0x10^4$	8	1.017	26.71	23.13
2.0	2.0	$2.0x10^{17}$	$2.0x10^{18}$	$1.0x10^4$	$1.0x10^4$	15	1.032	27.11	24.17
2.0	2.0	$5.0x10^{17}$	$2.5x10^{18}$	$1.0x10^4$	$1.0x10^4$	15	1.048	26.83	24.40
2.0	2.0	$5.0x10^{17}$	$2.5x10^{18}$	$1.0x10^4$	$1.0x10^4$	20	1.054	26.95	24.76
				Design optimization					
1.2	1.2	$6.0x10^{17}$	$2.5x10^{18}$	$1.0x10^4$	$1.0x10^3$	15	1.055	27.04	24.75
1.3	1.1	$6.0x10^{17}$	$2.5x10^{18}$	$1.0x10^4$	$1.0x10^3$	20	1.059	27.10	25.05
1.5	1.1	$6.0x10^{17}$	$2.5x10^{18}$	$1.0x10^4$	$1.0x10^3$	30	1.063	27.19	25.31
1.9	1.1	$6.0x10^{17}$	$2.5x10^{18}$	$1.0x10^4$	$1.0x10^3$	55	1.068	27.31	25.62

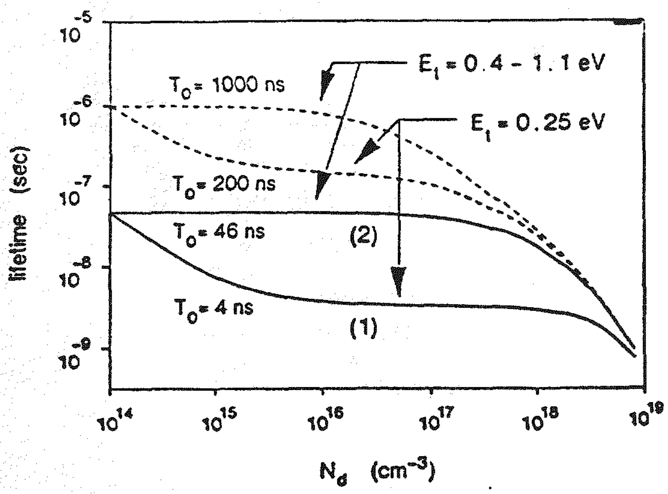


Fig. 8. Minority carrier lifetime as a function of doping in n-GaAs for materials with starting lifetimes of 1000 and 46 ns at $N_D = 1x10^{14}cm^{-3}$ for different trap levels and values of T_o as indicated.

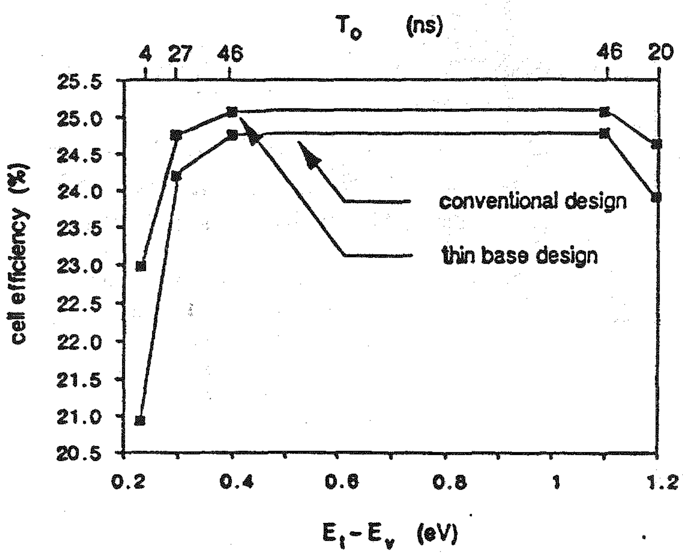


Fig 9. Cell efficiencies calculated by PC-1D for conventional and thin base designs as a function of trap level (with respect to E_v) and T_o. All calculations assume a 5% uniform surface loss, front and back surface recombination velocities of $1x10^4$ and $1x10^3$ cm/s, respectively, and one sun AM1.5 conditions.

Title: Research on High-Efficiency Silicon Cells

Contractor:
Georgia Institute of Technology
School of Electrical Engineering
Atlanta, GA 30332

Principal Investigator:
Dr. Ajeet Rohatgi
Telephone:
404-894-7692

Current Contract Number:
42-3377
Current Contract Period:
From: 05/89 **To:** 08/90
Project/Area/Task:
Crystalline Cell Research
Task 3: One-sun Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
James M. Gee
Telephone:
505-844-7812
Contract History:

Number	FY	Level	Source
57-6152	1988	72,500	DOE
42-3377	1989	90,000	DOE

Objective: Investigate high-efficiency silicon solar cells, with an emphasis on understanding the effect of processing on lifetime of various crystalline silicon materials.

Approach/Present Tasks: (1) Determine processes that limit lifetime in high-lifetime float-zone-refined silicon. (2) Investigate effect of cell fabrication processes on high-lifetime silicon.

Status/FY 1989 Accomplishments: (1) Assembled a photo-conductive decay lifetime measurement system. (2) Investigated lifetime controlling mechanisms in high-lifetime Ga-doped FZ silicon. (3) Theoretically investigated effect of trap location on silicon cell performance. (4) Developed a program to calculate the photogeneration in a light-trapping solar cell, with output compatible with PC-1D/2. (5) Established basic silicon solar cell processing sequence.

FY 1989 Milestones: Establish high-lifetime silicon cell processing sequence.

Major Project Reports:

- A.W. Smith and A. Rohatgi, "Modeling the effect of trap levels on the optimum resistivity of silicon solar cells," Proc. of 20th IEEE Photovoltaic Specialists Conf., Las Vegas, NV, Sept. 1988.
- S.K. Pang and A. Rohatgi, "Doping dependence on minority-carrier lifetime in Ga-doped silicon," Proc. of 20th IEEE Photovoltaic Specialists Conf., Las Vegas, NV, Sept. 1988.
- * A. Rohatgi, A.W. Smith, S.K. Pang, and P.A. Basore, "Impact of deep level position and light trapping on silicon cell performance," Techn. Digest of the 4th Photo. Science and Eng. Conf., Sydney, Australia, Feb. 1989.

Summary Date
June 1989

Title: One-Sun Crystalline Silicon Solar Cells

Contractor:
Westinghouse R&D Center
1310 Beulah Road
Pittsburgh, PA 15235

Principal Investigator:
Richard H. Hopkins
Telephone:
(412) 256-1341
Current Contract Number:
02-6639
Current Contract Period:
From: 2/87 **To:** 12/88
Project/Area/Task:
Crystalline Cell Research
Task 3 One-Sun Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
John D. McBrayer
Telephone:
(505) 844-7327
Contract History:

Number	FY	Level	Source
02-6639	1987	$290,000	DOE
02-6639	1988	$400,000	DOE

Objective: The objective of this research is to demonstrate that the high efficiency and stability of crystalline silicon can be coupled with an inexpensive growth process that lends itself to continuous, large-scale production of solar cells.

Approach/Present Tasks: The approach of this program is to conduct research that provides a better understanding of the performance potential of dendritic web technology. The program is structured into three tasks aimed at significantly increasing the understanding of the relationships between solar cell efficiency, material defect structure and chemistry, and the thermal conditions during web crystal growth.

Status/FY 1989 Accomplishments: Final report has been distributed.

Major Project Reports:

- Seidensticker, R. G., et al., "Dendritic Web Silicon Photovoltaic Cell Research," SAND88-7040, January 1989.

Summary Date
June 1989

Title: Frequency-Domain Analysis of Transient Silicon Cell Parameters

Contractor:
University of Florida
13th and W University Ave
Gainesville, FL 32611

Principal Investigator:
Arnost Neugroschel
Telephone:
(904) 392-4949
Current Contract Number:
23-5366
Current Contract Period:
From: 7/87 **To:** 1/89
Project/Area/Task:
Crystalline Cell Research
Task 3 One-Sun Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
Paul A. Basore
Telephone:
(505) 846-4516
Contract History:

Number	FY	Level	Source
23-5366	1987	$35,000	DOE

Objective: This project involves the development of nondestructive techniques for studying the transient short-circuit response of low-resistivity planar silicon solar cells as a means of extracting recombination and transport parameters for the tested device.

Approach/Present Tasks: The unique aspect of this research is the application of Fourier-transform techniques to analyze the transient response to optical excitation in the frequency domain, whereas previous short-circuit response techniques have been based on time-domain analysis. Analysis in the frequency domain has the advantage of closed-form solutions for comparing the measured results with theory, and permits the effects of non-ideal optical pulses to be extracted from the data. The result is a determination of the recombination lifetime and surface recombination velocity at the edge of the back-surface field of the cell.

Status/FY 1989 Accomplishments: The frequency-domain transient analysis (FDTA) technique has been fully explored and applied to a variety of silicon solar cells. Like other transient methods, the technique is quite sensitive to the value of minority-carrier diffusion constant (D), which is often not known accurately. A separate experiment in which strongly-absorbed light is incident on the back surface can be used to independently determine the value of D, although in most cells this requires removal of the back-surface metal.

Major Project Reports:
R.E. Haney, A. Neugroschel, K. Misiakos, and F. Lindholm, "Frequency-Domain Transient Analysis of Silicon Solar Cells," SAND88-7039, March 1989.

R.E. Haney, K. Misiakos, A. Neugroschel, "Characterization of Solar Cells by Frequency-Domain Transient Analysis," 20th IEEE Photovoltaic Specialists Conf., September 1988.

Summary Date
June 1989

Title: Numerical Cell Model Evaluation

Contractor:
University of Delaware
Newark, DE 19716

Principal Investigator:
Karl W. Böer
Telephone:
(302) 451-8048
Current Contract Number:
23-5997
Current Contract Period:
From: 6/87 **To:** 12/88
Project/Area/Task:
Crystalline Cell Research
Task 3 One-Sun Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
Paul A. Basore
Telephone:
(505) 846-4516
Contract History:

Number	FY	Level	Source
23-5997	1987	$27,068	DOE

Objective: The basic goal of this effort is to evaluate the accuracy of assumptions commonly employed in computer programs designed to predict the performance of crystalline silicon solar cells.

Approach/Present Tasks: The most efficient programs for evaluating cell performance are based on the finite-element method. But it is difficult to modify these programs to incorporate new physical phenomena. The Runge-Kutta method is very inefficient, but can easily incorporate complex functional relationships to describe physical phenomena. This research will apply the Runge-Kutta technique to seek ways to improve the models used in the finite-element computer programs.

Status/FY 1989 Accomplishments: The finite-element program PC-1D was selected for comparison with the Runge-Kutta program. The two programs produce similar results for several test cases involving a narrow region surrounding the junction space-charge region. Within the junction region, the effect of various recombination-center occupancy rules was evaluated. It was found that variation in the charge state of a trap as a function of carrier occupancy significantly affects the recombination rate due to that trap. This implies that the PC-1D default assumption that carrier capture cross-sections in the space-charge region are the same as in the quasi-neutral regions can lead to an underestimation of recombination in the space-charge region.

Major Project Reports: Report is in final review prior to publication.

Summary Date
June 1989

Concentrator Silicon Cell Research

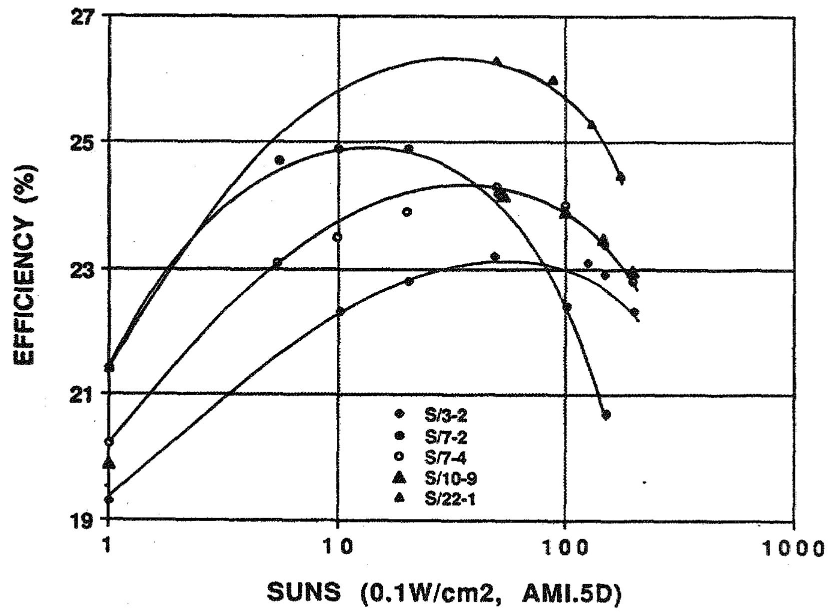
Silicon Concentrator Solar Cells

R. A. Sinton, A. Cuevas*, R. R. King, N. Midkiff, and R. M. Swanson
Stanford University
*On leave from Madrid Polytechnic

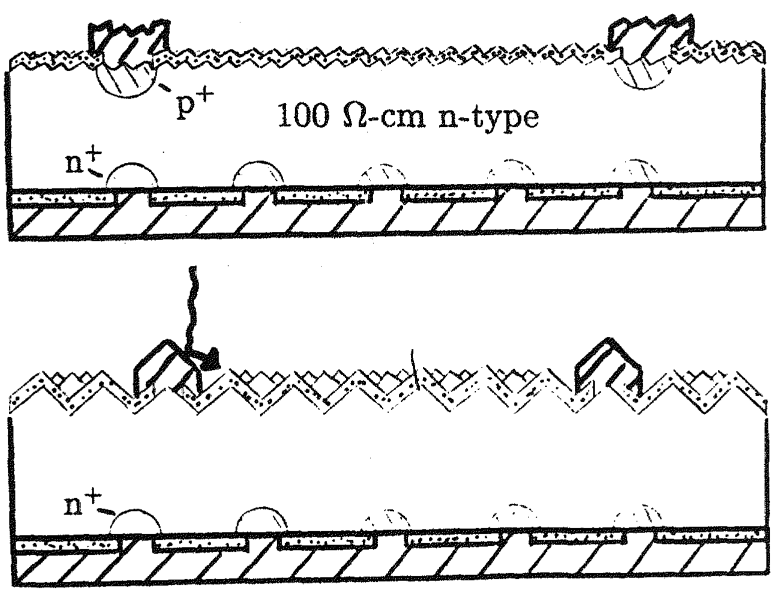
MILESTONES TO DATE:

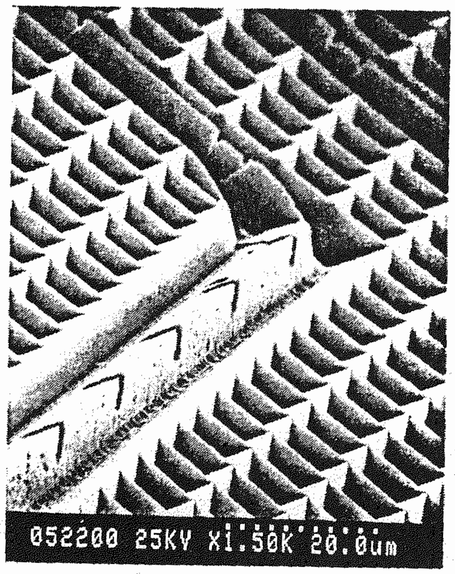
- Improvement in basic 1.56 cm^2 front-grid cell efficiencies. (no prismatic covers).
  - 25% at 20 suns
  - 24% at 100 suns
- Development of state-of-the-art 1.56 cm^2 front-grid cells. (also without prismatic coverglasses).
  - 26% at 90 suns
  - 25% at 150 suns
- Demonstration of simplified backside contact solar cells.
  - 10.5 cm^2 1-sun cell, 22%.
- Emitter modeling
  - Full characterization of n^+ emitters.
  - Surface recombination velocity as a function of doping.

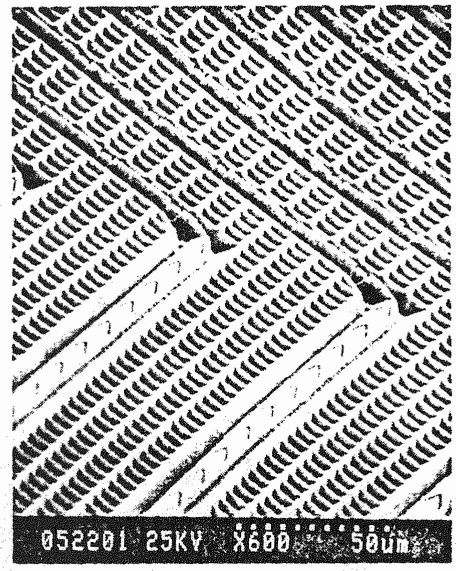
FRONT-GRID CELLS:

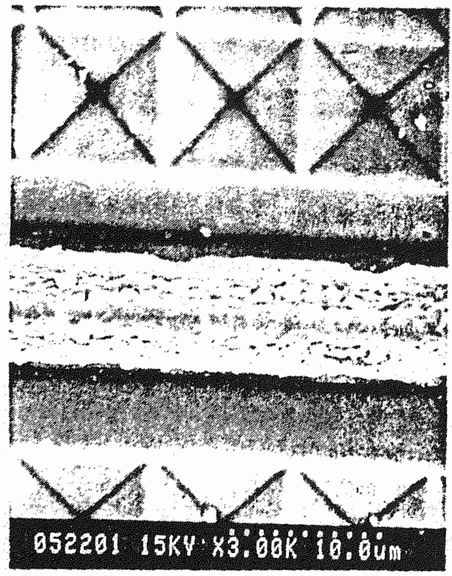


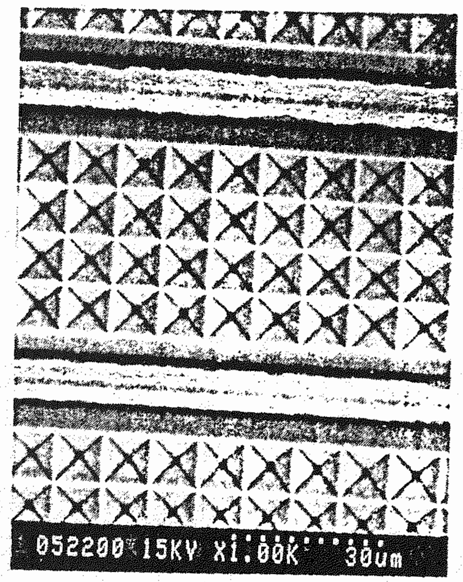
New designs and increased process control have allowed an increase in the peak efficiency for these 1.56 cm^2 cells from 23% to 26% during the last year. 24 process runs have been fabricated utilizing four distinct designs.







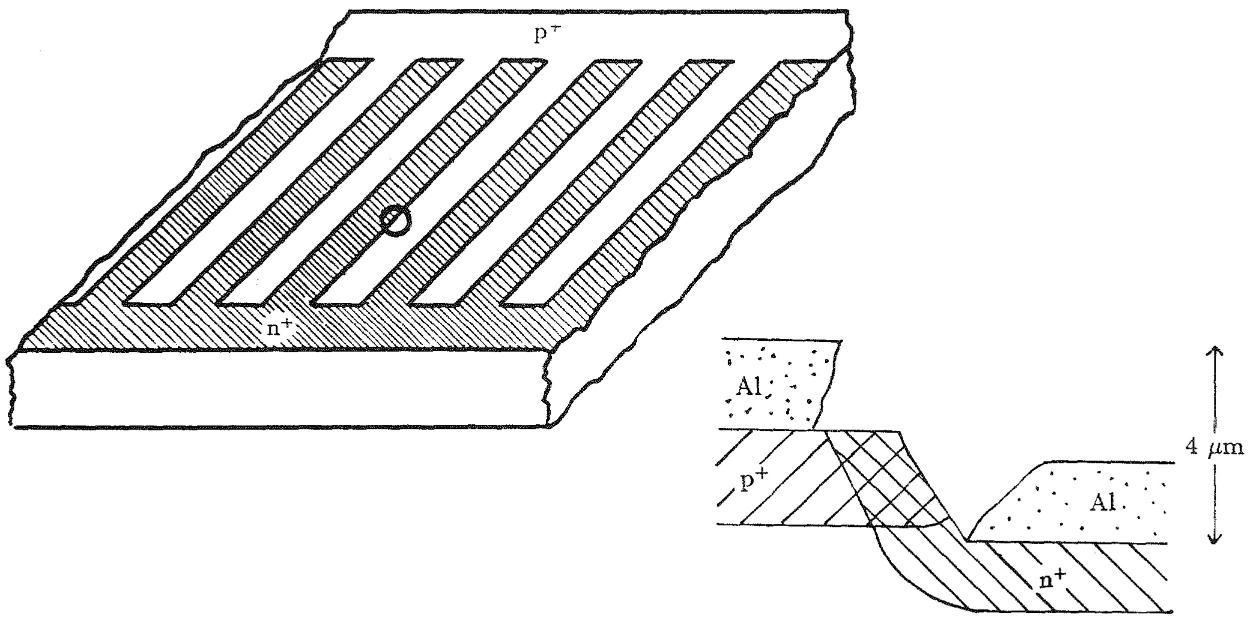


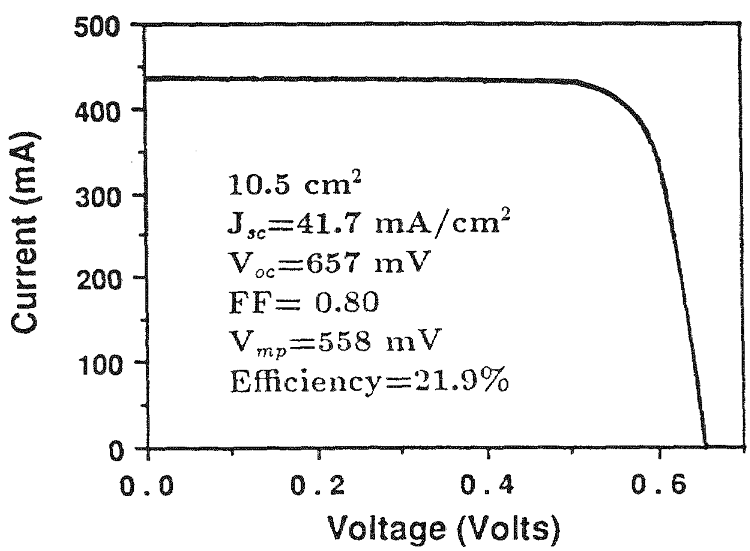


*Cuevas et al, To be published in the Proc. EPSEC 1989.

SIMPLIFIED BACKSIDE-CONTACT SOLAR CELLS:

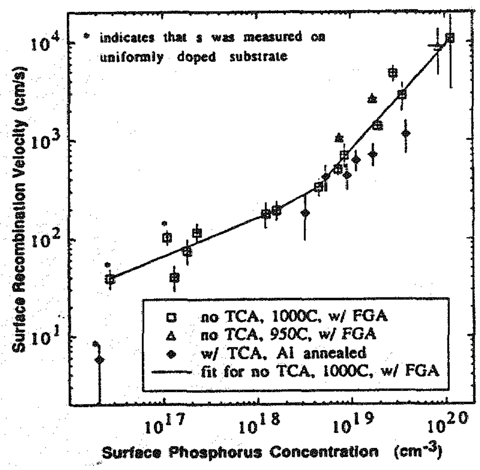
- 2 masks, 1 metal deposition step.
- Can be totally self-aligned.

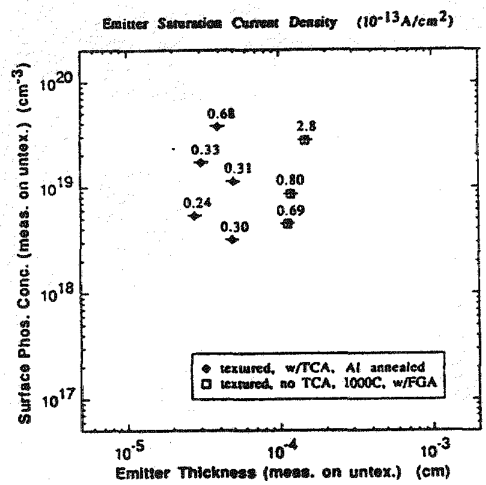


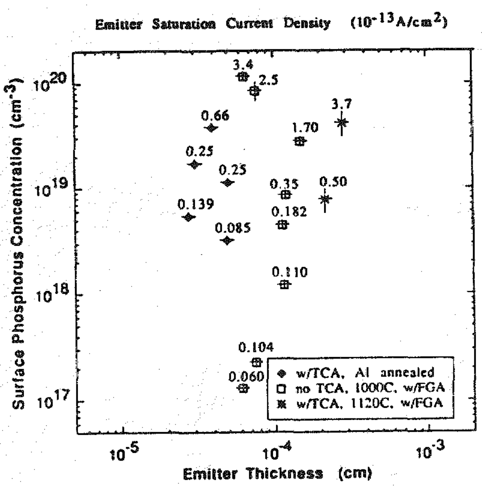


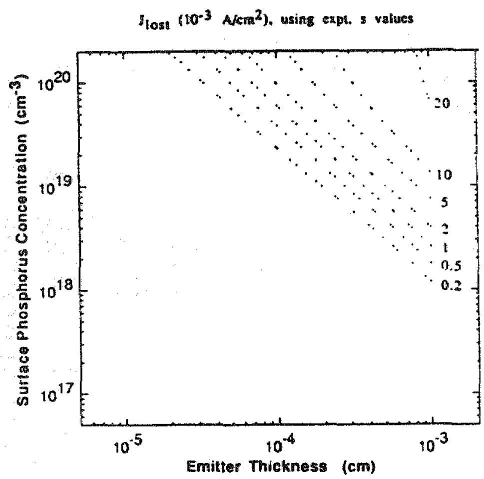
*Sinton and Swanson, Manuscript submitted for publication.

- Extensive experimental data of emitter saturation currents for n+ diffusions over textured and planar surface.
- An analysis of this data to extract the surface recombination velocity as a function of the doping level, a necessary parameter for accurate simulations using models such as PC-1D.
- Calculations for the recombination of photogenerated carriers in frontside n+ emitters utilizing the updated data.









* R. R. King et al, Manuscript submitted for publication.

Title: Advanced Silicon Concentrator Solar Cell Development

Contractor:
Stanford University
Office of Sponsored Programs
Encina Hall
Stanford, CA 94305

Principal Investigator:
Richard M. Swanson
Telephone:
(415) 723-0804
Current Contract Number:
75-6318
Current Contract Period:
From: 2/89 **To:** 1/90
Project/Area/Task:
Crystalline Cell Research
Task 4.1 Concentrator Silicon Cells

Directing Organization:
Sandia National Laboratories
Project Engineer:
Paul A. Basore
Telephone:
(505) 846-4516
Contract History:

Number	FY	Level	Source
58-6134	1984	$ 98,274	DOE
32-8112	1985	100,000	DOE
32-8112	1986	28,314	DOE
32-8112	1986	69,588	DOE
02-7063A	1987	388,126	DOE
75-6318	1989	316,725	DOE

Objective: This research is aimed at developing high-efficiency (25%) module-ready silicon concentrator cells for 150X to 500X concentration.

Approach/Present Tasks: Several cell designs will be investigated, including delivery of (1) fifty 1.563-cm^2 two-sided cells for 150 suns with separate contacts on the front and back, (2) five simplified back-contact cells for 300 suns mounted to substrates, (3) fifty 1.563-cm^2 two-sided cells for 100 suns designed for use with prismatic covers, and (4) ten 0.317-cm^2 back-contact cells designed for use as a bottom cell under GaAs. Also, a fundamental study of recombination at doped surfaces will be performed, for phosphorous, boron, and aluminum dopants at both <100> and <111> silicon surfaces.

Status/FY 1989 Accomplishments: Two-sided cells have been produced which have efficiencies of 26% at 100 suns, and 25% at 150 suns. Plating these cells to make them solderable currently degrades the performance to about 23%. Large-area simplified backside-contact cells have been produced with one-sun efficiencies of nearly 22%. Experiments to determine the recombination parameters of phosphorous-doped surfaces are in progress.

Major Project Reports:

R.A. Sinton and R.M. Swanson, "Improved High-Efficiency Silicon Concentrator Cells for Medium Concentration Applications," SAND88-7037, February 1989.

R.A. Sinton, R.R. King, and R.M. Swanson, "Novel Implementations of Backside-Contact Silicon Solar Cell Designs in One-Sun and Concentrator Applications," Presented at the 4th PVSEC Conf., Sydney, February 1989.

R.M. Swanson, "Studies in Advanced Silicon Solar Cells," SAND88-7026, June 1988.

Summary Date
June 1989

Computer Modeling of Silicon Concentrator Cells

J. L. Gray and R. J. Schwartz
School of Electrical Engineering
Purdue University
West Lafayette, IN 47907

Summary

A physical consideration not often included in the analysis of highly injected silicon solar cells is the bandgap shrinkage due to free carrier interactions in the base. Theoretical efforts have typically focused on the bandgap narrowing effect in heavily doped silicon. However, advanced concentrator cells, such as the point contact cell (PCC), will have electron-hole concentrations in excess of 10^{17} cm^{-3} under high solar concentration. A many-body theory of a dense electron-hole plasma (high injection) developed by Abram *et al.* [1] indicates that a sizable reduction of the energy bandgap in silicon occurs for carrier densities of this magnitude.

In this presentation, the effect of bandgap narrowing in the highly injected base of silicon solar cells on cell performance is investigated. A modification of the open circuit voltage limit of solar cells operating under high injection conditions developed by Green [2] is presented. It is shown that the intensity dependence of the open circuit voltage as measured in PCC [3] and IBC [4] solar cells can be explained without resorting to the higher values of the Auger recombination coefficients recently proposed in [3]. In addition, it is shown that while the open circuit voltage is signifcantly reduced by this bandgap narrowing mechanism, the resulting effect on cell efficiency is quite small until very high intensities are reached.

It is also shown that by modeling the minority carrier mobility with a value of about one half of that obtained from majority carrier measurements of the mobility, the experimently observed sublinearity of the intensity dependence of the short circuit collection efficiency is well modeled.

---

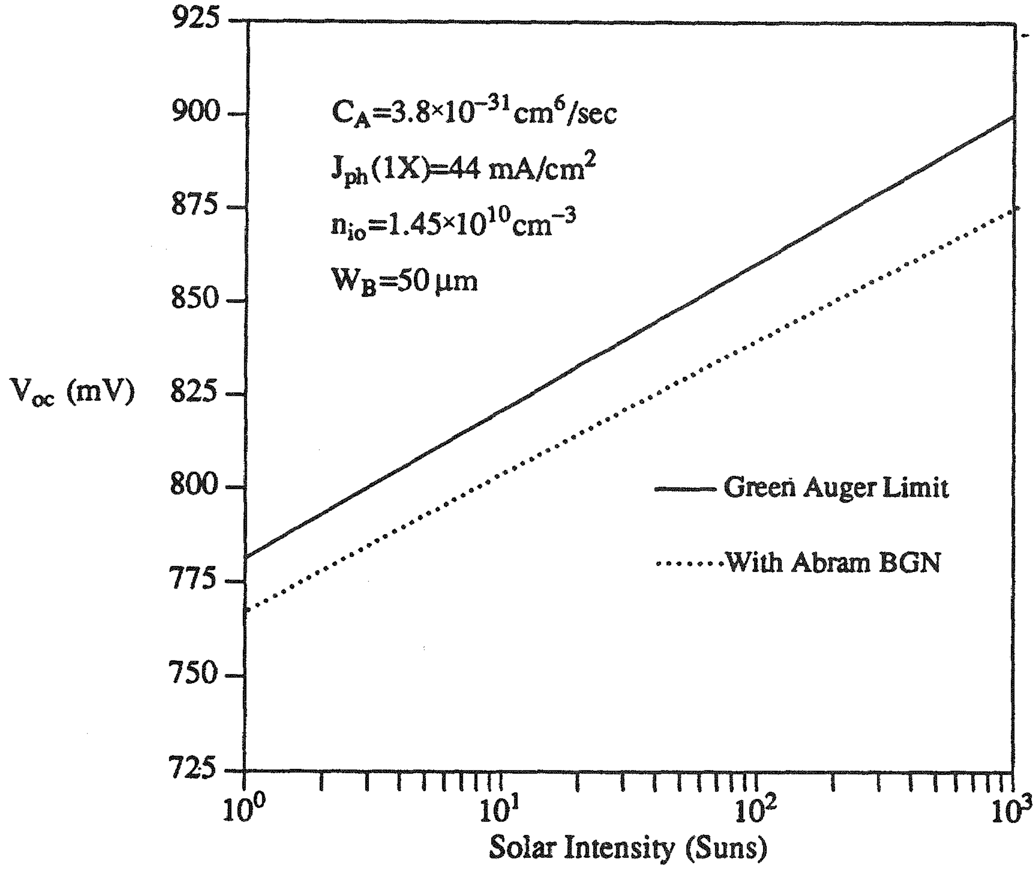
[1] R. A. Abram, G. N. Childs, and P. A. Saunderson, "Bandgap Narrowing due to Many-Body Effects in Silicon and Gallium Arsenide," *J. Phys. C: Solid State Phys.*, vol. 17, 1984, pp. 6105-6125.

[2] M. A. Green, "Limits on the Open-Circuit Voltage and Efficiency of Silicon Solar Cells Imposed by Intrinsic Auger Processes," *IEEE Trans. Electron Devices*, vol. ED-31, no. 5, May 1985, pp. 671-678.

[3] R. A. Sinton and R. M. Swanson, "Recombination in Highly Injected Silicon," *IEEE Trans. Electron Devices*, vol. ED-34, no. 6, June 1987, pp. 1380-1389.

[4] R. A. Sinton, "Device Physics and Characterization of Silicon Point-Contact Solar Cells," Ph.D. Thesis, Stanford University, Stanford, CA, 1987.

Open Circuit Voltage Limit

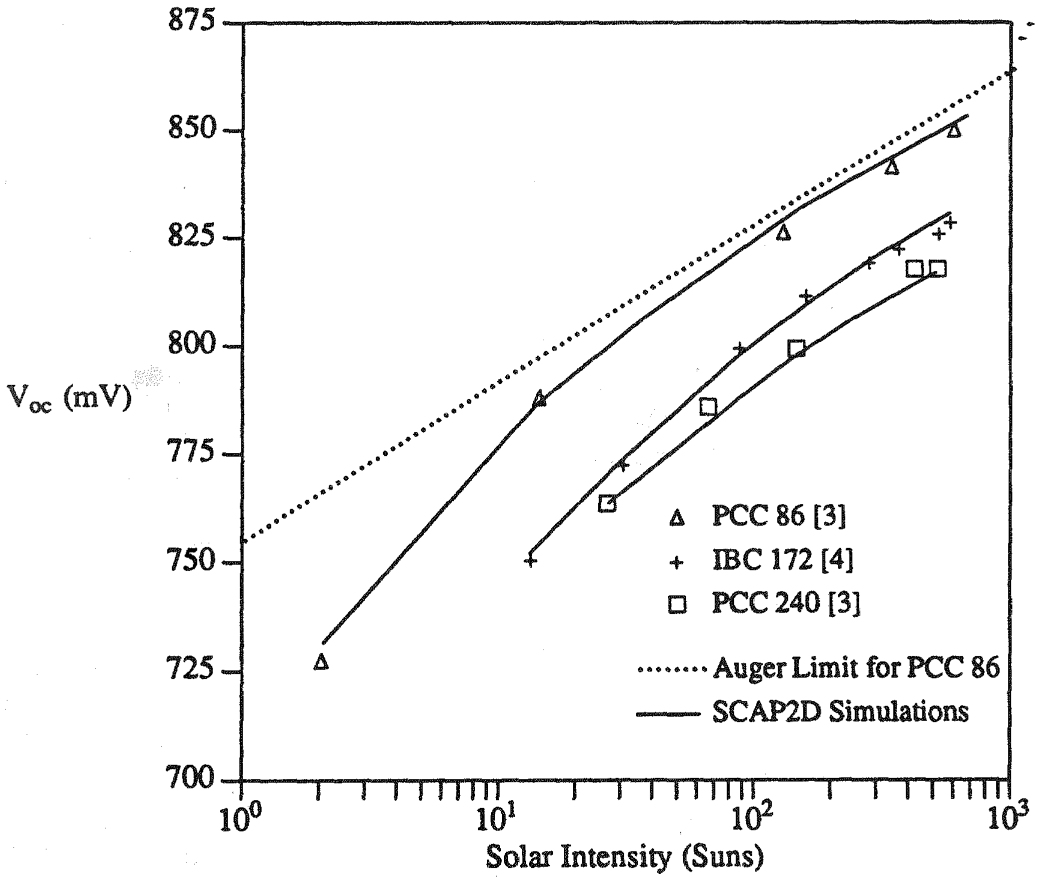


When the Auger limit of the open circuit voltage [2] is modified to account for BGN in the base due to high injection, the following expression results:

$$V_{oc} = \frac{2}{3}\frac{kT}{q}\ln\left[\frac{J_{ph}}{qn_{io}^{3}C_A W_B}\right] - 0.321\ mV \times \left[\frac{J_{ph}}{qn_{io}^{3}C_A W_B}\right]^{\frac{1}{12}}$$

where J_{ph} is the short circuit current for 100% collection efficiency, n_{io} is the intrinsic carrier concentration in lightly doped silicon, W_B is the thickness of the base, and C_A is the ambipolar Auger recombination coefficient. The second term in the above equation accounts for BGN in the base due to high injection.

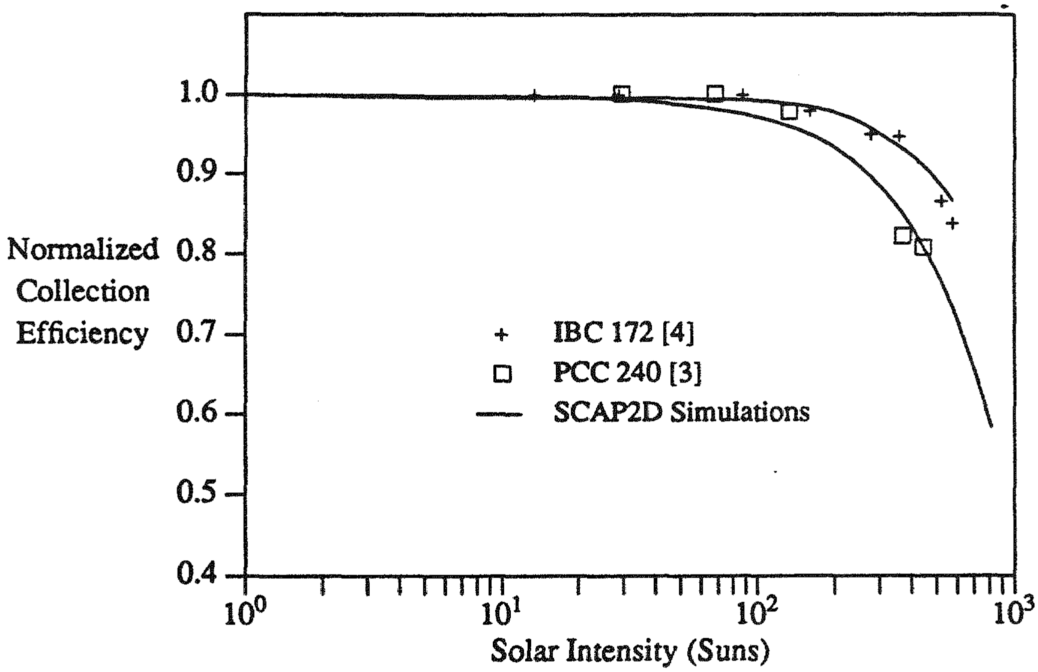
Modeling V_{oc} of PCC and IBC Solar Cells



The SCAP2D simulations above were made using C_A=3.8×10^{-31} cm^6/sec and the Abram BGN model [1] for the highly injected base region. The agreement with experiment is excellent.

Well designed thin cells (such as PCC 86 which is 86 μm thick) with low surface recombination velocities and long SHR lifetimes can be dominated by Auger recombination in the base. The open circuit voltage of PCC 86 is very close to the Auger limit.

Modeling the Collection Efficiency of PCC and IBC Solar Cells

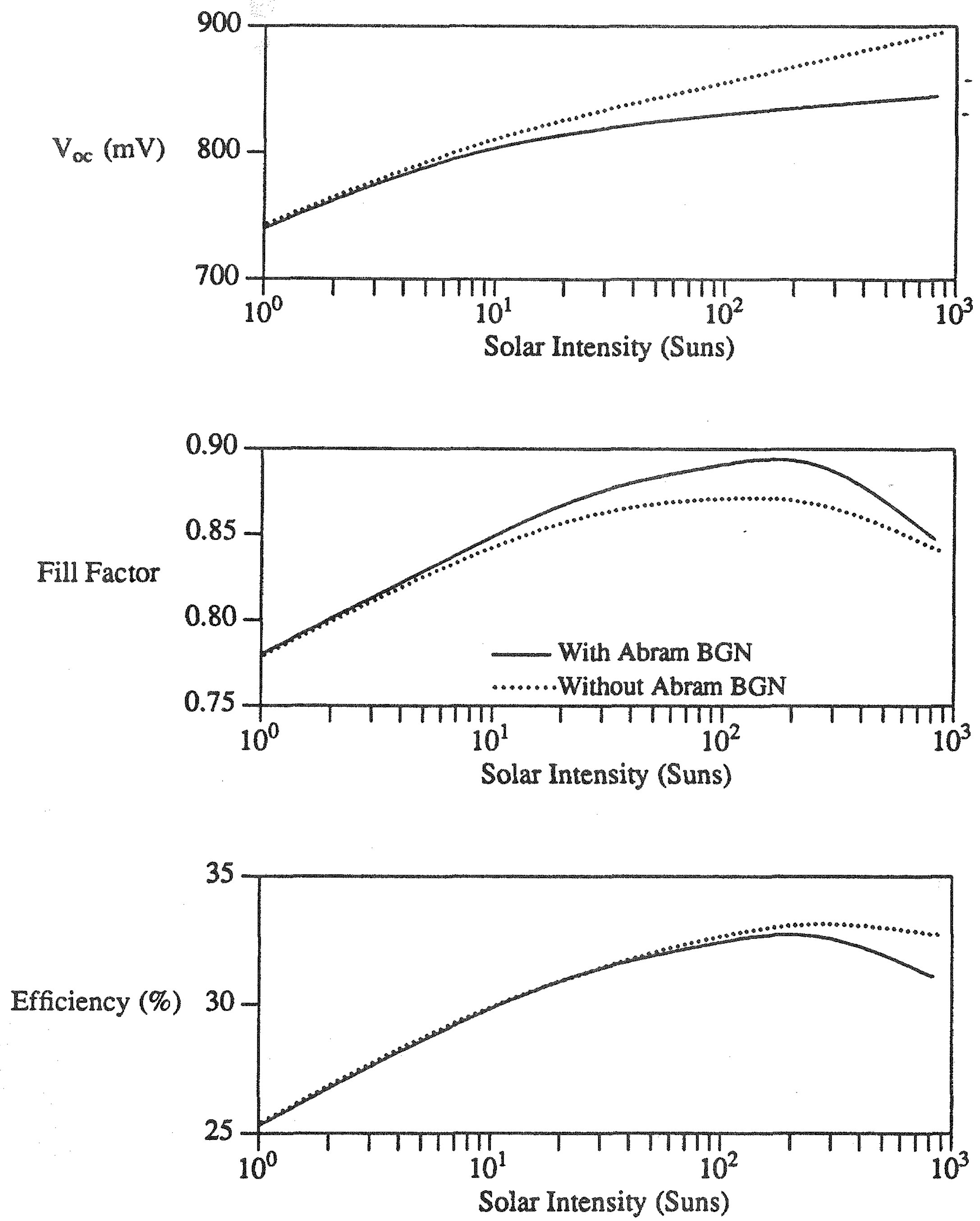


The measured sublinearity of the collection efficiency can be modeled if the minority carrier mobility is taken to be about one half the value obtained from majority carrier measurements of the mobility ($\approx 210\,cm^2/V{-}sec$ for the SCAP2D simulations above). The short circuit current is approximately given by:

$$J_{sc} = kT\mu_A \left. \frac{d\Delta n}{dx} \right|_{base}$$

where μ_A is the ambipolar mobility. If μ_A is reduced, the excess carrier concentration gradient must increase to sustain the current. The steeper gradient increases the excess carrier concentration near the illuminated surface, resulting in increased Auger recombination, and hence a degradation of the collection efficiency.

Performance Projections



The SCAP2D simulations shown above were for a 50 μm thick device with near perfect light trapping, low surface recombination, long SHR lifetimes, and minority carrier reflecting contacts.

Title: Recombination Parameters in Silicon Concentrator Cells and Computer Modelling of Solar Cells

Contractor:
Purdue University
School of Electrical Engineering
West Lafayette, IN 47907

Principal Investigator:
R.J. Schwartz

Telephone:
317-494-3536

Current Contract Number:
05-4190

Current Contract Period:
From: 9/88 **To:** 9/89

Project/Area/Task:
Crystalline Cell Research
Task 4.1 Silicon Concentrator Cells

Directing Organization:
Sandia National Laboratories

Project Engineer:
James M. Gee

Telephone:
505-844-7812

Contract History:

Number	FY	Level	Source
33-3299	1987	150,000	DOE
56-6612	1986	100,000	DOE
21-5424	1985	168,000	DOE
05-4190	1988	60,000	DOE

Objective: To improve the efficiency of silicon and GaAs concentrator cells by means of a detailed understanding of the device physics.

Approach/Present Tasks: (1) Develop free-carrier absorption (FCA) spectroscopy and advanced MOS-C techniques for measurement of recombination parameters (lifetime, surface recombination velocity, etc.) in highly injected silicon. (2) Develop and apply computer models to investigate the performance of silicon and GaAs concentrator cells.

Status/FY 1989 Accomplishments: (1) Developed technique and model for FCA spectroscopy of high-resistivity silicon for determination of lifetime and surface recombination velocity. (2) Investigated by means of computer modeling the sublinearity in Isc observed for high-resistivity silicon cells. Attributed sublinearity to mobility and bandgap-narrowing effects rather than increased Auger recombination. (3) Investigated by means of computer modeling optimized GaAs concentrator cell device structures.

FY 1989 Milestones: Apply FCA technique to highly injected silicon with various surface treatments. Extend computer modelling codes to polycrystalline silicon.

Major Project Reports:

* E.K. Banghart, J.L. Gray, and R.J. Schwartz, "The effects of high-level injection on the performance of high-intensity, high-efficiency silicon solar cells," Proc. 20th IEEE Photovoltaic Specialists Conf., Sept. 1988.
* P.D. DeMoulin and M.S. Lundstrom, "Assessment of design approaches for high-efficiency GaAs solar cells," ibid.
* F. Sanii and R.J. Schwartz, "The measurement of bulk and surface recombination by means of modulated free-carrier absorption," ibid.

Summary Date
June 1989

HIGH-EFFICIENCY SILICON CONCENTRATOR SOLAR CELLS FOR USE WITH PRISMATIC COVERS

Jerry S. Culik
Edward L. Jackson
Allen M. Barnett

AstroPower, Inc.
30 Lovett Avenue
Newark, Delaware 19711

ABSTRACT

Advanced-design silicon solar cells that are compatible with prismatic covers for operation at 20X concentration have been designed and fabricated. Our advanced-design device is based upon a micro-machined, deeply-grooved, 3-dimensional silicon structure and incorporates a dual-layer emitter, oxide surface passivation layers for front and rear surfaces, and back surface reflector light-trapping technologies. The effect of this front surface "texture" is to enhance optical absorption and improve carrier collection, which results in a significant increase in short-circuit current. Using "solar grade" Czochralski-grown silicon with a nominal resistivity of 1.3 ohm-cm, we obtained open-circuit voltages as high as 679 mV and active-area current densities of up to 38.4 mA/sq-cm. The best active-area efficiency, corrected for grid obscuration, of a half-sized, uncovered test device is 19.2% at 20 suns insolation. The best efficiency for a full-sized (50 sq-cm) solar cell with prismatic cover is 17.8%.

The performance of these solar cells is limited primarily by series resistance in the emitter and emitter contact due to the wide grid finger spacing (504 microns). In addition, the full benefit of the prismatic covers (with a facet pitch equal to the finger spacing) was not realized due to reflection from a ridge (an artifact of the grooving and metallization processes) halfway between the fingers; because of this, the short-circuit current density of the covered solar cells was reduced to about 34 mA/sq-cm. Increasing the density of front contact fingers to eliminate the center ridge, together with a matching, smaller pitch prismatic cover, will improve the fill-factor to over 80%, increase the short-circuit current to over 38 mA/sq-cm, and improve the efficiency to close to 21%. Additional improvements in this design, such as reducing the front contact recombination, together with optimization of the fabrication parameters (base resistivity, emitter characteristics, surface passivation), should increase the conversion efficiency of this solar cell design to over 22%.

DEVICE DESIGN SUMMARY

- o deeply-grooved structure produced by silicon micro-machining techniques; deep grooves (greater than 100 microns) enhance absorption, improve carrier collection, reduce base recombination.
- o direction of grooves -- parallel to the gridline fingers ("longitudinal").
- o base series resistance -- less than comparable thickness planar solar cell (effective base thickness is reduced)
- o emitter and surface passivation oxide: to enhance short-wavelength current collection, reduce surface recombination
- o front contacts -- regions under the metallization are heavily diffused: to decrease contact resistance, reduce contact recombination, reduce susceptibility to shunts
- o back surface -- P+ layer, oxide passivation layer, and grid/busbar contact: to reduce back surface and back contact recombination, to form back surface dielectric-metallic reflector
- o contact metallization -- evaporated Ti-Pd with electroplated silver conductors

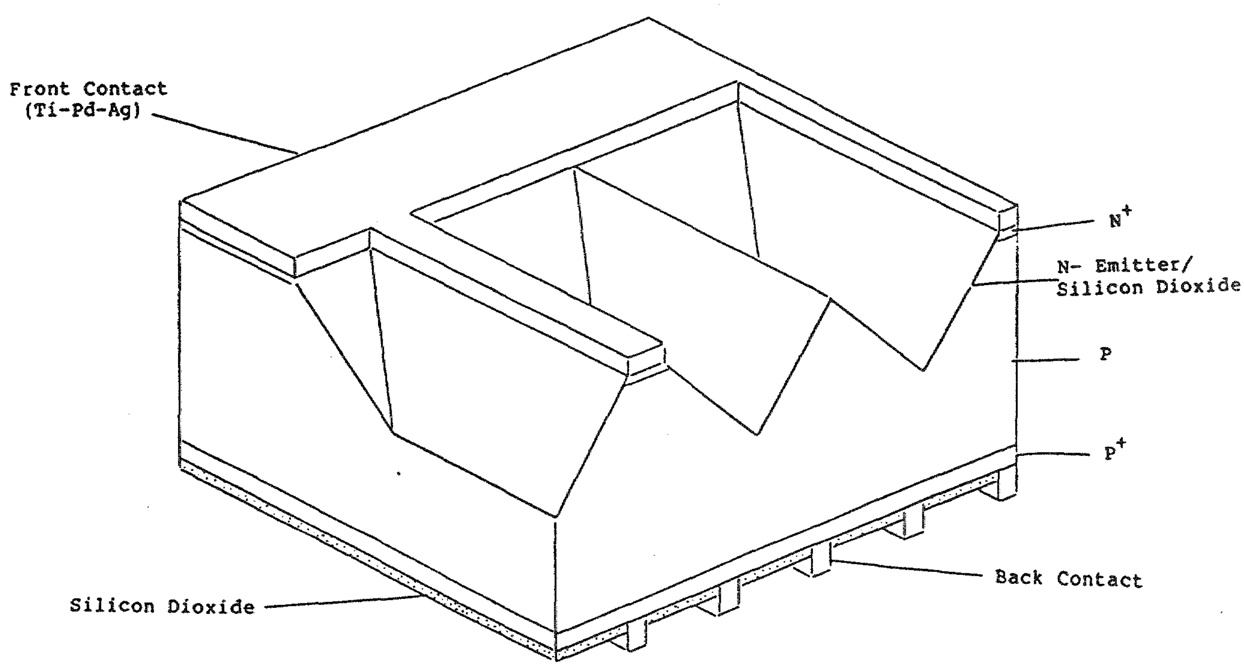


Figure: Advanced-design deep-groove silicon concentrator solar cell designed for use with prismatic covers.

Series 11: half-sized test devices

- o fabricated both longitudinal and laterally grooved devices; grooves nominally 150 microns deep; 1.3 ohm-cm CZ silicon
- o average current density (total area): 28.5 mA/sq-cm (longitudinal grooves, ARC, index matched to air, no prismatic cover, not corrected for grid obscuration)
- o best active-area current density: 38.4 mA/sq-cm (for device 11-1; assumes gridline obscuration of 24.5%, as determined by laser scans)

Table: Open-circuit voltage as a function of incident insolation

Device(type)	1 sun	10 suns	20 suns	50 suns
11-1 (LONG;ARC;IM)	596	655	670	682
11-2 (LONG;ARC;IM)	591	649	664	675
11-3 (LONG;ARC;IM)	594	651	665	677
11-4 (LAT)	584	648	666	684

- o at 1 sun, "shunted" I-V characteristic is indicative of substantial contact recombination, but open-circuit voltage is typical of 1 ohm-cm with 20-25% shading
- o at higher insolation levels, I-V characteristic is not shunted; open-circuit voltage about 670 mV at 20 suns.

Table: Fill-factor as a function of incident insolation

Device	1 sun	10 suns	20 suns	50 suns
11-1	79.9	78.3	74.7	66.8
11-2	77.9	76.3	72.4	63.9
11-3	78.2	77.3	74.6	67.0
11-4	74.7	78.6	76.5	70.7

- o behavior of fill-factor with insolation level is indicative of excess series resistance.
- o longitudinal groove: fill-factor decreases with insolation level; at 20 suns, fill-factor is less than 75%
- o lateral groove (device 11-4): best fill-factor at 10 suns, then decreases; but at 20 suns, fill-factor is still less than 77%

Full-sized concentrator solar cells (Series 12, 14, and 15)

- fabricated with longitudinal grooves; 1.3 ohm-cm CZ silicon; with ENTECH prismatic covers; measured at 20 suns insolation

Device(type)	Jsc (mA/sq-cm)	Jinc (%)	Voc (mV)	FF (%)	Eff (%)
planar:					
12-P4 (ARC)	29.4	17.6	664	75.6	14.8
12-P6 (ARC)	29.7	20.7	658	70.4	13.7
12-P9 (ARC)	30.4	20.6	663	73.4	14.8
grooved:					
12-2 (ARC)	34.0	18.9	654	72.6	16.1
12-3 (ARC)	34.1	24.9	650	70.2	15.6
12-4 (ARC)	34.0	----	654	72.7	16.1
12-6 (ARC)	34.3	----	657	64.7	14.6
12-7	34.1	18.4	671*	77.6*	17.8*
12-8	31.3	15.1	658	73.2	15.1
12-9	26.3	9.1	658	76.5	13.2
14-2	33.2	12.9	650	54.5	11.8
14-3 (Tex bottom)	35.7*	22.3	640	49.0	11.2
14-4 (Tex bottom)	32.6	16.0	668	63.6	13.8
14-5	23.1	-5.3	662	68.9	10.5
14-6	31.2	16.4	669	68.0	14.2
texture-etched; no grooves:					
15-1	34.6	23.1	654	51.5	11.6
15-3	33.2	27.7	658	61.3	13.4
15-4	32.8	29.6*	667	68.9	15.0
15-5	34.7	29.0	658	64.0	14.6

- the increase in current with the prismatic cover for the grooved devices is less than the grid obscuration (at least 20%) and less than that of devices with no center ridge (series 15)

- typical Jsc (planar-surface, AR-coated): 30 mA/sq-cm.
  (texture-etched, with no ARC): 33-35 mA/sq-cm
  (grooved, w or w/o ARC): 34-36 mA/sq-cm

- best open-circuit voltage, 671 mV (device 12-7, a deeply-grooved cell)

- best current density: 35.7 mA/sq-cm (device 14-3, deeply-grooved, textured groove bottom)

- best fill-factor at concentration, 77.6% (device 12-7, which has a considerable amount of metal on the center ridge)

- best efficiency at concentration, 17.8% (also device 12-7)

CONCLUSIONS

- deep longitudinal grooving is compatible with prismatic covers, but the full benefit of the covers is not realized when a center ridge is present

- deep grooving is "do-able", even for large-area devices

- there are significant benefits to deep grooving: enhanced optical absorption; reduced sensitivity to lifetime; increased tolerance to fab processes (high temp, ARC)

- obtained better than 38 mA/sq-cm using "solar grade" CZ silicon with unoptimized processing

- best full-size (50 sq-cm) covered device: 17.8% at 20 suns insolation; performance limited by low fill-factor (75%) due to series resistance (emitter, contact) and by ridge obscuration

RECOMMENDATIONS

- decrease gridline finger spacing; use matching cover -- efficiency increases to 20.4%:

  Jsc increases to 38 mA/sq-cm; new pattern: 50-micron wide grid fingers on 254-micron centers, no center ridge

  FF increases to 80%; series resistance losses reduced to less than 2% (present, greater than 5%); greatly reduced sensitivity to sheet resistance and specific contact resistivity

  additional processing benefits: higher finger density would eliminate center ridge and simplify photolith process; minimum linewidth increases to width of gridline; mask cost and sensitivity of mask to defects is reduced; greatly widened process windows for diffusion and metallization

- reduce the base resistivity -- efficiency, 21.6%

  reducing the base resistivity to 0.7 ohm-cm (nominal) should increase Voc to over 700 mV (presently getting over 670 mV with 1.3 ohm-cm) and further reduces base series resistance; fill-factor increases to 81%; the deep-grooved solar cell design is able to compensate for decrease in lifetime associated with low resistivity

- reduce contact recombination -- efficiency, >22%

  isolate busbar from emitter surface (will eliminate 12% contact area); reduced-area emitter contacts (from present 16% coverage to less than 5%); increases Voc to 720 mV

Title: High-Efficiency Si Concentrator Cells for Use with Prismatic Covers

Contractor:
Astrosystems, Inc.
AstroPower Division
30 Lovett Ave.
Newark, DE 19711

Principal Investigator:
Jerry Culik

Telephone:
(302) 366-0400

Current Contract Number:
75-0562

Current Contract Period:
From: 9/88 **To:** 3/89

Project/Area/Task:
Crystalline Cell Research
Task 4.1 Concentrator Silicon Cells

Directing Organization:
Sandia National Laboratories

Project Engineer:
Paul A. Basore

Telephone:
(505) 846-4516

Contract History:

Number	FY	Level	Source
75-0562	1988	$45,300	DOE

Objective: This contract supports the development of high-efficiency silicon solar cells for operation at 22X geometric concentration. These cells should have an active area efficiency of 21.5%, which will insure an illuminated-area efficiency of over 20.4% after application of prismatic covers.

Approach/Present Tasks: AstroPower's approach is based on the use of very deep (140 μm) V-shaped grooves parallel to the gridlines.

Status/FY 1989 Accomplishments: 20 full-sized cells were delivered, with an average active-area efficiency of 15.8%. After application of prismatic covers by ENTECH, the average efficiency was 14%. The two primary performance-limiting factors in these cells are the inability to fully remove metal during lift-off from the V-groove peaks that lie between the gridlines, and the high emitter series resistance due to the long path for current flow to the nearest gridline. Both problems can be essentially eliminated by switching to a gridline spacing less than 250 μm, compared to the current 510-μm spacing.

FY 1989 Milestones: Correct and publish final report.

Major Project Reports:
None

Summary Date
June 1989

SILICON CELL RESEARCH FOR 22X AND 160X CONCENTRATION

by
Jerry Silver

Solarex Aerospace Division
1335 Piccard Drive
Rockville, Maryland 20850

ABSTRACT

Solarex has been working on the development of manufacturable, silicon concentrator cells for two different focussing systems and concentration levels. The cells for both programs use heavily metallized front contacts combined with prismatic covers to steer light into the cell active area.

22 Sun Linear Focus Cells

Solarex developed a 38.4 cm^2 solar cell designed for operation in a 22 sun linear fresnel lens concentrator module produced by Entech, Inc. and intended for use in the PVUSA EMT-1 project. The best cell achieved 20.2% efficiency at 20 suns which we believe is the highest concentrator cell of this size produced as of this writing. The cells were fabricated using randomly textured fronts, dual layer anti-reflection coatings, passivated emitters, and reduced emitter/metallization contact areas.

Although these cells fell short of the overall program goal of 20.4% efficiency, they represent a substantial improvement over the 19% average covered cell efficiency for the same size cells produced for the 300 kW Entech/Austin program.

160 Sun Point Focus Cells

Development efforts for this program have focussed on using a deep heavily doped diffused region to reduce the effects of recombination under the gridlines. The surface concentration of the emitter, produced by a separate diffusion step, was then reduced without increasing contact resistance losses. A long, high-temperature step was used to grow a thin passivating oxide and to deepen the emitter. Initial phosphorus deposition was optimized to produce the requried sheet resistivity after the oxidation and drive-in.

Electrical shorts between the busbars and substrate dominated the 1 sun characteristics of the first cells produced this way. Three independant shorting mechanisms were identified and eliminated using infrared imaging. Open circuit voltages above 760mV and fill factors above .81 were measured on covered cells at 150 suns.

Evaluation of performance of covered cells in comparison with expectations was complicated by an overestimation of uncovered cell short circuit current densities based on apparent gridline shadowing. LBIC scans are presently being used to identify possible reflection of incident light from gridlines into the active area of uncovered cells and to analyze non-uniformities in current generation across covered cells.

The highest efficiency measured to date on a covered cell was 21.46%.

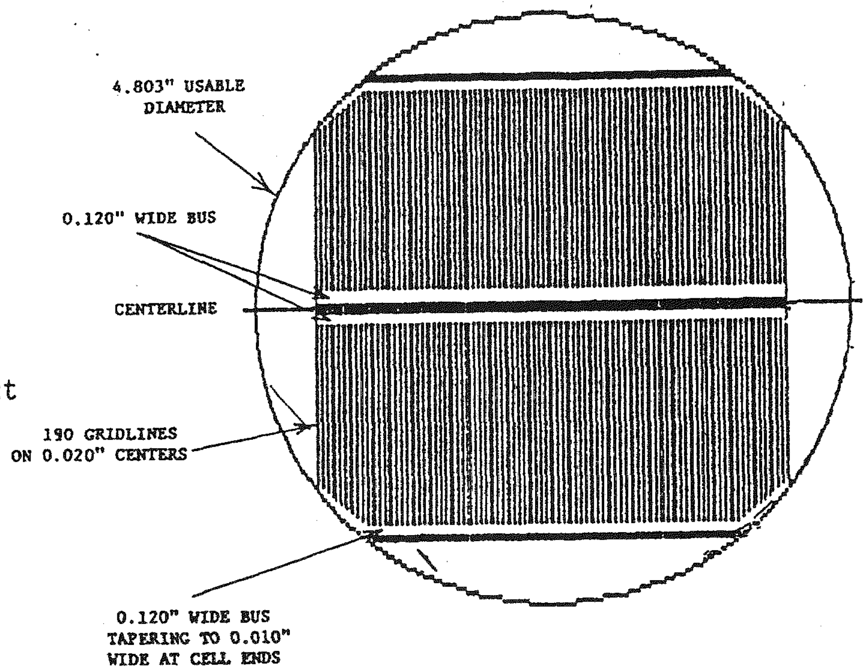


Fig. 1

22x cell layout on wafer

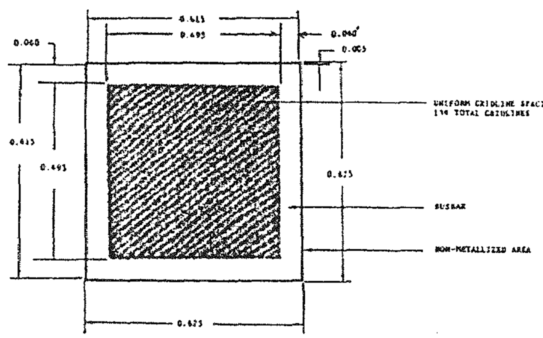


Fig. 2

160x cell

Fig. 3

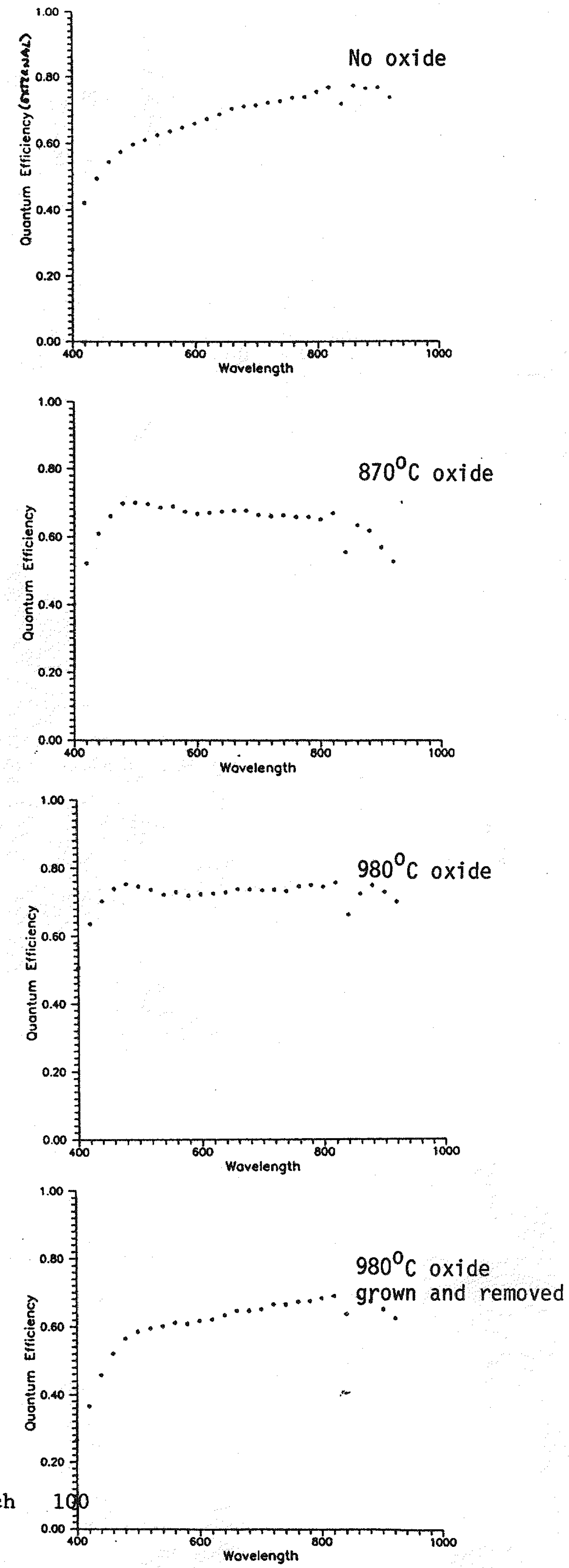

No oxide
Quantum Efficiency
Wavelength
870°C oxide
Quantum Efficiency
Wavelength
980°C oxide
Quantum Efficiency
Wavelength
980°C oxide
grown and removed
Quantum Efficiency
Wavelength

Fig. 4

EFFICIENCY VS CONCENTRATION (22x cells)

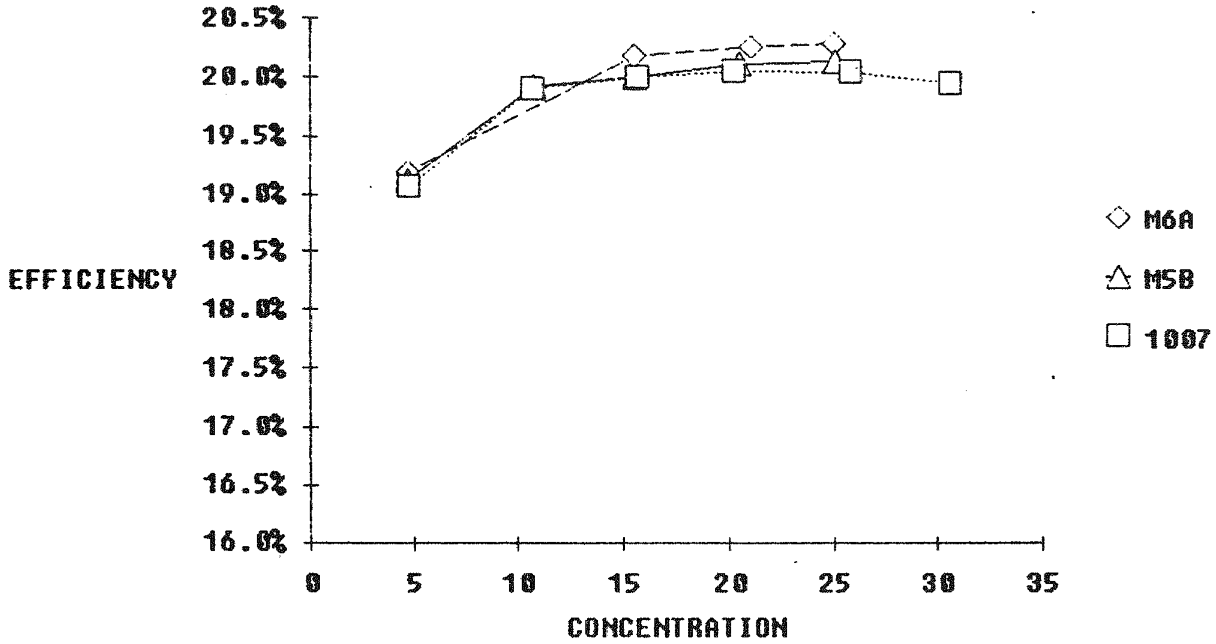


Fig. 5

EFF @ 20 SUNS VS FF (22x cells)

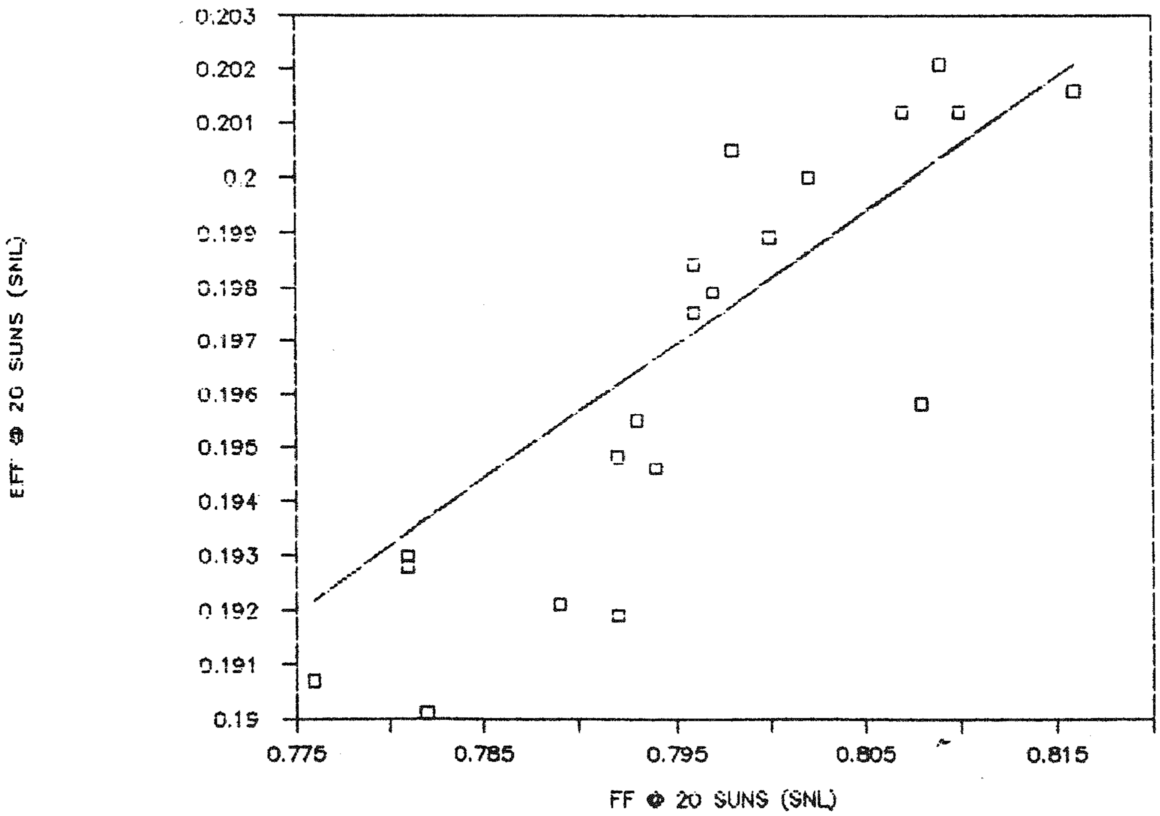


Fig. 6

Infrared images.
160x cells. Reverse bias.

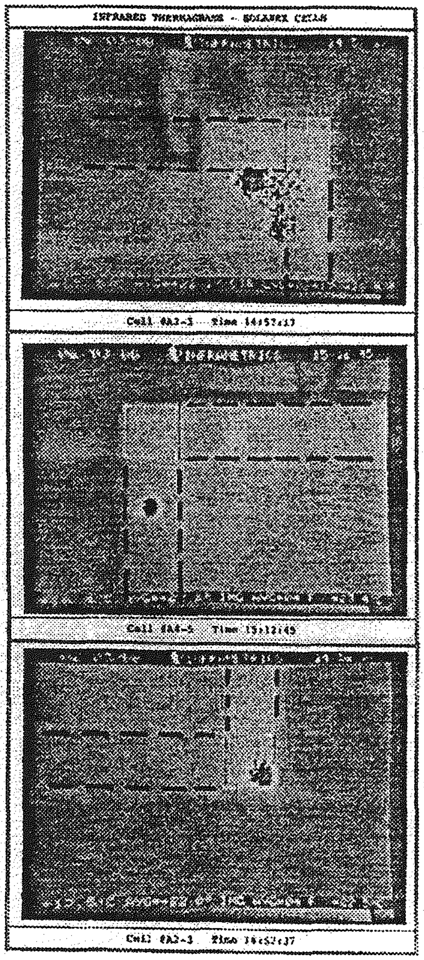
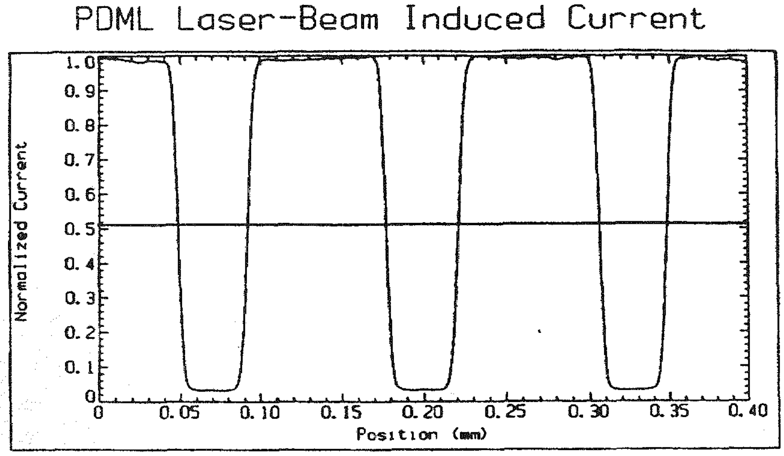
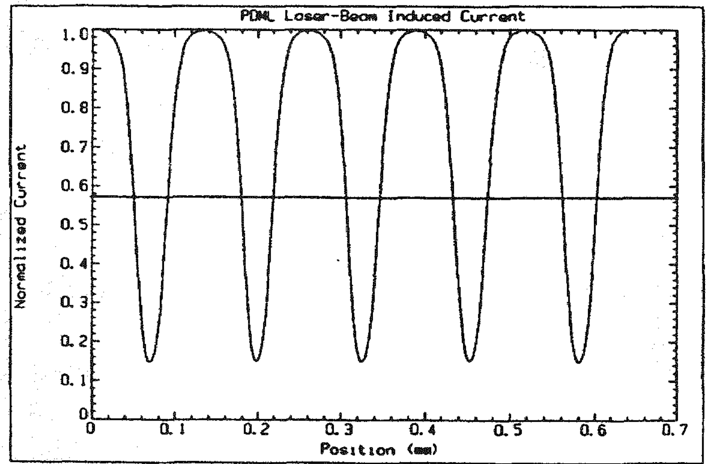


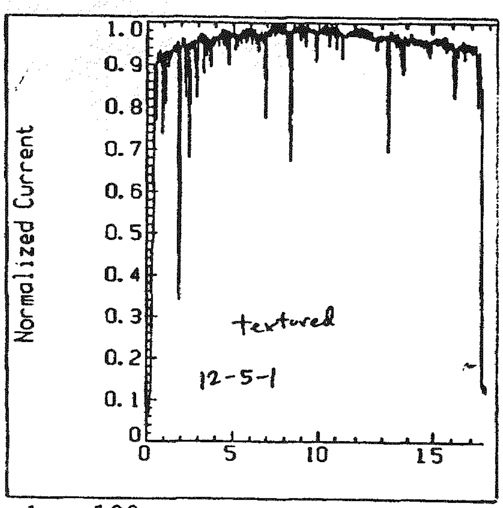
Fig. 7 160x cells



Data for Sample: Solarex 12-7-1 textured laser - 33.6%
Collected 4 MAR 89 at 1:57:08p m'scope - 34.4%
632.8 nm laser, 5 um spot size, 1.0 um step size



Data for Sample: solarex b2-5, area 1, scan 2 Shading = 31% - laser
Collected 25 MAY 89 at 10:42:14a
632.8 nm laser, 5 um spot size, 1.0 um step size 43.8% - m'scope



Title: Development of 20.4% Silicon Cells for a 22X Line-Focus Module

Contractor:
Solarex Aerospace Division
1335 Piccard Drive
Rockville, MD 20850

Principal Investigator:
Jerald R. Silver
Telephone:
(301)670-7269
Current Contract Number:
05-2557
Current Contract Period:
From: 9/88 **To:** 3/89
Project/Area/Task:
Crystalline Cell Research
Task 4.1 Concentrator Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
Douglas S. Ruby
Telephone:
(505)844-0317
Contract History:

Number	FY	Level	Source
05-2557	1988	$49,693	DOE

Objective: To enable a commercial cell supplier to demonstrate the capability to fabricate 38 cm^2 cells in a production environment with an active area efficiency of at least 21.5%. This will insure an illuminated area efficiency of over 20.4% at 20 suns and 25°C after application of prism covers that steer light away from the gridlines. These cells will then be considered available in the quantities needed to populate 20kW of 22X line-focus concentrator modules produced by Entech Corp. for the PVUSA EMT-1 project.

Approach/Present Tasks: Tradeoffs between cell thickness, bulk resistivity, and carrier lifetimes were measured and guided by computer modelling results. Improvements to surface texturing were employed, including pyramid rounding and alternate etchant sources. Various gridline coverages and back surface treatments were evaluated. Emitter diffusion profiles, concentrations, and patterns were optimized.

Status/FY 1989 Accomplishments: 84 concentrator cells were delivered to Sandia for testing. It was decided to send 29 cells to ENTECH, where they would have copper interconnects soldered to them to alleviate a measurement problem. These are the same interconnects that are attached when the cells are incorporated into a module. Prism covers were applied to these cells to remove any uncertainty about the precision to which the active area was known. The cells' performance was measured both at ENTECH and at Sandia. The lot's average efficiency measured at ENTECH was 20.3%, while Sandia measured 19.6%. These cells perform about 1.5 percentage points better than those used in ENTECH's 3M/Austin project. These results were communicated to PG&E, which then approved ENTECH's contract to build a 20-kW concentrator array for the PVUSA EMT-1 program.

Summary Date
June 1989

Title: High-Efficiency, Cost-Effective Silicon Concentrator Solar Cell

Contractor:
Solarex Aerospace Division
1335 Piccard Drive
Rockville, MD 20850

Principal Investigator:
Jerald R. Silver
Telephone:
(301)670-7269
Current Contract Number:
02-7063D
Current Contract Period:
From: 6/87 **To:** 07/89
Project/Area/Task:
Crystalline Cell Research
Task 4.1 Concentrator Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
Douglas S. Ruby
Telephone:
(505)844-0317
Contract History:

Number	FY	Level	Source
02-7063D	1987	$170,024	DOE
02-7063D	1989	29,706	DOE

Objective: To improve the performance of a 160X cell with a large grid coverage fraction by reducing its front and rear surface recombination. The cell is to be used in conjunction with a prism cover which redirects incident light between the cell's gridlines.

Approach/Present Tasks: To use thermally grown oxide masks to reduce the contact area between gridlines and the cell. Double front surface diffusions will be done to further reduce the recombination occurring near the gridline contacts. Rear surface aluminum alloying is used to effectively passivate the back surface.

Status/FY 1989 Accomplishments: Covered cells have been delivered with efficiencies of upto 21.5% measured at 150 suns and 25^{o}C and one-sun short circuit current densities of 36 mA/cm^{2}.

Major Project Reports:

- Shea, S.P.; Wohlgemuth, J.H.; Silver, J.R., "Fundamental Parameter Measurements of High-Efficiency Single Crystal Silicon Concentrator Cells." Conference Record of the 20th IEEE Photovoltaic Specialists Conference, Sept. 26-30, 1988; Las Vegas, NV.

- Silver, J. (July 1988). "Concentrator Silicon Cell Research." Joint Crystalline Cell Research and Concentrating Collector Projects Review, July 19-21, 1988; Albuquerque, New Mexico. SAND88-0522, pp. 207-214 and p. 300.

Summary Date
June 1989

CONCENTRATOR SILICON SOLAR CELL RESEARCH

University of New South Wales
Kensington, Australia 2033

Principal Investigator: Martin A. Green

1. <u>Objectives</u>

This project seeks to improve silicon concentrator cell performance by combining relatively conventional bifacially contacted cell structures with prismatic covers as shown in Figure 1.

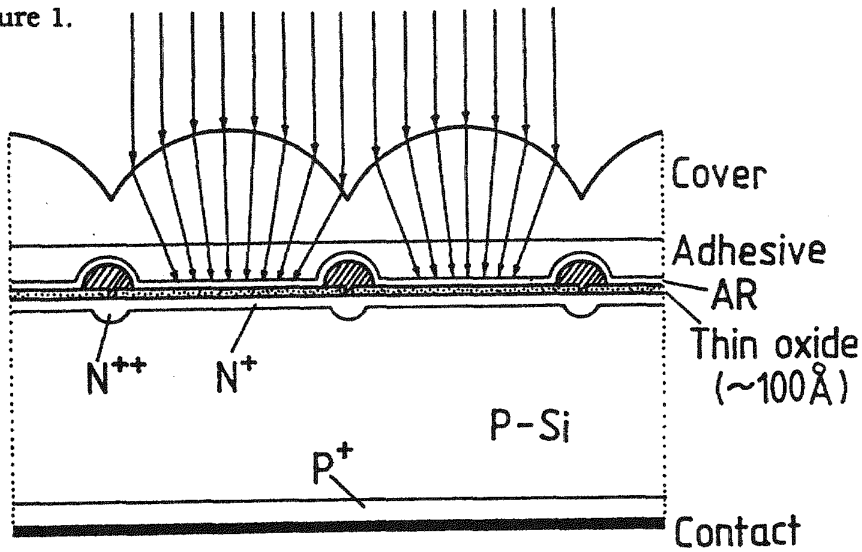


Figure 1: Silicon prismatic cover solar cell.

2. <u>Results to Date</u>

Several hundred solar cells with the metallization pattern of Figure 2 have been supplied to Sandia for use in experimental modules. After application of prismatic covers, efficiency up to 25.2% has been demonstrated for the design concentration level in the 100-150 suns range.

Devices of about 24% efficiency at such concentration levels have demonstrated combined lens/cell efficiencies in the 20-21% range both at Sandia and Entech.

More recently, 12 such cells have been incorporated into the Sandia Experimental Module (D. Arvizu, Conf. Record, 17th IEEE Photovoltaic Specialists Conf., 1984, p. 805). Resulting module efficiency was 20.4% referenced to 800 W/m^2 illumination intensity and 25°C cell temperature. This is believed to be the first photovoltaic module ever to break the 20% efficiency barrier. With recent developments in silicon, GaAs and tandem solar cells, this achievement should become commonplace in the future.

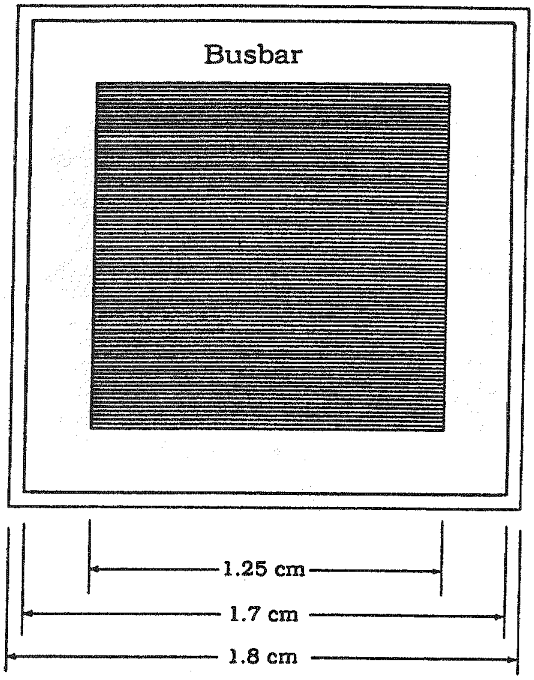


Figure 2: Cell metallization pattern.

4. Future Improvements

The cells responsible for this improved performance had the passivated emitter solar cell structure (PESC) structure of Figure 3.

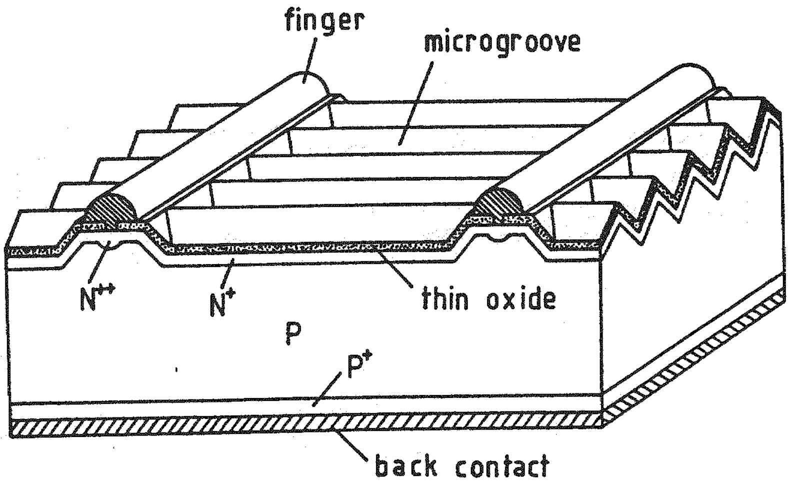


Figure 3: PESC cell

Recent improvements in one-sun silicon solar cell performance have been demonstrated with a passivated emitter and rear cell structure (PERC structure) described elsewhere in these proceedings. Current work is directed at adapting this structure for concentrator cells. An efficiency improvement of approximately 10% relative is expected over the creditable performance levels already established.

Title: Concentrator Silicon Cell Research

Contractor:
University of New South Wales
School of Elect. Engineering
P.O. Box 1
Kensington, New South Wales
Australia 2033

Principal Investigator:
Martin A. Green

Telephone:
(612) 697-4018 (Australia)

Current Contract Number:
40-6845

Current Contract Period:
From: 1/89 **To:** 8/90

Project/Area/Task:
Crystalline Cell Research
Task 4.1 Concentrator Silicon

Directing Organization:
Sandia National Laboratories

Project Engineer:
David L. King

Telephone:
(505) 844-8220

Contract History:

Number	FY	Level	Source
64-7134	1985	$104,000	DOE
64-7134	1986	19,971	DOE
01-8551	1986	138,758	DOE
01-8551	1987	22,101	DOE
57-6486	1988	143,823	DOE
40-6845	1989	149,597	DOE

Objective: The objective of this activity is to continue the development and improvement of both low and high resistivity Si concentrator cells.

Approach/Present Tasks: (1) Optimization of baseline low resistivity silicon concentrator cell technology with emphasis on rear surface passivation and cell thinning. (2) Continue development of concentrator cells with n-type bases. N-type bases have potential for higher performance due to reduced bulk resistance due to relatively higher electron mobility, to reduced sublinearity effects, and simplified rear surface passivation compared to cells with p-type bases. (3) Fabricate high efficiency concentrator cells for use in experimental Sandia concentrator modules. The efficiency goal is 26 to 27% at concentrations of 150 to 400 suns.

Status/FY 1989 Accomplishments: (1) Fabricated and supplied a sufficient number of module-ready 1.58-cm^2 silicon cells with efficiencies between 24 and 25% for Sandia to demonstrate a 20% concentrator module efficiency. (2) Adapting the new PERC cell processing technology to concentrator cells. (3) Laser-grooved silicon cells are being optimized for use at low concentration levels as part of separate UNSW one-sun silicon cell research contract.

FY 1990 Milestones: Complete tasks defined and published final report.

Major Project Reports:

- Green, M.A., et al, "High Efficiency Silicon Concentrator Solar Cell Research," Sandia Contractor Report. Work performed by University of New South Wales. To be published.
- Green, M.A., et al (Sept. 1988). "Silicon Concentrator Solar Cell Research." SAND88-7032. Sandia Contractor Report. Work performed by University of New South Wales, Kensington, Australia.
- Zhao, J. et al, "High Efficiency Prismatic Cover Silicon Concentrator Solar Cells," Proc. 20th IEEE PV Specialists Conf., Las Vegas, NV, Sept. 1988.

Summary Date
June 1989

Title: Silicon Concentrator Solar Cell Development

Contractor:
University of New South Wales
School of Electrical Engineering
P.O.Box 1
Kensington, New South Wales
Australia

Principal Investigator: M. Green

Telephone: 9-011-612-697-4018

Current Contract Number: 06-6885

Current Contract Period:
From: 8/10/87 **To:** 1/10/89

Project/Area/Task:
Photovoltaic Technology Project
Task 6.1: Concentrator Module Research

Directing Organization:
Sandia National Laboratories

Project Engineer: A. B. Maish

Telephone: 505-844-8771

Contract History:

Number	FY	Level	Source
06-6885	87	51,910	DOE
06-6885	87	13,842	DOE

Objective:
Fabricate and deliver bifacially-contacted, low-resistivity cells for use in the Sandia Baseline Module and the Black & Veatch module.

Approach/Present Tasks:
* Optimize the cell design for peak performance when used with a 200X geometric concentration optical system, including a prismatic cover.
* Fabricate masks and deliver 100 dummy cells for mechanical assembly, 150 electrically active cells for qualification testing, and 300 electrically active cells of high peak efficiency for use in module fabrication.

Status/FY 1989 Accomplishments:
* The remainder of the cells were delivered as per the contract specifications. Most of the cells exhibited peak efficiencies in the 22-24% range. A peak cell efficiency of 25% was achieved.
* A draft final report was delivered.

Major Project Reports:
Silicon Concentrator Solar Cell Development

Summary Date
June 1989

Title: Advanced Si Concentrator Cells

Contractor:
M/A-COM PHI, Inc.
1742 Crenshaw Blvd.
Torrance, CA 90501

Principal Investigator:
Sewang Yoon
Telephone:
(213) 320-6160
Current Contract Number:
02-7063B
Current Contract Period:
From: 6/87 **To:** 9/89
Project/Area/Task:
Crystalline Cell Research
Task 4 Concentrator Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
David L. King
Telephone:
(505) 844-8220
Contract History:

Number	FY	Level	Source
02-7063B	1987	$162,726	DOE

Objective: The objective of this activity is to develop a 1.56 cm^2 module-ready, high resistivity, thin, silicon concentrator cell for use in the concentration range of 100 to 200 suns.

Approach/Present Tasks: (1) Develop the processing technology to produce large area (1.56 cm^2) interdigitated-back-contact (IBC) silicon solar cells using thin, high resistivity silicon. Extend this technology to incorporate a double layer metallization scheme that will allow conventional cell mounting techniques to be used. (2) Continue the development of the thin, high resistivity, polysilicon emitter, back junction cell previously demonstrated by M/A-COM PHI.

Status/FY 1989 Accomplishments: Contract initiated and experimental (small area) cells of both types have demonstrated good one-sun performance (19%) with short circuit current densities near 40 mA/cm^2. Functional large area (1.56 cm^2) cells have been fabricated with double layer rear metallization that have achieved near 17% at one-sun. Performance at concentration has currently been limited by series resistance and surface recombination.

FY 1989 Milestones: (1) Complete contract activities and publish final report. (2) Contract goal is to achieve greater than 20% one-sun efficiency and greater than 25% efficiency at 100X concentration.

Major Project Reports: None

Summary Date
June 1989

Title: Development of a Point-Contact IBC Solar Cell

Contractor:
SERA Solar Corporation
3151 Jay Street
Santa Clara, CA 95054

Principal Investigator:
Gary E. Miner
Telephone:
(408)727-3747
Current Contract Number:
02-7063C
Current Contract Period:
From: 6/87 **To:** 10/88
Project/Area/Task:
Crystalline Cell Research
Task 4.1 Concentrator Silicon

Directing Organization:
Sandia National Laboratories
Project Engineer:
Douglas S. Ruby
Telephone:
(505)844-0317
Contract History:

Number	FY	Level	Source
02-7063C	1987	$220,211	DOE

Objective: To investigate the possibility of producing solar cells of the record efficiency point contact design using techniques and facilities that are more consistent with the industrial environment.

Approach/Present Tasks: Use of selective area wafer thinning techniques, whole wafer thinning techniques, thin wafer handling studies, lifetime-enhancing phosphorus gettering process for Czochralski-silicon wafers, optical confinement structures, and doped-oxide diffusion sources.

Status/FY 1989 Accomplishments: IBC cells were produced on wafers that were selectively thinned only in the small regions that contained the cells. This has allowed processing using mass production techniques and the facilities of an integrated circuits manufacturer. Although this environment was not well-suited for the type of high-lifetime processing performed, excellent cell-performance results were obtained. The best cell achieved an efficiency of 25% at a concentration of 86 suns. Other cells upto 0.661 cm^2 in area demonstrated very high short-circuit current densities of 41 mA/cm^2/sun. These cells were limited by the interdigitated back contact metallization resistance, and would perform even better with thicker metal gridlines or a double-layered metal structure.

Major Project Reports:

• Miner, G.E.; Christel, L.A. (1988). "High-Volume Processing of Point-Contact Solar Cells." Conference Record of the 20th IEEE Photovoltaic Specialists Conference-1988, Sept. 26-30, 1988; Las Vegas, Nevada.

Summary Date
June 1989

Title: Development of Concentrator Cell Evaluation Procedures

Contractor:
Arizona State University
College of Engineering and Applied Sciences
Tempe, AZ 85287

Principal Investigator:
D.K. Schroder and C.E. Backus

Telephone:
602-965-1725

Current Contract Number:
33-1525

Current Contract Period:
From: 4/87 **To:** 10/88

Project/Area/Task:
Crystalline Cell Research
Task 4.1 Silicon Concentrator Cells

Directing Organization:
Sandia National Laboratories

Project Engineer: James M. Gee

Telephone: 505-844-7812

Contract History:

Number	FY	Level	Source
33-1525	1987	99,000	DOE
56-5346	1986	100,000	DOE
21-3452	1985	83,000	DOE

Objective: Investigate the behavior of silicon and GaAs concentrator cells when operated under high intensities.

Approach/Present Tasks: (1) Provide an independent testing capability for high-intensity outdoor testing. (2) Measure the recombination parameters of silicon solar cells while operated under high concentration. (3) Measure the responsivity of silicon and GaAs concentrator cells at high intensities.

Status/FY 1989 Accomplishments: (1) Have measured the small-signal open-circuit voltage decay of various silicon concentrator cells with high intensity light bias. (2) Have developed a theory to account for their measurements. (3) Have investigated temperature effects on their white-light response responsivity measurement technique, and have measured the responsivity (Isc/irradiance) of GaAs concentrator cells for irradiances up to 1000 suns.

FY 1989 Milestones: Complete final report.

Major Project Reports:

K. Joardar, D.K. Schroder, C.E. Backus, "Investigation of effective minority-carrier lifetime degradation in silicon concentrator solar cells," Proc. 20th IEEE Photovoltaic Specialists Conf., Las Vegas, NV, Sept. 1988.

Summary Date
October 1988

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Concentrating Collectors

1989 DOE/ Sandia
Crystalline Photovoltaic Technology Project Review Meeting

July 11-13, 1989

Marriott Hotel
Albuquerque, New Mexico

EPRI HIGH-CONCENTRATION PHOTOVOLTAIC PROGRAM

Presentation by

Frank Dostalek

Project Manager
Solar Power Program

Outline

- Program Objective
- Component Development
- Module Development
- Array Development
- Test Program
- Program Plan

Program Objective

To sponsor basic research and development in the field of high-concentration photovoltaics and to apply this technology through the development of high-concentration PV modules, arrays and systems for the purpose of commercial use in power generation applications in the United States and abroad.

Component Development

Cell Development:

- Stanford University is doing the research on high-concentration point-contact (HCPC) PV cells for EPRI and achieved the highest recorded efficiency (28.5%) on silicon PV cells.

- Stanford developed a 1 cm x 1 cm HCPC PV cell design for EPRI use in a high-concentration module.

- The Stanford technology was transferred to Acrian, Inc., San Jose, CA in 1986 where manufacturing feasibility was demonstrated in a pilot manufacturing environment. Acrian supplied pre-production prototype cells for the EPRI HCPC PV program from June 1987 through October 1988.

- Acrian discovered in late 1987 that the cell performance degrades when exposed to UV light.

- Stanford has been working on the degradation problem and identification of the mechanism and a solution are at at hand. Delivery of stable cells for EPRI evaluation is scheduled for later in 1989.

- Cell procurement contracts are being negotiated with two companies for future EPRI field testing and demonstration program needs.

Cell Package and Lens Development:

- Black & Veatch, Engineers-Architects (B&V) did preliminary design studies on PV systems and components from 1982 to 1987. They developed designs for the cell package and the primary concentrator and secondary optics. Their cell package design was used as the baseline for the EPRI cell package work at Acrian, Inc.

- Acrian developed a cell mounting technique using a modified B&V cell mounting package design.

- Cummings Engineering, Wilmington, MA, continues the cell package development with design and cost improvements targets.

- Fresnel Optics, Inc., Rochester, NY, supplies 500X Fresnel lens parquet prototypes that were developed by B&V. Current work involves process improvements for better performance and lower cost.

Module Development

- Cummings Engineering was placed under contract by EPRI in 1986 to design and build HCPC PV modules starting with the B&V design as a baseline and developing the design into a prototype.

- Module Design Approach:

  Mod 0 Black & Veatch baseline design

  Mod 1 Provided a test bed for lens, PV cell and cell package performance evaluation.

  Mod 2 Takes into consideration manufacturability and cost.

Unit Configuration Mod 1 and Mod 2	Technical Problems Addressed	
- Form Fit	Fit of Parts Stiffness	Weatherability Leakage
- Thermal	Thermal Performance	Weatherability
- Optical	Lens Performance	
- Electrical	Electrical Function Degradation Weatherability	Off-axis Performance Shading Performance Efficiency Power Production

- Module Deployment:

	Mod 1 Quan.	Date Deployed	Mod 2 Quan.	Date Deployed
- Form Fit	1	Apr 87	1	Mar 89
- Thermal	1	Jun 87	1	Dec 88
			60	May 89 (thermal array)
- Optical	1	Sep 87	-	
- Electrical				
Unit 1	1	Nov 87	-	
Unit 2	1	Jan 89	-	

- Module Performance:

Mod 1 Electrical Prototype No. 1 was initially deployed at Georgia Power Company's (GPC) Shenandoah Solar Center, Newnan, GA. This module had a 10% efficiency and produced an average 115 watts under normal operating condition (850 w/sq.m, 70 deg.F ambient). This module is now in operation at PG&E's, San Ramon, CA test facility.

Mod 1 Electrical Prototype No. 2, initially deployed at GPC reached an efficiency of 18.3% and produced 238 watts under normal operating condition.

Unit 2 power output is within 50 watts of 287 watts specified by Black and Veatch in the EPRI report no. AP-4752, High Concentration Module Design (Aug 1986).

Array Development

- B&V, in their system studies done for EPRI, developed a design approach for a high-concentration PV array. This array design was used as the baseline for the EPRI array program.

- EPRI issued an RFP in September 1987 for the Design, Construction and Deployment of a High-Concentration Array. Scientific Analysis, Inc., (SAI) Montgomery, AL, and Bechtel Group, San Francisco, CA, were selected to submit preliminary array designs. In June 1988, SAI was selected to construct the first prototype high-concentration array.

- Advanced Thermal Systems, Inc., Englewood, CO, was contracted by EPRI to procure and install ARCO Solar trackers and control systems for the first two prototype arrays. The trackers were installed at GPC and have been operating since December 1988.

- Due to a shortage of PV cells, the decision was made to, first, build a thermal array to evaluate the thermal and optical behavior of the array and to determine how well the structure flatness and pointing accuracy could be maintained. When cells become available, a prototype electrical array will be built and deployed in 1990.

- SAI began construction of the Prototype Thermal Array structure in January 1989. The Thermal Array was completed on May 8, 1989. Preliminary test results indicate that temperature gradients and tracking accuracy will not be a problem.

EPRI Solar Test Program

- Cell Testing:

  Stanford Solar Test Facility, Palo Alto, CA - Cell Testing capability is set up at the Stanford Roof Top Solar Test Facility and is done in sunlight using a heliostat and concentrating parabolic collector.

  Acrian Solar Test Facility, San Jose, CA - Acrian established limited testing capability using a Kratos solar simulator and other environmental cycling capability. The Acrian test capability was transferred to Daedalus, Inc., Mountain View, CA, in December 1988, and is being improved for future program use.

  DSET Laboratories, Phoenix, AZ Cell environmental and degradation studies are now being conducted. Long-term study of Acrylic materials degradation are also underway.

- Cell Package Testing:

  Sonoscan, Bensenville, IL Solder bond integrity is being studied using acoustic microscopy techniques developed by Sonoscan.

  Daedalus, Inc., Mountain View, CA Environmental cycling is being carried out to verify cell package lifetime.

  Ford Aerospace & Communications Corp., Palo Alto, CA - Flexture and fatigue testing was carried out on samples to verify mechanical strength of the solder bonds.

- Utility Field Testing:

  Arizona Public Service Co., Tempe, AZ

  - Mod 1 Thermal Module
  - Mod 2 Thermal Module

  Georgia Power Co., Newnan, GA

  - Mod 1 Electrical Unit No. 2
  - Prototype Thermal Array

  Pacific Gas & Electric Co., San Ramon, CA

  - Mod 1 Electrical Unit No. 1

- Other Test Sites:

  Cummings Engineering, Wilmington, MA

  - Mod 1 Form Fit Module
  - Mod 2 Form Fit Module

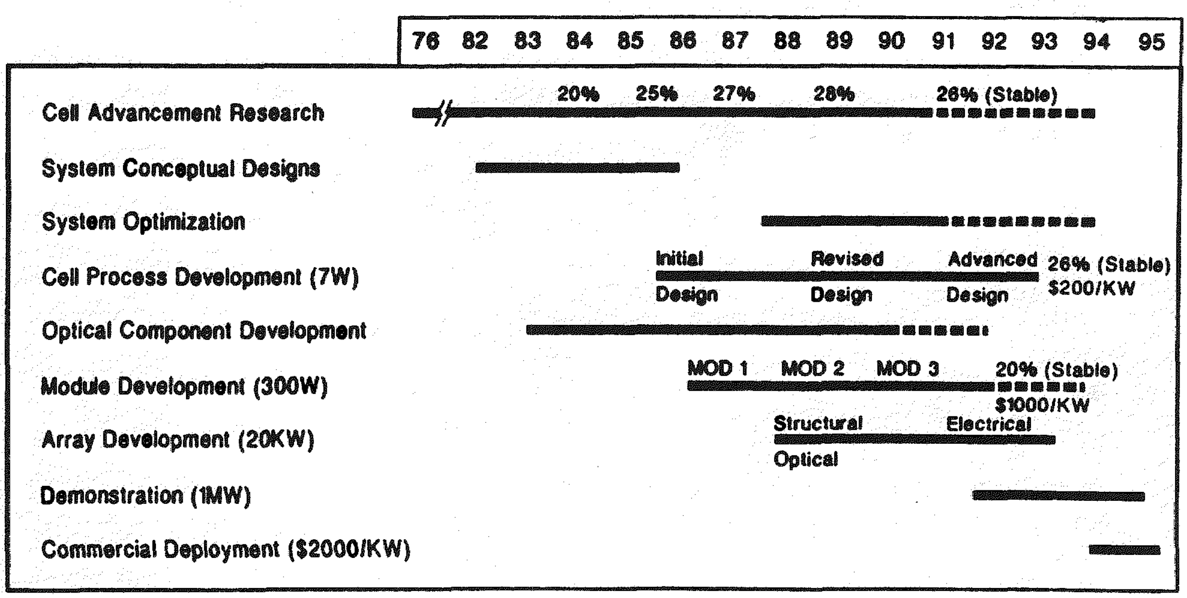
  DSET Laboratories, Phoenix, AZ

  - Mod 1 Module

  Future Tracker Installation, S. F. Bay Area

  - For cell and cell package development support

HIGH-CONCENTRATION PHOTOVOLTAIC DEVELOPMENT PROGRAM



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RECENT DEVELOPMENTS IN ENTECH'S PHOTOVOLTAIC CONCENTRATOR TECHNOLOGY

Mark J. O'Neill

ENTECH, Inc.
P.O. Box 612246
DFW Airport, TX 75261

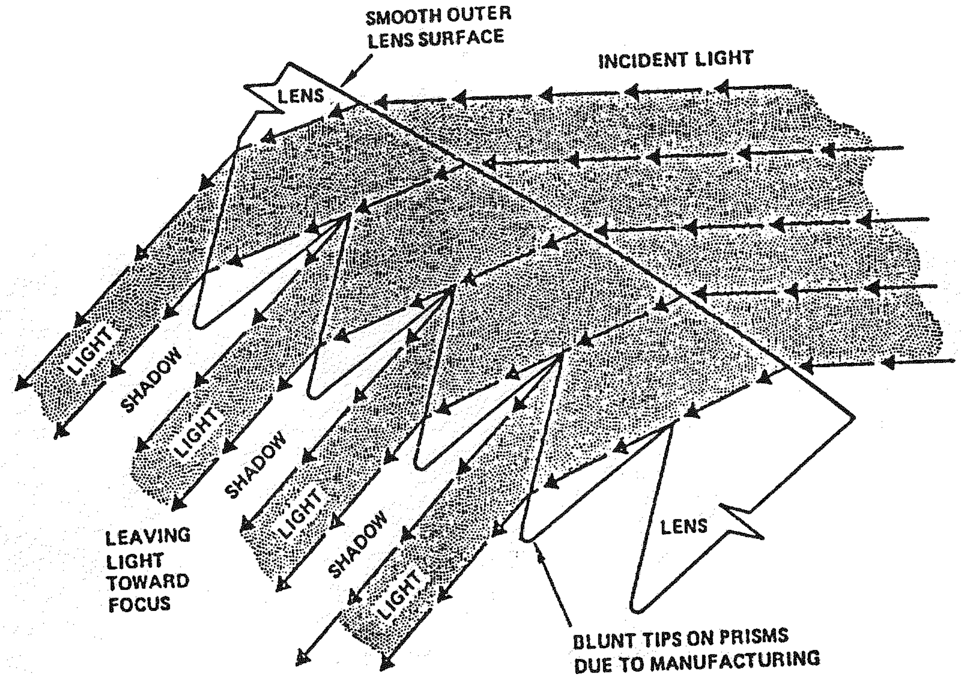
Since the last DOE/Sandia Project Review Meeting, significant progress has been achieved in research, development, and commercialization of ENTECH's photovoltaic concentrator technology. In the following paragraphs, our key component technologies will be briefly discussed; our current photovoltaic concentrator module and system approaches will be summarized; and recent performance improvements in both production and laboratory hardware will be presented. The progress reported here is the result of the combined efforts of ENTECH, DOE, Sandia, and our key component suppliers.

Key Component Technologies

Two unique technololgies are incorporated into all of ENTECH's photovoltaic concentrator modules and systems. The first is a unique Fresnel lens approach (Figure 1), wherein solar rays are symmetrically refracted by the smooth, convex outer lens surface and by the faceted, concave inner lens surface (U.S. Patent No. 4,069,812). By configuring the lens to maintain equality between the angle of incidence and the angle of emergence for solar rays passing through each prism in the lens, reflection losses are minimized, tolerances for manufacturing and operational inaccuracies are maximized, and outstanding optical performance is achieved. This unique lens approach can be used to achieve a line focus with an arch-shaped, quasi-cylindrical lens; a point focus with a dome-shaped, quasi-spherical lens; or a point focus with a scalloped, arch-shaped, quasi-cylindrical crossed lens. Of primary interest to ENTECH is the line-focus lens, which is made by laminating 3M Lensfilm to a thicker acrylic superstrate. Production line-focus lenses of very large aperture area (3 feet by 10 feet) are routinely achieving over 90% net optical efficiency at 22X geometric concentration ratio. The most dramatic advantage of the symmetrical refraction lens is its slope error tolerance, which is 100 times better than for a flat lens and 200 times better than for a reflective concentrator. This unequaled tolerance for slope errors easily accommodates real-world variations in lens shape caused by temperature/humidity cycling, lens orientation changes relative to the gravity vector, and wind-induced deflections.

The second unique technology is the prismatic cell cover (Figure 2), which allows a concentrator cell to be very heavily gridded on its illuminated surface, while avoiding the normal grid shadowing loss (U.S. Patent No. 4,711,872). By refracting sunlight away from the gridlines and onto active cell material between the gridlines, the low-cost prism cover can significantly boost the performance of a concentrator cell, not only by eliminating the shadowing loss, but also by reducing the series resistance loss. In particular, the prism cover has allowed the efficient use of relatively low-cost, large-area, one-sun-type silicon cells in our 22X concentrator module. Production cells (over 25,000 in number) made by Solarex for the 3M/Austin 300 KW system have averaged approximately 19% in efficiency at 20 suns irradiance and 25 C cell temperature. In addition, our prismatic covers are currently being used by a number of organizations to boost the performance of various types of cells and modules, for both terrestrial and space applications.

FIGURE 1 - MAGNIFIED VIEW OF SEVERAL PRISMS WITHIN THE ENTECH SYMMETRICAL-REFRACTION FRESNEL LENS



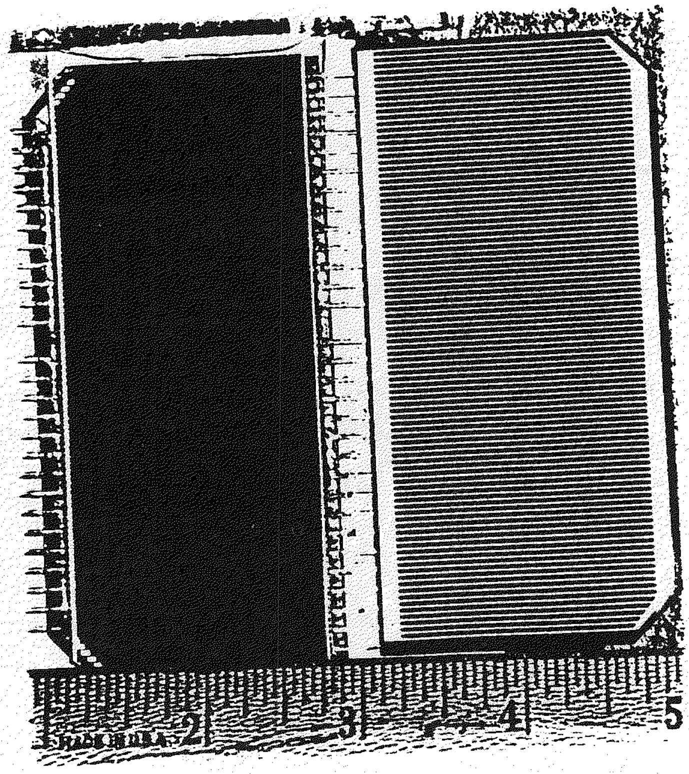


FIGURE 2 - HEAVILY GRIDDED PHOTOVOLTAIC CONCENTRATOR CELLS WITH AND WITHOUT THE ENTECH PRISMATIC CELL COVER

Current Module and System Approaches

Our current production 22X module (Figure 3) consists of one line-focus lens; thirty-one series-connected, prism-covered silicon cells, mounted on one aluminum extrusion; and a sheet aluminum housing (two sidewalls and two endplates). We are currently producing 720 of these modules for incorporation into the nominal 300 KW 3M/Austin system, which is being constructed under joint funding from DOE, 3M Company, the City of Austin, and ENTECH. Sixty of these modules are integrated together in a single row, which uses a unitized steel structure and two microprocessor-controlled drives for sun-tracking (Figure 4). Twelve such rows will be installed above a parking garage at the 3M/Austin site to provide a total collector field aperture of 2,000 square meters.

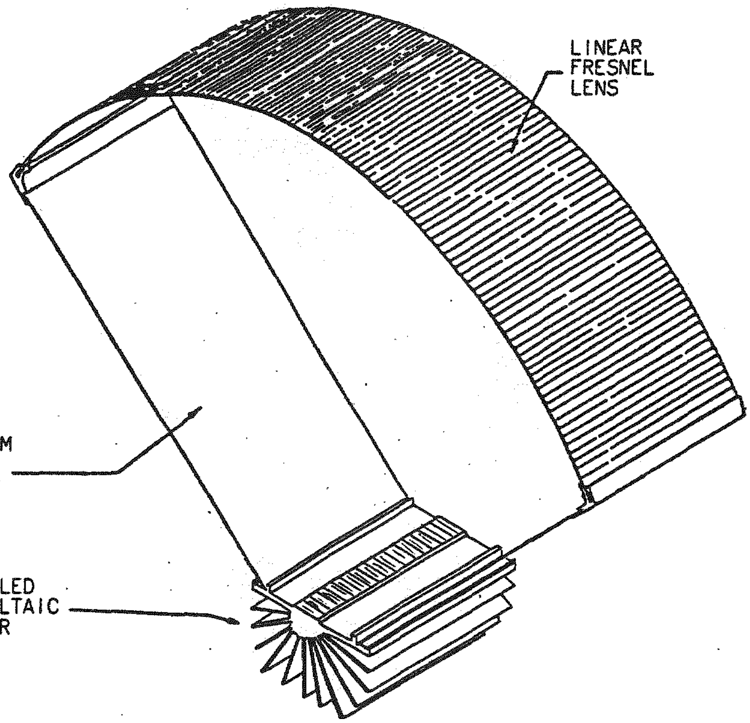
The 3M/Austin project represents ENTECH's largest production job to date. Our concentrator manufacturing approach has involved the use of proven suppliers and subcontractors for major components and subsystems, including Lensfilm from 3M, silicon cells from Solarex, and module housings and tracking structures from Consumers, Inc. Our in-house manufacturing efforts have centered on photovoltaic receiver assembly. We have learned a great deal during the production of over 700 photovoltaic receivers, including the manufacturing tasks most amenable to future automation. We are currently working with the Automation and Robotics Research Institute of Ft. Worth to design an automated facility for producing photovoltaic receivers at single-shift rates exceeding 10 MW per year. With such automation, we are confident that our 22X line-focus concentrator technology can meet the near-term DOE performance and cost goals exemplified by a levelized electricity price of 12 cents per KWH.

Recent Performance Advances

Two years ago, we completed the first major deployment of our 22X concentrators at Sandia, using 17% efficient polycrystalline silicon cells from Solarex. Production modules for this system averaged about 15% peak module efficiency (Figure 5). Last year, by using 18% efficient Czochralski (CZ) silicon cells from Solarex, our peak module efficiencies improved to about 16% (Figure 5). Over the past year, by texturing the CZ cells, Solarex has improved their production cell efficiency to about 19%. Test results on a full-size 22X module using a production receiver have verified about 17% peak module efficiency (Figure 5). We believe that this represents the highest production module efficiency yet achieved for any type of photovoltaic technology. However, we don't expect this record to last very long. We have just begun work on a nominal 20 KW system under the PVUSA EMT-1 Program; we expect to deliver 18% efficient modules under this program.

Including the 17% production module efficiency record mentioned above, we believe that our prism covers and/or lenses have been involved in at least seven recent photovoltaic performance records for cells and/or modules (Figure 6). These records include a 21% lens/cell efficiency, using a prism-covered silicon cell from the University of New South Wales under a 22X linear Fresnel lens. We believe that the excellent performance of this laboratory 22X module will make its way to the production line by the early 1990's. We are also proud to be involved (via our prism covers) in several advanced cell performance records for silicon, gallium arsenide, and cascade cells (Figure 6).

FIGURE 3 - CROSS-SECTIONAL SCHEMATIC OF THE ENTECH AIR-COOLED 22X LINEAR FRESNEL LENS PHOTOVOLTAIC CONCENTRATOR



<u>UNIQUE LENS</u>: THE TRANSMITTANCE-OPTIMIZED LENS PROVIDES 90% NET OPTICAL EFFICIENCY (WITHOUT THE NEED FOR SECONDARY CONCENTRATORS), EXCEPTIONAL TOLERANCES FOR MANUFACTURING AND OPERATIONAL INACCURACIES (E.G., >100 TIMES THE SLOPE ERROR TOLERANCE OF FLAT LENSES), AND IS MASS-PRODUCED BY 3M'S LENSFILM PROCESS.

<u>ONE-SUN TYPE CELLS</u>: THE MODEST CONCENTRATION RATIO ALLOWS THE USE OF LOW-COST, LARGE-AREA, ONE-SUN TYPE CELLS (CZ, POLY, OR WEB SILICON), WHICH ARE ALREADY IN PRODUCTION AT NUMEROUS COMPANIES WORLDWIDE.

<u>PRISMATIC COVERS</u>: CELLS ARE ENCAPSULATED WITH SILICONE PRISM COVERS, WHICH ELIMINATE GRID OBSCURATION LOSSES FOR HEAVILY METALLIZED CELLS.

<u>SIMPLE HEAT DISSIPATION</u>: CELLS ARE BONDED DIRECTLY TO AN EXTRUDED ALUMINUM HEAT SINK WITH A THERMALLY CONDUCTIVE DIELECTRIC ADHESIVE.

<u>LARGE MODULE/FEW PARTS</u>: EACH MODULE PROVIDES 2.787 SQ.M. OF APERTURE (470 PEAK DC WATTS @ 1,000 W/SQ.M. DNI AND 25C CELL), WITH A SINGLE LENS, 31 CELLS, ONE HEAT SINK, AND ONE HOUSING.

<u>SIMPLIFIED TRACKING APPROACH</u>: USING AN OPEN-LOOP, COMPUTERIZED CONTROL SYSTEM, A LIMITED-MOTION TILT/ROLL TRACKING APPROACH, TWO MOTOR-DRIVEN LINEAR ACTUATORS, AND A UNITIZED STEEL STRUCTURE, EACH TRACKING UNIT COMPRISES UP TO 167 SQ.M. OF APERTURE WITH 22-28% GROUND COVERAGE RATIO.

FIGURE 4 - KEY FEATURES AND ADVANTAGES OF THE ENTECH LINEAR FRESNEL LENS PHOTOVOLTAIC CONCENTRATOR APPROACH

FIGURE 5 - RECENT TRENDS IN THE MEASURED PERFORMANCE OF PRODUCTION 22X CONCENTRATOR MODULES

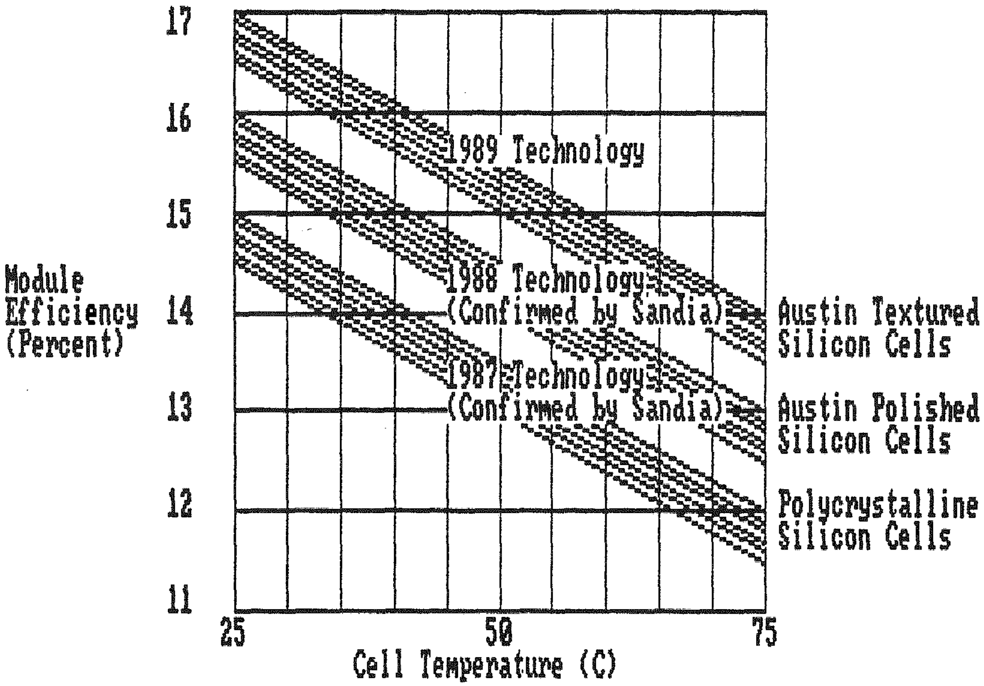


FIGURE 6 - RECENT PHOTOVOLTAIC PERFORMANCE RECORDS USING ENTECH TECHNOLOGY

Highest Efficiency Yet Measured for a Single-Junction Terrestrial Photovoltaic Cell of Any Kind (Gallium Arsenide with Prism Cover, Tested at 200 AM1.5 Suns and 25C, by Sandia National Laboratories)	Varian Associates	29.2%
Highest Efficiency Yet Measured by NASA-Lewis Research Center for a Space Cell of Any Kind (Gallium Arsenide with Prism Cover, Tested at 100 AM0 Suns and 25C, by NASA Lewis Research Center)	Varian Associates	24.3%
Highest Efficiency Yet Measured for a Terrestrial Cell at One-Sun (Monolithic Two-Terminal Cascade Cell, Aluminum Gallium Arsenide/ Gallium Arsenide with Prism Cover, Tested at 1 AM1.5 Sun and 25C, by Solar Energy Research Institute)	Varian Associates	27.6%
Highest Efficiency Yet Measured by Solar Energy Research Institute for a Space Cell at One-Sun (Monolithic Two-Terminal Cascade Cell, Aluminum Gallium Arsenide/ Gallium Arsenide with Prism Cover, Tested at 1 AM0 Sun and 25C, by Solar Energy Research Institute)	Varian Associates	23.0%
Highest Efficiency Yet Measured for a Terrestrial Low Resistivity Silicon Cell (Microgrooved Cell with Prism Cover, Tested at 120 AM1.5 Suns and 25C, by Sandia National Laboratories)	Univ. of New South Wales	25.1%
Highest Efficiency Yet Measured for a Silicon-Based Laboratory Concentrator Module (ENTECH 22X Linear Fresnel Lens and Silicon Cell with Prism Cover, Tested Outdoors by ENTECH)	Univ. of New South Wales	21.0%
Highest Efficiency Yet Measured for a Production Photovoltaic Collector Module of Any Kind (ENTECH 22X Linear Fresnel Lens, with Total Aperture of 2.8 sq.m., Focussing onto 31 Series-Connected Silicon Cells with Prism Covers, Tested Outdoors by ENTECH)	Solarex Corporation	17.0%

Title: 20X Line-Focus Photovoltaic Module

Contractor:
ENTECH, Inc.
P. O. Box 612246
DFW Airport, TX 75261

Principal Investigator:
Mark J. O'Neill
Telephone:
(214) 456-0900
Current Contract Number:
25-2272
Current Contract Period:
From: 8/84 To: 3/89
Project/Area/Task:
Photovoltaic Technology Project
Task 6 Concentrator Collector
Subtask 1 Module Research

Directing Organization:
Sandia National Laboratories
Project Engineer:
Jay L. Chamberlin
Telephone:
(505) 844-6394
Contract History:

Number	FY	Level	Source
25-2272	1984	$223,000	DOE

Objectives: The objectives of this contract were to develop a low concentration module that can use inexpensive cells made by a one-sun fabrication process and to develop the economic feasibility of a concentrator system based on the module.

Approach/Present Tasks: (1) Design a passively cooled module that will accommodate 20X cells made by using one-sun processing techniques. The modifications required to use one-sun cells at 20X are within the capabilities of processing used for one-sun cells. (2) Conduct a feasibility study to determine an optimum near-term collector design.

Status/FY1989 Accomplishments: The contract is complete except for the final report. (Modifications to reduce cost and improve performance resulted in module design for use in 300-kW DOE/3M/Austin array being fabricated and installed by ENTECH.)

Major Project Reports: None

Summary Date:
June 1989

Title: One-Axis Tracking Photovoltaic Array

Contractor:
ENTECH, Inc.
P.O.Box 612246
DFW Airport, TX 75261

Principal Investigator:
Mark J. O'Neill
Telephone:
(214) 456-0900
Current Contract Number:
01-1163
Current Contract Period:
From: 10/85 **To:** 3/89
Project/Area/Task:
Photovoltaic Technology Project
Task 6 Concentrator Collector
Subtask 1 Module Research

Directing Organization:
Sandia National Laboratories
Project Engineer:
Jay L. Chamberlin
Telephone:
(505) 844-6394
Contract History:

Number	FY	Level	Source
01-1163	1987	$148,221	DOE

Objective: The objective of this contract was to develop a low-concentration photovoltaic array which incorporates single-axis tracking.

Approach/Present Tasks: (1) Design a linear-focus lens that will optimize annual module performance over a range of declination angles. The cell's prism cover design must also tolerate solar declination. (2) Design module housing and roll-axis tracking to maximize the cost reduction made possible by the simplicity of single-axis tracking design.

Status/FY1989 Accomplishments: The contract is complete except for the final report. (Prototype module based on this contract served as the intended design for one row of the 300-kW DOE/3M/Austin array being fabricated and installed by ENTECH.)

Major Project Reports: None.

Summary Date:
June 1989

Title: Evaluation of Concentrator Designs for a GaAs Cell Module

Contractor:
ENTECH, Inc.
P. O. Box 612246
DFW Airport, TX 75261

Principal Investigator:
A. J. McDanal

Telephone:
(214) 456-0900

Current Contract Number:
64-7553

Current Contract Period:
From: 7/86 **To:** 6/89

Project/Area/Task:
Photovoltaic Technology Project
Task 6 Concentrator Collector Research

Directing Organization:
Sandia National Laboratories

Project Engineer:
Elizabeth H. Richards

Telephone:
(505) 844-6951

Contract History:

Number	FY	Level	Source
64-7553	1985	$75,813	DOE
64-7553	1987	$37,776	DOE
64-7553	1988	$17,370	DOE

Objective: To explore the ability of the cross-coupled linear Fresnel lens to generate an approximate 500X geometric concentration image for use with GaAs or silicon concentrator cells and to develop a cell assembly for this application. To design a prismatic cover for University of New South Wales (UNSW) silicon cells and apply covers to 300 cells.

Approach/Present Tasks: (1) To optimize the cross-coupled Fresnel lens design for use as a 500X point-focus concentrator. (2) Construct and test samples of the lens. (3) Design and build cell assemblies for use with the lens and cells. (4) Design and apply prismatic covers.

Status/FY 1989 Accomplishments: Prismatic cover design for UNSW cells was refined. Method for molding prismatic covers directly to cells developed. Prismatic covers applied to about 50 UNSW cells.

FY 1989 Milestones: (1) Complete testing of module design. (2) Apply prismatic covers to 300 cells. (3) Write reports covering work under this contract.

Major Project Reports: None.

Summary Date
June 1989

ALPHA SOLARCO'S PROOF-OF-CONCEPT ARRAY

Edward Schmidt
Don Carroll
Alpha Solarco, Inc.
11534 Gondola Dr.
Cincinnati, Ohio 45241

Alpha Solarco has been developing a Silicon based high concentration proof-of-concept array. Nominal peak power of the array has been projected at 15 kilowatts d.c. Our report will provide a brief overview of this limited production and construction program plus a review of the available test data.

The Alpha Solarco Array Construction Program goal is to demonstrate a reliable high concentration two-axis PV array capable of being mass produced at the required utility cost or lower. Mass production tooling and assembly procedures have been utilized in many areas to manage quality and enhance system reliability.

Major areas of the development program are:

- Developing and producing fresnel lens laminating equipment.

- Producing a lens score and break machine.

- Development and construction of a 500X cell flash tester.

- In-house ultrasonic imaging equipment.

- Prototyping and mass producing the secondary optical element.

- Soldering station capable of high speed production.

- Field testing of the Peerless Winsmith drive mechanism.

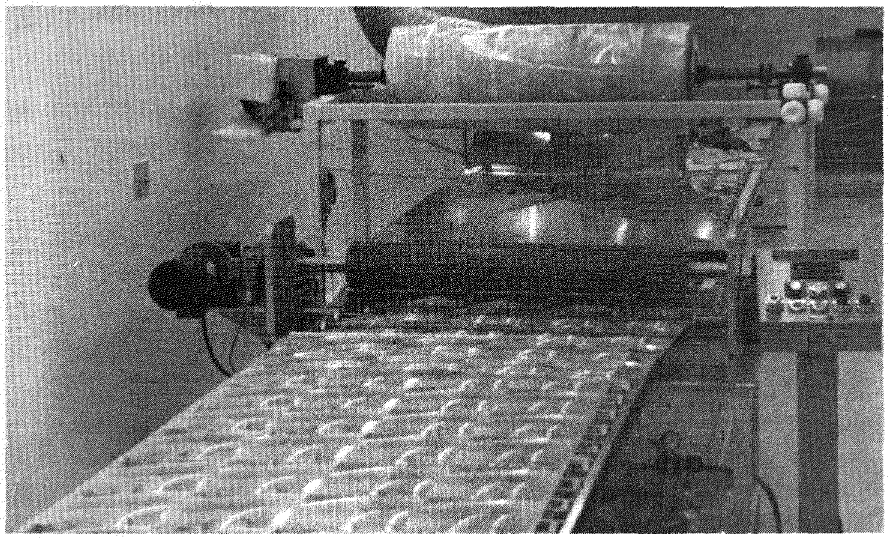
- Construction of a test facility in Pahrump, Nevada.

Technology transfer from Sandia Laboratories was fundamental to this entire program. Guidance in selecting our development team, Baseline 3 research and production assistance from the Sandia PV group greatly enhanced our entire project.

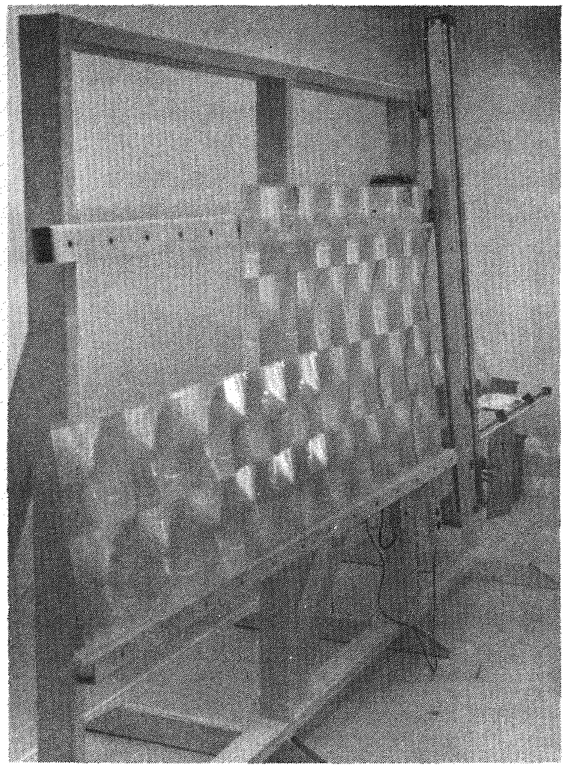
The photovoltaic group of the Electric Power Research

Institute gave valuable assistance by funding the system monitoring equipment and weather data station.

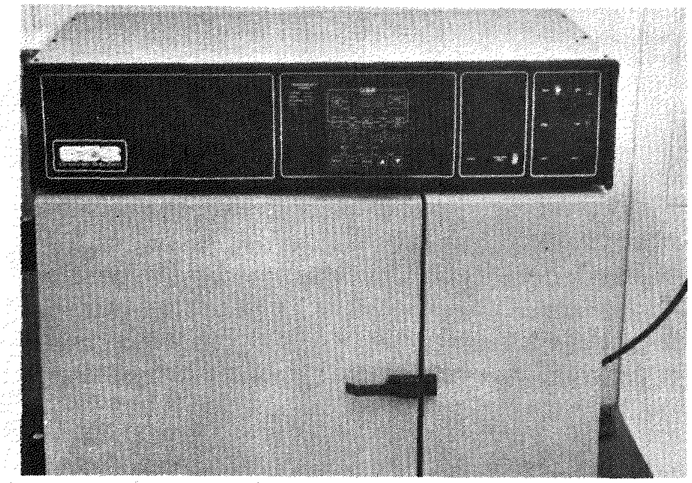
Performance data will be evaluated by PVUSA to determine Alpha Solarco's participation in the US 1 program. Future refinements include analyzing secondary optical element, studying benefits of anti-reflective coating, testing effects of moisture build-up in the module, automated production lines and effective construction systems.



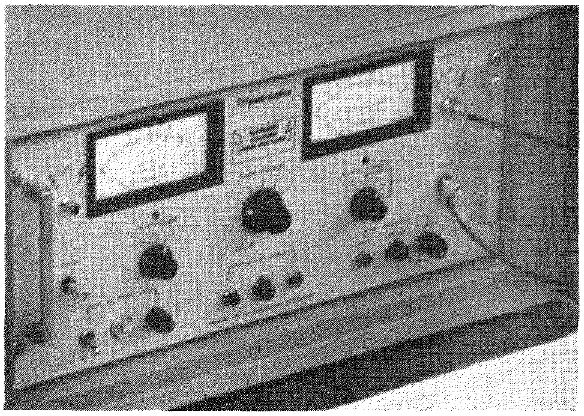
LENS LAMINATOR--Lens material received from 3M Corporation is chemically bonded to an acrylic sheet to form the lens parquets used on the modules. Each lens will focus 406 "suns" onto a photovoltaic cell that converts the light into electric power.



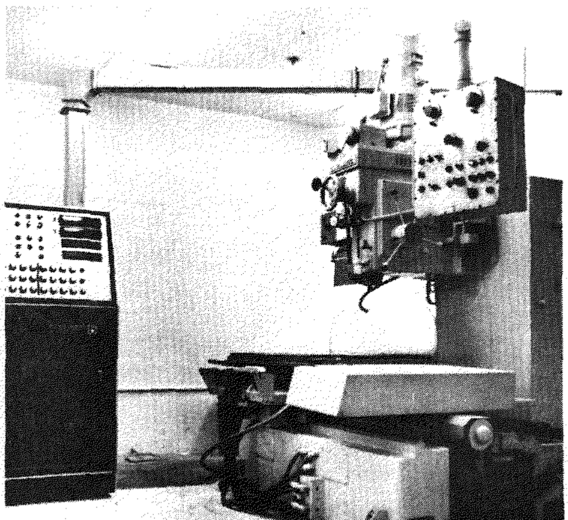
SCORE & BREAK MACHINE--Motorized control allows the operator to accurately align each lens parquet, which is manually scored and broken off into precision parts.



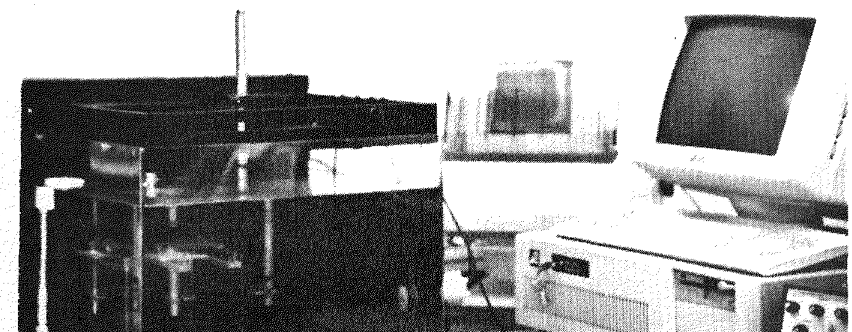
THERMAL CYCLE CHAMBER--Part of the quality control program includes the testing of completed cell assemblies in this special oven. The oven is heated to 110 C, then cooled to -40 C. Each cycle represents one day of system operation.



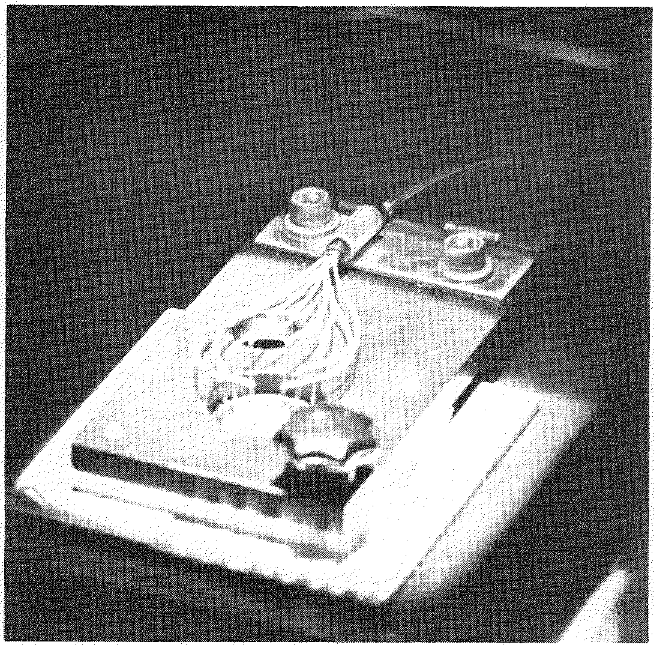
HI-POT TESTER--Some 2,500 volts of DC power is applied to the completed module to test for any dangerous power leaks.



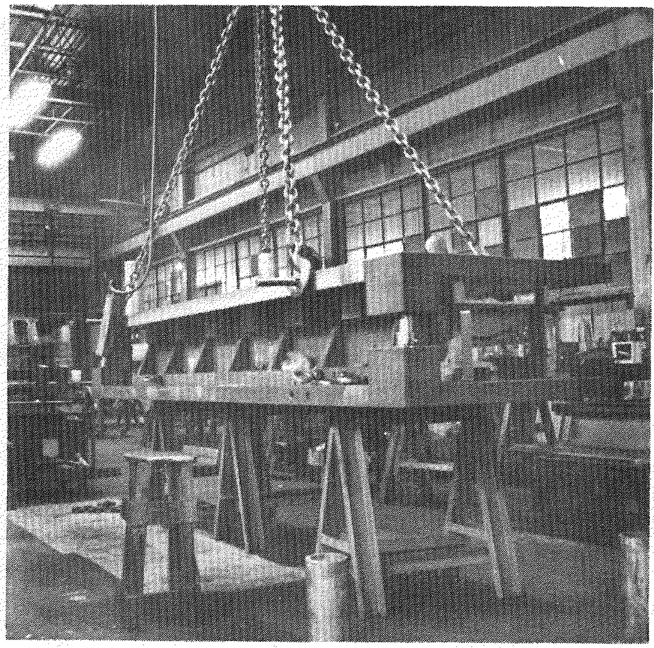
NUMERICAL CONTROL VERTICAL MILLING--This milling machine cuts registration slots into the lens parquets. When completely assembled, the center of the lens is directly over the center of the photovoltaic cell.



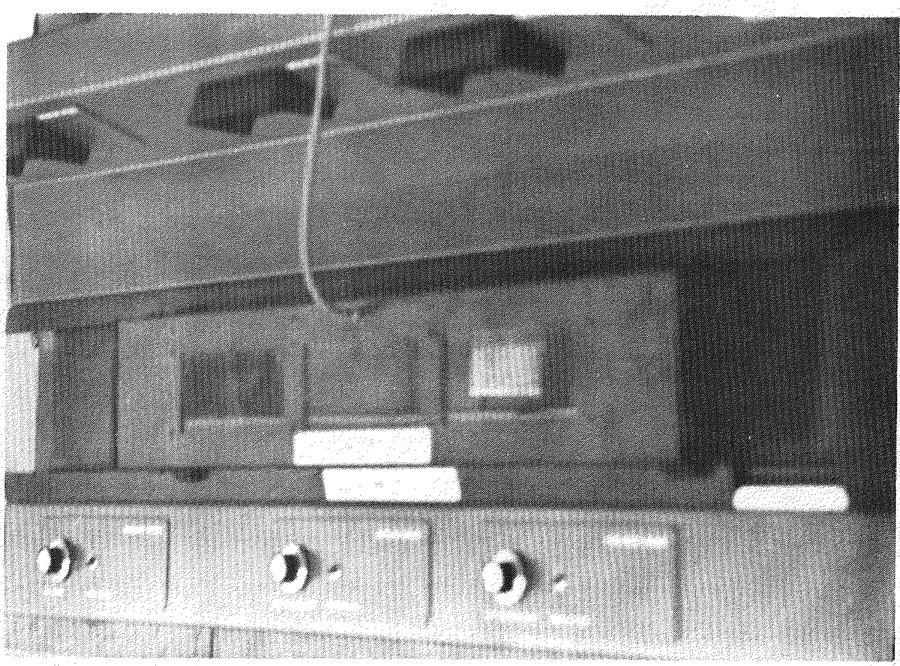
ULTRASONIC TESTER--Every cell is carefully examined by computer controlled transducers, which produce a digital image that is used to determine the cell solder bond acceptability.



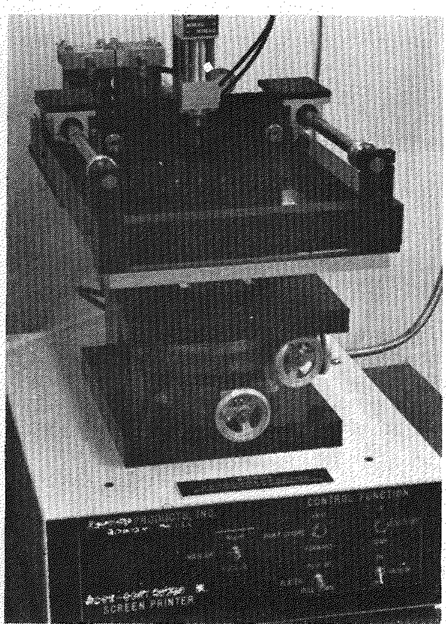
CELL TEST HOLDER -- Eight spring-loaded detectors send the electrical signal from the cell to a computer that generates an efficiency curve to determine cell acceptability. Cells are tested at 390 suns exposure.



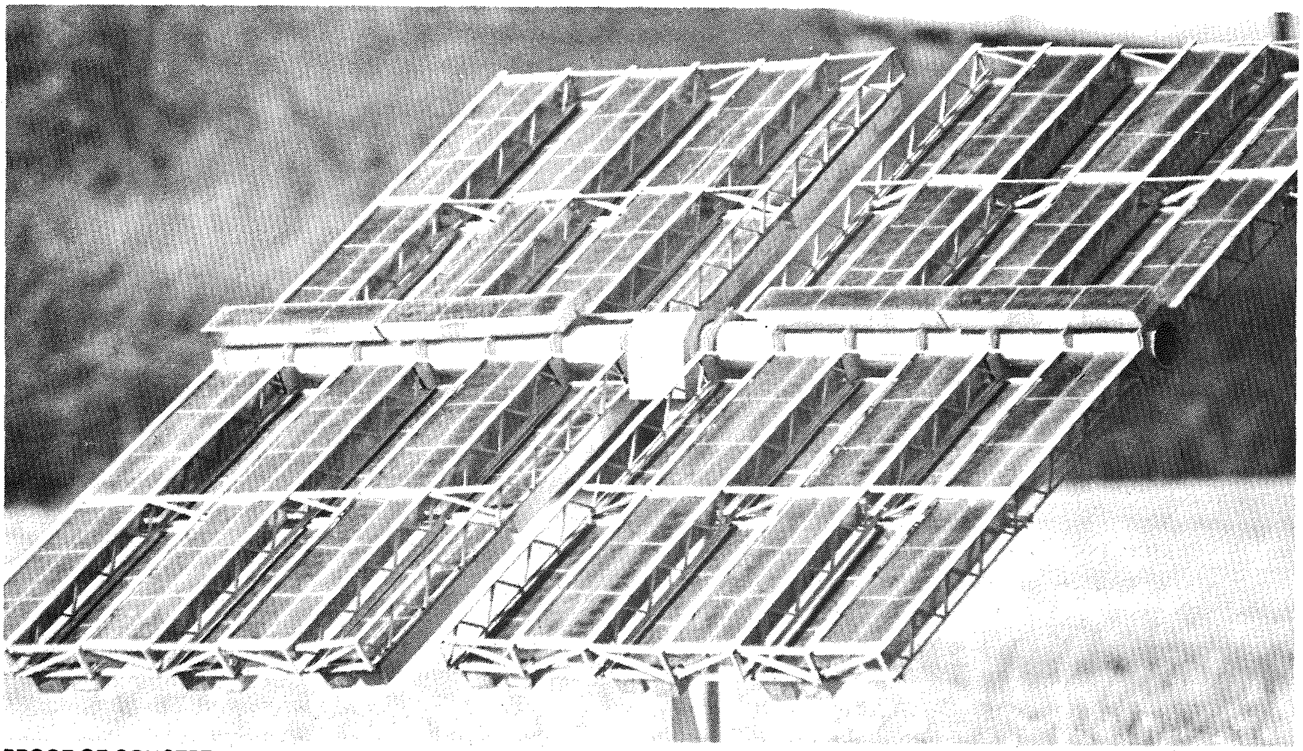
MODULE TOOL -- The large deep draw die is used on a 1200 ton stamping press. Finished module housing weighs 40 lbs.



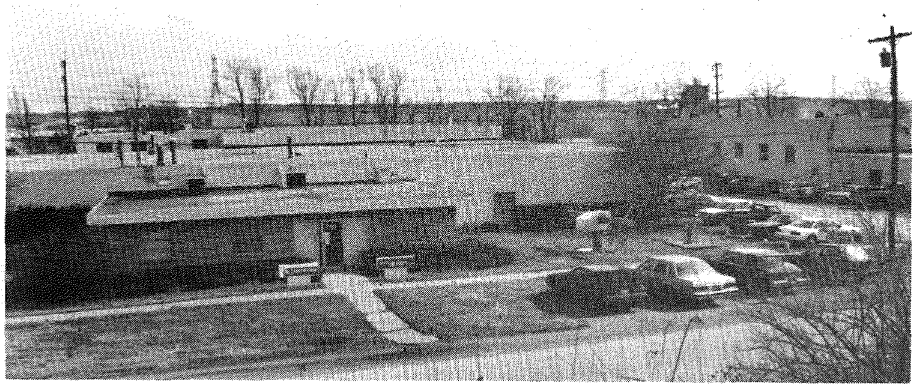
SOLDERING STATION -- Cell and top contact are soldered to the heat spreader in a controlled atmosphere. This one station is capable of producing 4.5 megawatts of cell assemblies annually.



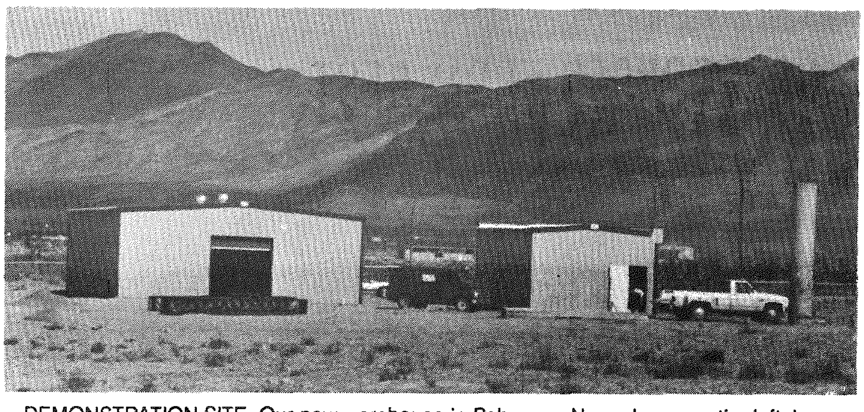
AUTOMATIC SOLDER PRINTER--This machine locates the exact center of the cell assembly area and applies a thin layer of solder automatically.



PROOF-OF-CONCEPT ARRAY--This model of the unit was shown to shareholders at our annual meeting last year. The modules are offset to allow the unit to survive higher wind loads.



CORPORATE HEADQUARTERS -- Located in Cincinnati, Ohio. Recently remodeled for high-tech assembly of MSEPG modules. A two-axis tracker, on the right, is used for development purposes.



DEMONSTRATION SITE--Our new warehouse in Pahrump, Nev., shown on the left, is completed. Interior lighting, plumbing, carpeting, and furnishings are in progress at the adjacent control/monitoring building. Compression test results on the concrete pedestal indicate that the material surpasses all requirements. Steel joists and horizontal structural tubing have been delivered to the site.

STATUS: PHOTOVOLTAIC CONCENTRATOR MODULE IMPROVEMENTS

Sheldon L. Levy
Black & Veatch Engineers-Architects
P. O. Box 8405
Kansas City, Missouri 64114

M. Nowlan
Spire Corporation
Bedford, MA 01730

K. Kerschen
Black & Veatch
Kansas City, MO 64114

J. Hutchison
Solar Kinetics, Inc.
Dallas, TX 75220

The objective of this project is to deliver two concentrator modules to the Sandia PV Advanced Systems Test Facility (PASTF) for test and evaluation in operating conditions. It is expected that module assembly will begin within two months, with module delivery to occur by the end of the summer. The principal components of these prototype modules include a 20 gauge aluminized steel housing with corrugated bottom, a Sandia Baseline Module II lens, SNLA 200X cells from M. Green, specially designed prismatic cell covers to match the module optics, anodized aluminum secondary optical elements, and a cell package for thermal transport and electrical isolation.

At present, approximately sixty cell assemblies are being fabricated by Spire. Each module will be populated with 24 cell assemblies. Cell performance has been measured during all phases of the fabrication process. Preliminary cell assemblies have meet Sandia's thermal cycling qualification requirements. A prototype module has been fabricated and dimensionally characterized by SKI. Placement of cell assemblies, electrical interconnects, lens parquet, and ancillary components (e.g. air breathers and heat dissipators) will be conducted by SKI.

Module Improvements

Project/Area/Task:
Photovoltaics Technology Project; Concentrator Module Research

Contractor:
Black and Veatch
P.O. Box 8405
Kansas City, MO 64114

Principal Investigator: S. Levy

Telephone: (913) 339-7119

Contract Number: 56-7211

Current Contract Period From: 12/86 **To:** 9/89

Directing Organization:
Sandia National Laboratories

Project Engineer: C.B. Stillwell

Telephone: (505) 844-2130

Contract Funding:		**Source:**
FY 1986	$362,371	DOE
FY 1988	$62,600	DOE
FY 1989	$60,000	DOE

Objectives:

To develop a high efficiency, cost-effective, passively cooled, point-focus module using silicon cells.

Approach/Present Tasks:

- Black and Veatch will perform the necessary optimization to determine the design parameters which will maximize electrical efficiency while allowing for sufficient manufacturing tolerances.
- Spire Corporation and Solar Kinetics, Inc., have been subcontracted to provide a cost-effective, durable cell assembly, and a readily manufacturable, cost-effective module.

Status/FY 1988 Accomplishments:

- Complete design of the cell assembly and module housing completed.
- Work delayed due to lack of solar cell debris.
- Completed module design.
- Defined prototype celled assemblies to SNLA for temperature cycles.

FY 1989 Milestones:

- Test and thermal cycle module cell assemblies.
- Test prototype modules.

Major Project Reports:

None.

Summary Date: November 1988

PARABOLIC DISH PHOTOVOLTAIC CONCENTRATOR DEVELOPMENT

Kelly Beninga
SCIENCE APPLICATIONS INTERNATIONAL CORPORATION, San Diego, California

Mammen Thomas
TACTICAL FABS, INC., San Jose, California

July 12, 1989

INTRODUCTION

Science Applications International Corporation (SAIC) and Tactical Fabs, Inc. (TFI) are developing a parabolic dish photovoltaic concentrator system. The system is intended to provide a low cost/unit energy power system for penetration into the utility, independent power, and remote power markets.

The power system design is distinctly different than the more traditional one lens/one cell photovoltaic concentrators. Instead of relying on refractive optics for solar energy concentration, the system utilizes large scale reflective optics to concentrate solar energy on a photovoltaic receiver. The reflective optical element and tracking system used are essentially the same as those used successfully in the solar thermal program for several years. However, instead of placing a heat engine at the focal point of the concentrator, an actively cooled photovoltaic receiver consisting of a densely packed array of high efficiency photovoltaic cells is used.

The parabolic dish photovoltaic concentrator system has several potential advantages over one lens/one cell photovoltaic systems:

1) Reflective parabolic concentrators can be manufactured at a lower cost per square meter than fresnel lenses and their associated module enclosures.
2) Cell inter-connection and mounting costs are lower due to the close proximity of all the cells.
3) The concentrator element is more efficient due to higher reflectivity as compared to the transmissivity of lenses.
4) Cell temperatures can be controlled more precisely with the central active cooling system.
5) Maintenance or replacement of the PV cells is easier because of the central location.
6) The waste thermal energy is in a usable form for some applications.

SYSTEM DESCRIPTION

The basic components of a parabolic dish photovoltaic concentrator system are the parabolic dish reflector, the dish azimuth/elevation tracking system, the photovoltaic receiver, the photovoltaic receiver cooling system, and the DC to AC converter. As shown in **Figure 1**, the system closely resembles conventional solar thermal parabolic dish systems. However, the thermal receiver and heat engine has been replaced by a photovoltaic receiver and a receiver cooling system. The parabolic dish utilizes two-axis tracking to concentrate the reflected direct-normal solar energy at a single focal point. The photovoltaic receiver is placed near the focal point of the parabolic dish under a concentration of about 500 suns. In order to maintain high efficiency and protect the PV cells from damage, the receiver panel is cooled from the rear with either a liquid cooled cold plate or a pool boiler. The thermal energy is then either rejected to the atmosphere via a liquid-to-air heat exchanger, or used in various low temperature thermal energy applications. For small system sizes, rejection of the heat to the atmosphere may be possible using passive cooling fins.

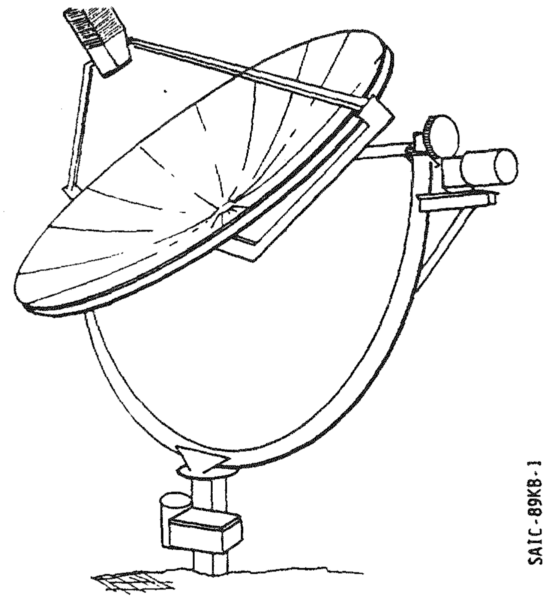


Figure 1. Artists's Concept - 3 m diameter (1Kw) Photovoltaic Dish System

The cells in each module are interconnected with the patented bus-bar which acts to electrically interconnect the cells in the desired network configuration, and also acts as a heat sink to conduct heat from the cells to the cooling system. Photovoltaic modules are interconnected to form photovoltaic receivers, as shown in **Figure 2**. The number of modules interconnected is dependent on the size of the receiver desired. For larger dishes and central receivers, the modules may be arranged in a round pattern to better match the solar image produced by the concentrator system.

A critical aspect of photovoltaic receiver design is accommodating the non-uniform flux profile typically produced by parabolic dishes. Photovoltaic devices produce a nearly constant voltage and current that is approximately proportional to the incident solar flux. Therefore, if cells or parallel banks of cells are connected in series and subjected to non-uniform flux, the cell or parallel bank of cells which has the lowest incidence flux will generate the lowest output current. This will limit the possible output current of all series-connected cells of parallel banks. In order to even out the flux distribution and reduce the peak flux value, the photovoltaic receiver can be moved in or out from the focal plane. This has the effect of reducing the peak flux and producing a more even flux distribution.

Several methods are available to design for the remaining flux non-uniformity on the receiver in order to maximize the output power. These methods include: 1) use of a terminal concentrator to redistribute the incident flux in order to achieve a more uniform distribution space, and 2) design the cell or module interconnection network to accommodate the non-uniform flux.

PHOTOVOLTAIC RECEIVER DESCRIPTION

TFI has developed and patented a new cell mounting technology and cell design which enable groups of cells to be arranged at the focus of a large parabolic concentrator. The design is based on back-surface collection of carriers, which allows the front surface to be fully utilized for photon incidence and carrier generation. TFI designed this cell with manufacturability and efficiency as prime considerations. The fundamental aim was to produce a cell with consistent efficiency of over 20%. Further improvements in efficiency to 25% or 30% in the future is expected to occur through evolution of the technology.

The cell is a 0.5 cm x 0.5 cm silicon cell which works with concentrators of 100-600x. The small cell size substantially improves die yield. The collection of carriers occurs through diffused p and n areas on the back surface of the cell. These carriers are conducted from the collection points through contacts etched

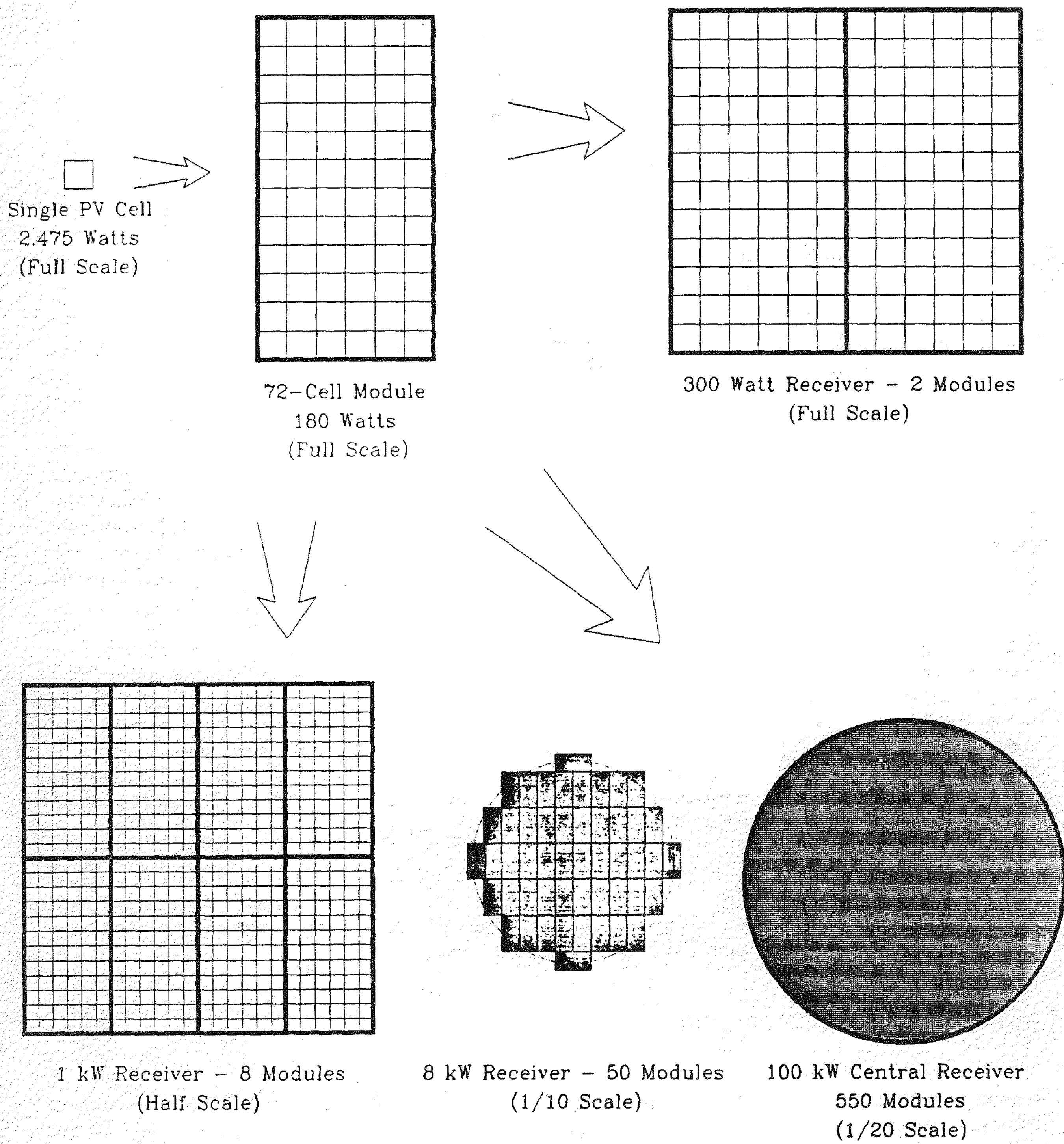


Figure 2. Photovoltaic Receiver Assembly

in oxide, which contact the diffusions, and thence through inter-digitated single layer metallization. This cell construction is shown schematically in **Figure 3**. Redundancy and collection efficiency are introduced by the design of the interdigitated fingers and via the structure used to attach the die to the bus-bars.

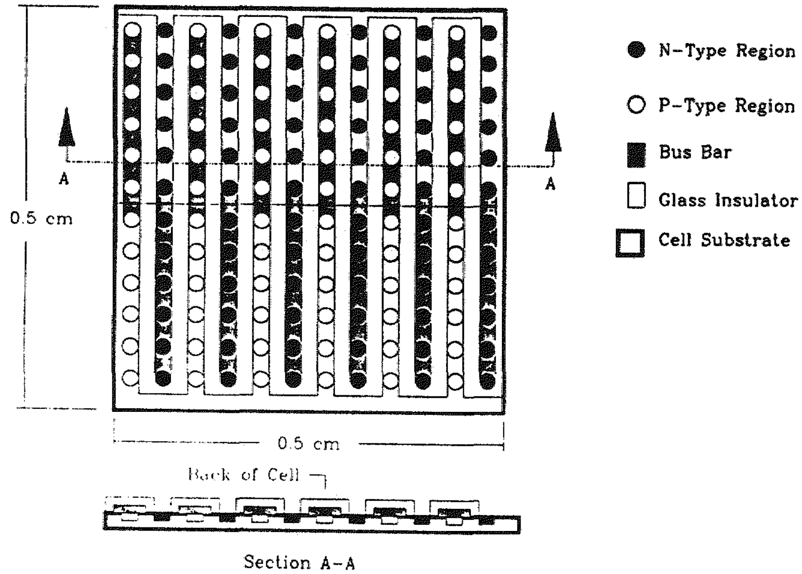


Figure 3. Layout of Tactical Fabs, Inc. Concentrator Photovoltaic Cell

The bus-bar assembly design is patented by TFI and offers some truly unique features that assure efficient carrier collection, thermal transfer, and manufacturability. This is accomplished by employing a symmetrical design that reduces and balances electrical paths while providing efficient, uniform heat conduction. The design of the cell is such that 100% of the area exposed to the sun is usable for conversion: thus, in concert with a series of parallel bus-bars the cells can be assembled together, edge-to-edge, in a solid array, to form a receiver of arbitrary size or shape.

PHOTOVOLTAIC RECEIVER COOLING SYSTEM

At the fluxes present in concentrating photovoltaic systems, damage would result to the receiver if it were not cooled at all times. Also, because the efficiency of photovoltaic devices is a strong function of temperature, it is important to maintain the receiver temperature within a narrow range of temperatures in order to maximize receiver efficiency.

The receiver cooling system is shown in **Figure 4**. The preferred system consists of a pool boiler with an active liquid heat transfer loop to a liquid-air heat exchanger. The evaporator of the pool boiler is located directly behind the PV receiver panel. The evaporator surface is separated from the backs of the bus-bars by a thin layer of electrically insulating, thermally conductive material. The pool boiler operates in the same manner as a heat pipe: The fluid in the boiler absorbs heat from the PV receiver panel and boils at a saturation temperature of between 50°C and about 90°C. The vapor then travels to the top of the boiler, where it condenses on tubes carrying a heat transfer fluid. The geometry of the pool boiler is such that the liquid free surface is above the top of the evaporator surface for all orientations of the receiver.

When the system is used in a utility system, the heated fluid circulates through a liquid-air heat exchanger to transfer the heat to the ambient air. Alternatively, this heat could be used to provide domestic hot water/heating or industrial process heat by substituting a load heat exchanger for the liquid-air heat exchanger.

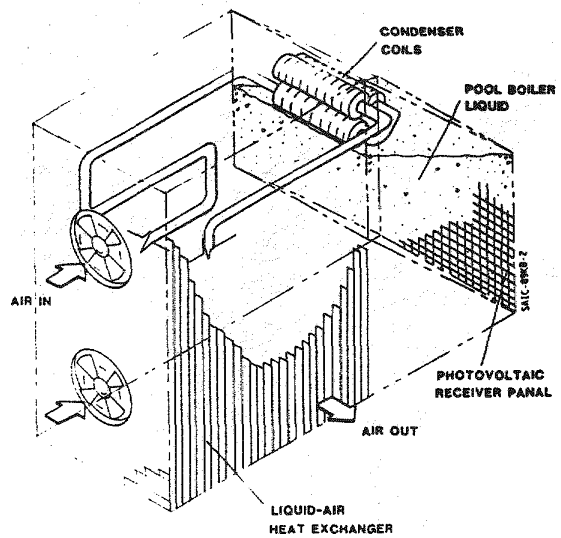


Figure 4. Photovoltaic Receiver Unit

SYSTEM PERFORMANCE AND ECONOMICS

Figure 5 shows the estimated system efficiency "waterfall" for design-point conditions. As shown in the figure, the system is expected to have an overall solar-to-AC efficiency of 21.7%. Including an allowance for parasitic energy requirements, the total net energy delivery of the system is estimated to be 27,533 kWh per year. In addition to the electrical energy, about 325,000 MJ per year of thermal energy at temperatures of 50°C to 90°C, suitable for domestic hot water or industrial process heat loads, could be delivered by the heat rejector.

The system has several unique attributes which hold the potential for significant energy cost reductions as compared to refractive systems. The system is expected to exhibit economics which meet the DOE near-term goals (Ref 11) of $0.12/kWh for concentrator photovoltaic systems at a production level of about 500 8-kW_e (50-m^2) systems per year, corresponding to a production level of 4 MW per year. At a production rate of about 6,250 systems per year, SAIC's goal of $0.06/kWh can be achieved. The excellent economics of this system result from a combination of the high efficiency of the PV cells used in the design, the efficient photovoltaic receiver construction approach, and the low-cost dish technology.

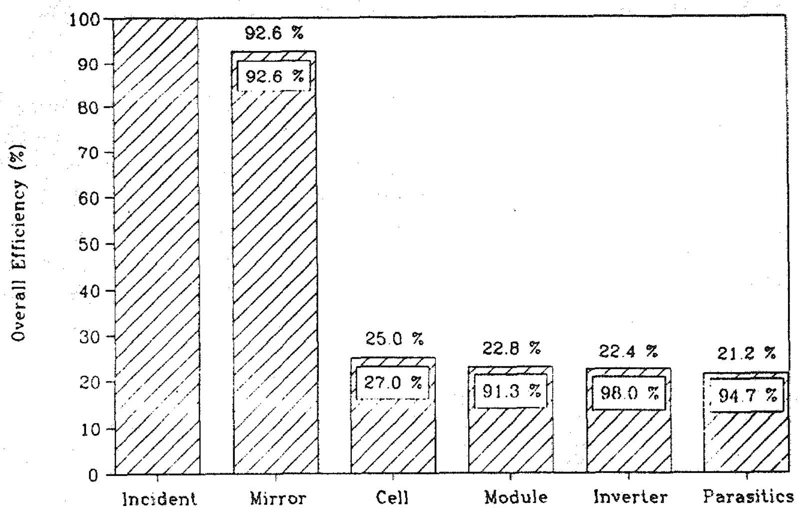


Figure 5. Estimated Step and Cumulative Efficiency of PV Dish System

THE WATTSUN CORPORATION
SHORT FOCAL LENGTH CONCENTRATING PV MODULE OUTLINE
JULY 12, 1989 DOE/SANDIA LABORATORIES
CRYSTALLINE PHOTOVOLTAIC TECHNOLOGY PROGRAM REVIEW MEETING

I. Introduction

  A. Philosophical approach

  B. Module / System description and characteristics

II. Optimization

  A. Concentrator lens sheet
    1. optics evaluation
    2. material selection

  B. Support structure

  C. Photovoltaic cell efficiency
    1. cell material
    2. metalization

  D. Receiver sheet
    1. materials
    2. bonding techniques

  E. Overall package

III. Manufacturability

  A. Manufacturing techniques
    1. Lens sheet
    2. Support structure
    3. PV cells
    4. Receiver sheet

  B. Production assembly
    1. Lens sheet / Support structure
    2. PV cell / Receiver sheet integration

IV. Overall Cost

  A. Module cost

  B. Tracking system

V. Reliability

VI. Space Applications

VII. Closing

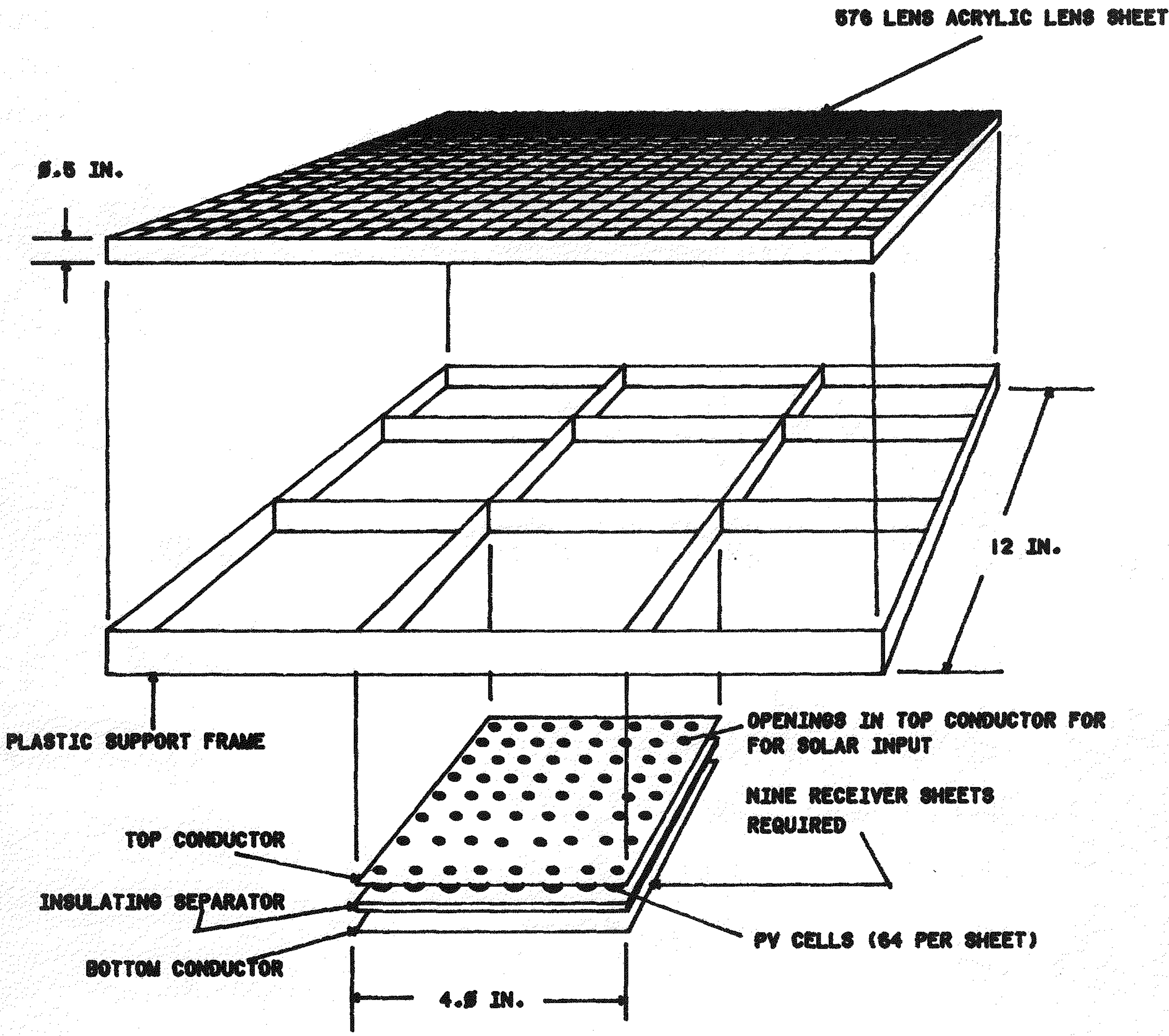
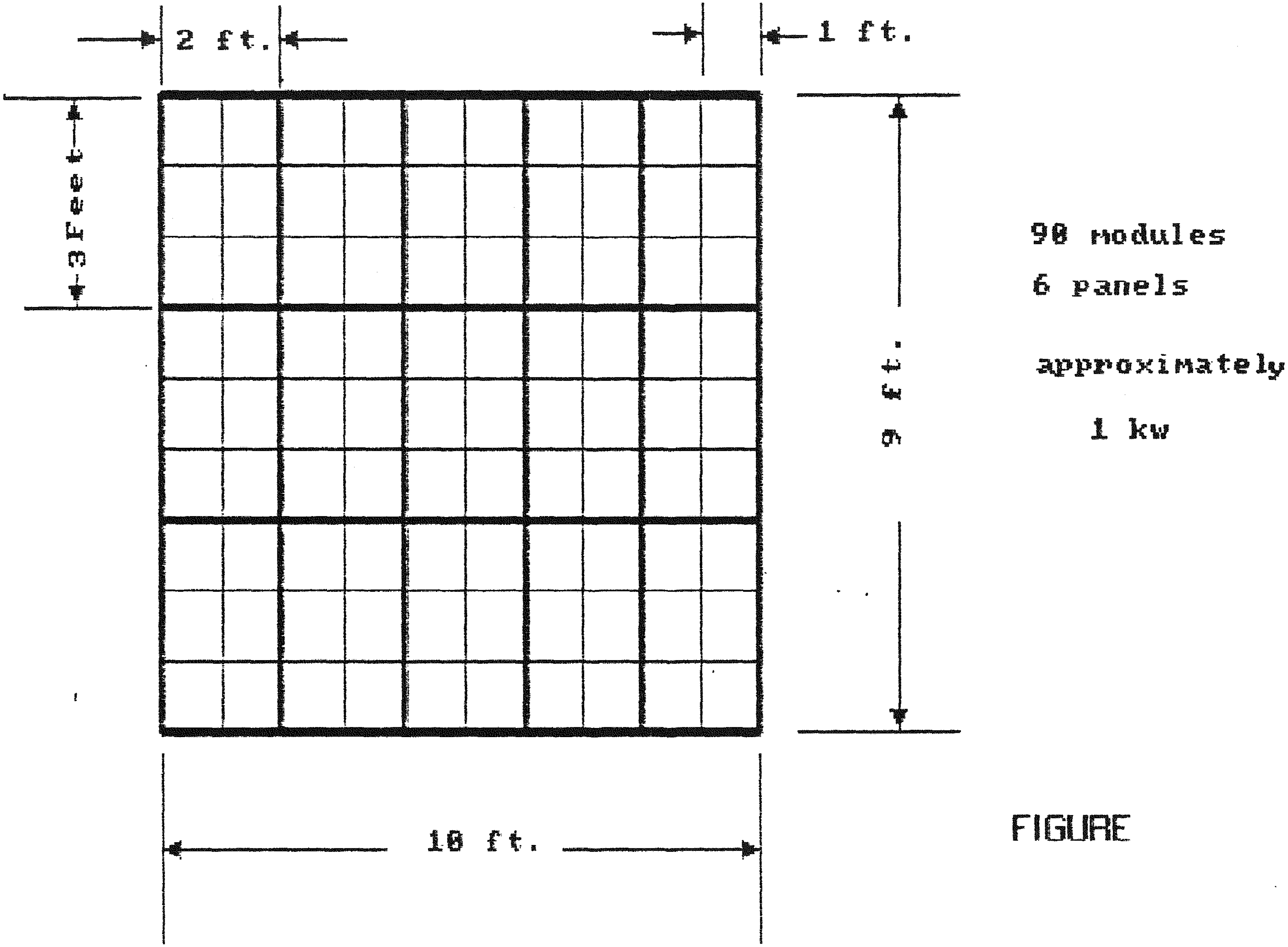


FIGURE 1 NEW WATTSUN MODULE DESIGN.



FIGURE

FIGURE 2 Tracker array

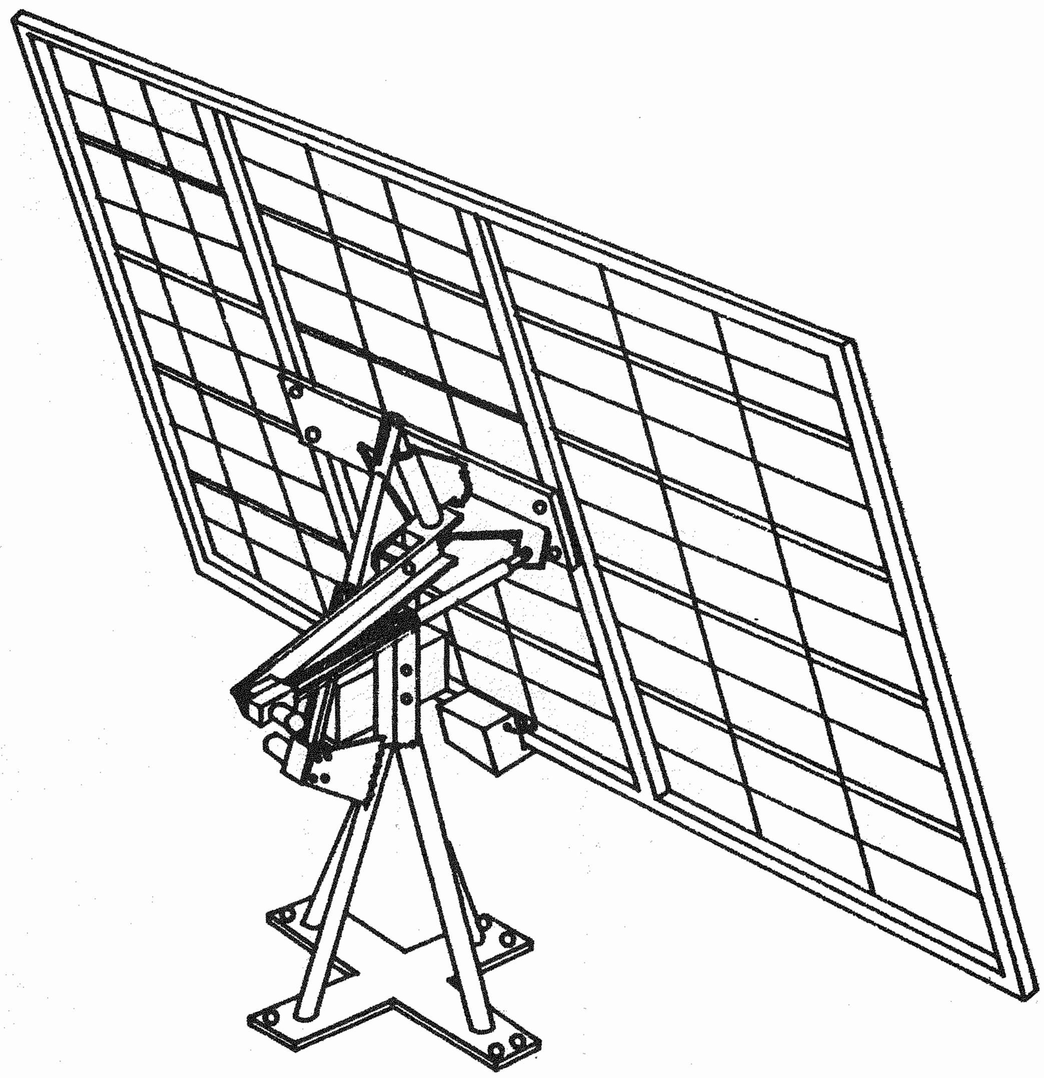


FIGURE 3 WATTSUN LOW COST TRACKER.
9 X 1Ø FOOT ARRAY.
45Ø VOLTS. ONE KILOWATT

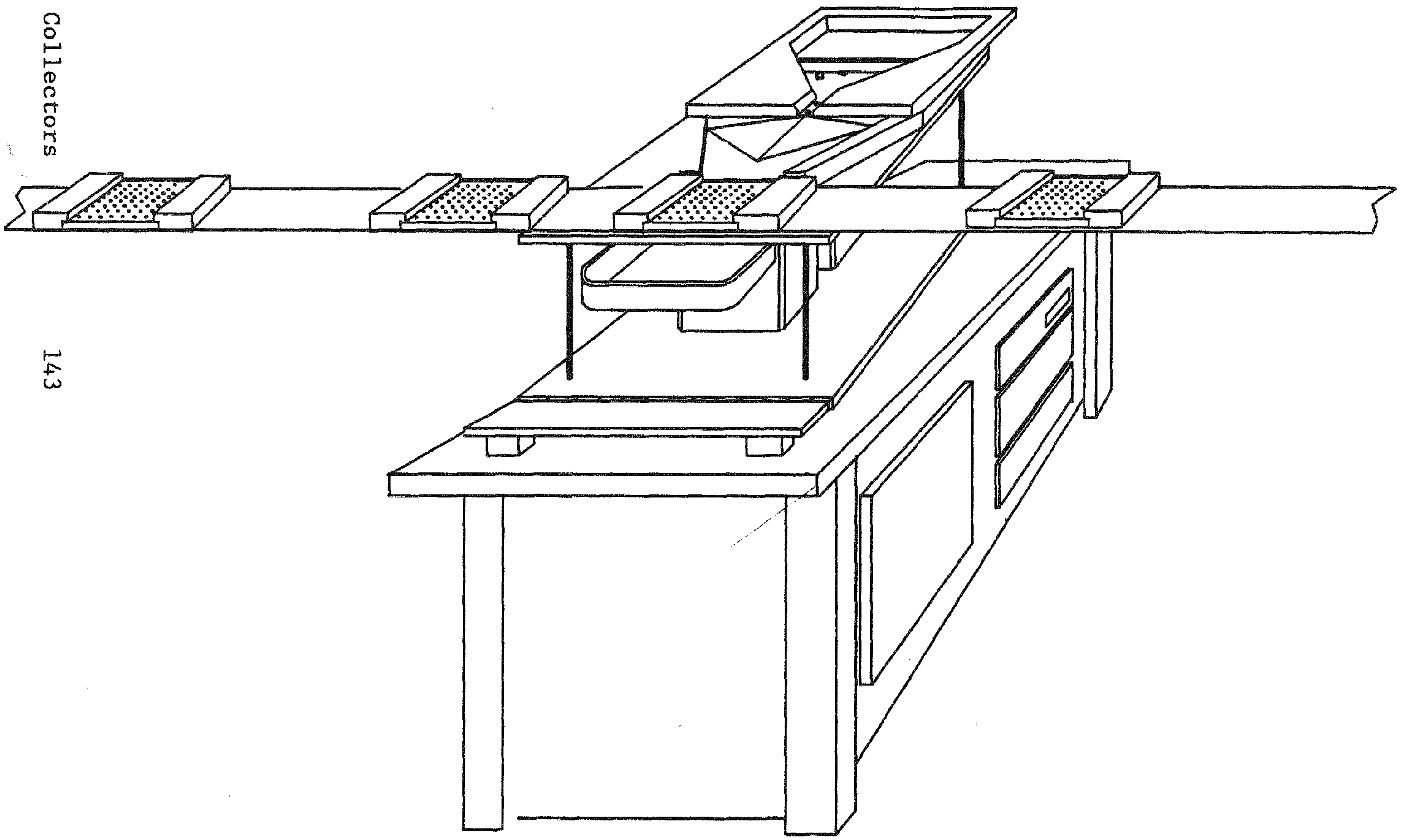


FIGURE 4 RANDOM PHOTO-CELL LOADER

Title: Short Focal Length Photovoltaic Concentrator

Contractor:

Wattsun Corporation
P. O. Box 751
Albuquerque, NM 87103

Principal Investigator:
Virgil Erbert
Telephone:
(505)-281-1489
Current Contract Number:
57-7300
Current Contract Period:
From: 8/88 **To:** 8/89
Project/Area/Task:
Photovoltaic Technology Project
Task 6.1: Concentrator Collector Research, Module Research

Directing Organization:
Sandia National Laboratories
Project Engineer:
Clement J. Chiang
Telephone:
(505)-846-3983
Contract History:

Number	FY	Level	Source
57-7300	1987	$75,000	DOE
57-7300	1988	$75,000	DOE

Objective: The objective of this contract is to develop a novel type of concentrating solar collector. Its unique features include small cells and small facetless lenses, a thin profile, and an integral cell assembly and module backplane. Its advantages are small volume, high optical efficiency due to the facetless lenses, high cell efficiency due to low series resistance and effective cooling of small cells, and potential for high voltage output.

Approach/Present Tasks: (7) Development of an optimum module design, (8) development of a reliable and durable module, (9) module construction, and (10) automated module production. Tasks 1 through 6 are not currently active.

Status/FY 1989 Accomplishments: While maintaining the size of the lens and approximately the same concentration ratio, the lens and cell were re-designed for a ± 3-degree tracking error. Initial computer results suggested that this tolerance to tracking error could be obtained with only a small performance penalty. Currently, a second phase of cell procurement is underway to resolve the low cell performance measured for the first batch of cells. An alternate means for automatically locating the cells on the receiver sheets is being considered to avoid the high capital cost of pick-and-place machinery. A supplier for the new lens has been located.

Major Project Reports:

1. V. Erbert, "Short Focal Length Concentrating Photovoltaic Collector," Proceedings of the 20th IEEE Photovoltaics Specialists Conference, Las Vegas Nevada, September 1988, pp. 1144-1149.

2. V. Erbert, "Wattsun Module Development," Presented at the Joint Crystalline Cell Research and Concentrating Collector Projects Review, Albuquerque NM, SAND88-0522, July 1988.

Summary Date
June 1989

Advances in 3M Lensfilm Fabrication

A. Zderad, 3M

(Material not available at time of printing)

Title: 3M Thick-Film Lens Film

Contractor:
3M Company
Optical Technology Center
3M Center
St. Paul, MN 55144-1000
Principal Investigator:
A. J. Zderad
Telepnone:
(612) 733-4892
Contract Number:
63-5668
Current Contract Period
From: 10/88 **To:** 8/89
Project/Area/Task:
Photovoltaics Technology Project;
Concentrator Module Research

Directing Organization:
Sandia National Laboratories
Project Engineer:
Charles B. Stillwell
Telephone: (505) 844-2130
Contract History:

Number	FY	Level	Source
63-5688	1988	$87,000	DOE

Objectives: To produce thick (0.08 - 0.125") lens films 2 x 7 lens parquets and ENTECH 22X lenses using the polymeric web process that will not require laminating to an acrylic superstrate.

Approach/Present Tasks: (1) Design and fabricate the tooling modifications necessary to adapt the continuous film polymeric web process to allow producing lens film in the 0.80" to 0.125" thick range. (2) Produce sample lens film 2 x 7 lens parquets and 22X lenses with the thicker dimension. Evaluate the parquets. (3) Perform a study to determine the trade-off in lens thickness and lens size.

Status/FY 1988 Accomplishments: (1) Request for quotation sent and response received and evaluated. (2) Contract award awaiting agreement on contract terms and conditions.

FY 1989 Milestones: (1) Contract awarded 11/88. (2) Fabricate thick film 2 x 7 lens parquets. (3) Evaluate parquet and 22X lens performance. (3) Perform trade-off study.

Major Project Reports: None.

Summary Date:
June 1989

SEACorp Module Development

Don Curchod
SEA Corp
2030 Fortune Dr. San Jose, CA 95131
(408) 434-6600

1 .Abstract

Solar Engineering Applications (SEA Corp) is a new, innovative company that is taking a fresh look at concentrator design with the goal of reducing PV electrical costs to below utility market penetration threshold. Cost figures, based on quotes from reputable vendors, indicate energy costs of 8.3 ¢/kW-hr at a 25mW per year production rate with estimates of 4.3¢/kW-hr for a 100+ mW per year production rate.

Our module design utilizes low cost, one-sun cells operating at 10x concentration with single- axis tracking. A curved, linear focus Fresnel lens is co-molded with the module housing in a high production rate linear extrusion. An integral back-plane, extruded aluminium receiver snap-assembles to the bottom of the housing, thus forming the fourth side of the module. The inside of the housing is metalized, acting as a secondary optical element for increased off-axis tracking performance.

SEA Corp is presently engaged in prototype lens development. Progress has been slow but steady and indicates that the goal of a 70% minimum lens transmission is within reach, as per test data presented. Our immediate plans for the future include a prototype module within one year.

2.Back ground

The high concentration, high efficiency design has been promoted in the past as the route to low cost electrical power: a philosophy based on theoretical computations. The cells and hardware necessary for this route have been generally unobtainable or very high in cost. To date, the least expensive and more successful commercial systems have tended to have lower concentration using inexpensive cells.

SEA Corp has taken a fresh approach to concentrator design, based on actual cost quotes, not theoretical computations. We have focused the design on the reduction of a system to its simplest and most easily produced form using:

1. The most cost effective overall design.
2. The most cost effective cells.
3. The most cost effective production methods.

3. SEA Corp Concentrator Design

3.1 General

The SEA Corp design uses established principles and has a number of unique design improvements which enables a low volume energy cost of less than 8.3 ¢/kW-hr to be achieved with currently available cells and processes (See figure 1). The system utilizes single-axis tracking and wide acceptance angles for low installation and tracking mechanism costs. No close tolerances are required while frame and installation are simple and inexpensive. The novel features include:

1. A short focus extruded Fresnel primary lens.
2. Integral extrusion of primary lenses and housing.
3. Inexpensive one sun cells operating at 10x concentration.
4. Internal fully reflective module sides operating as secondary optics.
5. Wide acceptance angles.
6. One axis wide tolerance tracking.
7. Low cost cell wiring design.
8. A minimum cost, extruded heatsink to complete enclosure.
9. A fully waterproof enclosure.
10. Low cost frame and installation.

Typical Module Cross Section

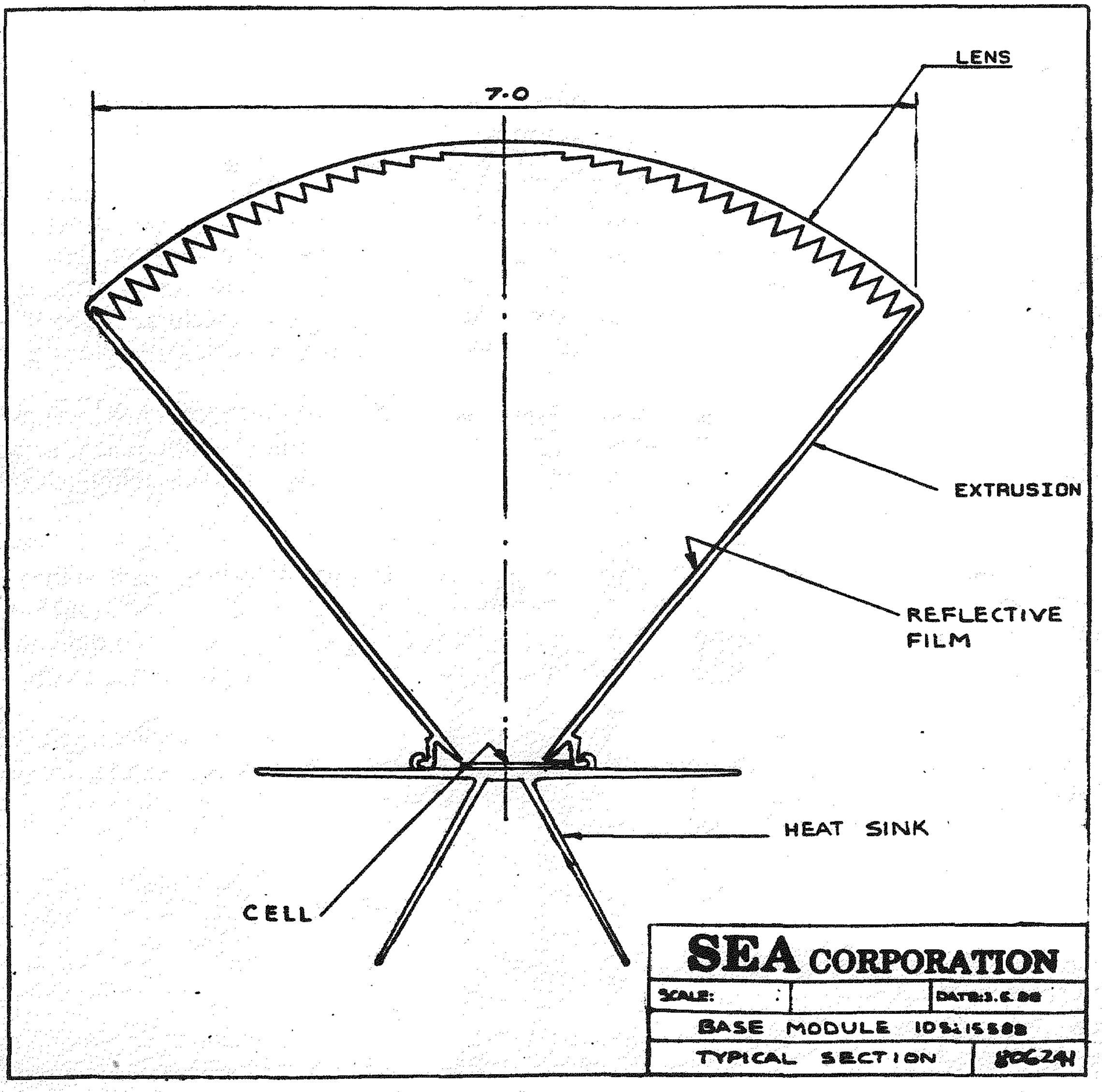


Figure 1

3.2 Optical

The primary optical element consists of a curved linear-focus Fresnel lens. Refraction is shared by the top and bottom surfaces of the lens in order to reduce losses. Tip radii losses are eliminated by tilting the tips out of the optical path. Over 90% transmission is possible with this design. With a curved lens, a shorter focal length can be used thus effecting manufacturing cost and tracking error tolerance.

The Fresnel lens, being a linear extrusion, is molded in conjunction with the sides of the module and is the least expensive manufacturing process available. The inside surfaces of the module sides are coated with a reflective material and form a secondary optical element. This system is then used to collect the rays that are otherwise lost during off-track operation and provides for up to 4° of tracking error (see figure 2). Although a solid secondary lens will provide additional off-track performance, the added material costs negate any advantages. Thus, the Fresnel lens and module housing and secondary optical elements are all formed in one operation.

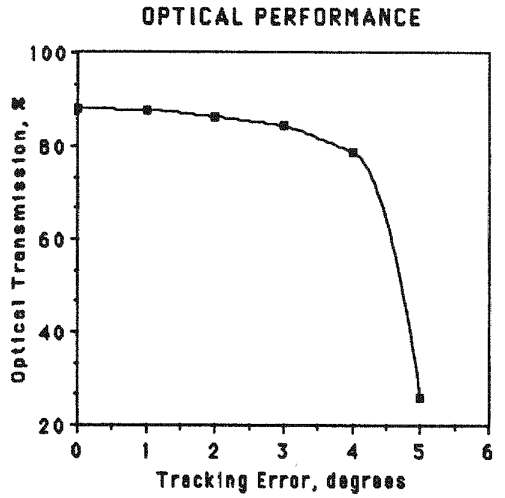


Figure 2

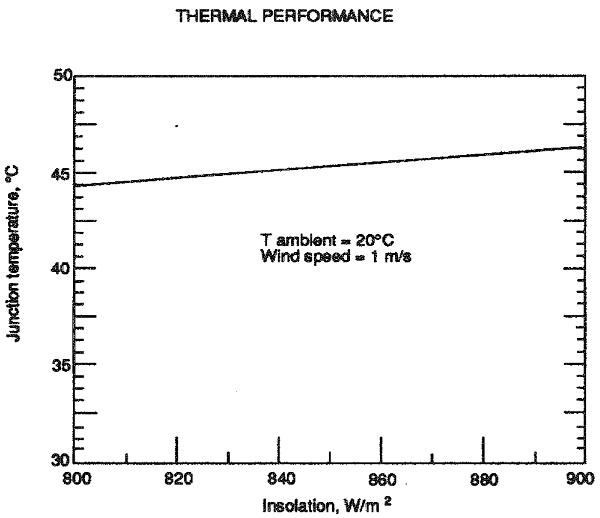


Figure 3

3.3 Receiver Section

The cells of the module are bonded to an anodized alumium extrusion heat-dissipator using a heat conductive room temperature vulcanizing silicone rubber (RTV). An electrophoretic coating, in combination with the anodizing and the RTV, provides the necessary electrical standoff. The heat-dissipator snap assembles to the module housing side, providing the bottom of the enclosure. With this concept, part count and assembly time is at a minimum and performance is maximized.

There are no solder joints between the cell and the heat dissipator which eliminates many of the problems associated with soldering. The heat conductive RTV is applied in such a way that it excludes air (voids). It will give practically infinite fatigue-life when used in this application. Because of the low aperture area and the low concentration of this design, soldering and costly heat-spreaders are not necessary in order to obtain low cell junction temperature. The normal operating cell temperature of this design is approximatley 45°C (see figure 3). The integral primary lens and side construction of the module have excellent weatherproofing features. The bottom of the housing is also fully sealed by the addition of two rows of silicone-type sealant prior to the assembly of the heat-dissipator. End caps are chemically bonded to the housing extrusions, making each module a completely enclosed and weatherproofed unit.

3.4 Array Assembly and Installation

Each module end cap has a molded shaft which sits in a bearing carried by two long members. These are held apart by two cross members . A drive arm is bolted to the end of each module. These arms are linked together and driven by a common tracker drive. One of the long members is supported by legs sized to provide the proper array angle and to maximize yearly output at the specific site. All the array elements are made of environmentally protected, stamped steel.

4. Lens Development

The most significant aspect of this low cost design is the ability to extrude a lens with an optical efficiency of approximatly 70% or more. SEA Corp is currently involved in developing a protoype lens extrusion under Sandia contract .

Design and cost analysis demonstrate that the least expensive concentrator module should involve a linear extrusion, particularly if the lens and sides are extruded in one piece. The module is thus configured to allow for this construction. The surface finish, tooth definition, tip and root radii cannot be held to better than approximately .005 inches so a lens design was necessary to give better than 70% optical efficiency using these parameters. The relatively large facets and the fully reflective sides of the module (see figure 1) give us the required theoretical efficiency. Actual extruded samples have acheived shapes close to these design tolerances, as presented.

5. Costs

Assumptions:

1. Small to medium volume, i.e. approximately 20 to 50mW.
2. All major parts are subcontracted.
3. All assembly is done in-house.
4. 70% minimum optical efficiency lens system.
5. 15% cell efficiency.
6. Low capital investment.
7. All major component costs are based on outside vendor quotes.

Energy cost:

Energy cost is calculated from the formula presented in the DOE Five Year Research Plan 1987-1991, Table a-2, using a fixed change rate of 0.091 (constant dollars).

EC = Energy Cost = 0.083 $/kW-hr.

System cost/price, medium volume (25mW):

1.	Module material	25.0
2.	Module assembly/labor	3.0
3.	Array material (excluding module)	8.0
4.	Array assembly/labor	2.0
5.	Array installation/labor	0.3
6.	PV cell 10x Si (15%)	25.0
7.	Other (20%)	12.8
	Total direct cost	**76.0 c/W**

Add 10% for losses in inverter and wiring	83.6 c/W
Allowance for 40% gross margin	$1.39 /W
Add 15 c/W for subcontracted inverter	$1.54 /W
Total price of installed system	**$1.54 /W**
or	**8.3 c/kW-hr.**

Higher volumes of approximately 100+ mW are expected to give considerable cost reductions through the following:

1. Higher volumes.
2. Vertical integration.
3. Improved efficiency of labor and tooling.
4. Improved cell costs.
5. Improved cell efficiency (20%).
6. Improved optical efficiency.

We feel that, given the above factors, SEA Corp can reasonably substantiate the proceeding volume costs.

System Cost/Price high volume (100+mW):

1.	Module material cost	15.0 c/W
2.	Module assembly / labor	3.0 c/W
3.	Array material	5.0 c/W
4.	Array assembly / labor	2.0 c/W
5.	Array installation / labor	.5 c/W
6.	PV Cells 10x Si (20%)	12.0 c/W
7.	Other (10%)	5.0 c/W
	Total direct cost	**42.5 c/W**
	Add 10% for losses in inverter wiring	47.0 c/W
	Allowance for 26% gross margin	63.0 c/W
	Add 10 c/W for subcontracted inverter	
	Total price of installed system	**73.0 c/W**
	or	**(4.3 c/kW-hr)**

6. Status

SEA Corp is presently engaged in lens development stages . Design work has been underway since 1986, and actual lens development has been continuing for the last 9 months, under Sandia Contract number 63-85733. This work is nearing completion and lens samples have lately shown promise of meeting the 70% minimum goal within projected costs, per data presented.

7. Plans

SEA Corp is continuing with the evolution of the lens. We are investigating post-molding forming techniques to enhance our optical efficiency. We hope to start development of the receiver section, including the heat-dissipator extrusion and to have a working protoype module within one year. Such work is contingent upon augmentation of SEA Corp's private funding by other outside sources.

Photovoltaic Module Lens

Project/Area/Task:
Photovoltaics Technology Project; Concentrator Module Research

Contractor:
Solar Engineering Applications Corporation
2030 Fortune Drive
San Jose, CA 95131

Principal Investigator: D. Curchod

Telephone: (408) 434-6600

Contract Number: 63-8573

Current Contract Period From: 7/11/88 **To:** 4/11/89

Directing Organization:
Sandia National Laboratories

Project Engineer: C.B. Stillwell

Telephone: (505) 844-2130

Contract Funding:		**Source:**
FY 1988	$25,000	DOE

Objectives:

To design and have fabricated a lens for a novel proprietary photovoltaic module.

Approach/Present Tasks:

- Perform trade-off studies to determine optimum lens size for module.
- Design the lens.
- Have lens fabricated.
- Evaluate lens.
- Prepare report on lens work.

Status/FY 1988 Accomplishments:

- Trade-off studies complete.
- Lens design complete.
- Lens fabricator selected.

FY 1989 Milestones:

- Fabricate lenses.
- Evaluate lenses.
- Prepare report on lens work.

Major Project Reports:

None.

Summary Date: November 1988

CONCENTRATOR RELIABILITY RESEARCH*

Jet Propulsion Laboratory
R. G. Ross, Jr. and R. S. Sugimura

Project Description

The objective is to perform reliability research aimed at understanding the physics of selected failure mechanisms associated with photovoltaic concentrator modules and to develop generic reliability enhancement techniques to improve concentrator array performance. The ongoing FY89 research tasks and recent results are described below.

Task 1

Perform research on high-voltage electrical breakdown in the receiver assemblies of concentrator modules to determine susceptibility to failures and to identity design guidelines for improving reliability. The focus is on the reliability and durability of Sandia-provided samples consisting of electrophoretically applied thin-film insulation materials on aluminum substrates.

Recent Results: A hard anodic layer is a good electrical insulator, with the exception that pinhole flaws inherently exist as a result of the anodization process. The subsequent application of the styrene acrylate through the electrophoretic process is intended to completely fill those flaws thus producing a pinhole-free dielectric layer.

To characterize resistance to electrical breakdown, samples of aluminum coated with the electrophoretic (EP) coating material were subjected to high-voltage stresses using a Biddle Instruments partial discharge detection apparatus to measure (1) the corona inception voltage levels (the voltage at which the average magnitude of detected pulses within the EP material voids is 5 pC) and (2) the 60-second pulse-energy spectrum of the insulation, from which the average power dissipated in void discharges can be determined. The latter quantity is important because each discharge results in a small amount of damage to the void walls; continual discharges form trees within the insulation that ultimately develop into breakdown channels.

Corona inception voltage (CIV) and voltage breakdown (Vbd) measurements of ten 2" x 3" samples are shown in Table 1. Each sample is 40-mil thick 5005 H-34 aluminum with approximately 1 mil of hard anodic layer and about 0.5 mil of electrophoretically deposited styrene acrylate. Data scatter on these samples was greater than previously obtained with another set of samples consisting of styrene acrylate on aluminum without the anodization. At first we thought that perhaps pinhole flaws or impurities exist in these later samples, resulting in high electrical stress concentrations, but further work at Sandia indicates that the problem may be due to the particular EP coating process used to coat these samples.

---

* This activity represents one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, for Sandia National Laboratories, U.S. Department of Energy, through an agreement with the National Aeronautics and Space Administration.

As the data in Table 1 shows, measured CIV's vary from under 1 kVdc to over 3 kVdc. In almost all cases where breakdown occurred, the measured breakdown voltage was very near the corona inception level. For high-quality (pinhole-free) samples, the corona inception voltages are higher than field operating voltages, and in many cases exceed the voltage level used by the industry as a measure of satisfactory long-term field performance. For concentrator systems whose system voltage is no more than 750 V, these high-quality samples would pass the UL high-voltage breakdown test (twice system voltage + 1000 Vdc).

TABLE 1

Test Results Indicating Corona Inception Voltage (CIV) and Voltage Breakdown (Vbd) Levels for Ten Samples of Hard Anodized 5005 H-34 Aluminum Electrophoretically Coated with Styrene Acrylate.

Sample ID	CIV (kV)	Vbd (kV)	Sample ID	CIV (kV)	Vbd (kV)
Z06F40B5	3.71	--	Z11F40B5	3.70	--
Z07F40B5	1.67	--	Z12F40B5	0.85	2.74
Z08F40B5	1.12	3.35	Z13F40B5	3.54	--
Z09F40B5	2.00	--	Z14F40B5	2.91	--
Z10F40B5	2.47	2.47	Z15F40B5	2.82	--

Task 2

Conduct exploratory research to address recent concerns raised regarding the susceptibility of concentrator modules to degradation and/or failures caused by moisture intrusion. Analyze the effect of moisture inside the modules, including long-term degradation, high-voltage failures (shorts), and safety considerations. Develop appropriate test procedures for qualifying concentrator modules to withstand the effects of moisture intrusion. Document the research, findings, proposed test procedures, and recommendations in an informal report to Sandia.

Recent Results: This activity has been initiated recently. JPL is awaiting receipt of a module housing to use in tests to determine the effect of moisture on leakage currents between the cell string and housing.

Task 3

Continue to assist Sandia in the areas of PV concentrator design and reliability on an as-requested basis.

Recent Results: This is an ongoing task addressing topics such as electrical design, high-voltage standoff considerations, materials analysis, and advice on testing standards.

Task 4

Participate on the PVUSA Technical Review Committee.

Recent Results: Support to the PVUSA Technical Review Committee is ongoing.

Title: Reliability Research on Photovoltaic Concentrator Modules

Contractor:
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Principal Investigator:
Ron Ross

Telephone:
(818) 354-9349

Current Contract Number:
42-4458

Current Contract Period:
From: 4/89 **To:** 4/90

Project/Area/Task:
Photovoltaic Technology Project
Task 6 Concentrator Collector Research

Directing Organization:
Sandia National Laboratories

Project Engineer:
Elizabeth H. Richards

Telephone:
(505) 844-6951

Contract History:

Number	FY	Level	Source
04-4848	1986	$50,000	DOE
02-2047	1987	$130,000	DOE
63-6078	1988	$40,000	DOE
42-4458	1989	$40,000	DOE

Objective: To make use of JPL's expertise in qualification testing and reliability modeling in the development of qualification tests and the the design of new concentrator modules.

Approach/Present Tasks: (1) Continue on-going research of the reliability and durability of electrophoretic coatings used for high-voltage electrical isolation. (2) Conduct experiments and provide recommendations on the applicability of a wet insulation-resistance test for concentrator modules. (3) Assist Sandia in research on advanced concentrator module design and reliability, including assessing existing technologies, developing test methods to identify/resolve problems, and recommending corrective action. (4) Provide support to the PVUSA Project by serving on the Technical Review Committee.

Status/FY 1989 Accomplishments: (1) Conducted experiments to determine the properties of electrophoretically deposited styrene acrylate coatings. (2) Provided support to the PVUSA Project by serving on the Technical Review Committee.

FY 1989 Milestones: (1) Complete high-voltage breakdown studies and publish report. (2) Conduct wet insulation-resistance experiments on concentrator module housing. (3) Continue serving on the PVUSA Technical Review Committee.

Major Project Reports:

- Gonzales, C. C.; Ross, R. G., Jr.: Design of Fault-Tolerant Circuits for Photovoltaic Concentrators, SAND88-7027 (Albuquerque: Sandia National Laboratories, July 1988).

Summary Date
June 1989

HOLOGRAPHIC NON-DESTRUCTIVE EVALUATION OF PHOTOVOLTAIC CONCENTRATOR CELL ASSEMBLIES

Larryl Matthews and Gina Rightley
New Mexico State University

The reliability of a photovoltaic concentrator depends to a large extent on the reliability of its cell assemblies. The cell assemblies are responsible for all of the energy produced by a module, so their survival is critical. Also, the failure of one cell assembly is likely to remove others from the energy-producing circuit. The cell assemblies experience much larger temperature gradients than the rest of the module and must survive repeated thermal cycling for thirty years. Testing, both in the field and in the laboratory, has identified many weaknesses in the reliability of concentrator cell assemblies, especially in their solder bonds.

Two non-destructive testing techniques used in the course of studying cell assembly reliability are X-ray and ultrasonic analysis. These techniques are very useful in examining the quality of solder bonds in cell assemblies. Holographic non-destructive evaluation (HNDE) was first considered as a supplement to these two methods in identifying internal flaws or defects in solder bonds.

Holographic interferometry (holography) involves taking a reference hologram of an object, thermally (or otherwise) stressing the object, and then taking a second hologram to produce a double exposure. The interference fringes produced show the deformations caused by the applied stress. These deformations can be viewed in real time and recorded using a video camera. To see if HNDE could detect defects in cell assemblies, an assembly was heated with a spot heater, and a double exposure hologram was taken as it cooled, Figure 1. While limited information about the defects in the solder bonds was obtained, HNDE showed greater promise of being able to detect the deformations experienced by the cell assembly as it was thermally stressed. This type of information would be very useful in understanding the stresses in solder bonds and in designing reliable cell assemblies. The primary focus of the project then became the qualitative determination of the movement of the various cell assembly components as they were thermally cycled.

It was soon established that holography could be used to detect the type and direction of motion experienced by the components in the assemblies. Holometry also allows for realistic testing conditions, both with overall and direct heating of cell assemblies. Overall heating is done in an oven with a quartz window. Direct heating is applied to the cell assembly with a spot heater directed at the cell. This second method most closely represents actual field use conditions and is also the most easily repeatable both in terms of results and time. Now that it was possible to "see" the movement of the cell and cell assembly components, it became desirable to determine the magnitudes of these movements.

Currently, the emphasis of this project is to develop a technique to study the long term reliability of photovoltaic concentrator cell assemblies, specifically concentrating on the solder bonds and associated thermally induced deformations. It is desirable to determine how various combinations of solder materials and assembly design affect the stresses experienced by the

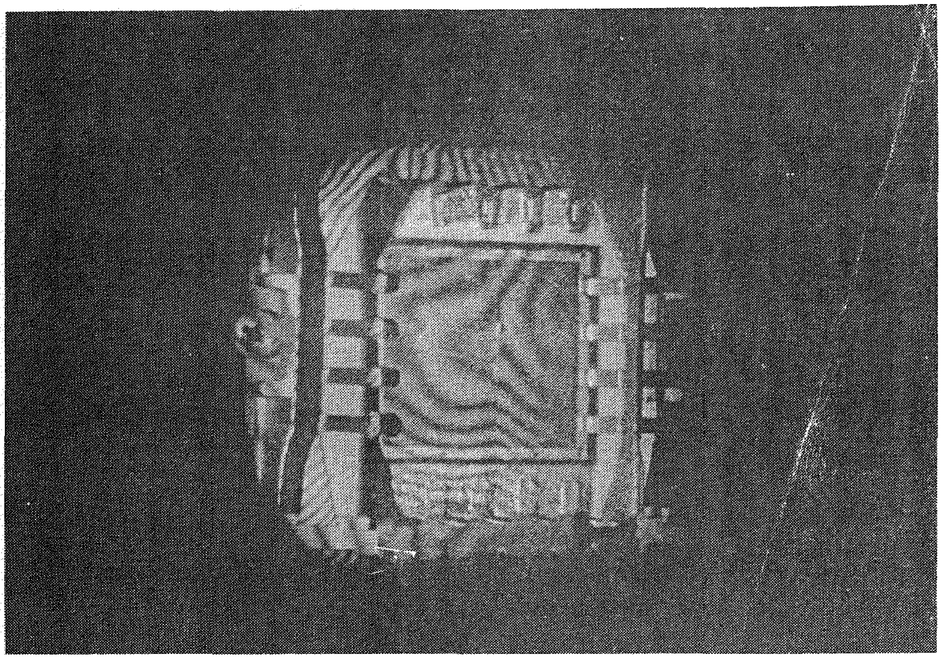


Figure 1. Double Exposure Hologram of a Cell Assembly.

solder bonds as the cell assembly is thermally cycled. A quantitative evaluation of the results from HNDE should help in optimizing cell assembly design. It may also provide valuable information about how to qualify these parts for thirty-year life in the field.

Ideally, the values of displacement and strain would be available to the experimenter in a real-time process, enabling a deformation and strain history of an object to be recorded as the deformation is occurring. The software is currently being developed to allow an experimenter immediate access to this displacement and strain information. This will be accomplished by combining the method of holographic interferometry with Abramson's Holodiagram String Analogy (a technique whereby actual displacement measurements can be obtained by visual observation of fringe patterns). Other computer programs being developed for the project include a program to compare the accuracy of the string analogy to a standard matrix model and a program designed to determine an optimal location for the placement of the holograms to minimize the error associated with their physical location. An error analysis will be included in the software to output the range of error on the calculated deformations.

Title: Holographic Non-Destructive Testing of Photovoltaic Concentrator Cell Assemblies

Contractor:
New Mexico State University
Office of Grants and Contracts
Box 3699
Las Cruces, NM 88003

Principal Investigator:
L. Matthews and G. Rightley

Telephone:
(505) 646-2221

Current Contract Number:
33-3506

Current Contract Period:
From: 2/87 **To:** 6/89

Project/Area/Task:
Photovoltaic Technology Project
Task 6 Concentrator Collector Research

Directing Organization:
Sandia National Laboratories

Project Engineer:
Elizabeth H. Richards

Telephone:
(505) 844-6951

Contract History:

Number	FY	Level	Source
56-6990	1986	$45,692	DOE
33-3506	1987	$49,069	DOE

Objective: To develop holographic interferometry (holometry) as a nondestructive testing method for photovoltaic concentrator cell assemblies. To use holometry to assess the deformations experienced by cell assemblies during thermal cycling.

Approach/Present Tasks: (1) Expand technique to view deformations in three dimensions. (2) Develop means to quantify deformations. (3) Use holometry to analyze cell assemblies.

Status/FY 1989 Accomplishments: (1) Holographic data has been taken in two dimensions. (2) A computer program that calculates deformations in three dimensions is operational. (3) A method for estimating errors has been developed.

FY 1989 Milestones: (1) Modify computer program to accommodate deformations in three dimensions. (2) Expand computer program to take holographic data directly and compute deformations in three dimensions. (3) Write report covering all work under this and the previous contract.

Major Project Reports:
- Rightley, G. S.; Mulholland, G. P.; Matthews, L. K.; "A Computer Analysis of 3-D Deformations: Using N. Abrahamson's Holodiagram String Analogy to Obtain Quantitative Results". Presented at the 2nd International Symposium on Industrial Uses for Holography, October 4-6, 1988.

Summary Date
June 1989

DESIGN AND DEVELOPMENT OF AN INJECTION MOLDED FOUR LENS ARRAY

by

AMERICAN OPTICAL CORPORATION
PRECISION PRODUCTS BUSINESS
14 Mechanic Street
Southbridge, MA 01550

Principal Investigator: Clark L. Grendol
(508)765-9711, Ext. 2417

Contract No.: 23 - 7089
Contract Amount: $296,302
Contract Duration: 23 months

PROJECT DESCRIPTION

The objective of this contract is to design and develop an injection molded four lens array. This array is to be one unit as molded and will contain curved facet Fresnel lenses. Each lens segment in the array is to have an efficiency greater than 80%. The array will be molded with a .125" cross section in order to function as a 'stand - alone' system.

This contract will build upon technology developed in a prior contract for a single injection molded Fresnel lens. This technology involves the use of a curved facet lens design, center gating in each lens segment, vacuum assist for molding and diamond turning to produce the Fresnel mold inserts.

The arrays will then be tested at SNL to determine the efficiencies and the 'stand - alone' capability.

CURRENT STATUS

The lens design for the individual lenses is complete and the fabrication of the diamond turned Fresnel inserts is in progress.

The full array mold and hot runner system are being fabricated. Test molding on the individual Fresnel inserts will begin in June.

KEY RESULTS

As this contract is in the tooling fabrication phase, there are no results to report.

Injection-Molded Lens Parquet

Project/Area/Task:
Photovoltaics Technology Project; Component Research

Contractor:
American Optical
14 Mechanic Street
Southbridge, MA 01550

Principal Investigator: C.L. Grendol

Telephone: (617) 765-9711 ext. 2417

Contract Number: 23-7089

Current Contract Period From: 12/87 **To:** 8/89

Directing Organization:
Sandia National Laboratories

Project Engineer: C.B. Stillwell

Telephone: (505) 844-2130

Contract Funding:		Source:
FY 1987	$273,600	DOE
FY 1988	$22,700	DOE

Objectives:

To develop a 2 x 2 injection-molded Fresnel lens parquet. To deliver 100 parquets.

Approach/Present Tasks:

- Design a Fresnel lens for use in injection-molding process.
- Procure four mold inserts for lenses in parquet.
- Make trial run of individual and parquet molds to optimize molding process.
- Deliver 100 final parquets.
- Deliver final report.

Status/FY 1988 Accomplishments:

- Lens design complete.
- All subcontractors selected.

FY 1989 Milestones:

- Make direct cut acrylic lens.
- Make individual lens mold inserts.
- Mold and evaluate lenses made from each insert.
- Make lens parquets.
- Evaluate lens parquets.
- Prepare final report.

Major Project Reports:

None.

Summary Date: November 1988

Impact Load Drive Model

Project/Area/Task:
Photovoltaics Technology Project; Concentrator Array Research

Contractor:
Oklahoma State University
School of Mech and Aero
Engineering North 218
Stillwater, OK 74078

Principal Investigator: T. Cook

Telephone: (405) 624-5900

Contract Number: 95-4188

Current Contract Period From: 10/11/85 **To:** 10/31/88

Directing Organization:
Sandia National Laboratories

Project Engineer: A.B. Maish

Telephone: (505) 844-8771

Contract Funding:		**Source:**
FY 1985	$49,080	DOE
FY 1986	-0-	DOE
FY 1987	$7,998	DOE

Objectives:

To develop a dynamic computer model of the interfaces between various gears so that impact loads can be determined. The results are applicable to analyzing fatigue load failure of solar array drives and to designing new drives to minimize fatigue load failures.

Approach/Present Tasks:

- Develop dynamic models of spur/spur, worm, and chain drive interfaces.
- Develop a code to link input loads and various drive element combinations.

Status/FY 1988 Accomplishments:

- Technical work was completed on the contract and a draft final report was drafted.

FY 1989 Milestones:

- Complete final report.

Major Project Reports:

None.

Summary Date: November 1988

Title: Imaging Secondary for Photovoltaic Concentrators

Contractor:
James Associates
1525 East County Road 58
Ft. Collins, CO 80524

Principal Investigator:
L. W. James

Contract Number: 05-8713

Current Contract Period
From: 9/26/88 **To:** 1/26/89

Project/Area/Task
Photovoltaics Technology
Concentrator Module Research

Directing Organization:
Sandia National Laboratories

Project Engineer:
C. B. Stillwell

Telephone: (505) 844-2130

Contract History:

Number	FY	Level	Source
05-8713	1988	$8700	DOE

Objectives: To furnish to Sandia updated version of imaging lens/Secondary Optical Element (SOE) software. To complete study of imaging lens/SOE and to prepare a final report.

Approach/Present Tasks: (1) Furnish updated software. (2) Complete study of characteristics and performance of imaging lens/SOE configuration. (3) Prepare final report.

Status/FY 1988 Accomplishments: (1) Request for quotation issued and response received and evaluated. (2) Contract placed.

FY 1989 Milestones: (1) Deliver software and report.

Major Project Reports: James, L. W., Using Refractive Secondaries in Photovoltaic Concentrators, SAND89-7029, Albuquerque: Sandia National Laboratories, July 1989. Work performed by James Associates.

Summary Date:
June 1989

Title: Fresnel Lens Material Aging

Contractor:
DSET Laboratories, Inc.
Box 1850 Black Canyon Stage I
Phoenix, Arizona 85029

Principal Investigator:
Chris Smith
Telephone:
(602)-465-7356
Current Contract Number:
32-9298
Current Contract Period:
From: 1/86 **To:** 1/91
Project/Area/Task:
Photovoltaics Technology Project
Task 6.3: Concentrator Collector Research
Concentrator Reliability

Directing Organization:
Sandia National Laboratories
Project Engineer:
Clement J. Chiang
Telephone:
(505)-846-3983
Contract History:

Number	FY	Level	Source
32-9298	1986	$1,100	DOE
32-9298	1987	$1,100	DOE
32-9298	1988	$1,280	DOE
32-9298	1989	$1,100	DOE

Objective: The objective of this contract is to determine the effect of both concentrated and one-sun sunlight on the optical transmittance properties of two types of acrylic lens materials over an extended period of time. Acrylic Fresnel lenses are essential components of current photovoltaic concentrating collectors. Detailed data concerning the optical transmittance properties of acrylic materials following prolonged outdoor exposure have not been systematically measured or well documented.

Approach/Present Tasks: The optical transmittance properties of two types of acrylic lens materials are measured as functions of duration of exposure to both concentrated and one-sun exposure environments. One type of material is suitable for compression molding and the other type is suitable for injection molding.

Status/FY 1989 Accomplishments: Exposure tests continue at DSET. Initial results from material characterization will be presented at the PRM meeting in Albuquerque in July 1989.

Major Project Reports: None.

Summary Date
June 1989

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III-V Cell Research

GaAs Cell Development at Spire

(Material not available at time of printing)

III-V Based Monolithic Multijunction Solar Cells at Varian

varian
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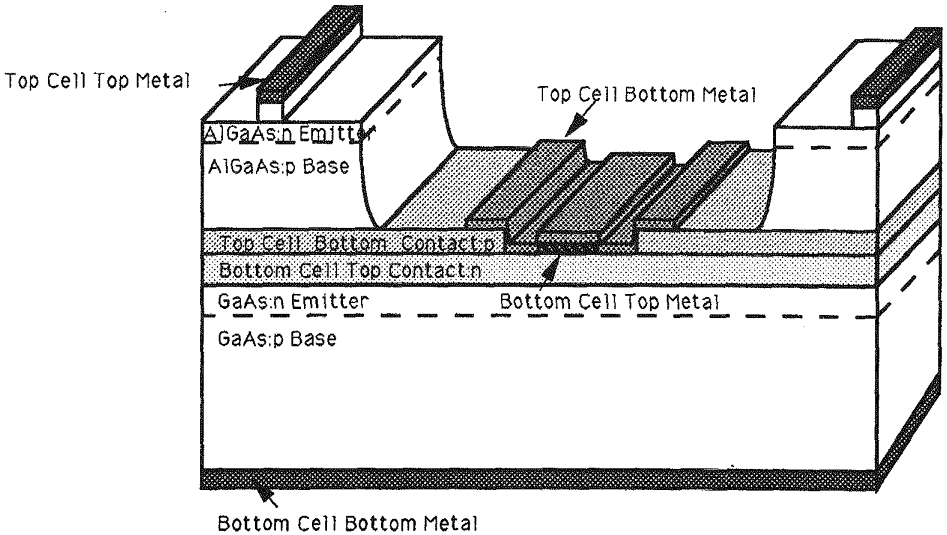

Gary Virshup
Varian Associates
Palo Alto, California

Present 1-Sun MICC Mask

varian
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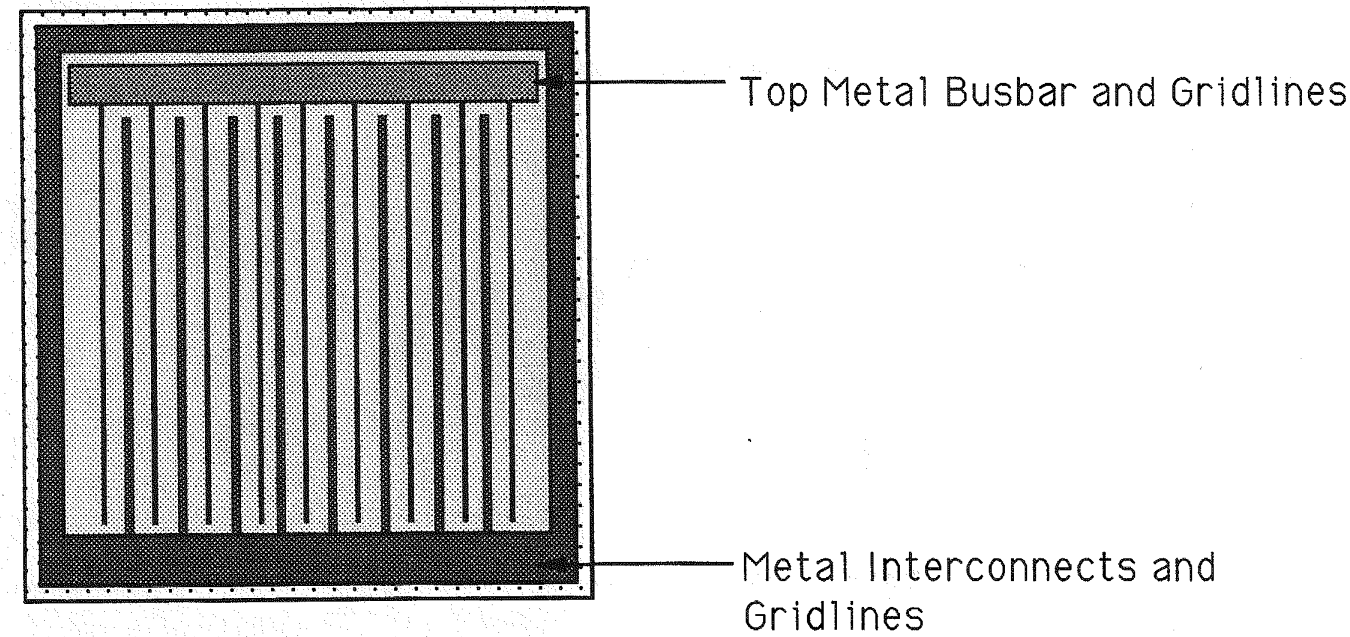

- Interconnect Spacing 254 µm
- Effective Gridline Spacing 204 µm

AlGaAs/GaAs MICC
1-Sun AM 1.5 Global

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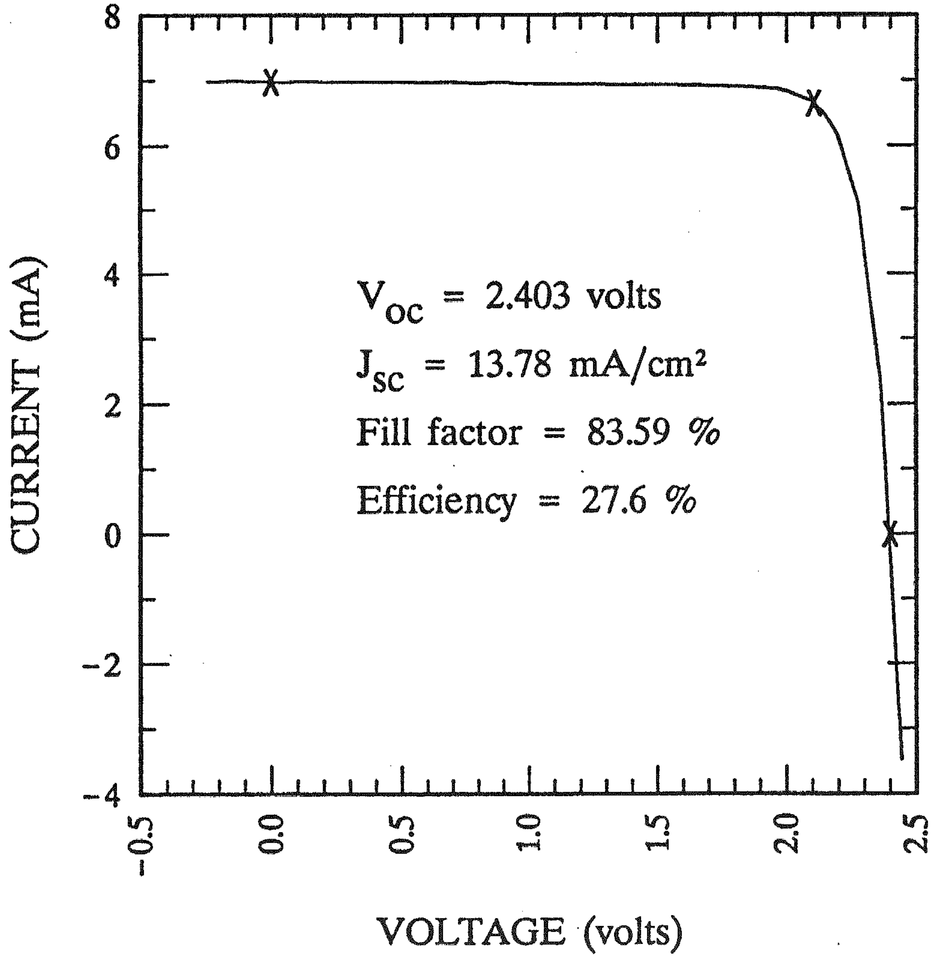

AlGaAs/GaAs MICC Measurements At AM1.5G and AM0

varian
RESEARCH CENTER

AM1.5G 100 mW/cm^2

AlGaAs	16.0	13.92	1.40	.818
GaAs	11.3	13.78	1.00	.820
MICC	27.6	13.78	2.40	.834
Three Terminal	27.3			

AM0 136.7 mW/cm^2

	h(%)	Jsc	Voc	FF
AlGaAs	14.6	17.34	1.41	.815
GaAs	9.33	15.44	1.01	.821
MICC	23.02	15.44	2.41	.845
Three Terminal	23.93			

Concentrator MICC Mask

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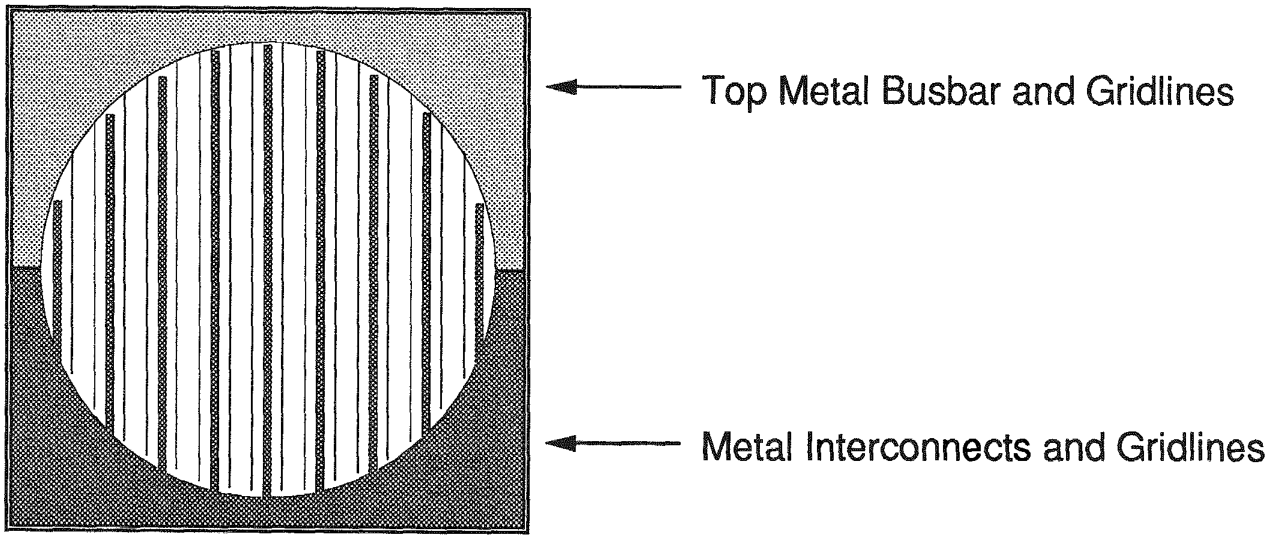


- Interconnect Spacing 127 μm
- Effective Gridline Spacing 50 μm

Development of Mechanically Stacked, Tandem Concentrator Cells

Project/Area/Task:
Crystalline Cell Research Task 4.2 Advanced Concentrator Cells

Contractor:
Varian Research Center
611 Hansen Way
Palo Alto, CA 94303

Principal Investigator: G.F. Virshup

Telephone: (415) 424-5091

Contract Number: 21-8460

Current Contract Period From: 12/85 **To:** 10/88

Directing Organization:
Sandia National Laboratories

Project Engineer: J.M. Gee

Telephone: (505) 844-7812

Contract Funding:		Source:
FY 1983	$175,000	DOE
FY 1985	$171,000	DOE
FY 1987	$20,000	DOE

Objective:

The objective of this contract is to develop an efficient top cell for a mechanically stacked, multijunction (MSMJ) solar cell.

Approach/Present Tasks:

The two top cells under development include a thin AlGaAs (1.75 eV) and a GaAs cell.

Status/FY 1988 Accomplishments:

- Thin AlGaAs cell was abandoned due to difficulties in processing of a thin cell.
- Stackable GaAs cells were fabricated on a low-doped substrates. Efficiencies of 27% were recorded under concentration, that led to demonstration of 30%-efficient GaAs/silicon mechanically stacked, multijunction solar concentrator cells.

FY 1989 Milestones:

- Complete final report.

Major Project Reports:

- J.M. Gee and G.F. Virshup, *A 31%-efficient GaAs/Silicon Solar Concentrator Cell.* Presented at the 20th IEEE Photovoltaic Specialists Conference, Las Vegas, Nevada, September 1988.

Summary Date: November 1988

HIGH EFFICIENCY GaAs/GaSb TANDEM SOLAR CELLS AND TANDEM CIRCUIT CARDS

Lewis Fraas, James Avery, John Martin, V. Sundaram, Gerald Girard, Van Dinh, N. Mansoori, and J. W. Yerkes

Boeing High Technology Center
Seattle, Wa. 98124-6269

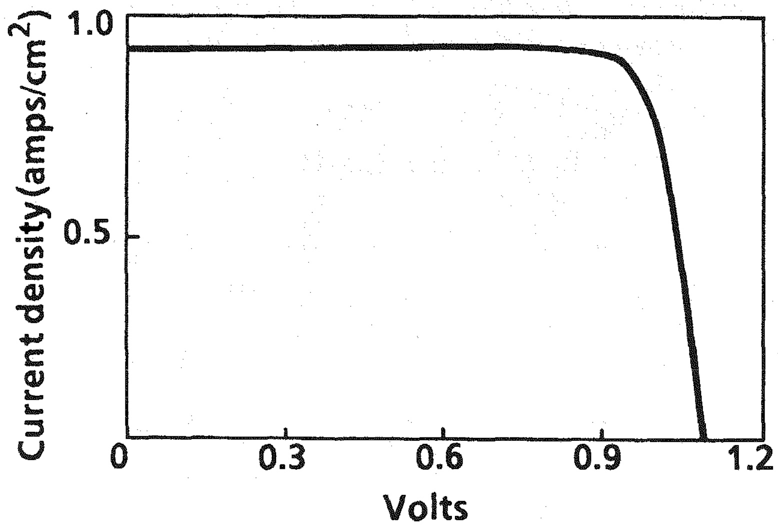
Although a GaAs solar cell has the highest energy conversion efficient currently available, this efficiency can be substantially increased by locating an infrared-sensitive booster solar cell behind a transparent GaAs cell. Herein, infrared-sensitive GaSb cells and visible-light-sensitive GaAs cells designed for satellite applications are described. As shown in figure 1, the best satellite component cell efficiencies add up to 28.1% under concentrated sunlight (30x AM0). Two terminal tandem cell circuit cards (2.25" x 2.25") containing nine transparent GaAs cells mounted over holes on the front side of a ceramic double sided printed circuit card and nine GaSb cells mounted on the back side of the same card are fabricated and tested (see the photograph of a tandem cell circuit card in figure 2). Satellite module circuit level conversion efficiencies over 25% (AM0) are demonstrated.

The tandem cell circuit card shown in figure 2 uses two separate silk screen printed wiring patterns on the front and back to voltage match the nine GaAs cells on the front of the card with the nine GaSb cells on the back of the card. Three groups of three parallel connected GaAs cells are wired in series on the front while the nine GaSb cells on the back are connected in series. The result is that the maximum power voltage for the GaAs circuit of 3 x 949 mV (from figure 1) = 2.85 V is nearly identical to the maximum power voltage for the GaSb circuit which is 9 x 360 mV (from figure 1) = 3.24 V. The tandem cell card becomes a two terminal voltage matched card when the front and back wiring patterns are interconnected with platted through holes at diagonal corners on the card.

Although we have focused our attention on satellite applications using sunlight concentration levels of approximately 40x, from measured GaSb cell quantum yield data and from the terrestrial AM1.5D solar spectrum, we project that a GaSb infrared cell will boost the conversion efficiency of a GaAs cell by from 7.0 to 8.7 percentage points depending on the sunlight concentration ratio (see tables 1 & 2). As can be seen from table 2, the best published GaAs cell data and our GaSb cell data show that tandem cell efficiencies in the vicinity of 35% are achievable for terrestrial applications.

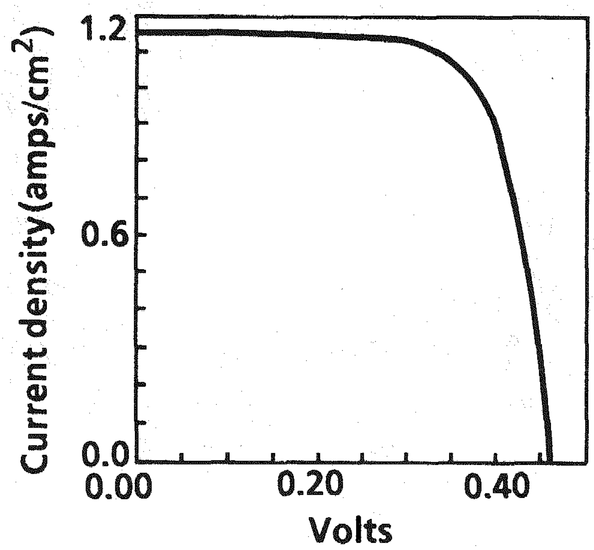
Best Boeing Component Cells

GaAs transparent cell



Efficiency	21.6%
Fill fact	83.6%
Volts oc	1087.8 mV
J sc	953.4 mamps/cm^2
Volts mp	948.5 mV
J mp	914.6 mamps/cm^2
#Suns	30 suns AM0

GaSb cell behind GaAs filter



Efficiency	6.5%
Fill factor	72%
Voc	465 mV
Isc	1150 mamps/cm^2
Vmax	360 mV
Imax	1060 mamps/cm^2
#Suns	44 suns AM0

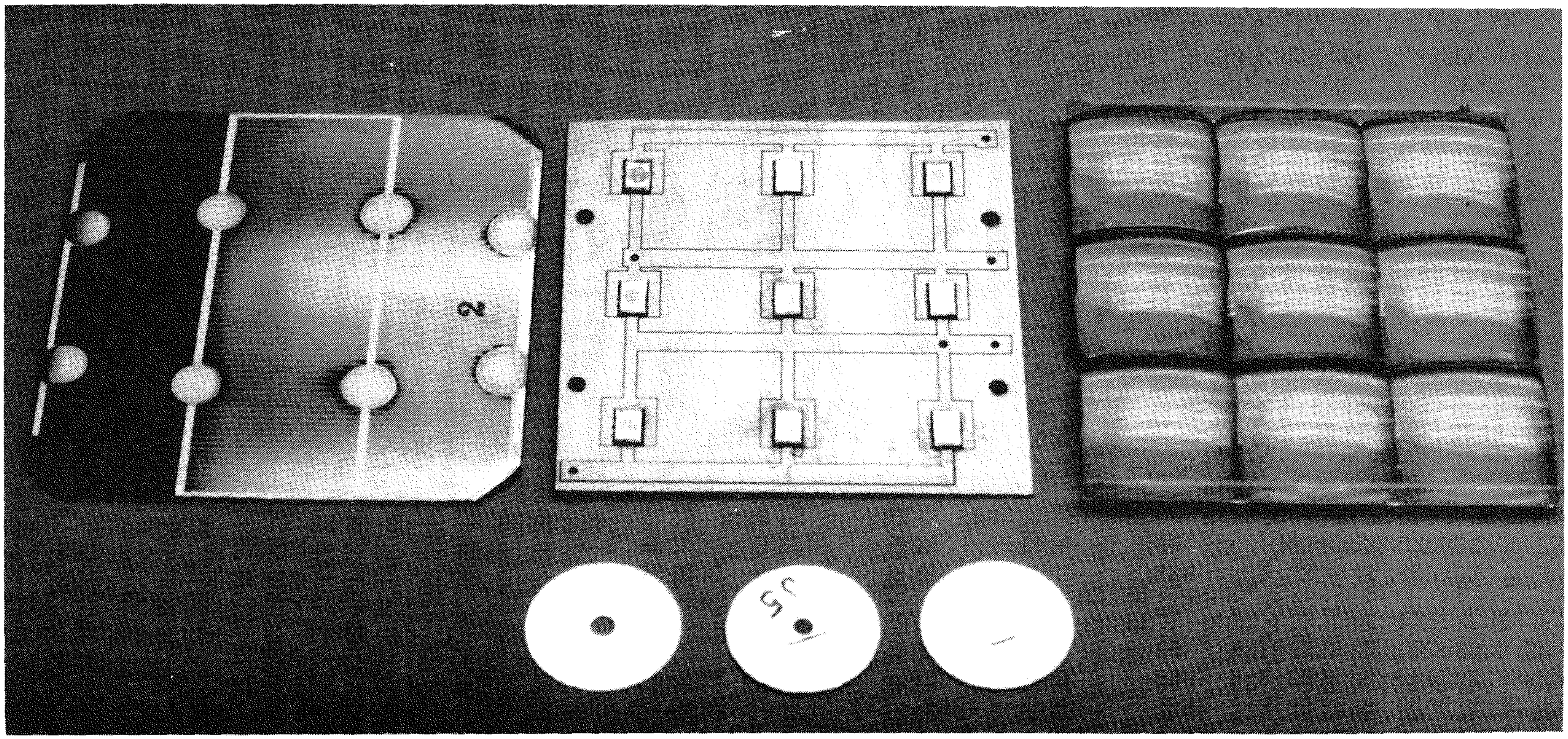


Figure 2: The 3 x 3 tandem cell printed circuit card (middle) is designed to be used with the 3 x 3 lens array (right). Designed to be used on satellites, the tandem cell circuit card efficiency of 25% is considerably higher than the 14% efficiency of a standard Si satellite cell (left). Three views of a single cell stack are also shown (bottom).

TABLE 1: AM 1.5D

MEASURED PERFORMANCE SUMMARY

	J*	V	FF	Effic.
GaSb 50X	21.0	.465	.72	7.0%
GaAs 50X	27.7	1.12	.86	<u>26.7%</u> 33.7%

*At 100 mW/cm^2 AM 1.5 direct

TABLE 2: AM 1.5D

PERFORMANCE PROJECTIONS

	J	V	FF	Effic.
GaSb 50X	21.0	.465	.77*	7.5%
GaAs 50X	27.7	1.12	.86	26.7% 34.2%
GaSb 500X	21.0	.52	.80*	8.7%
GaAs 500X	27.7	1.18	.86	28.1% 36.8%

* assuming negligible series resistance

AlGaAs/GaAs Superlattice Alloys as Solar Cell WIndow Layers

T. Drummond, Univ. of Michigan

(Material not available at time of printing)

Title: AlGaAs/GaAs Superlattice Alloys as Solar Cell Window Layers

Contractor:
University of Michigan
Dept. of Elect. Engineering
and Computer Science

Principal Investigator:
Dr. T. Drummond
Telephone:
313-936-2966
Current Contract Number:
75-7782
Current Contract Period:
From: 01/89 **To:** 04/90
Project/Area/Task:
Concentrator Solar Cells
Task 4.2: Advanced Concentrator Cells

Directing Organization:
Sandia National Laboratories
Project Engineer:
James M. Gee
Telephone:
505-844-7812
Contract History:

Number	FY	Level	Source
75-7782	1989	36,600	DOE

Objective: The objective of this program is to investigate use of AlGaAs/GaAs superlattice alloys (SLA) as a window material for GaAs solar cells.

Approach/Present Tasks: (1) Crystals are grown by MBE at Sandia Laboratories, and are then characterized at U. Michigan. (2) Perform a theoretical investigation of the properties of finite SLAs.

Status/FY 1989 Accomplishments: An approach for theoretically calculating the properties of a finite SLA using the R-matrix method has been developed. SLA samples have been grown and delivered to U. Michigan.

FY 1989 Milestones: Characterization of the SLAs.

Major Project Reports:
None.

Summary Date
June 1989

Sandia
In-House
Research

GaAs-Based Mechanically Stacked, Multijunction Solar Concentrator Cells

James M. Gee and Clement J. Chiang
Sandia National Laboratories

1. INTRODUCTION

A GaAs/silicon mechanically stacked, multijunction (MSMJ) solar concentrator cell was recently reported with an efficiency in excess of 30% [1]. This achievement was possible due to the maturity of GaAs and silicon cell technologies that were used as component cells. Use of GaAs as a top cell is particularly advantageous because the top cell produces the majority of the power output of a stacked cell and GaAs cells are already highly developed and have a wide enough bandgap for use as a top cell.

The purpose of the present study is to investigate the performance of an MSMJ concentrator cell with a GaAs top cell for use in high-concentration (>500X) modules. We first present a description of the concentrator module and the MSMJ concentrator cell. Next, we present a thermal analysis of the MSMJ cell assembly in the module. Finally, implications of the module operating conditions on design of the MSMJ cell are considered.

2. MODULE AND CELL DESCRIPTIONS

The allowable cell cost for a concentrator module increases with the geometric concentration ratio (GCR) of the module. Modules with GCR's of 500X and 1000X are considered in our analysis, since this is where an expensive high-efficiency MSMJ cell may be economically practical. A typical cell assembly for a high-concentration module is presented in Table 1. The optical efficiency of the module is taken to be 85%. The peak direct normal insolation value is taken to be 880 W/m^2, so that the the irradiance on the cells for the 500X and 1000X modules are 37.4 and 74.8 W/cm^2, respectively.

An MSMJ cell is schematically illustrated in Figure 1. Visible light is absorbed in the GaAs top cell, while infrared light is transmitted to the bottom cell. Design of the GaAs cell for optical transparency has been discussed elsewhere [1]. Two features of the mechanical design of an MSMJ cell are unique compared to single-junction solar cells. First, the cell assembly must have a four-terminal package, which is very important since this allows a wider selection of bandgaps (and therefore materials) for the component cells. Figure 1 presents one method for fabricating a four-terminal MSMJ cell.

The second unique feature of an MSMJ cell is the interlayer between the component cells. This interlayer (labeled "adhesive" in Figure 1) must serve the following purposes: (1) mechanical adhesion of the stacked cell, (2) electrical isolation between the top and bottom cells, (3) optical coupling between the top and bottom cells, and (4) thermal conduction between the top and bottom cells. The electrical isolation requirement is established by the electrical circuit of the module. There is no isolation requirement if the component cells are connected in series, and it is relatively modest (a few multiples of the upper cell voltage) if the component cells are wired in a voltage-matched configuration [2]. (Voltage-matched configuration refers to wiring the component cells in a series/parallel circuit such that the design criterion for selection of the component cell bandgaps is matched operating voltages.) If the top and bottom cells were to have independent loads, prudent design practices require that the electrical standoff between the top and bottom cells be on the order of the array voltage in order to protect the array from ground faults [2]. This is a difficult requirement to meet, so we feel that independent operation of the component cells is not feasible.

Silicone adhesives are well suited to the requirements for mechanical adhesion, modest electrical isolation, and optical transparency. Unfortunately, they have relatively poor thermal conductivities. Glasses have a higher thermal conductivity, but require high temperature processing that may damage the cells. We have therefore restricted our study to a silicone adhesive interlayer.

3. THERMAL ANALYSIS

The dominant ΔT in the MSMJ cell assembly is across the interlayer of the MSMJ cell due to the poor thermal conductivity of the adhesive. This ΔT can be estimated as follows. The heat load from the top cell is equal to the total power absorbed in the top cell minus the electrical power extracted from the top cell. Assume that the GaAs cell is 25% efficient at the module operating temperature. Approximately 60% of the incident solar light is absorbed in an ideal GaAs top cell, which has no absorption of sub-bandgap photons ($h\nu<E_g$) and no front-surface reflection. The remaining 40% of the incident solar light is transmitted to the bottom cell. Note that achieving good transparency for the top cell not only increases the power from the bottom cell, but also minimizes the thermal load from the top cell. The heat load q (W/cm^2) from the top cell that needs to be transmitted through the adhesive is thus equal to about 35% (60% absorbed minus 25% extracted) of the incident power. This corresponds to a heat load of 13.1 and 26.2 W/cm^2 for the 500X and 1000X modules, respectively. Neglecting interfacial resistance, the ΔT across the interlayer is given by:

$$\Delta T = \frac{q\delta}{k} \quad (1),$$

where δ is the thickness and k is the thermal conductivity or the interlayer. The calculated ΔT as function δ is shown in Figure 2 for an adhesive that we are considering (GE RTV 615, k=0.19 W/m/°C). Note that the ΔT is quite large unless a very thin layer (<25 μm) is used.

The temperature profile of the MSMJ cell and of the cell assembly presented in Table 1 was calculated with a two-dimensional finite element code. The finite element code has 278 nodes and can have up to 7 layers; it has been described elsewhere [3]. The code was modified so that power could be absorbed in and extracted from the first (top) and third layers, which correspond to the component cells of an MSMJ cell. Table 1 shows the calculated temperature profile through the center of the cell assembly for a 500X and a 1000X module. The temperature of the bottom cell from our calculations is 57.2°C and 59.8°C for the 500X and 1000X modules, respectively. The temperature of the silicon cell is largely determined by the heat sink temperature. The GaAs top cell has a much higher temperature due to the ΔT of the adhesive interlayer. The thickness of the adhesive interlayer was only 12.5 μm in these calculations to minimize the ΔT. For comparison, Table 1 also presents the calculated temperature profiles of the same cell assemblies with single-junction GaAs concentrator cells.

Table 1. Calculated temperature profile through the center of an MSMJ cell and of a GaAs cell assembly for 500X and 1000X modules. The lens size is 316 cm^2 and the flux distribution on the cell is a typical profile for well designed optics with a secondary concentrator. (NA = not applicable.)

Layer	Thickness (mm)	Radius (mm) 500X	Radius (mm) 1000X	k (W/m/°C)	Temperature (°C) 500X MSMJ/GaAs	Temperature (°C) 1000X MSMJ/GaAs
GaAs	0.305	12.7	9.0	46.0	68.7/58.4	80.0/62.7
Adhesive	0.0125	12.7	9.0	0.2	65.2/ NA	73.7/ NA
Silicon	0.305	12.7	9.0	150.0	57.2/ NA	59.8/ NA
Solder	0.051	12.7	9.0	30.0	56.6/56.3	58.5/58.5
Copper	3.175	76.2		380.0	55.4/55.0	56.4/55.9
Adhesive	0.127	76.2		0.8	54.2/53.6	54.7/54.1
Heatsink	1.588	200.6		200.0	52.5/51.9	52.7/52.0

GaAs concentrator cells are generally small (<1 cm^2), so that the total area ("die") of the cell is much larger than the illuminated area due to the relatively large contacting area required for attaching leads. This is particularly true for a stackable GaAs cell that has an elongated die in order to allow for four terminal packaging (Figure 1). The larger cell die suggests the possibility of heat spreading in the GaAs, which would lower q and thereby ΔT across the interlayer. This possibility was investigated with the finite element code. The temperature profile for a GaAs/silicon MSMJ cell in the cell assembly of Table 1 was calculated for GaAs cells with a die to illuminated area ratio between 1 and 5. It was found that the ΔT decreased by <3°C when the ratio was varied from 1 to 5. Heat spreading in the GaAs is present, but it is not a large effect. The lateral thermal resistance of the GaAs is too large to allow the cell to act as a heat spreader. The temperature profile of the top cell is very sensitive to the illumination profile for the same reason. For a peaked illumination distribution, we calculated a peak temperature of 95.8°C in the center of the top cell for the 1000X module, which is an increase of nearly 16°C compared to the more uniform illumination profile used for the calculations of Table 1. The optics of the concentrator module must therefore be carefully designed for uniformity for use with an MSMJ cell.

4. MSMJ CONCENTRATOR CELL DESIGN

The high temperature of the GaAs top cell is a serious concern, since the expected performance advantage associated with the bottom cell is offset by the decrease in performance of the top cell due to the ΔT of the interlayer. We have measured η temperature coefficients of 0.04%/°C (absolute) for GaAs concentrator cells. (All efficiencies are quoted in units of % absolute.) For ΔT's of 10 to 50°C, the loss in performance of the GaAs top cell due to the adhesive interlayer is 0.4% to 2.0%. This loss in top cell performance due to the interlayer can be a significant fraction of the bottom cell output, unless the adhesive layer is made very thin. Reliably producing such a thin bond without shorting the top and bottom cells is a concern. One option that we are exploring is loading the adhesive with a small amount of glass beads (less than 10% by volume). The beads, which are available with diameters of <1μm to 150μm [4], will space the two cells during assembly. A reproducible bond line as thin as 10μm may be obtainable by this method.

Table 2. Temperature coefficients for n^+pp^+ silicon concentrator cells for one-sun illumination (AM1.5) with high and low base resistivities. Cells were tested with and without a GaAs filter stacked on top under a solar simulator (Spectrolab, XT-10).

Cell	Filter	$d\eta/dT$ (%/°C)	dI_{sc}/dT ($\mu A/cm^2/°C$)	dV_{oc}/dT (mV/°C)	dFF/dT ($10^{-4}/°C$)
Low-ρ	None	-0.0613	29.0	-1.93	-8.26
	GaAs	-0.0131	-1.50	-2.12	-9.23
High-ρ	None	-0.0755	27.1	-1.98	-10.6
	GaAs	-0.0195	-2.10	-2.17	-11.3

The high operating temperature also has an impact on selection of an optimal bandgap for the bottom cell. While narrow bandgap cells such as Ge (0.66 eV), InGaAs lattice-matched to InP (0.75 eV), and GaSb (0.72 eV) are attractive candidates for the bottom cell, their temperature coefficients need to be carefully examined. Under full spectrum illumination, narrow-bandgap solar cells have large η temperature coefficients due to their low V_{oc} and high I_{sc} (see Eqn. 2). To assess the effect of stacked cell operation on the temperature coefficients of a bottom cell, we measured the temperature coefficients of a silicon cell at one-sun with and without a GaAs filter stacked on top. The results are presented in Table 2.

The V_{oc} and FF temperature coefficients increase only slightly under the filter due to lower V_{oc} at the lower current. The I_{sc} temperature coefficient actually changes sign when operated under a filter. I_{sc} temperature coefficients of single-junction solar cells are positive because the bandgap of semiconductors decrease with temperature. The bandgap of the top cell, however, decreases more rapidly than the bandgap of the bottom cell. There is thus less light reaching the bottom cell as the temperature is raised, so that the bottom cell of a stacked cell has a negative I_{sc} temperature coefficient.

The η temperature coefficient of the silicon cell is considerably improved when operated under a GaAs filter compared to full spectrum illumination. This is due to the reduced I_{sc} value, as can be understood with the following relation:

$$\frac{d\eta}{dT} = \frac{1}{P_{in}} \left[I_{sc}V_{oc}\frac{dFF}{dT} + I_{sc}FF\frac{dV_{oc}}{dT} + V_{oc}FF\frac{dI_{sc}}{dT} \right] \quad (2).$$

While the V_{oc} and FF temperature coefficients increase slightly, the magnitude of the first two terms decrease sharply when the silicon cell is operated under the GaAs filter because I_{sc} is reduced by a about factor of 7. The last term of Eqn. 2 becomes negative, so that it counteracts the decrease of the first two terms. The net result is that the η temperature coefficient of a solar cell decreases when operated as the bottom cell in a stack.

The performance of an MSMJ cell in a module may be estimated using the calculated temperatures of Table 1 and an η temperature coefficient of 0.04%/°C and 0.02%/°C for the top and bottom cells, respectively. Note that the temperatures of Table 1 are the peak temperatures of a non-uniform temperature profile. Our calculations therefore overestimate the effect of module operating conditions. The reduction in efficiency of the MSMJ cell from the reference temperature value (25°C) due to the temperatures of Table 1 are about 2.4% and 3.0% for the 500X and 1000X modules, respectively. For comparison, these same values for a single-junction GaAs cell are 1.34% and 1.5%, respectively.

5. CONCLUSIONS

A significant issue regarding operation of an MSMJ cell in a high-concentration module is the operating temperature. Our calculations showed that the top cell of an MSMJ cell operates at a much higher temperature than a single-junction solar cell due to the ΔT across the adhesive interlayer. The loss of performance due to this ΔT can be a significant fraction of the bottom cell output, so that very thin adhesive layers must be used. The η temperature coefficient of the bottom cell, however, is improved by operation in a stack. An efficiency approaching 35% is possible with GaAs-based MSMJ concentrator cells at 25°C [1]. This corresponds to a potential efficiency of 30% for a GaAs-based MSMJ concentrator cell at normal module operating temperatures.

6. ACKNOWLEDGEMENTS

We would like to thank M. Lehrer for assistance in the measurements. Some of this work was previously presented at the 4th International Photovoltaic Science and Engineering Conference, Sydney, Australia, February 1989.

7. REFERENCES

PVSC refers to the IEEE Photovoltaic Specialists Conference.

1. J.M. Gee and G.F. Virshup, 20th PVSC, pg. 754 (1988).
2. J.M. Gee, Solar Cells 24, 147(1988).
3. C.J. Chiang, 20th PVSC, pg. 1327 (1988).
4. MO-SCI Inc., Rolla, Missouri.

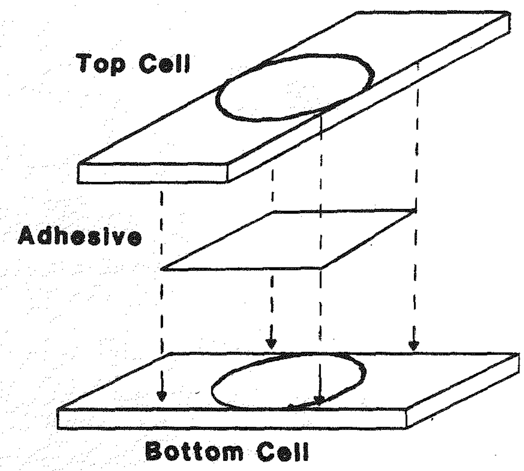


Figure 1. A schematic illustration of an MSMJ cell.

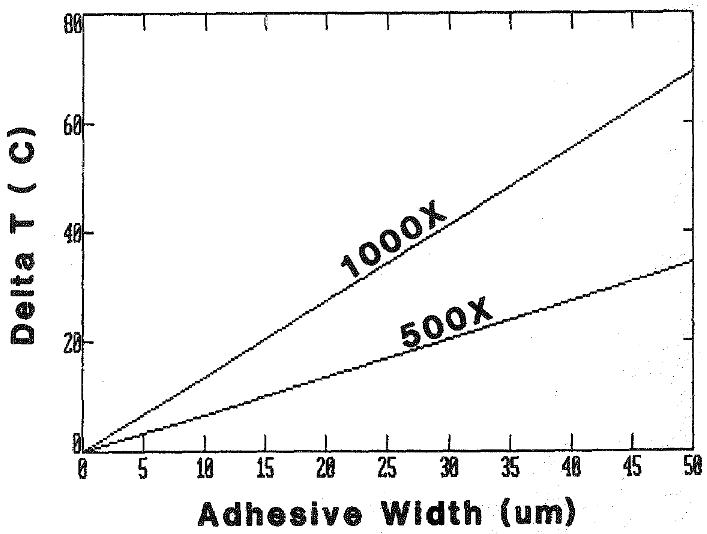


Figure 2. The calculated ΔT of a silicone adhesive layer.

STUDIES OF HYDROGEN MOTION AND BONDING IN SILICON

C. H. Seager and R. A. Anderson

Sandia National Laboratories, Albuquerque, N. M.

ABSTRACT

Hydrogen, introduced either by exposure to plasma environments or directed ion beam sources, is widely used to passivate defects in silicon solar cells. Knowledge of the diffusivity, charge states, and bonding configurations of H in silicon would be of considerable assistance in optimizing passivation processes, but our present understanding of these issues is in a quite primitive state.

We have recently developed a method of introducing hydrogen into Schottky barrier structures with low energy ion beams which allows us to measure H motion and bonding on a "real time" basis. This is accomplished by high frequency capacitance analysis of the barrier charge profiles while hydrogen is diffusing/drifting into the silicon. Figure 1 is a schematic of the apparatus used. By biassing the barrier structures during H introduction, the presence of charged states of H can be detected. While the space charge on the H can be seen in special cases, the primary observable effects are due to passivation of charged acceptors or donors. These experiments are particularly informative since mild (200°C), in-situ thermal anneals debond H from acceptors and donors, thereby returning the samples to their virgin state; this permits many time evolution profiles to be obtained on a single sample. Numerous experiments of this type have been performed on n and p-type silicon metallized with Al,Au,Pd, and Pt. Because of limits on the length of this presentation we will only summarize the major findings of our studies.

Experiments on both n and p-type diodes show that hydrogen is very mobile at 300K and possesses two primary charge states in silicon. In the depletion regions of diodes of both doping types neutral H is the primary species with positively charged hydrogen contributing perhaps 1/10 of the total amount. This mixture of two species may represent occasional charging of H at one lattice position or occupation of two (or more) distinct sites. In p-type diodes depletion field-induced drift of the positive species dominates diffusion effects. This is illustrated in Figure 2. Decreases in charge density due to passivation of the boron acceptors are clearly seen, and the passivation depth is a strong function of the bias applied to the diode during hydrogenation. Finite-element analysis of the data assuming all hydrogens are positive (dashed lines) do not fit the data well in the low field (forward biassed) case, and we

conclude that the majority species are neutral (solid line fits for 90% neutral H). This conclusion is consistent with the data observed on n-type diodes. In this case depletion fields retard passivation because occasional conversion of neutrals to positive species causes a drift component which opposes in-diffusion. This is evident from the data in Figure 3. The effect of a substantial concentration of positive hydrogens is also seen in negative shifts of the Mott-Schottky capacitance plots and as a greatly increased diode leakage due to a narrowing of the space charge region of the barrier near the metal interface. These effects disappear rapidly when the diodes are forward biassed because positive hydrogens are rapidly neutralized by the flux of majority carriers (electrons) to the interface. From studies such as these the 300K H diffusivity is estimated at $\sim 10^{-10} cm^2/sec$, a number consistent with early, high temperature diffusion studies.

Extensive measurement of these effects has also been done at various incident ion energies and fluxes. It appears that all the H ions entering the silicon come from the low energy implant "tail" that penetrates the metal and is stopped in the region close (20 - 80 Angstroms) to the interface. Because of the momentum mismatch, the energy of a hydrogen needed to displace a silicon atom is above 75 eV, ensuring that little permanent damage is done during these experiments. Modelling shows that our incident ion flux causes a near surface H concentration to build up and stabilize to a constant value in a matter of a few seconds. This surface H density is proportional to the incident beam flux and is relatively insensitive to the value of the electric field in the silicon. The incident beam flux can be precisely controlled during these experiments by regulating the backround H pressure in our vacuum chamber.

More recently, studies of H penetration at very long exposure times have yielded a time dependence of penetration depth which is consistent with an additional loss of H to traps other than unpassivated donors or acceptors. We will speculate on the nature of these traps and why their density is strongly correlated with the shallow dopant level.

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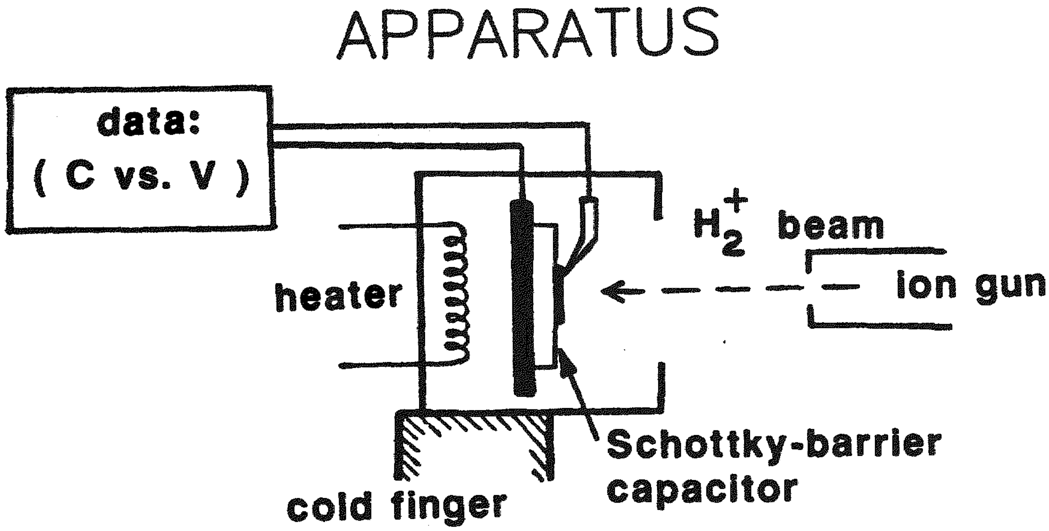

Figure 1. A schematic of the apparatus used in the "real time" hydrogenation measurements. The sample holder is located in a medium high vacuum (2×10^{-8} Torr base pressure) chamber. Beam flux from the ion gun is set by regulating the backround H pressure in the chamber. Capacitance scans are made in about 0.1 sec, insuring that the measurement fields do not affect the penetration process.

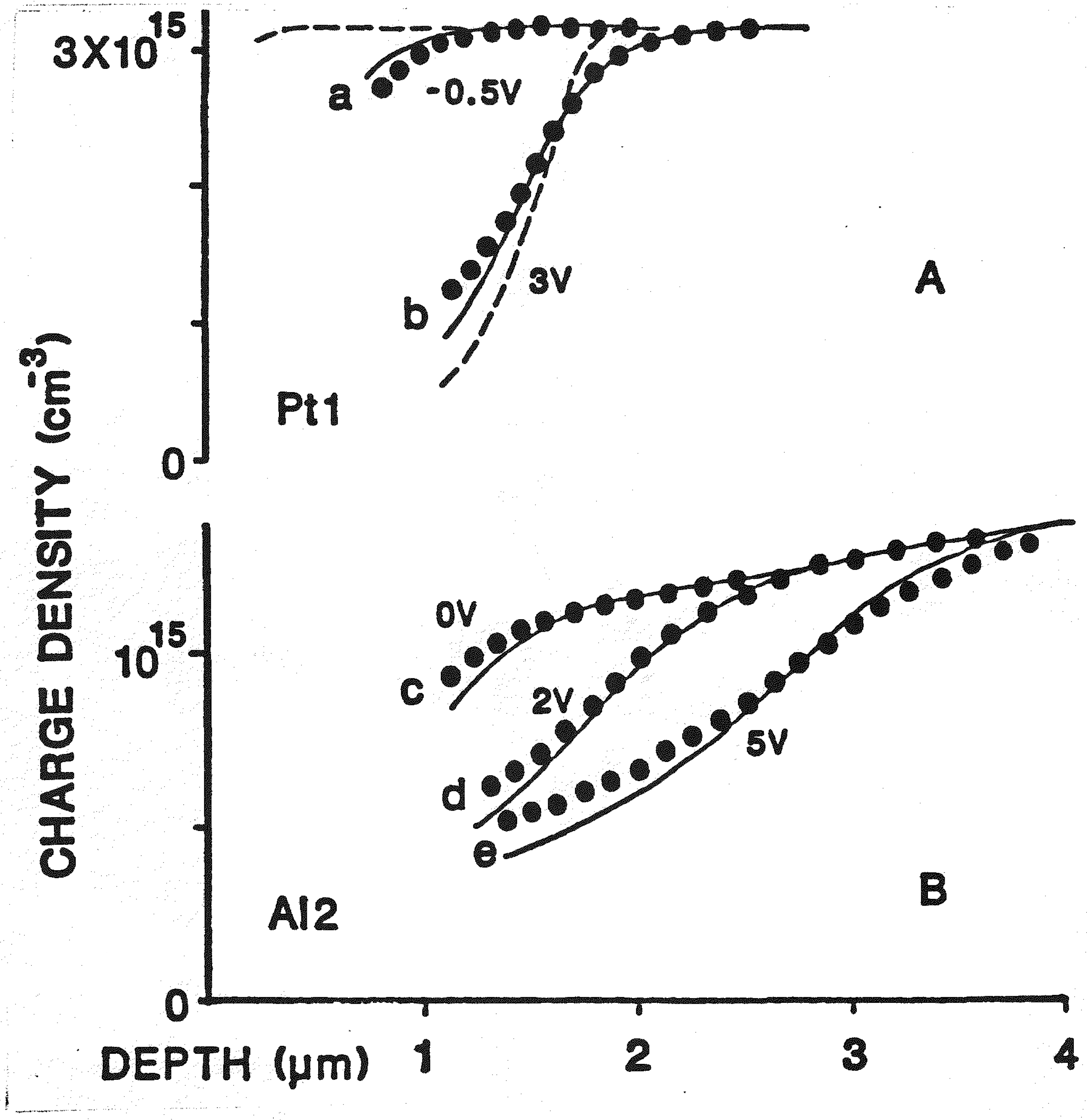

Figure 2. Net charge density versus depth after 243 sec of H beam exposure for p-type Pt and Al Schottky barrier samples with various biasses applied to the gate. Dashed lines are finite-element code fits to the data assuming all hydrogens are positively charged; solid line fits are for 10% positive, 90% neutral species.

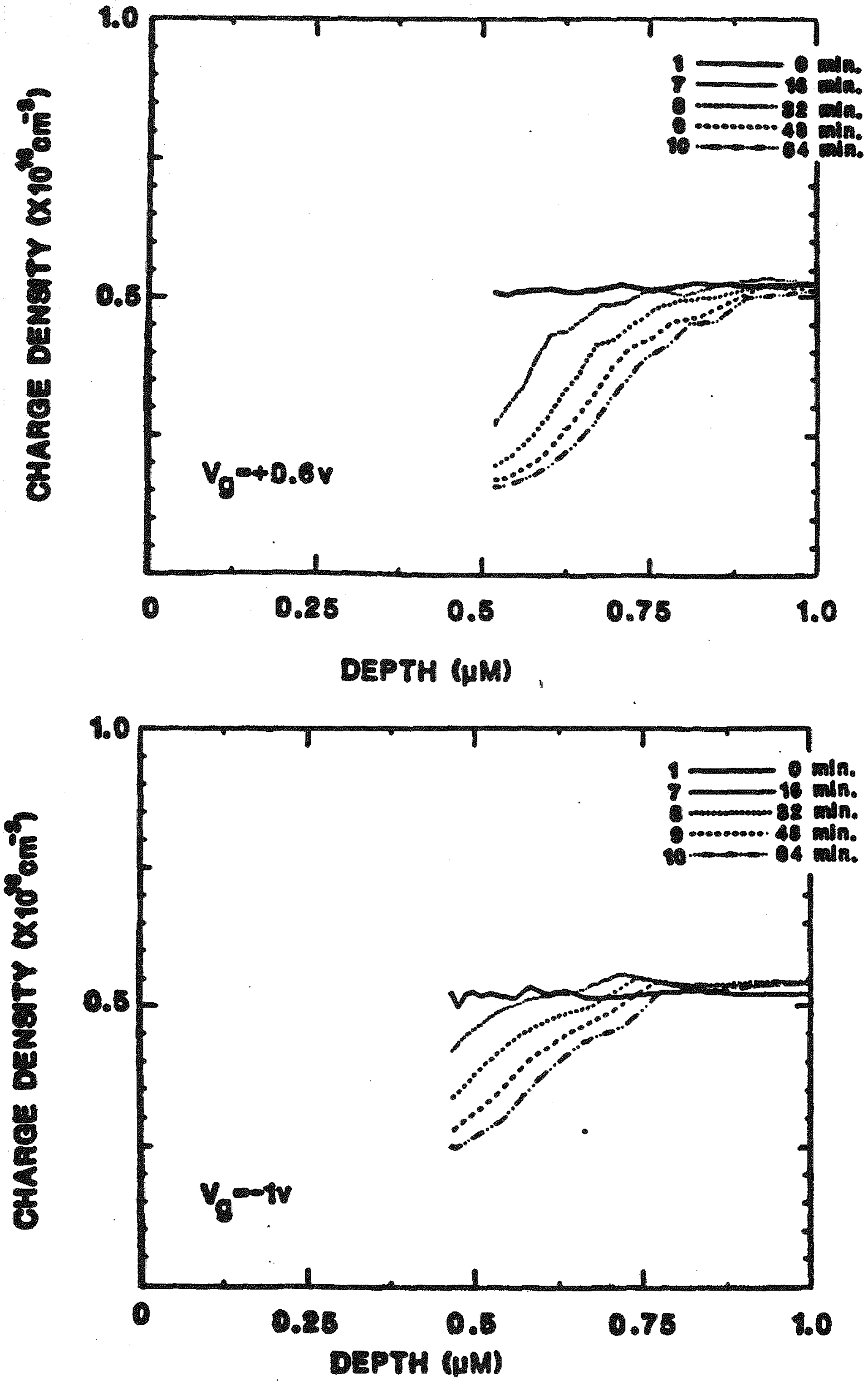

Figure 3. Charge density versus depth for n-type Al Schottky diodes H exposed at forward (upper plot) and reverse (lower plot) bias. Reverse bias noticeably retards H penetration consistent with a small fraction of positvely charged H species. The inserts list the exposure times for each curve.

Photovoltaic Device Fabrication Laboratory

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The Photovoltaic Device Fabrication Laboratory (PDFL) is now operational. Equipment installation is complete and the characterization process is on-going.

This state-of-the-art semiconductor fabrication facility features 600 ft^2 of class-100 clean room, with adjacent equipment chase, storage area, office and gowning room totalling 2500 ft^2. Capabilities include high-temperature diffusion from gaseous, liquid, solid-disk, or doped-oxide sources; wet and dry TCA oxidations, 2-μm infrared photolithography; thermal metal depositions; laminar-flow benches for both organic and inorganic immersion processing; and analytical equipment including a photoconductive decay (PCD) lifetime monitor, microscope, 4-point probe, profilometer, and ellipsometer. A network of five IBM PS/2 computers tied to a central MicroVAX graphics workstation is used to control and monitor the environment, process equipment, test data, and inventory. The PDFL is designed to emphasize clean processing techniques, versatility and efficient space utilization. See Figure 1.

Future plans for the improvement of the PDFL include the addition of a anti-reflection coating (ARC) machine, spin-on doped glass equipment, and plasma etching/deposition equipment. In addition, the Photovoltaic Device Patterning/Plating Laboratory (PDPL) will be operational within the next year. This laboratory will add laser-patterning and plating capabilities to complete our ability to examine the full range of important cell fabrication processes.

The primary goal of the PDFL is to demonstrate the ability to sustain a precisely controlled, quality processing environment, characterized by the routine fabrication of cells in high-quality material with one-sun efficiency exceeding 20%. From this baseline, we will launch numerous investigations designed to better understand the effects of processing on cell performance. This information should lead to the industrial development of cell designs that avoid the adverse effects of low-cost cell processing and demonstrate efficiencies previously relegated to the research laboratory. Thus the ultimate goal is to act as a "half-way house" between industrial production and university demonstrations, as suggested by Figure 2.

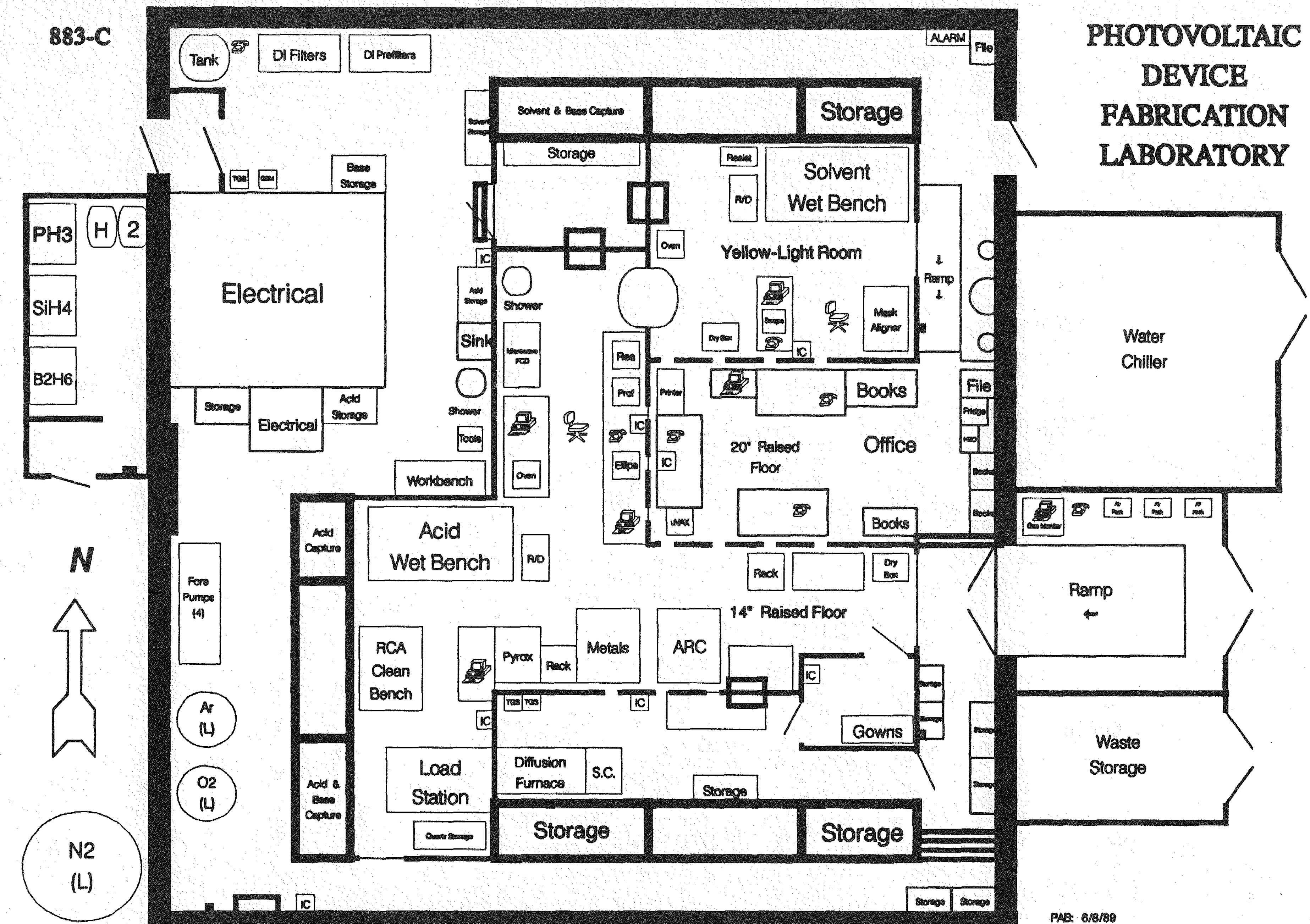
To help achieve our goals a new approach to process control will be used. This approach includes cross-referencing control wafers to electrical/process test structures, and routine continuous exercising of all equipment. Three types of control wafers are needed for this approach. The first type are equipment checkout and maintenance controls (Process Controls). The second type are controls to correlate between active lots and process controls (Procedure Controls). The third type are controls to correlate between active wafers and a known process control wafer (Lot Controls). In addition, all equipment is routinely exercised by continuous processing of the baseline device. To be successful with this approach a large number of measurements will be needed, both during processing and after cell completion. In realization of this requirement, all lot runs are scheduled so that they will be immediately tested in the Photovoltaic Device Measurement Laboratory (PDML). A lot is not started if it can not be tested. The lot turn around time (three weeks) is defined to include all testing to emphasize this point.

Successful implementation of this approach will increase understanding of device performance, processing parameters and will improve the chances for controlling the fabrication line well enough to achieve successful technology transfer. Reaching our goals will depend heavily on this approach being successful.

To further enhance the value of the PDFL to the photovoltaic community, we encourage researchers from both universities and industry to participate as visiting scientists. A key element of this program will be the ability of the visiting scientist to utilize the resources of the PDFL to develop and better understand proprietary processes. Extensive process automation and data collection will assist in transferring successful processes to the home laboratory.

In conclusion, the PDFL is now ready to begin the development of the first baseline process. Scientists wishing to visit the PDFL can now begin to make arrangements.

PHOTOVOLTAIC DEVICE FABRICATION LABORATORY



The PDFL Role

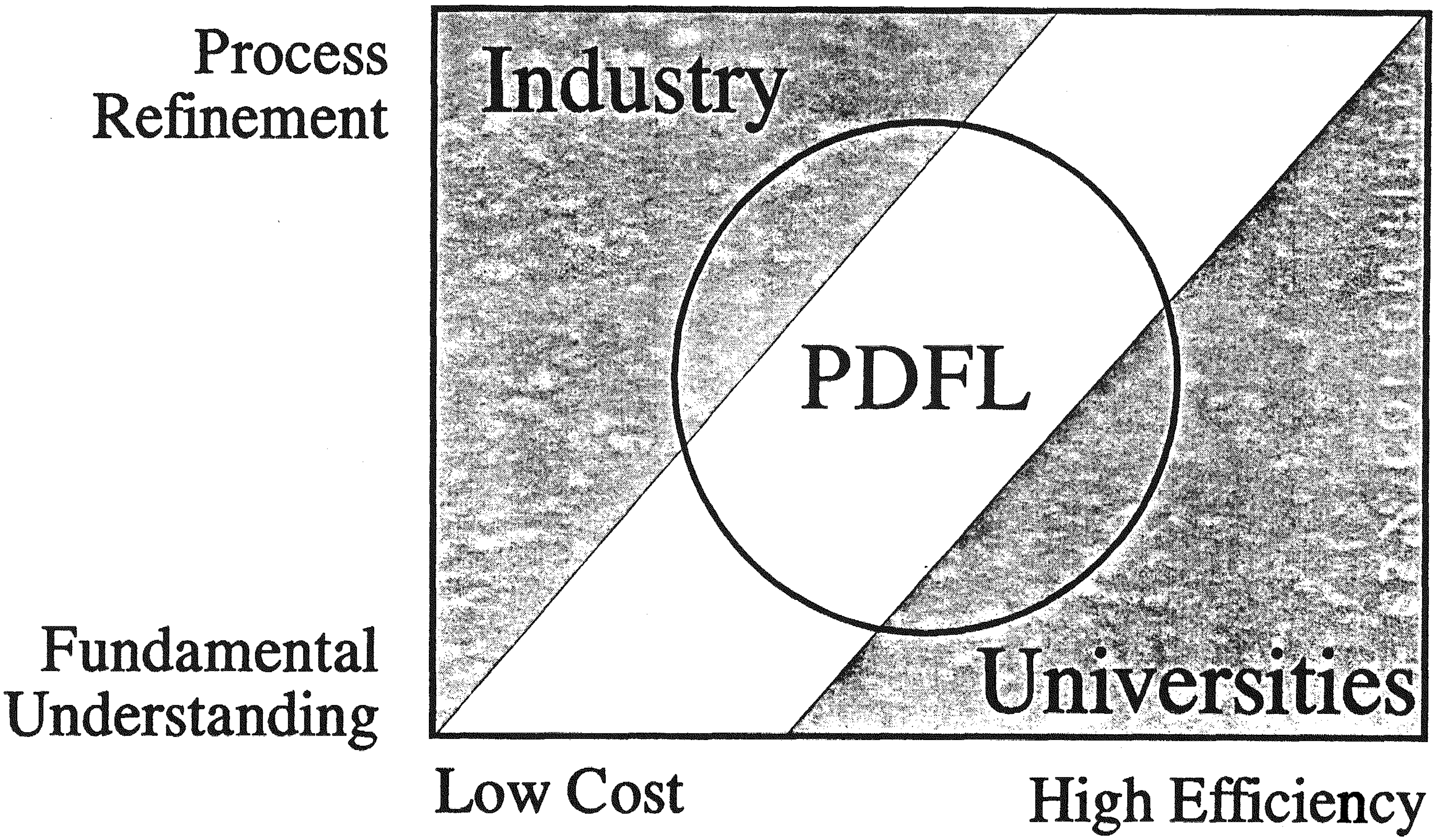


Figure 2

Sandia's Array Tracking Controller

Alexander B. Maish
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Significant progress has been achieved during the past year on the development of an open-loop array tracking controller for photovoltaic arrays. Hardware and software development is nearing completion, and units are being tested on different trackers by two photovoltaic array manufacturers. A final report on the controller system is nearing completion.

The control system is designed to significantly improve the reliability and reduce the cost of solar array tracking. This is achieved by minimizing the number of components on the control board, by using non-contacting sensors for the limit switches, position references, motor turn counters and wind speed sensors, and by minimizing the requirements on the field operator. The control board contains no potentiometers that would require adjustment by the operator. There is no sun sensor to align, as the tracker is open-loop and calculates the sun position internally. Unlike most open-loop controllers, this system even performs its own initial installation alignment by finding the peak current output of the array in two axes over the course of an initial day and computing several alignment error parameters. After these parameters are determined, the system returns to open-loop tracking and automatically performs a coordinate transformation of the computed sun position to get the sun position in the coordinates of the misaligned tracker.

The systems consists of a controller board, a motor-interface and power board, and a user-interface board. Two versions of the controller board have been fabricated, one for the development phase, which has 24-kilobytes of modifiable program memory (Fig. 1), and one for use in final applications (Fig. 2). The 3-by-5 inch applications controller board uses the microcontroller's on-chip memory, and thus it is much smaller and simpler. To use this board, the program needs to be fabricated into the chip, with minimum quantities being 1000 parts. However, Motorola plans to release a one-time-programmable version of the microcontroller chip in late 1989 which will make it possible to use this applications board for individual arrays.

The motor-interface board contains the 5-volt power supply and the solid-state relays to turn the motors on. The board can be custom-designed for each array and motor configuration. One version, for a pair of 3-wire ac motors (using four solid-state relays), is shown in Fig. 3. The user-interface board (Fig. 4) is not needed for operation of the system, but can be used by the operator to modify the controller's parameter table or to reset the clock. These boards are all operational now.

Software development for the controller and user-interface boards is essentially complete. The controller uses a common control code for all applications. A modifiable parameter table holds the variables to tailor the code to the specific application. The controller can currently be used on azimuth/elevation, tilt/roll or polar-axis trackers by setting a flag in the parameter table. Upon startup the controller first locates its limits, then drives to the position it calculates the sun to be and begins tracking. At night it stows in a designated orientation until it automatically awakes in the morning.

A separate stow orientation can be designated for emergency stow. There are three emergency stow inputs, one for a high wind, one for coolant over-temperature for use on an actively-cooled system, and one which can be activated manually (using a toggle switch on the control board) or by a field-stow signal. The tracker can stow in 0, 1 or 2 axes. The operator can designate the length of the signal (in seconds) required to initiate the stow conditions, and the length of time (in minutes) that the wind and temperature stows will continue after the end of the initiating signal. The global field stow line can also be used to reset the internal clocks of all the controllers in a field at one time. An output signal is available for actively-cooled systems to signal the cooling pumps to turn on when the controller is tracking.

The tracking routine was improved this past year to minimize the deadband which can be achieved without using a brake on the motor. The controller "learns" and automatically determines the best length of time to turn the motor on in each direction. A deadband of 0.05° (at the motor end of the drive train) can now be achieved without hunting. Due to the drive train backlash, the array panel on the unit being tested at Sandia tracks within ±0.25°. If the sun goes beyond a limit in one axis, the controller will orient the tracker to the best angle in the other axis for use with flat-plate or line-focus modules. By throwing a toggle switch, the operator can activate the joystick on the controller board to enable manual driving. The joystick directions can be programmed to correspond to different motor directions for use with different trackers.

The self-alignment routine has been written and debugged. It locates the sun position in two axes by sweeping across the sun in each axis and monitoring the array output current. This is normally done during installation with the array short circuited. The difference between the measured and the computed sun position is determined throughout the day, then the controller performs a 6-by-6 element matrix inversion to compute 6 alignment parameters. Thereafter the array does not monitor the array current, but tracks in an open-loop manner computing the sun's position and using the alignment parameters to transform the sun's coordinates to the array's misaligned orientation. The routine is now being tested at Sandia to determine its accuracy and sensitivity to various conditions.

In addition to being tested on the Sandia azimuth-zenith tracker, the unit is currently being tested on an Entech tilt-roll array which is actively-cooled and has an east-west orientation and a nonlinear screwjack drive. The controller is also being installed on the Alpha Solarco azimuth-zenith tracker in Nevada which also has a nonlinear screwjack drive.

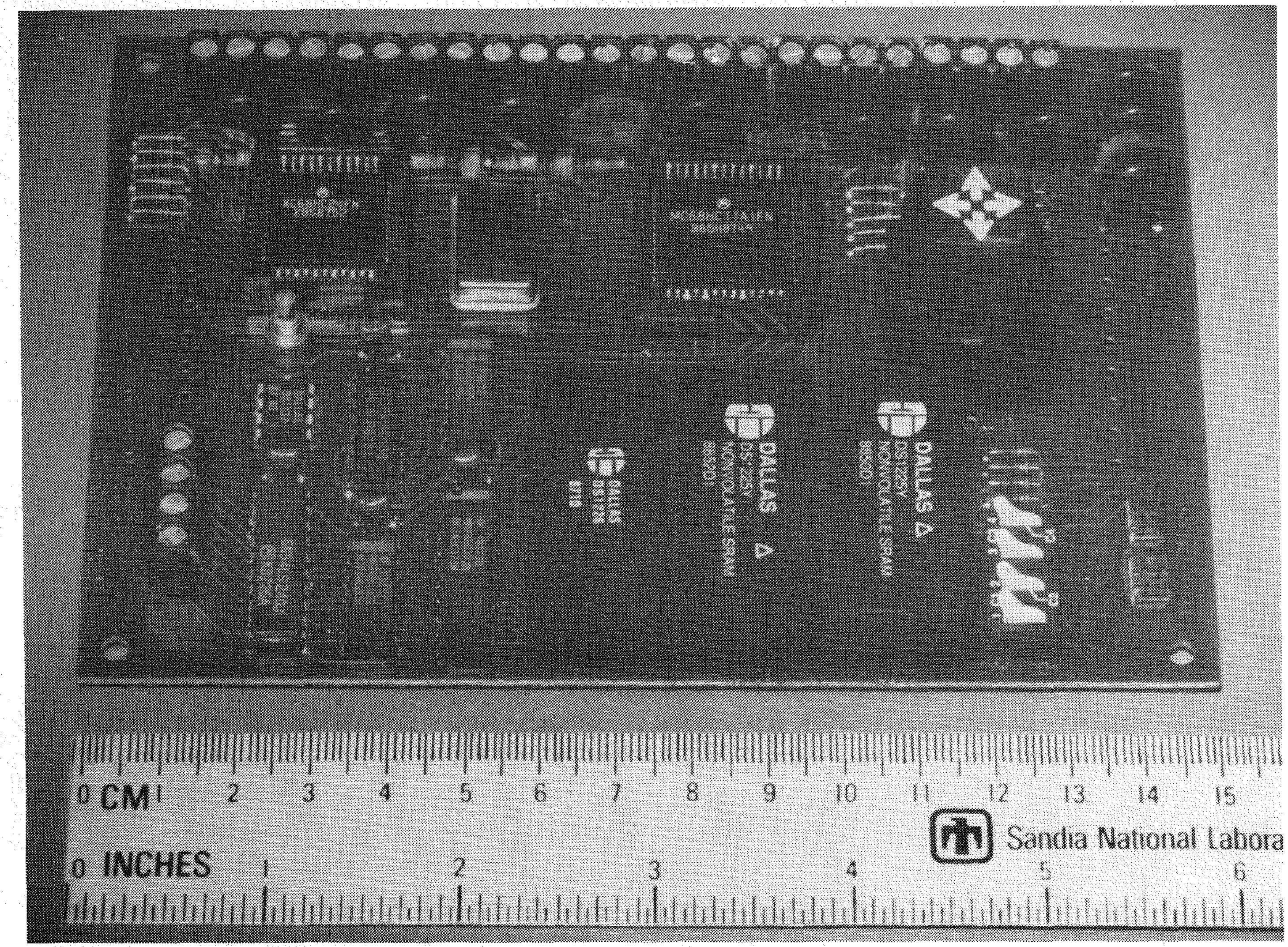

Figure 1 - Development Control Board

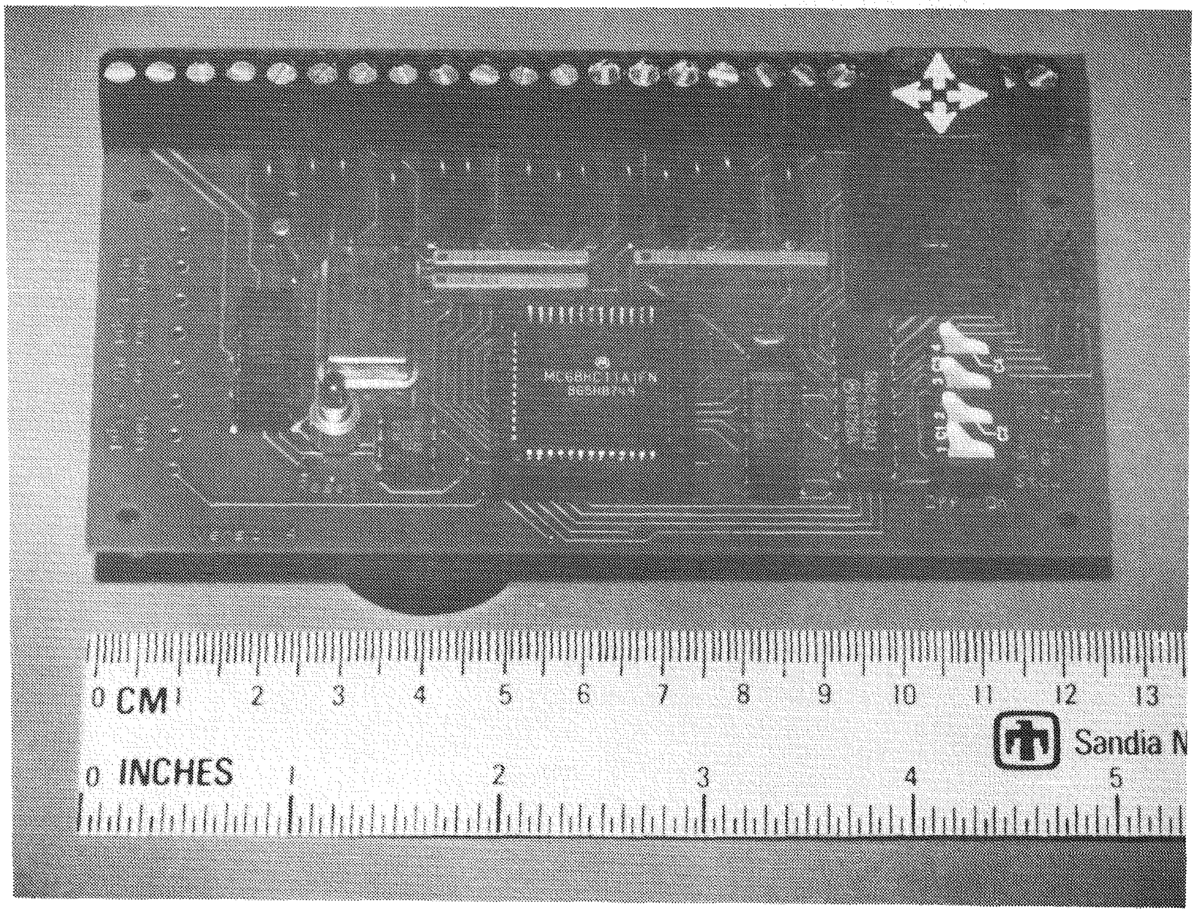

Figure 2 - Applications Control Board

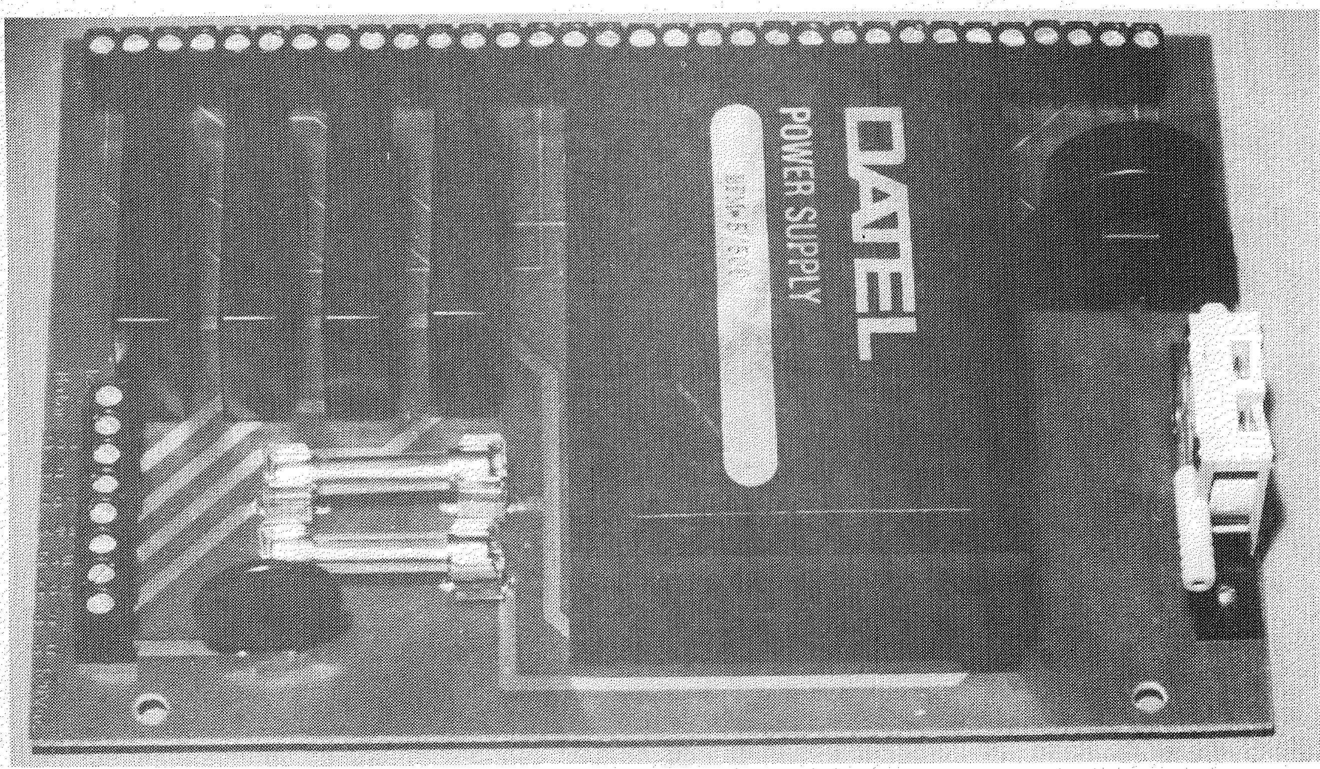

Figure 3 - Motor and Power Board

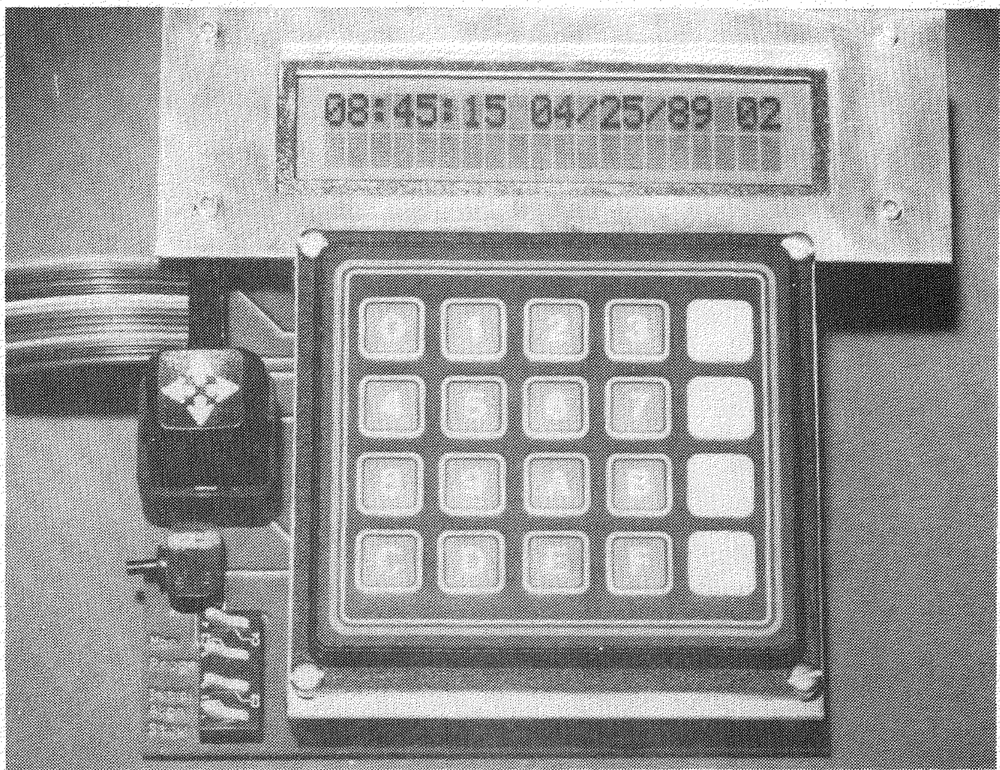

Figure 4 - User-Interface Board

SANDIA'S BASELINE 3 PHOTOVOLTAIC CONCENTRATOR MODULE

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Sandia is now completing development, construction, and testing of a new photovoltaic concentrator module, the Sandia Baseline Module 3 (SBM3). The SBM3 combines recent advances in cells, cell assemblies, and electrical isolation techniques to produce a high-efficiency module that can be readily adapted for commercial production. The module efficiency goal is 20% with an output of 140 W at peak conditions. We have made the design available to manufacturers interested in commercially producing the SBM3 or similar designs.

This paper gives an overview of the design and describes the recent progress on this project. For more detailed information about the design, please refer to Reference 1.

MODULE DESCRIPTION

The SBM3 consists of a 2 by 12 parquet of lenses arranged with 24 cells in an aluminum housing, Figure 1. The geometric concentration is 185. The cells were designed at the University of New South Wales and have a prism cover designed by ENTECH. The module features a new concept in cell assemblies in that the cells are soldered directly to a copper heat spreader, eliminating the expensive ceramic wafer that has been used in previous concentrator designs. The aluminum housings are anodized and electrophoretically coated with a high-temperature acrylic, creating a thin electrically isolating layer capable of withstanding high voltage. No additional electrical insulation

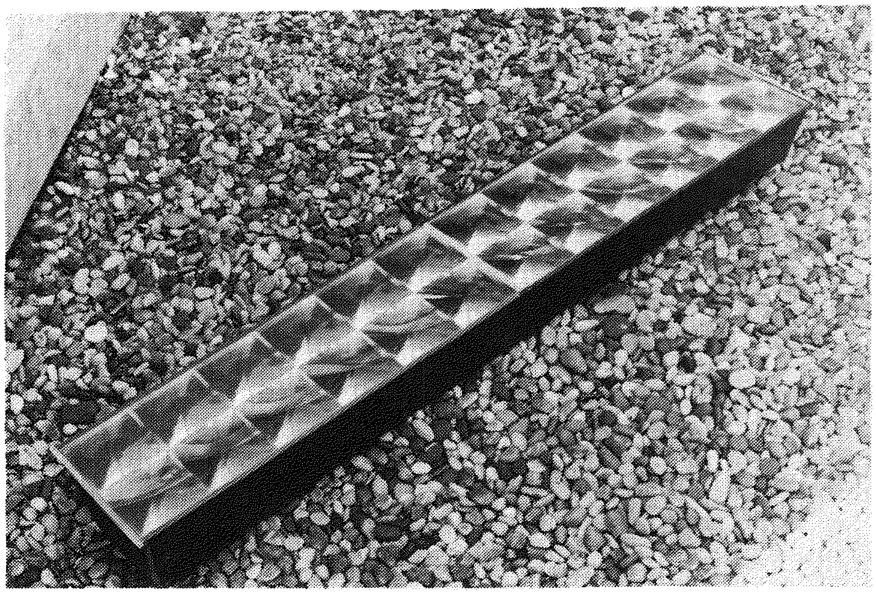

Figure 1. Sandia Baseline Module 3.

between the cell assemblies and the housing is required. The thinness of the layer enhances heat transfer between the copper heat spreaders and housing, eliminating the need for a separate heat sink.

The module is approximately 2 meters (7 feet) long. The cell assemblies are connected in two series strings of 12 cells each and are attached to the housing with a thermally conductive adhesive. The lens parquet is positioned in a channel in the housing and sealed with an ultraviolet-stabilized butyl rubber [2].

Optical Design

The optical system consists of a point-focus Fresnel lens developed for the Sandia Baseline Module 2 (SBM2) and an anodized aluminum secondary reflector. The SBM2 lens was designed by General Electric and compression molded from acrylic by Fresnel Optics into 5 x 6 parquets in 1982 [3]. Each lens element is 17-cm (6.7-in) square and has 0.8-mm (.03-in) facets with a 3° draft angle. We cut the 5 x 6 parquets into two 2 x 6 parquets to fit the SBM3. The lens-to-cell spacing is 20.32 cm (8.00 in).

The SBM3 design uses a reflective secondary optical element on each cell assembly to improve the uniformity of the flux profile and provide tolerance to tracking errors. The secondaries are cut from polished anodized aluminum, bent into shape, and attached to the upper cell interconnects with an adhesive. They have a reflectivity of about 82%.

In addition, ENTECH developed a prismatic cover, based on its patented design, to be used with the UNSW concentrator cell. The prismatic cover eliminates losses due to shadowing by the grid-lines, which are parallel and cover 15% of the cell at 0.13-mm (5-mil) intervals. The cover is designed to accept light up to 50° from normal without illuminating the grid lines. The prismatic covers improve module performance about 15% by allowing us to increase the grid line metallization fraction on the front surface of the cell to 15% from the 6% that is optimum for uncovered cells, thereby reducing series-resistance losses in the cell.

Housing Design

The housing is made from 1-mm (.040-in) aluminum sheet stock. The 5005-H34 alloy was selected based on thermal conductivity, ease of forming (minimum bend radii), ease of anodization, and cost. End plates with breather ports are attached with rivets and sealed. Five bulkheads provide stiffness; holes in the bulkheads provide necessary air circulation. Channels along the edges of the housing are designed to provide accurate lens-to-cell spacing and seal against water. Our prototypes are made by bending; we anticipate that a roll forming or deep drawing process would be used in actual production.

The housings employ a technique that has not been used before in photovoltaic modules. The aluminum housings are first anodized and then electrophoretically (EP) coated with styrene acrylate, leaving a thin (50 μm) electrically insulating layer capable of withstanding 3000 volts [4]. Anodization alone provides reasonable electrical isolation, but is subject to flaws or "pin-holes" that cause breakdown of the insulating layer. The electrophoretic coating alone provides excellent electrical isolation (greater than 6000 volts for a 30 μm layer in the laboratory), but impedes heat transfer from the cell assembly to the housing. Using the two processes in sequence, the electrophoretic coating fills in the pores in the anodized layer and, during curing, covers the anodized layer with a thin coat. No additional electrical insulation between the electrically-live heat spreader and the housing is required, thereby enhancing heat transfer compared to other electrical isolating methods and, in combination with the copper heat spreader, eliminating the need for a separate (expensive) heat sink.

Cell Assembly

The cell assembly for the SBM3 is described in Reference 5 and will not be described in detail here. Basically, it consists of a concentrator cell soldered to a copper heat spreader, which acts both as the bottom cell contact and as a means to transfer heat away from the cell. The top cell contact is also copper and supports the aluminum secondary reflector. The heat spreaders are attached directly to the housing with a thermally conductive adhesive (Figure 2); the expensive ceramic wafer used in previous concentrator cell assemblies has been eliminated.

The cells, designed by Dr. Martin Green of the University of New South Wales, incorporate some of the recent advances in concentrator cell technology, such as light-trapping microgrooves, surface passivation, double-layer anti-reflective coating, and a thin low-resistivity base [6]. Prismatic covers are molded directly onto the cells after the cell assembly soldering process.

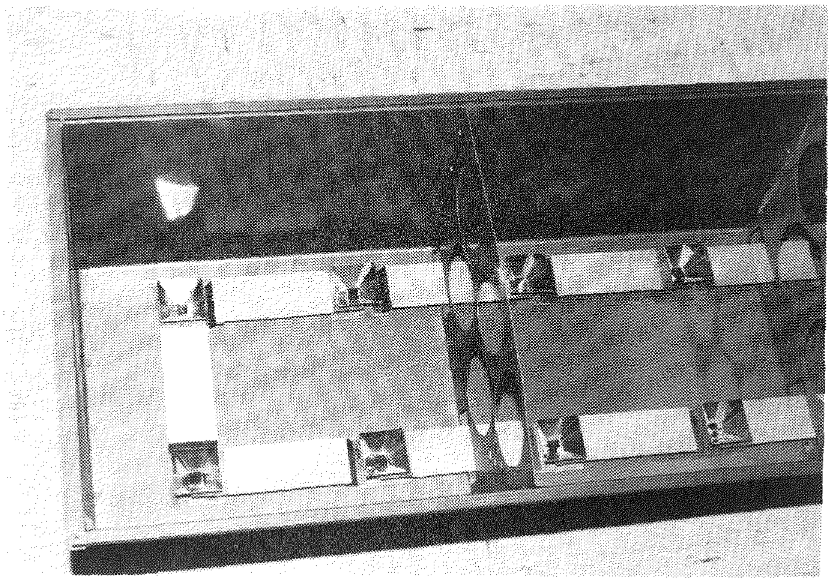

Figure 2. Cell assemblies installed in SBM3 housing.

Cost

Cost estimates for this module are given in Reference 1 and are briefly summarized here. Assuming limited production of 2 MW/year, the cost per module is estimated to be $196, or $280 per square meter. While this cost is higher than the near-term goal of $195 per square meter for 20% concentrator modules (for 12¢/kWh) given in the Department of Energy's five year photovoltaic research plan [7], it could be significantly reduced in two ways. Approximately $100 per square meter are labor costs; if a higher production rate was assumed and the assembly process was automated, the labor costs would be much lower. Also, the lens size is not optimized -- increasing the geometric concentration ratio by increasing the lens size may increase the area of the module without substantially increasing the cost per module because the number of parts would remain the same.

RECENT PROGRESS AND STATUS

We are now assembling prototype modules to subject to Sandia's module qualification tests [8]. The cell assemblies passed qualification testing last year, although we need to requalify the prismatic covers because they are now molded directly to the cells instead of being formed first and then glued on. Six prototype housings have been thermally cycled to verify that the lens sealing system will work. We have refined the electrophoretic coating process to the point where we now feel we have a uniform high-voltage standoff layer that can be applied commercially. We have also constructed an experimental module based on the SBM3 design but containing only four cell assemblies. This module is used for lens-cell testing and to experiment with anti-reflective coatings on the lenses.

Cell Assemblies and Prismatic Covers

ENTECH applied prism covers to the first 43 cell assemblies we made with UNSW cells, giving significant improvements in cell performance as measured in our flash tester. The projected efficiency for the cells with prism covers was about 24%; we measured 24.3% on one of the first cell assemblies to have a prism cover applied and achieved 25% at 125 suns on a subsequent cell assembly [6].

However, during lens-cell testing last fall, we identified a problem with the prismatic covers -- they were apparently too thick and did not have the angular acceptance necessary for the lens. In the process of trying to make them thinner, ENTECH and Sandia devised a method for molding them directly to the cells. This new procedure can produce excellent quality covers and shows promise for being adaptable to automated production, although at the prototype level it is very time-consuming and the yields are not very good.

We have achieved 25%-efficient cell assemblies with the new prismatic cover molding process. However, it appears that there is a tradeoff between high efficiency (as measured in the flash tester) and performance under a lens. The best cell assemblies after application of the prismatic covers apparently still have problems with angular acceptance. This could be due to cover thickness and/or imperfections in the molds. ENTECH and Sandia are continuing to work on this issue.

Stanford has recently provided us with cells designed to fit the SBM3 cell assemblies. These cells have gridlines on the front (as opposed to Stanford's point-contact cells), but show promise of 25% efficiencies without prismatic covers.

Housings and Electrophoretic Coating

The housings for the SBM3 prototypes were obtained from Sandia's in-house shop and were made by bending sheet aluminum. The SBM3 was designed with mass production in mind and obtaining acceptable prototypes was not trivial [1]. Our recent efforts with the housings have been spent refining the electrophoretic coating process.

Our attempts to transfer the EP coating technology to a local plating shop were less than satisfactory. Quality control problems at the plating shop, especially dust contamination, resulted in non-uniform coatings that had areas susceptible to voltage breakdown and raised questions regarding the feasibility of coating large areas. We have now successfully coated housings in-house and feel that the process could be implemented commercially. The successful coatings were obtained when we washed the housings with detergent and deionized water and filtered the EP solution before coating.

JPL, under contract to Sandia, is continuing to evaluate the properties of EP coatings. One area they have identified as needing further work is the ultraviolet stability of the coatings. Sandia is currently working to identify an ultraviolet stabilizer and incorporate it into test samples for JPL to evaluate.

ACKNOWLEDGEMENTS

Many people have contributed to this effort. In particular, the authors would like to thank Misch Lehrer and Barry Hansen for their assistance in testing cells and cell assemblies; Don Sharp for helping us apply EP coatings; Jack Cannon, Karl McAllister, Don Ellibee, and Bill Boyson for help with outdoor testing; and Laurence Brown for lens testing and AR coating work.

REFERENCES

1. E. H. Richards, "Sandia's Baseline 3 Photovoltaic Concentrator Module," Proceedings of the 20th IEEE Photovoltaics Specialists Conference, Las Vegas, Nevada, 1988.

2. K. B. Wischmann, Protective Coatings and Sealants for Solar Applications, 0097-6156/83/0220-0115 (American Chemical Society, 1983).

3. R. C. Hodge, General Electric, Design and Development of a Laminated Fresnel Lens for Point Focus PV Systems, SAND82-7127 (Albuquerque: Sandia National Laboratories, December 1982).

4. L. C. Beavis, J. K. G. Panitz, and D. J. Sharp, "Thermally Conductive Alumina/Organic Composites for Photovoltaic Concentrator Cell Isolation," Proceedings of the 20th IEEE Photovoltaics Specialists Conference, Las Vegas, Nevada, 1988.

5. C. J. Chiang, "Design of Cell Mounts for Photovoltaic Concentrator Modules," Proceedings of the 20th IEEE Photovoltaics Specialists Conference, Las Vegas, Nevada, 1988.

6. J. Zhao, A. Wang, A. W. Blakers, and M. A. Green, "High Efficiency Prismatic Cover Silicon Concentrator Solar Cells," Proceedings of the 20th IEEE Photovoltaics Specialists Conference, Las Vegas, Nevada, 1988.

7. Five Year Research Plan 1987-1991, Photovoltaics: USA's Energy Opportunity, DOE/CH10093-7 (Washington, D.C.: U.S. Department of Energy - National Photovoltaics Program, May 1987).

8. R. S. Barlow and E. H. Richards, Qualification Tests for Photovoltaic Concentrator Cell Assemblies and Modules, SAND86-2743 (Albuquerque: Sandia National Laboratories, January 1988).

A Twenty Percent Efficient Photovoltaic Concentrator Module*

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ABSTRACT

We have achieved a solar-to-electric efficiency greater than 20 percent using a silicon-based photovoltaic concentrator module. The module uses 12 point-focus cells and has a total lens aperture area of 1875 cm^2. This measurement represents a record photovoltaic module efficiency and the achievement of a key program milestone for the Photovoltaic Technology Project. The cells and cell mounts of the module were designed for our commercial-prototype Sandia Baseline Module 3, and it is expected that concentrator modules with this efficiency will be available commercially within a few years. In this paper, we describe the approach, hardware, and results of our experiment.

INTRODUCTION

Increase in the efficiency of photovoltaic concentrator modules is important for two reasons. First, large increases in efficiency are possible. The theoretical limit of silicon cell efficiency ranges from 33 to 35 percent [1,2]. Combining this cell efficiency with a maximum optical efficiency of about 95 percent for a facetless antireflective (AR)-coated lens, limits silicon-based photovoltaic concentrator module efficiency to between 31 and 33 percent. This represents an increase in efficiency of more than 50 percent over current levels. Second, since modules generate all of the electricity produced by a solar plant, an increase in module efficiency causes a proportional decrease in overall energy cost.

Efficiencies near 27 percent for modules using silicon cells can be extrapolated from existing measurements. Currently, small laboratory cells have efficiencies in the neighborhood of 28.5 percent [2]. Optical efficiencies greater than 90 percent have been measured for line-focus lenses without AR coatings [3]. The efficiency of facetless uncoated lenses would equal the transmission of acrylic sheet, which is 92 percent. With AR coatings, lens efficiencies are several points greater. High-efficiency module technology is not necessarily complicated or expensive. However, focused and sustained efforts are required to develop the knowledge, processes, and tooling necessary to bring laboratory devices and components through the prototype demonstration phase to commercial production.

Our experiment demonstrates the potential efficiency of prototype hardware designed for low-cost energy production. For more information concerning a commercial module based on this technology, refer to the paper describing the Sandia Baseline Module 3 (SBM3), also presented at this meeting.

* Prepared by Sandia National Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550, operated for the U. S. Department of Energy under Contract DE-AC04-76DP00789.

APPROACH

The objective of our experiment was to achieve an efficiency of 20 percent using a module consisting of at least 4 cells and having a total lens area comparable to that of high-efficiency one-sun modules. The housing we used is that of the Sandia 200X Experimental Module, which was designed, built, and first tested in 1983 to reach the 17 percent efficiency milestone for a silicon-based photovoltaic module [4]. It uses 12 cells connected in series and has a total lens aperture area of 1875 cm^2. For our experiment, we used our best module-ready cells mounted in cell assemblies designed for the SBM3. Although the module employs independent cell positioning and liquid cooling for accurate temperature control, these features provide flexibility and accuracy in experimentation and would not be needed in a commercial module. The magnesium flouride antireflective lens coating that we used is not yet durable or cost-effective for commercial modules. Other design features of the module, in particular the cells and cell mounts, are considered readily adaptable to commercial production in the next few years.

The following is a description of the high efficiency acrylic fresnel lenses, the module-ready, planar-junction, silicon solar cells, the prismatic covers molded directly to the cells, the SBM3 cell assemblies, our Sandia Experimental Module, and our experimental procedure.

Fresnel Lenses

The lenses are 12.5 by 12.5 cm and were compression molded by Fresnel Optics in Rochester, New York. They were designed in 1983 using a code written by James Associates in Ft. Collins, Colorado [5]. At a lens-to-cell spacing of 6.0 inches, 90 to 95 percent of the transmitted direct normal irradiance (DNI) is focused into a circular region, 1.0 cm in diameter. The lenses were coated on both sides with magnesium flouride by CVI Laser in Albuquerque, New Mexico. The thickness of the coating on the flat side was chosen to be 1750 Å, corresponding to 1/4-wavelength in the middle of the silicon response range. On the facetted side of the lenses, the coating thickness was decreased to account for the angle of the facet located one-half radius from the center of the lens.

Silicon Solar Cells

The bi-facial, low-resistivity silicon cells were made by the University of New South Wales in Kensington, Australia. The active area of the cells is 12.5 by 12.5 mm, giving a geometric concentration ratio of 100 in the experimental module. The overall size of the cells is 18.0 by 18.0 mm. The cells were designed to use prismatic covers to direct incident light away from the gridlines. Details of the cell design are described in reference [6].

Prismatic Covers

The prismatic covers for the cells were designed by ENTECH. We developed processes for molding the covers directly to the cells using molds supplied by ENTECH. The covers were applied to the cells at Sandia. Our process requires a great deal of manual skill, due to the fineness of the point-focus grid pattern. Commercial use of prismatic covers requires development of application methods for mass production.

Cell Assemblies

The cell mounts we used were designed for the SBM3. They are intended to be commercial-prototypes, minimizing the number of parts and the number of assembly steps. The cells are soldered directly to copper heat spreaders. The top contact to the cell is also the mount for the secondary reflector. Although the image from the lens is round and somewhat smaller than the square active area of the cells, we found that the fill factor of the cells was not increased significantly by decreasing the lens-to-cell spacing to give a more uniform flux distribution on the cells. Therefore, we tested the module without the SBM3 secondary reflectors. The cell assembly design is described in detail in reference [7].

Module

Figure 1 shows the Sandia Experimental Module. It employs active cooling and independent 3-axis cell positioning. The cell assemblies were fastened in place using nylon screws. Electrical isolation of the heat spreaders from the module housing was provided by Kapton tape. The outside dimensions of the module cover an area about 8 percent larger than the area of the lenses. The results presented in the following section are based on the area of the lenses. The module is more fully described in reference [4].

Experimental Procedure

Indoor performance tests were conducted on bare cells, on mounted cells, and on mounted cells with prismatic covers. Outdoor performance tests were conducted at one-sun on single cell assemblies, and at concentration for single lens-cell units, for a minimodule using 4 lens-cell units, and for the full module. Indoor measurements were conducted at our Photovoltaic Device Measurement Laboratory (PDML) and outdoor measurements were conducted at our Photovoltaic Advanced Systems Test Facility (PASTF).

RESULTS

Results of the outdoor tests of the full module are included here. Results from individual cell and minimodule tests will be presented at the meeting. Outdoor testing of the full module occurred over a period of four days. Results obtained on April 19 are described here. Figure 2 plots the ratio of short-circuit current to DNI versus DNI. At lower irradiance intensities, the ratio is greater than at higher intensities by about 2 percent. This can be explained by differences in the solar spectrum during the day. Figure 3 plots DNI, the measured temperature of one cell assembly's heat spreader, and the calculated average cell temperature. The average cell temperature was calculated as a function of the open-circuit voltage and the short-circuit current. This function was determined based on indoor testing of the cells. The difference between the calculated cell temperature and the measured heat spreader temperature was about 1 to 2 °C, in agreement with our heat transfer calculations.

The module efficiency was determined as a function of the calculated average cell temperature and DNI. The 324 data points taken on April 19 cover a range of DNI from 740 to 1000 W/m^2. We maintained the cell temperature near 25 °C throughout the test. Our regression equation is:

$$\eta = 22.80 - .0390 \times Tc - .001904 \times DNI$$

Figure 4 plots the module efficiency versus DNI, with the efficiency values adjusted using the above equation to a cell temperature of 25 °C. The modest decrease in efficiency with increasing DNI can be accounted for completely by the decrease in the ratio of short-circuit current to DNI with increasing DNI, as shown in Figure 2.

CONCLUSIONS

Since the late 1970's, silicon-based concentrator module efficiency has nearly doubled, equivalent to a steady increase at a compound rate of nearly 6 percent per year. Based on theoretical limitations of cell and lens efficiency and on laboratory measurements of one-of-a-kind cells, this rate of increase can be extended well into the 1990's. At this stage in the development of photovoltaic concentrators, increasing efficiency continues to hold great promise for decreasing energy cost. Our achievement of a 20 percent module efficiency is evidence of that promise.

ACKNOWLEDGEMENTS

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REFERENCES

1. P. Campbell, M. Green, "The Limiting Efficiency of Silicon Solar Cells Under Concentrated Sunlight." *IEEE Transactions on Electron Devices*, Vol. ED-33, No. 2, February 1986, and C. Chong, M. Green, "Technical Brief", Vol. ED-34, No. 11, November 1987.

2. R. M. Swanson, "Why We Will Have a 30-Percent Efficient Silicon Solar Cell." *4th PVSEC*, Sydney Australia, February 1989.

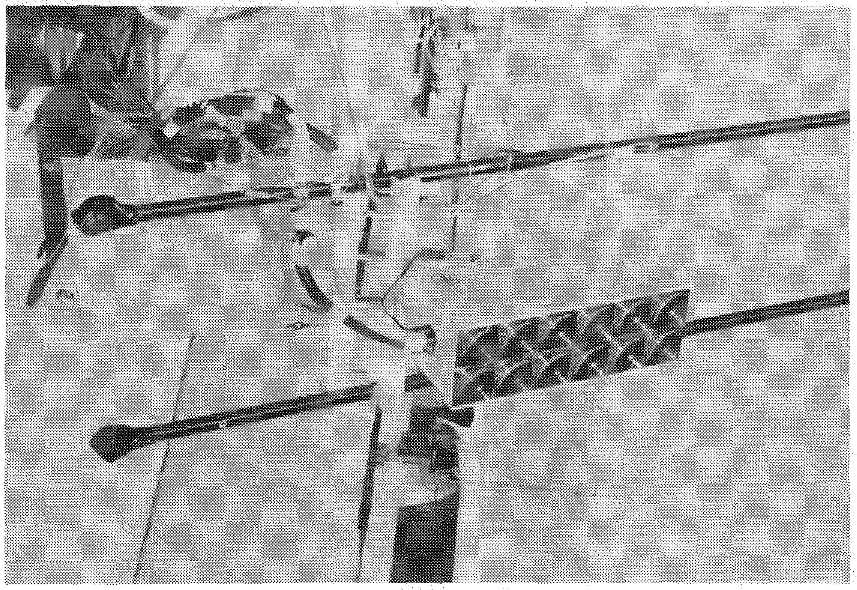
3. M. J. O'Neill, "A Low-Cost 22.5X Linear Fresnel Lens PV Concentrator Module..." *Proceedings of the 18th PVSC*, (1985): 1234-1239.

4. D. E. Arvizu, "Development of the Sandia 200X Experimental Silicon Module." *Proceedings of the 17th IEEE PVSC*, (1984): 805-813.

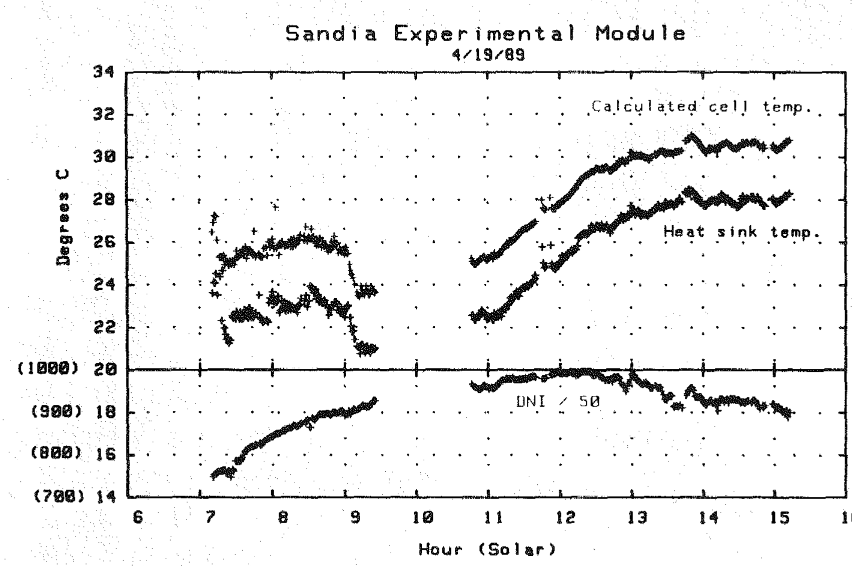
5. L. W. James, "Fresnel Lens Design Program", Sandia contract No. 50-5906, July 1983. Sandia contract monitor Charles Stillwell.

6. J. Zhao, A. Wang, A. Blakers, and M. Green, "High Efficiency Prismatic Cover Silicon Concentrator Solar Cells." *Proceedings of the 20th IEEE PVSC*, (1988): 529-531.

7. C. J. Chiang, "Design of Cell Mounts for Photovoltaic Concentrator Modules." *Proceedings of the 20th IEEE PVSC*, (1988): 1327-1332.



↑ Fig 1



↑ Figure 3

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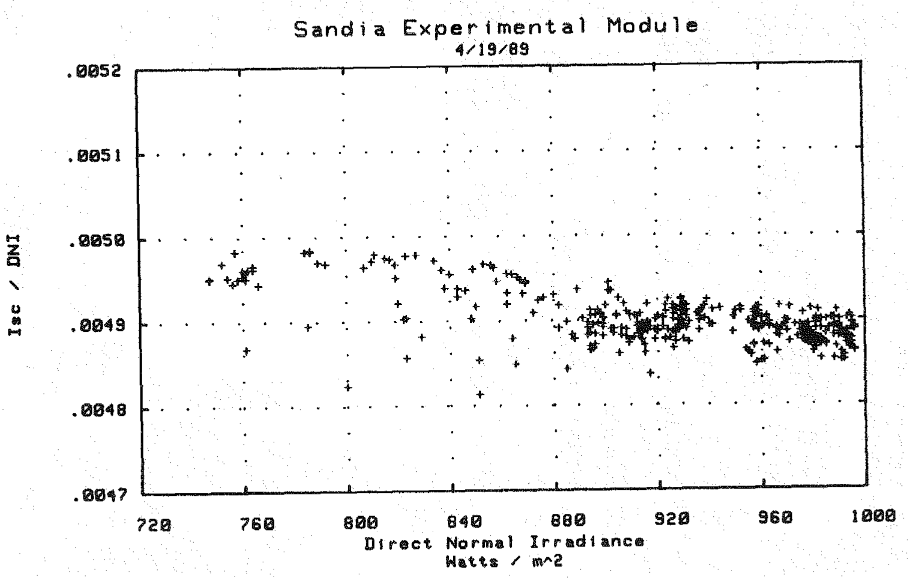

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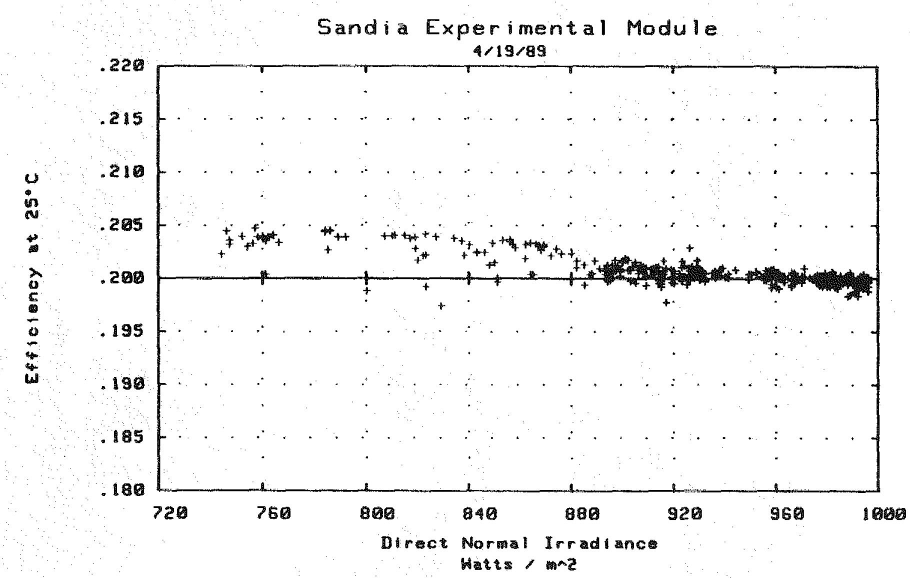

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