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Photovoltaics Advanced R & D Annual Review Meeting

September 17-19, 1979

Proceedings

Sponsored by

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PHOTOVOLTAIC ADVANCED R&D ANNUAL REVIEW MEETING PROCEEDINGS

SEPTEMBER 17-19, 1979
STOUFFER'S
DENVER, COLORADO

SPONSORED BY:

U. S. DEPARTMENT OF ENERGY

AND

SOLAR ENERGY RESEARCH INSTITUTE

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PLENARY SESSION

DOE/PV Overview

M. B. Prince
Dept. of Energy
Washington, D.C. 20585

Introduction

I want to extend greetings to you from DOE headquarters. Your work is crucial in meeting the long-range objectives of the Photovoltaic Program.

Today there are two subjects that I want to review with you. These are:

1. The Multi-Year Program Plan that has evolved after almost a year of planning and thoughtful trade-off studies.
2. The headquarters considerations on the R&D activities that you are involved in.

National Photovoltaic Program Multi-Year Plan

The objective of the Department of Energy DOE Photovoltaics Program is to reduce system costs to a competitive level in both distributed and centralized grid-connected applications. Equally important, the Program will also resolve the technical, institutionally, legal, environmental and social issues involved in fostering wide-spread adoption of photovoltaic energy systems. This will be done via substantial research, development and demonstrations aimed at achieving major cost reductions and market penetration, to the point where they are able to supply a significant portion of the United States' energy requirements. A key element in this program is the belief that photovoltaic residences will begin to be cost-effective within the Southwestern United States w en arrays are priced at 70¢/peak watt and the total installed systems will cost from $1.60 to 2.20/peak watt (in 1980 dollars.) The program now being planned anticipates this occuring in 1986.

The following figures give the most important data from the plan.

U.S. DEPARTMENT OF ENERGY PHOTOVOLTAICS PROGRAM

OVERALL OBJECTIVE:

To achieve major cost reduction—leading to competitive life-cycle costs—by aggressively pursuing advanced research, technology development, and real-world testing, to support the large-scale transfer of the technology to the market place.

BASIC GOALS	MODULE PRICES (FOB)*	SYSTEM PRICES*	PRIME APPLICATION
1982	$2.80/peak Watt	$6-13/W	Remote/International
1986	$0.70/peak Watt	$1.60-2.20/W	Residences
1990-2000	$0.15-0.50/peak Watt	$1.10-1.30/W	Utilities

*1980 constant $

Figure 1

PHOTOVOLTAIC PROGRAM STRATEGY
KEY ELEMENTS

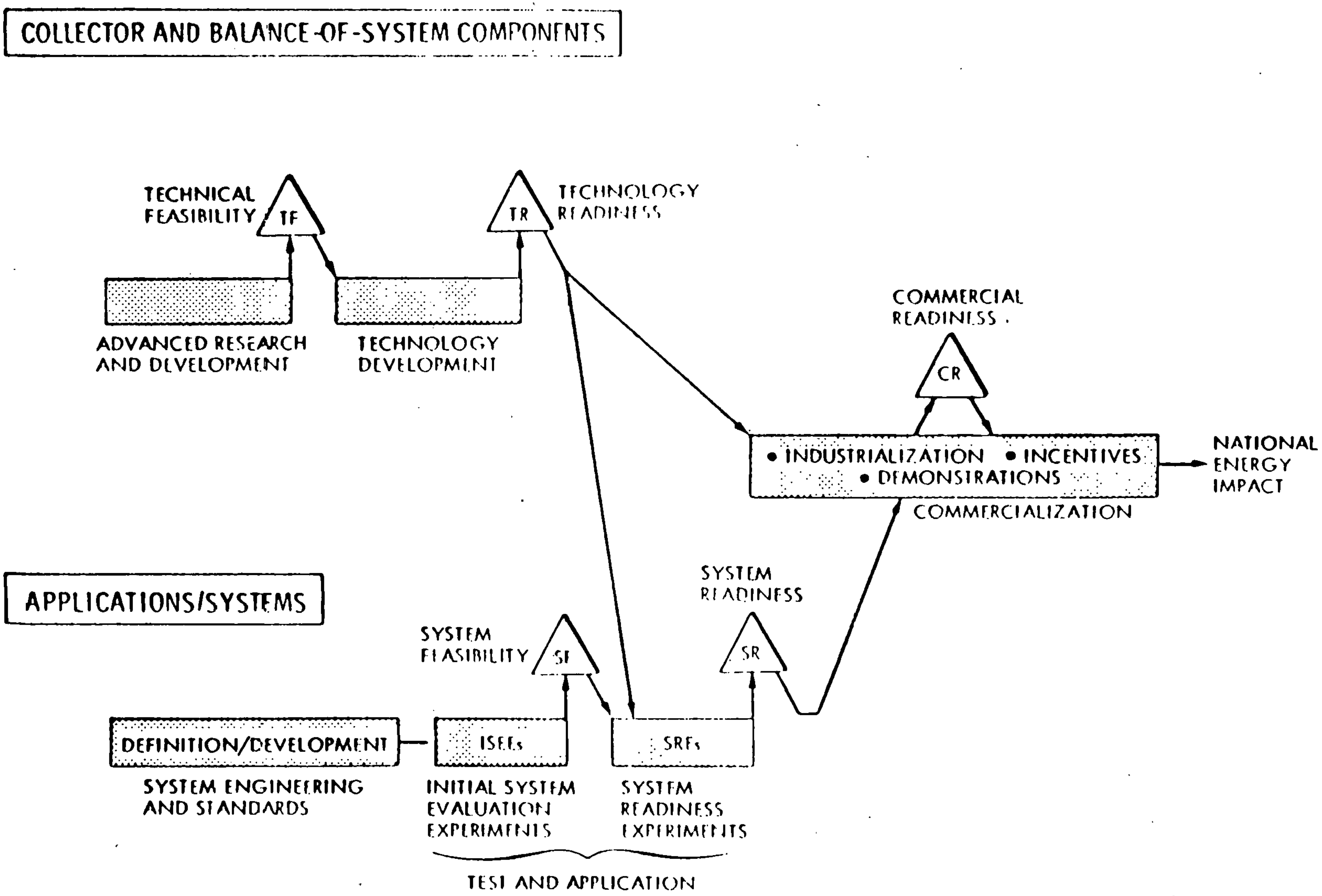
- SUBSTANTIAL PRICE REDUCTIONS VIA:
  - AGGRESSIVE R&D TO ESTABLISH TECHNICAL FEASIBILITY OF ADVANCED MATERIALS AND DEVICES (CDS, AMORPHOUS, SEMICRYSTALLINE SI AND OTHER THIN-FILM DEVICES, PHOTOCHEMICAL AND ADVANCED CONCENTRATOR CELLS, ETC.)
  - INTENSIVE TECHNOLOGY DEVELOPMENT OF FLAT-PLATE AND CONCENTRATOR SYSTEMS (BOTH SI AND GAAS).
  - ENGINEERING ANALYSES AND TECHNOLOGY DEVELOPMENT TO LOWER THE BALANCE-OF-SYSTEM COSTS (E.G., POWER CONDITIONING, STORAGE, STRUCTURES AND SUPPORT, MARKETING AND DISTRIBUTION, ETC.)
- DESIGN, DEVELOPMENT AND TESTING OF COMPLETE PV SYSTEMS IN ACTUAL USERS' ENVIRONMENT
- EMPHASIS ON GRID-CONNECTED DISTRIBUTED RESIDENCES AS AN EARLY U.S. WIDE-SCALE APPLICATION
- SUPPORT PV PERFORMANCE CRITERIA AND TEST STANDARDS DEVELOPMENT

FIGURE 2

KEY MILESTONES
IN THE PHOTOVOLTAIC RD&D PROCESS

MILESTONE	DEFINITION/REQUIREMENT
Technical Feasibility (TF) of Components	Technical feasibility is reached for a particular technology when: (a) stable and reproducible performance characteristics have been achieved; (b) a laboratory-scale process has been defined that yields products with consistent charactristics; and (c) analysis indicates that mass production is technically feasible and likely to yield a technically and economically viable product after suitable technology development.
Technology Readiness (TR) of Components	Technology readiness is achieved: (a) with a successful subscale demonstration of all of the individual steps in a production process that would yield economically competitive and reliable products if produced in sufficient quantity, and (b) when prototypes are available for intensive performance and reliability analysis.
System Feasibility (SF)	System feasibility is achieved in a given application when a photovoltaic system concept is first carried through design, installation and operation in an actual user's application.
System Readiness (SR)	System readiness is accomplished when fully integrated systems, using avilable technology-ready components or prototypes thereof, are designed, built and successfully operated in an actual user's environment.
Commercial Readiness (CR) of Components and Systems	Commercial readiness in a given application class is accomplished when products or systems are offered for sale at a given price.

Figure 3



RESEARCH, DEVELOPMENT AND DEMONSTRATION PROCESS FOR COMPONENTS AND SYSTEMS

Figure 4

DOE PHOTOVOLTAICS PROGRAM

SYSTEMS, ENGINEERING & STANDARDS
AND
TESTS & APPLICATIONS

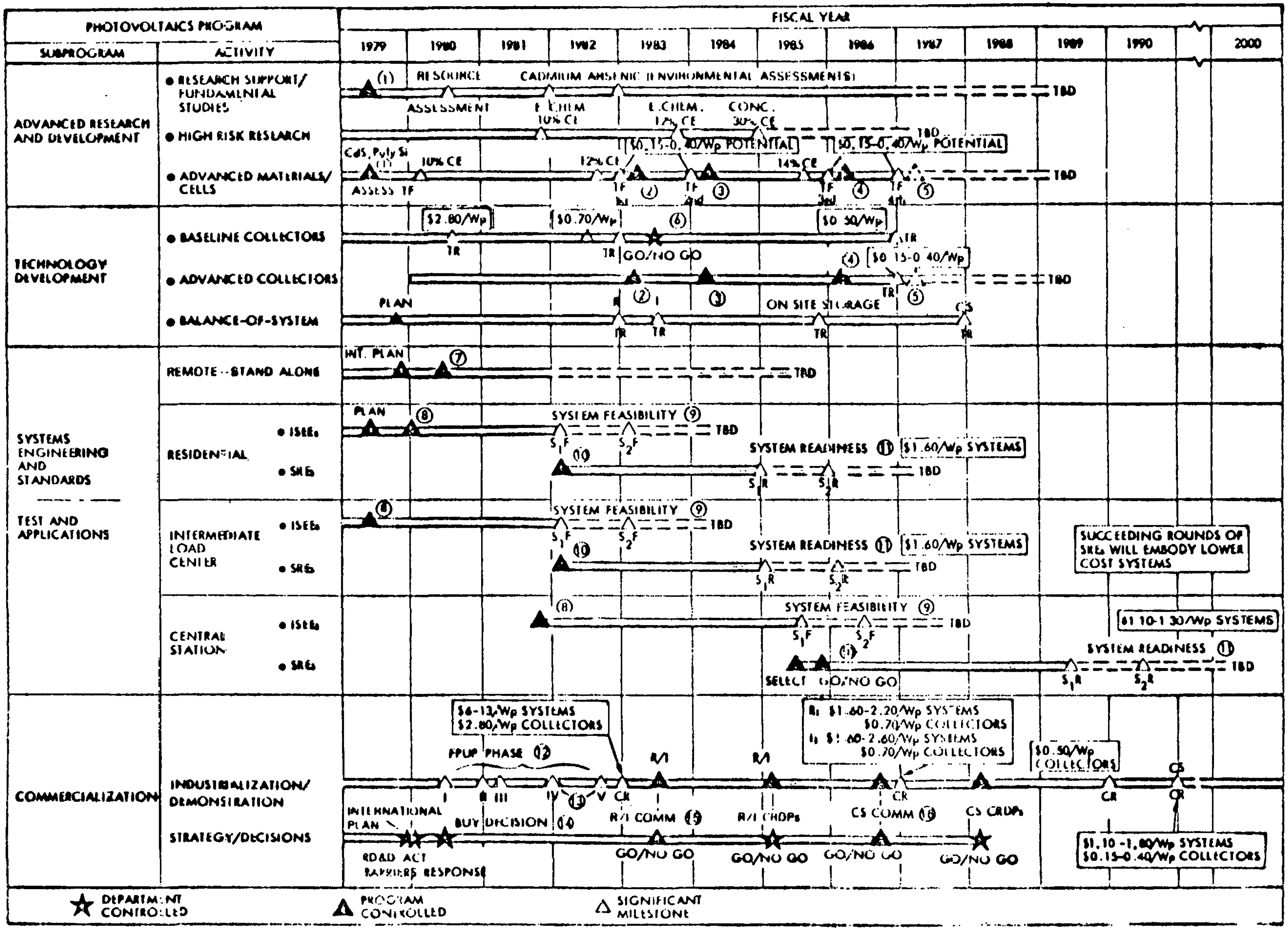
- SANDIA LABORATORIES
  - 20-500 kW INTERMEDIATE GRID-CONNECTED PROJECTS (PRDAs 35/38)
  - SYSTEM DESIGNS
- MIT/LINCOLN LABORATORY
  - 27 kW AGRICULTURAL PUMPING APPLICATION, MEAD, NEBRASKA
  - 100 kW NATURAL BRIDGES NATIONAL MONUMENT, UTAH
  - 20 kW DAYTIME AM RADIO STATION, BRYON, OHIO
- DOD
  - 60 kW GRID-CONNECTED RADAR STATION, MT. LAGUNA, CALIFORNIA
- OAK RIDGE NATIONAL LAB
  - 250 kW MISSISSIPPI COUNTY COMMUNITY COLLEGE, BLYTHEVILLE, ARKANSAS
  - NORTHWEST MISSISSIPPI JUNIOR COLLEGE, SENITOBIA, MISSISSIPPI
- SERI
  - 350 kW VILLAGE POWER SYSTEM, SAUDI ARABIA, (SOLERAS)
  - EGYPTIAN PROJECT
  - PERFORMANCE CRITERIA + TEST STANDARDS
- LEWIS RESEARCH CENTER
  - 3.5 kW SCHUCHULI INDIAN VILLAGE ARIZONA

1977—$16M 1978—$32M 1979—$42M 1980—$27M

U.S. NATIONAL PHOTOVOLTAIC CONVERSION PROGRAM BUDGET

	FY 1979 (Estimated Millions of Dollars)	FY 1980 (Requested Millions of Dollars)
Advanced Research and Development		
Advanced Materials/Cell Research	31.5	29.0
High Risk R&D	2.5	13.0
Research Support and Fundamental Studies	5.0	5.0
Subtotal	39.0	47.0
Technology Development		
Low-Cost Solar Arrays	30.0	33.0
Concentrators	8.0	10.0
Balance-of-Systems	0.0	13.0
Subtotal	38.0	56.0
Systems Engineering and Standards		
Systems Definition	3.9	2.0
Systems Development	7.4	10.5
Performance Criteria and Test Standards	2.0	2.0
Subtotal	13.3	14.5
Tests and Applications	13.2	12.5
Federal Photovoltaic Utilization Program (FPUP)	15.0	0.0
Total	118.5	130.0

Figure 8


PHOTOVOLTAICS PROGRAM
SUBPROGRAM
ACTIVITY
FISCAL YEAR
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
2000
ADVANCED RESEARCH AND DEVELOPMENT
● RESEARCH SUPPORT/ FUNDAMENTAL STUDIES
● HIGH RISK RESEARCH
● ADVANCED MATERIALS/ CELLS
(1)
RESOURCE ASSESSMENT
CADMIUM ARSENIC (ENVIRONMENTAL ASSESSMENTS)
TBD
E.CHEM 10% CE
E.CHEM. 12% CE
CONC. 30% CE
$0.15-0.40/Wp POTENTIAL
CdS, Poly Si (1)
ASSESS TF
10% CE
12% CE
14% CE
TF 1st
TF 2nd
TF 3rd
TF 4th
(2)
(3)
(4)
(5)
TECHNOLOGY DEVELOPMENT
● BASELINE COLLECTORS
● ADVANCED COLLECTORS
● BALANCE-OF-SYSTEM
$2.80/Wp
$0.70/Wp
$0.50/Wp
$0.15-0.40/Wp
(6)
TR
GO/NO GO
PLAN
ON SITE STORAGE
CS
SYSTEMS ENGINEERING AND STANDARDS
TEST AND APPLICATIONS
REMOTE--STAND ALONE
RESIDENTIAL
INTERMEDIATE LOAD CENTER
CENTRAL STATION
● ISEEs
● SREs
INT. PLAN
(7)
(8)
SYSTEM FEASIBILITY (9)
S1F
S2F
(10)
SYSTEM READINESS (11)
$1.60/Wp SYSTEMS
S1R
S2R
SUCCEEDING ROUNDS OF SREs WILL EMBODY LOWER COST SYSTEMS
$1.10-1.30/Wp SYSTEMS
SELECT
GO/NO GO
COMMERCIALIZATION
INDUSTRIALIZATION/ DEMONSTRATION
STRATEGY/DECISIONS
$6-13/Wp SYSTEMS
$2.80/Wp COLLECTORS
FPUP PHASE (12)
I
II
III
IV
V
(13)
CR
R/I
R: $1.60-2.20/Wp SYSTEMS $0.70/Wp COLLECTORS
I: $1.60-2.60/Wp SYSTEMS $0.70/Wp COLLECTORS
$0.50/Wp COLLECTORS
INTERNATIONAL PLAN
BUY DECISION (14)
R/I COMM (15)
R/I CRDPs
CS COMM (16)
CS CRDPs
RD&D ACT
BARRIERS RESPONSE
GO/NO GO
$1.10-1.80/Wp SYSTEMS
$0.15-0.40/Wp COLLECTORS
DEPARTMENT CONTROLLED
PROGRAM CONTROLLED
SIGNIFICANT MILESTONE

PHOTOVOLTAICS PROGRAM ORGANIZATION

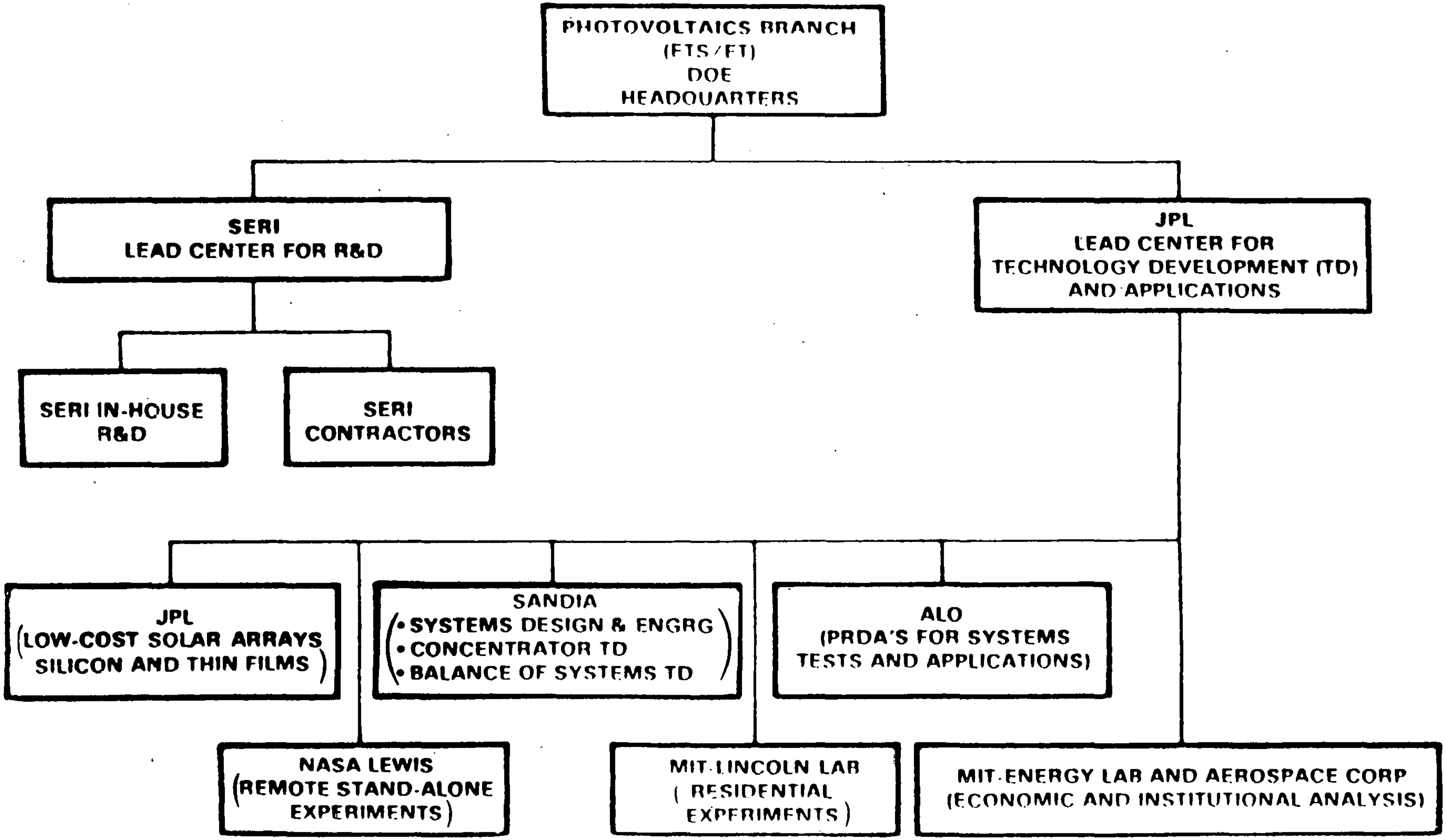


Figure 10

The next two speakers will go into some details on parts of the program.

Considerations on Photovoltaic R&D Activities

As we just reviewed, the Photovoltaic Program is highly mission oriented as it must be with milestones and objectives that must be met in order that photovoltaics will supply a significant amount of the electric power to the U.S. and world needs by the end of this century. One approach for meeting this goal is through the R&D activities that you are all involved in. Other approaches include single-crystal silicon, poly-crystalline silicon, concentrator subsystems, etc. I personally believe that a thin-film approach has the best chance for meeting our long-range objectives. In order to meet these long-range objectives, we have set several intermediary objectives for 1981, 1983, and 1984. These are 10% and 12% conversion efficiency for thin film cells and 30% conversion efficiency for concentrator cells. Along with the conversion efficiencies, the cells must be reproducible, stable, lend themselves to reliable module fabrication and be capable of being produced automatically at low cost.

These requirements lead us to a funding dilemma. On the one hand, in order to meet the near-term objectives, there is a tendency to fund engineering oriented projects; on the other hand, in order to truly understand the physical mechanisms at play in the materials, interfaces, boundary layers, etc., there is a tendency to want to support fundamental study projects. In the beginning of the program when funding for R&D was extremely limited, we leaned toward the engineering type projects. As funding for Photovoltaic R&D increased significantly during the last two years we have supported more and more fundamental work. Now that SERI has built up a staff under Don Feucht to help our very limited headquarters staff, we are reevaluating the distribution of the funding for these two types of activities, both of which are needed.

We will cut back on contractors whether they be basic mechamism oriented or new material oriented when it is obvious that the contractor has not made any headway and does not have a well thought out plan for moving forward. We feel that two years is more than adequate time to prove an approach. With universities we may stretch this time limitation to three years since we do want to protect graduate students somewhat since these individuals will be important to the industry later.

The need to cut back is two-fold;first of all, the more successful developments usually need to be expanded to make and test more devices which costs more, and second, new high-risk approaches continue to arise which hold high promise and therefore should be pursued. With a limited, even though large, budget, the only way to cover these activities is to eliminate the least success

The reason I've taken so much time on this subject is to let you know some of the considerations that we deal with in attempting to meet our goals and to reassure you that if your work is successful in meeting goals and milestones that you and your monitor at SERI set, then additional funding will be forthcoming.

NOTES

PHOTOVOLTAIC SYSTEM APPLICATION EXPERIMENTS*

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INTRODUCTION

System application experiments are an important element of the Department of Energy (DOE) Photovoltaics Program. The objectives of system application experiments are to obtain experience with operational photovoltaic power systems in a variety of potentially significant applications in Remote, Residential, Intermediate Load Center and Central Station market sectors. This paper will review the status of system application experiments in the Intermediate Load Center sector.

Experiment phases and major milestones are shown in Figure 1. Initial System Evaluation Experiments (ISEEs) will be built with currently available technology and will provide basic information on the performance, suitability, and acceptability of photovoltaics in real-world environments. As a result of the ISEE phase and parallel technology development and system definition efforts, System Feasibility for intermediate systems costing $1.60-$2.60 per peak watt will be established in the 1982 timeframe. System Readiness Experiments (SREs) built with technology ready hardware will establish the System Readiness milestones in the 1985 timeframe and will lead into the commercialization phase.

CURRENT ISEE PROJECTS

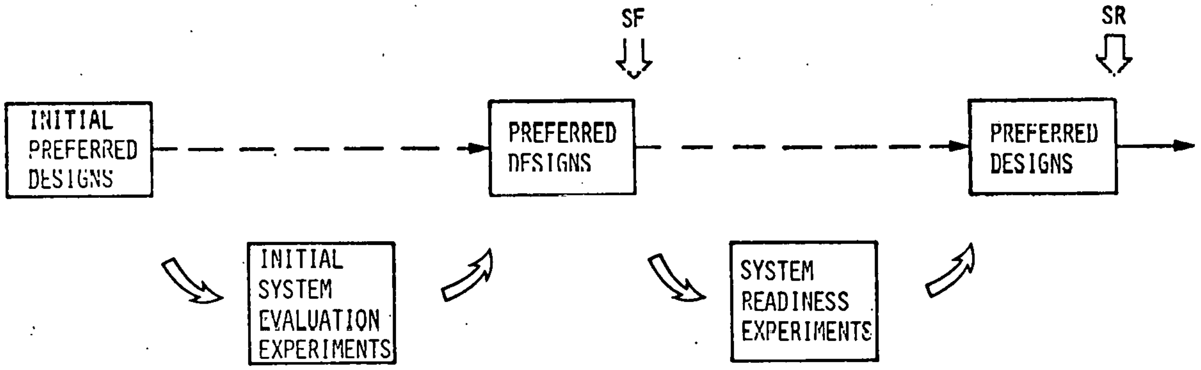
A number of on-going and beginning projects will form the ISEE phase for intermediate load center applications. Figure 2 shows the location and size (in peak kilowatts) of both on-going projects and beginning projects which result from two recent DOE Program Research and Development Announcements (PRDAs).

---

*This work was supported by the Distributed Solar Technology Division of the U. S. Department of Energy.

Following a competitive design phase, nine PRDA projects have been selected by DOE for system construction and operation. These nine projects are listed in Figure 3 and include five projects which use photovoltaic concentrator arrays and four projects which use photovoltaic flat panel arrays. Contracts for these projects are currently being negotiated and the first resulting systems are expected to be operational in approximately one year.

Uniform methods for acquiring system performance and operational data during the experimental phase of these projects and for analyzing and reporting this data are being established. This data system will consist of on-site data acquisition hardware and a centralized data reduction activity aimed at providing experimental results to a variety of users.



SF = SYSTEM FEASIBILITY IN 1982

SR = SYSTEM READINESS IN 1985

Figure 1. Experimental Phases and Major Milestones for Intermediate Load Center System Application Experiments.

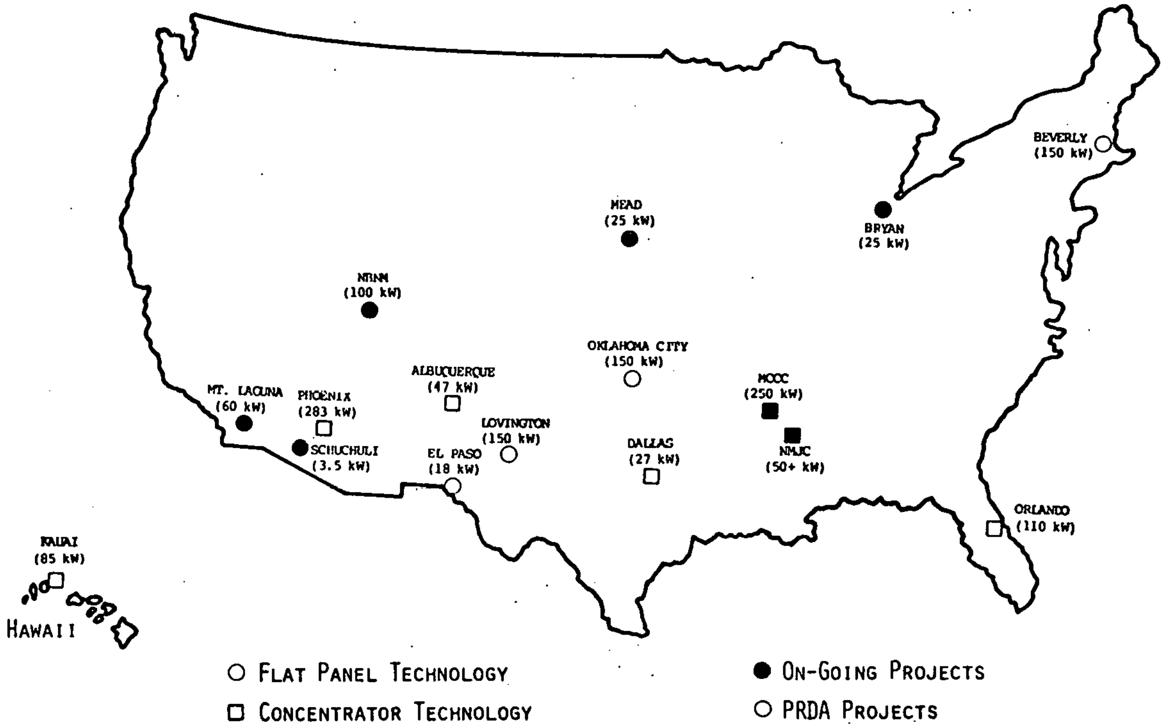


Figure 2. Location and Size of Initial System Evaluation Experiments (ISEEs) in the Intermediate Sector.

CONTRACTOR	LOCATION	APPLICATION	SIZE(kW$_P$)	DOE COST($M)	$/W$_P$
CONCENTRATORS:					
ACUREX	KAUAI, HI	HOSPITAL	85	1.37	16
ARIZONA PUBLIC SER.	PHOENIX, AZ	AIRPORT	283	6.57	23
BDM	ALBUQ., NM	OFFICE BLDG.	47	1.11	24
E-SYSTEMS	DALLAS, TX	AIRPORT	27	0.65	24
GENERAL ELECTRIC	ORLANDO, FL	AMUSEMENT PARK	110	3.43	31
			552	13.13	
FLAT PANELS:					
LEA COUNTY ELEC.	LOVINGTON, NM	SHOPPING CNTR.	150	2.74	18
NEW MEXICO STATE	EL PASO, TX	COMPUTER UPS	18	0.48	27
SCIENCE APPLICATIONS	OKLAHOMA CITY, OK	SCIENCE & ART CENTER	150	2.48	17
SOLAR POWER	BEVERLY, MA	HIGH SCHOOL	146	2.71	19
			464	8.41	

Figure 3. Photovoltaic System Application Experiments Resulting from PRDA 35 and PRDA 38.

NOTES

RESIDENTIAL EXPERIMENTS

Edward C. Kern, Jr.
Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173

MULTI-YEAR PROGRAM PLAN

The U. S. Department of Energy's Photovoltaic Program Multi-Year Program Plan (1) outlines a ten-year effort to reduce photovoltaic system costs to levels which are competitive with traditional energy sources. Authorized by the Solar Photovoltaic Energy Research, Development and Demonstration Act of 1978 (Public Law 95-590), the planned program organizes all applications into four application sectors: Remote-Stand Alone, Residential, Intermediate Load Center, Central Station. Specific program elements for each sector are set forth in four separate Implementation Plans.

The Residential Application Implementation Plan (2) describes the residential photovoltaic experiments envisioned by DOE. A sequence of tests first addressing individual system performance, and progressively incorporating utility system and societal impacts is planned through the mid-1980's. Through this activity DOE intends to attain system readiness--the operation of fully integrated systems which would be economically viable if produced in quantity--by October 1984 (1). During this period of system development activity a commercialization strategy will be adopted by DOE for implementation in the post 1986 period.

RESIDENTIAL PV ENERGY IMPACTS

The Project Independence Task Force (3) forecasts for housing units indicates an increase of approximately twenty-million units between 1985 and 2000. Single-family detached homes account for thirteen million; low-density units and mobile homes two million each. If all new residences built in the 1985-2000 period were fitted with 10 peak kilowatt arrays and all existing residences in 1985 were retrofitted with 5 peak kilowatt arrays, the total installed PV capacity would be 542 peak gigawatts. This figure only gives the scale of the residential market, complete penetration is obviously impossible. A most optimistic scenario would be to penetrate half the 1985-2000 new construction market and ten percent of the retrofit market. Such an accomplishment would require 130 peak gigawatts and result in a yearly 2.0 to 2.5 quad contribution to the United States primary energy economy.

DOE RESIDENTIAL PROJECT

The DOE Residential Project focuses on three categories of housing (single-family, low-density, mobile homes), three regions of the U. S.

(Southwest, Northeast, Southeast) and involves three phases of commercial product development and testing. Sensitivity to critical institutional issues such as electric utility interfaces, insurability, building codes, and public perceptions and acceptance is provided by the management structure of the planned experiments.

The residential project is limited to buildings into which PV devices can be integrated. Because of the small roof-area to energy-use ratios experienced in high-rise and low-rise housing, these categories of housing cannot be significantly served by structure-integrated PV systems. It appears that such high energy density residences will be best served by off-site intermediate size PV systems. Consequently, these categories are considered as part of the Intermediate Load Center Plan.

System Development Sequence

The DOE Residential Project will commence by selecting and promulgating Regionally Appropriate System Designs. These will be residential systems designs at a conceptual level indicating the approximate size, orientation and capacity of the required array, the electric balance-of-system and the heating and cooling system of the residence. Through a request-for-proposals, these designs will be used to solicit detailed designs and proposals to build Prototype Systems. Upon completing qualification testing of the Prototypes at Regional Residential Experiment Stations, the systems will be refined and reproduced in lived-in residences near the experiment station. Finally, in time to demonstrate System Readiness by October 1984, System Readiness Experiments will be conducted in each region. Uncoupled from the experiment station, these final experiments will concentrate on utility interaction effects and public acceptance of photovoltaic residences.

RESIDENTIAL EXPERIMENT STATIONS

During the first years of the residential project, Residential Experiment Stations will be the foci of activity. Both the concept and the name have evolved from the agricultural experiment stations operated at many state universities. They provide a common site at which to "plant" and compare directly a variety of experimental "crops." They encourage ties to all interested groups within the community and region, ties which will enhance the prospects for success of the most desirable solar designs and winnow out those judged less desirable.

Prototype System Testing

Each experiment station will establish both physical "hard data" and institutional "soft data" ties within its community and region. The hard ties will be real-time data links to energy-use monitored residences in the neighborhood. Such data will be first used to gain a better understanding of residential energy use patterns. When Prototype Systems are installed at the stations, a single monitored residence--chosen for its representativeness--will be used to control all prototypes. Subjecting all prototypes to identical energy usage will permit direct performance comparisons.

Initial System Evaluation Experiments

Following the successful operation of a Prototype System, a refined edition of the same system will be built in the community surrounding the experiment station. One stage closer to a commercial product, this will test the system with an occupied residence. At this stage the end-user's acceptance of and comments concerning solar photovoltaic residences will form an important part of the data gathered.

The soft ties to the region and community concern the numerous known and yet to be discovered societal and institutional impact/demands/constraints on residential PV systems. The experiment station is a place for all to see, to understand and to comment upon a promising renewable energy option seeking a place in the future.

SYSTEM READINESS EXPERIMENTS

Whereas the emphasis during the prototype and Initial System Evaluation Experiments is on the engineering performance of individual residential systems, the System Readiness Experiments focus on markets and institutional responses. These experiments will be conducted at three regional sites independent of the Residential Experiment Stations. Each site will consist of a cluster of approximately one hundred residences covering all selected housing categories and both new and retrofit construction. The unifying element for each cluster will be a single distribution feeder originating from a utility substation.

The System Readiness Experiment clusters are sized so as to provide PV capacity to significantly perturb utility operations at the substation level. The intention is to confront, head-on, all the engineering problems that will result from widespread adoption of photovoltaics in the residential sector. These include voltage regulation, distribution line and transformer sizing, circuit breaking with two-way power flows and linesman safety procedures.

The second function of the System Readiness Experiments is to assess the market for residential photovoltaics. Each cluster will provide a diversity of PV designs with which to gauge the public response to PV. Since these experiment clusters will be built immediately preceeding the anticipated economic viability of PV systems, they are expected to form seed points for private marketplaces.

REFERENCES

1. U. S. Department of Energy, National Photovoltaic Program Multi-Year Program Plan, June 6, 1979 (Draft), Division of Solar Technology, Washington, DC.
2. U. S. Department of Energy, Photovoltaic Program, Residential Application Implementation Plan, July 1979 (Draft), Massachusetts Institute of Technology Energy Laboratory and Lincoln Laboratory, Cambridge, MA.
3. Project Independence Task Force, "Residential and Commercial Energy Use Patterns 1970-1990," Government Printing Office, Washington, DC, 1974.

PROGRAM GOAL

- A PRIVATE VIABLE MARKET FOR $1.60 PER PEAK WATT (1980 $S) PV AND PV/T SYSTEMS BY 1986

PROGRAM APPROACH

- DEVELOP AND TEST RESIDENTIAL COMPONENTS AND SYSTEMS:

DEVELOPMENT SEQUENCE
  - REGIONALLY APPROPRIATE DESIGNS
  - PROTOTYPE SYSTEMS (NO OCCUPANT)
  - INITIAL SYSTEMS EVALUATION EXPMTS
  - SYSTEM READINESS EXPERIMENTS

- DEVELOP A COMMERCIALIZATION STRATEGY FOR IMPLEMENTATION IN THE POST 1986 PERIOD

FORECAST U.S. RESIDENTIAL INVENTORY (YEAR-ROUND UNITS)

				PV MARKET SIZE (GW_{PK})	
	1985	2000	INCREASE	NEW	RETROFIT[2]
SINGLE FAMILY	55,370,000	68,227,000	12,857,000	129[1]	277
LOW DENSITY	14,059,000	16,285,000	2,226,000	22[1]	70
LOW RISE	8,237,000	10,126,000	1,889,000	--	--
HIGH RISE	4,309,000	4,918,000	609,000	--	--
MOBILE HOME	6,827,000	8,882,000	2,055,000	10[3]	34
				161	381

542 GW_{PK} TOTAL

1) 10 KW_{PK} DESIGNED INTO EACH UNIT

2) 5 KW_{PK} ADDED ON EACH UNIT

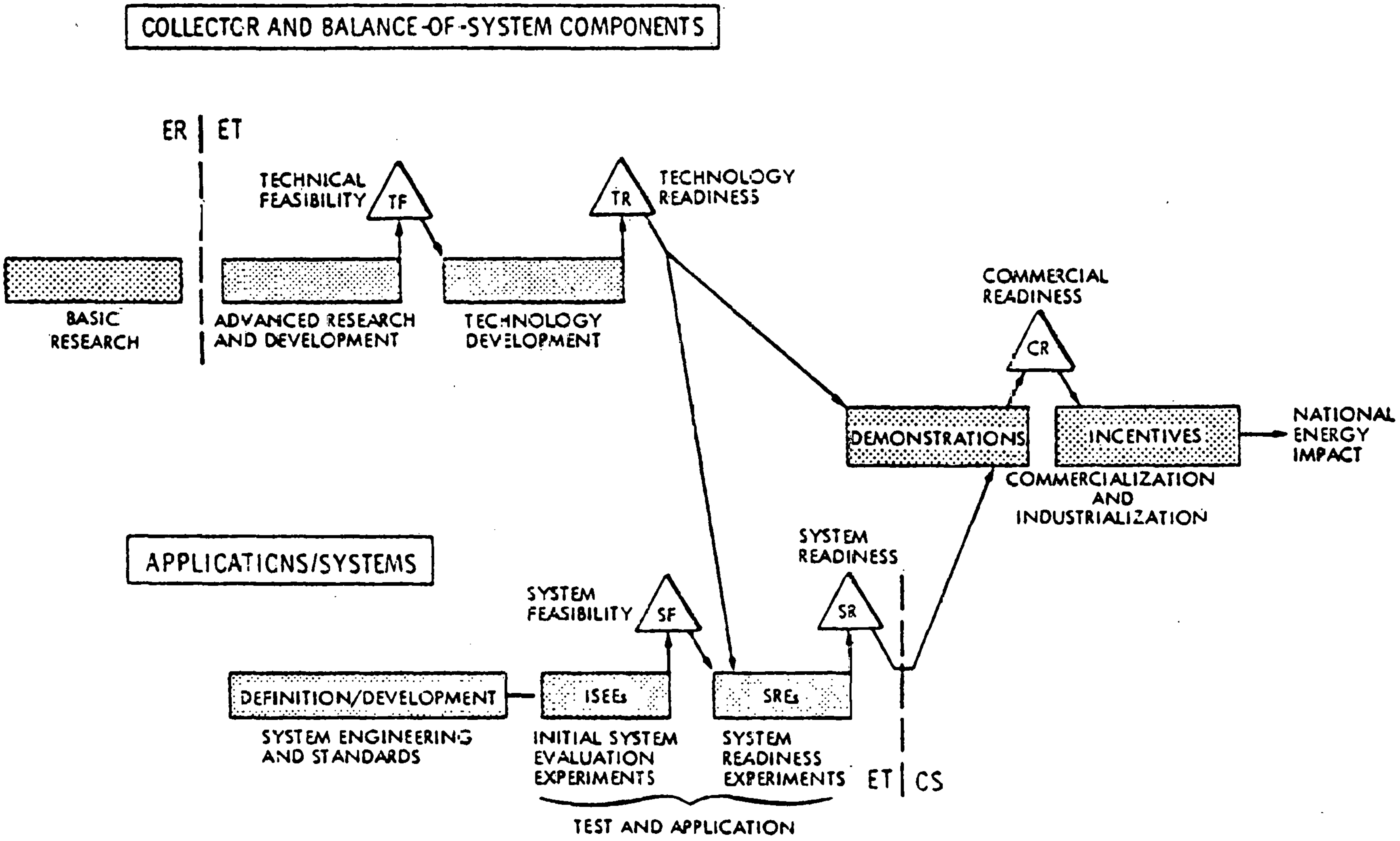
3) 5 KW_{PK} DESIGNED INTO EACH UNIT

RESIDENTIAL PV SYSTEMS

- USE ON-SITE PV COLLECTORS
- REGIONAL DESIGN VARIATION
- HOUSING CATEGORY VARIATION

DOE RESIDENTIAL PROJECT

- 1979-1989 PERIOD
- SINGLE-FAMILY, LOW-DENSITY AND MOBILE HOMES
- SOUTHWEST, NORTHEAST AND SOUTHEAST REGIONS
- COMMERCIAL PRODUCT DEVELOPMENT AND COMPARATIVE TESTING
- UTILITY PENETRATION, INSTITUTIONAL AND PUBLIC ACCEPTANCE ISSUES


COLLECTOR AND BALANCE-OF-SYSTEM COMPONENTS
ER
ET
TECHNICAL FEASIBILITY
TF
TR
TECHNOLOGY READINESS
BASIC RESEARCH
ADVANCED RESEARCH AND DEVELOPMENT
TECHNOLOGY DEVELOPMENT
COMMERCIAL READINESS
CR
DEMONSTRATIONS
INCENTIVES
NATIONAL ENERGY IMPACT
COMMERCIALIZATION AND INDUSTRIALIZATION
APPLICATIONS/SYSTEMS
SYSTEM FEASIBILITY
SF
SYSTEM READINESS
SR
DEFINITION/DEVELOPMENT
ISEEs
SREs
SYSTEM ENGINEERING AND STANDARDS
INITIAL SYSTEM EVALUATION EXPERIMENTS
SYSTEM READINESS EXPERIMENTS
ET
CS
TEST AND APPLICATION

RESIDENTIAL SYSTEM DEVELOPMENT

REGIONALLY APPROPRIATE SYSTEM DESIGNS

BASELINE DESIGNS

PROTOTYPE SYSTEM EXPERIMENT

RESIDENTIAL EXPERIMENT STATION

INITIAL SYSTEM EVALUATION EXPERIMENT

COMMUNITY NEARBY RESIDENTIAL EXPERIMENT STATION

SYSTEM READINESS EXPERIMENT

INDEPENDENT OF RESIDENTIAL EXPERIMENT STATION

REGIONALLY APPROPRIATE SYSTEM DESIGNS

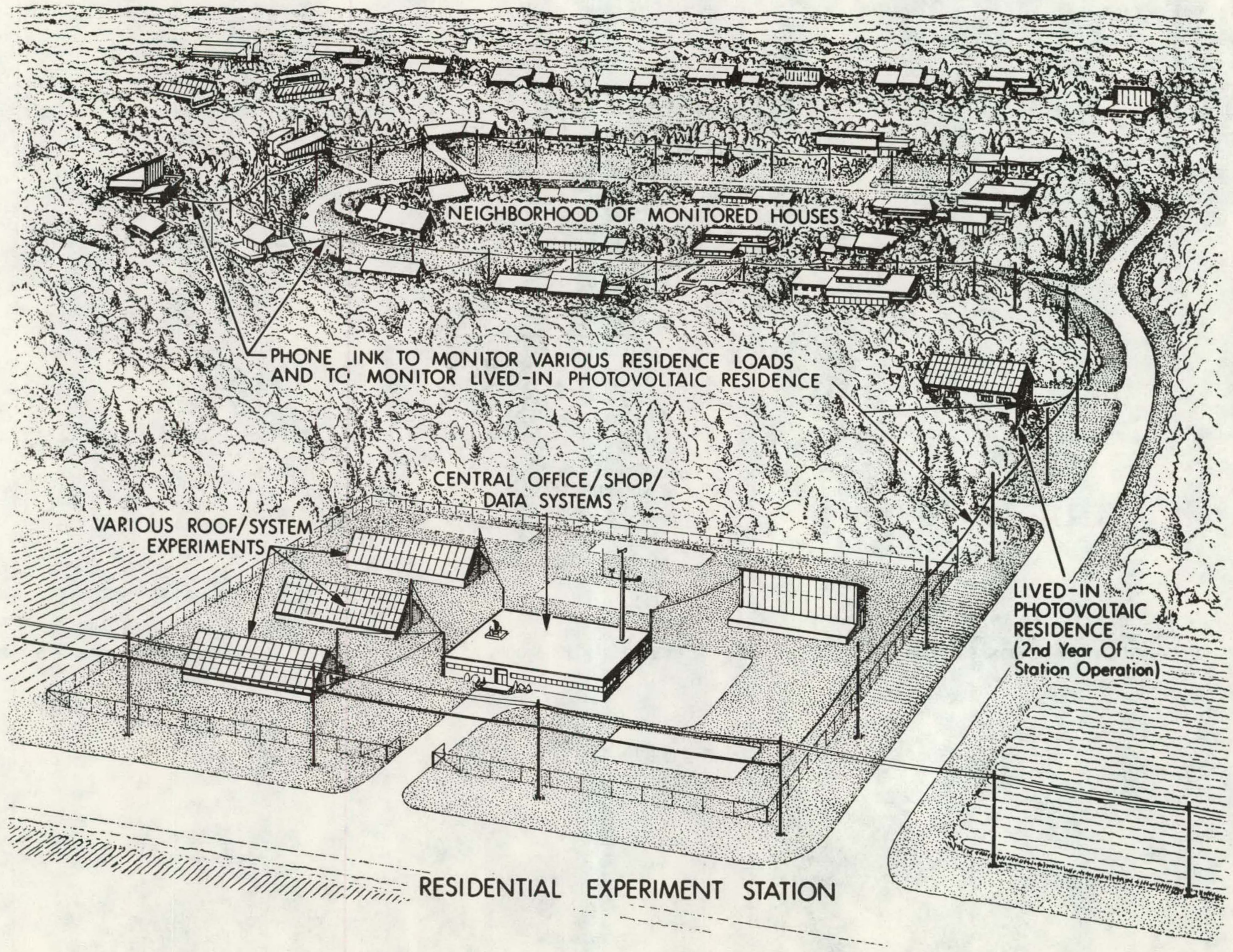
- BASELINE CONCEPTUAL SYSTEM DESIGNS

$$\begin{Bmatrix} \text{SINGLE FAMILY} \\ \text{LOW DENSITY} \\ \text{MOBILE HOME} \end{Bmatrix} \times \begin{Bmatrix} \text{SOUTHWEST} \\ \text{NORTHEAST} \\ \text{SOUTHEAST} \end{Bmatrix}$$

ELECTRIC POWER SYSTEM

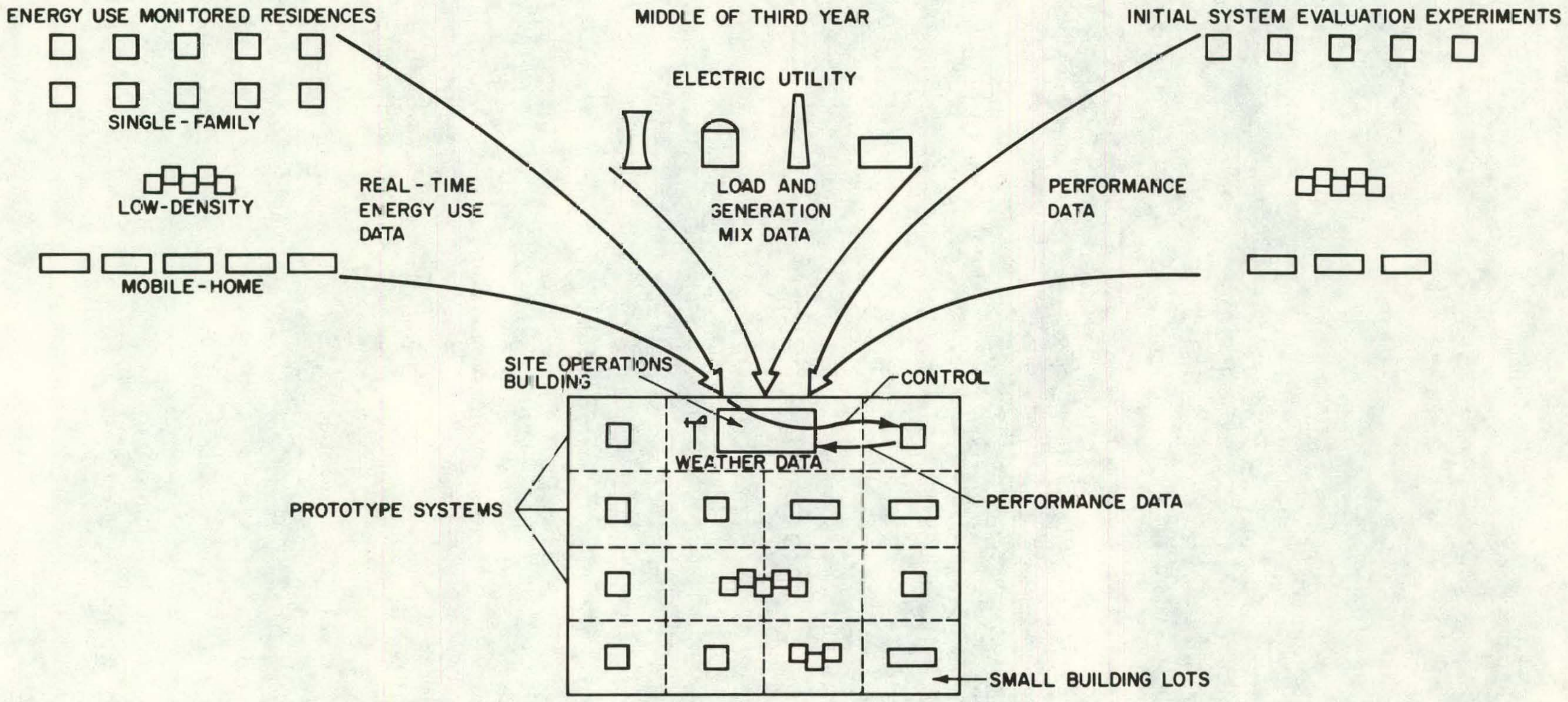
THERMAL POWER SYSTEM

- USED TO SOLICIT INDUSTRY PROPOSALS



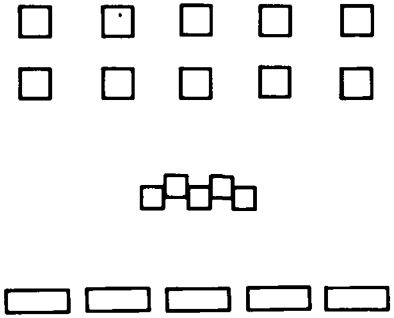
RESIDENTIAL EXPERIMENT STATION

RESIDENTIAL EXPERIMENT STATION



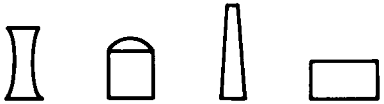
RESIDENTIAL EXPERIMENT STATION

CITIZENS



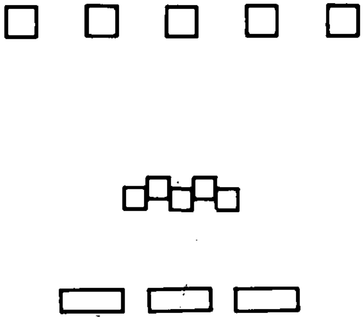
- RESIDENTIAL ENERGY AWARENESS
- ENERGY CONSERVATION
- ALTERNATE SOLAR DESIGNS
- COMPETING MANUFACTURERS

UTILITIES

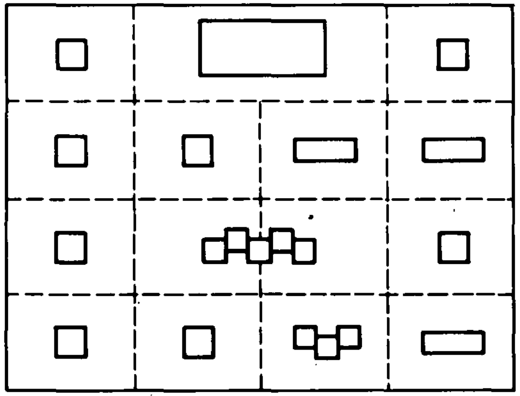


- FUEL DISPLACEMENT
- CAPACITY DISPLACEMENT
- TRANSMISSION AND DISTRIBUTION
- RATE SETTING

SOLAR AND BUILDING INDUSTRY



- SOLAR BUILDING PRACTICES
- OCCUPANT RESPONSES
- INSTITUTION RESPONSES
- MARKETING TECHNIQUES



INSTITUTIONS

- BUILDING CODES
- INSURANCE
- BANKS (Mortgages)
- PUBLIC UTILITY COMMISSIONS

RESIDENTIAL EXPERIMENT STATIONS

- Northeast 1979, Southwest 1980, Southeast 1981
- 20 MONITORED RESIDENCES AT EACH
- 10 TO 20 PROTOTYPE EXPERIMENTS AT EACH
- QUALIFICATIONS LEADING TO OCCUPIED TEST RESIDENCES

PROTOTYPE SYSTEM EXPERIMENTS

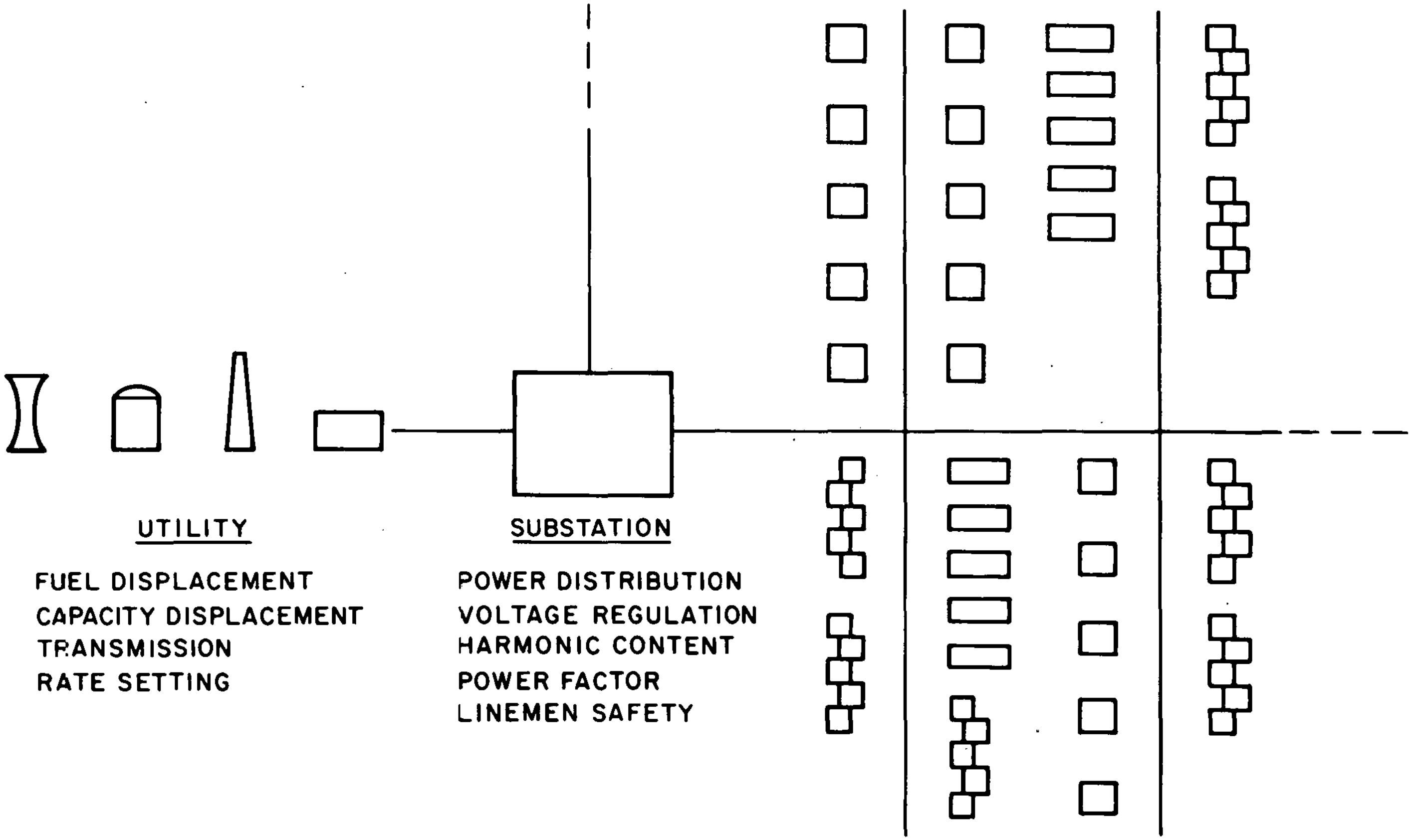
- INDUSTRIAL DESIGN AND ASSEMBLY
- BUILD ONLY PV ROOF ARRAY, ELECTRIC AND THERMAL SYSTEM
- DOE INSTRUMENTS AND CONDUCTS EXPERIMENT
- DIRECT COMPARISON WITH SIMILAR DESIGNS

INITIAL SYSTEM EVALUATION EXPERIMENTS

- SITED NEAR RESs FOR RESEARCH AND MAINTENANCE PURPOSES
- DESIGNED, ASSEMBLED AND OCCUPANT SELECTED BY INDUSTRY
- INSTRUMENTED AND TESTED BY DOE
- PERFORMANCE, COST, OCCUPANT AND INSTITUTIONAL RESPONSE DATA

SYSTEM READINESS EXPERIMENTS

APPROXIMATELY 100 RESIDENCES (0.5 to 1.0 MWpk PV Capacity)
CONNECTED TO A SINGLE 2 MW DISTRIBUTION FEEDER



UTILITY

- FUEL DISPLACEMENT
- CAPACITY DISPLACEMENT
- TRANSMISSION
- RATE SETTING

SUBSTATION

- POWER DISTRIBUTION
- VOLTAGE REGULATION
- HARMONIC CONTENT
- POWER FACTOR
- LINEMEN SAFETY

SOLAR AND BUILDING INDUSTRY

- MARKETING TECHNIQUES
- INSTITUTION RESPONSES
- BUILDING PRACTICES

INSTITUTIONS

- PUBLIC UTILITY COMMISSIONS
- BANKS
- INSURANCE
- BUILDING CODES

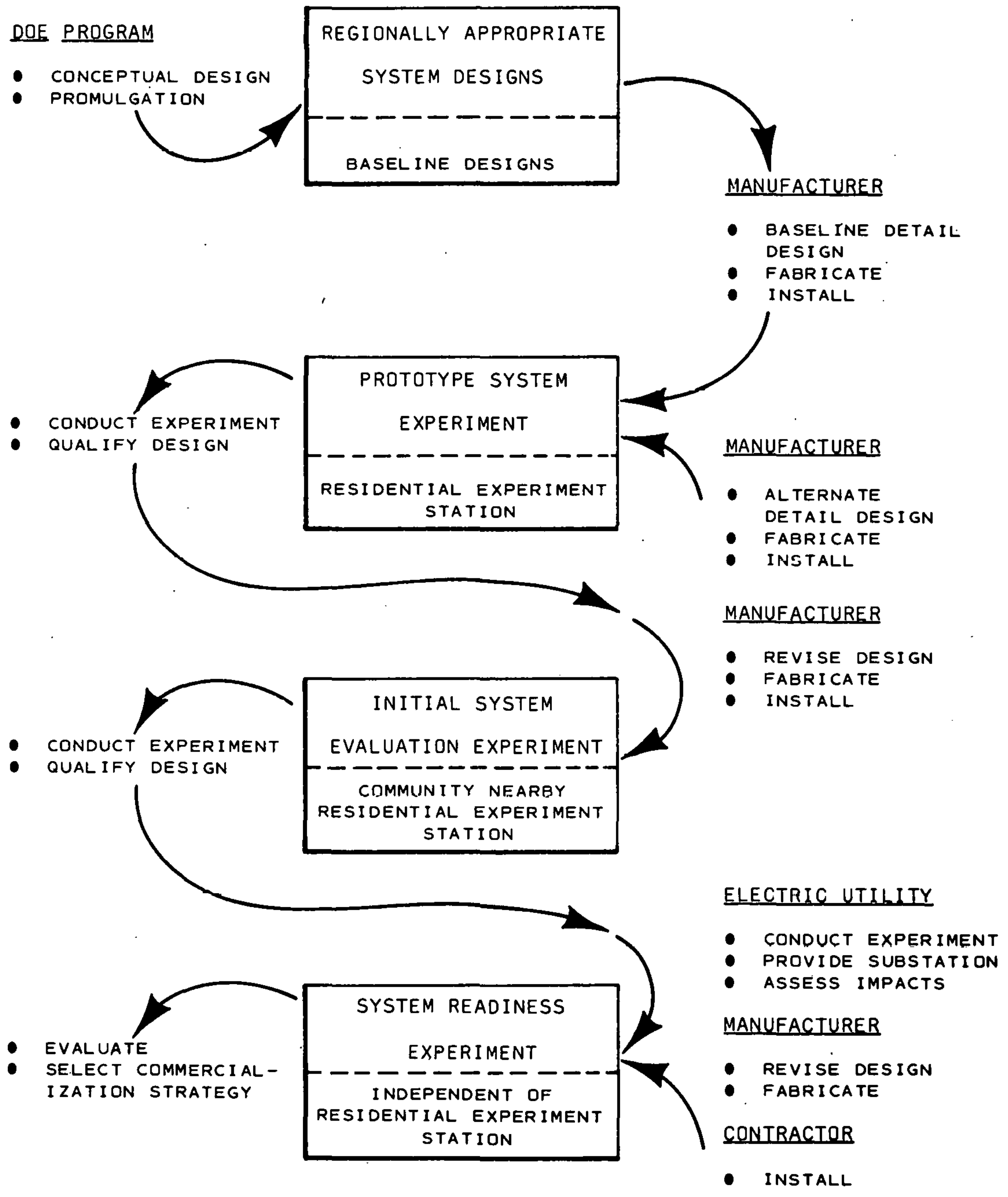
NEIGHBORHOOD

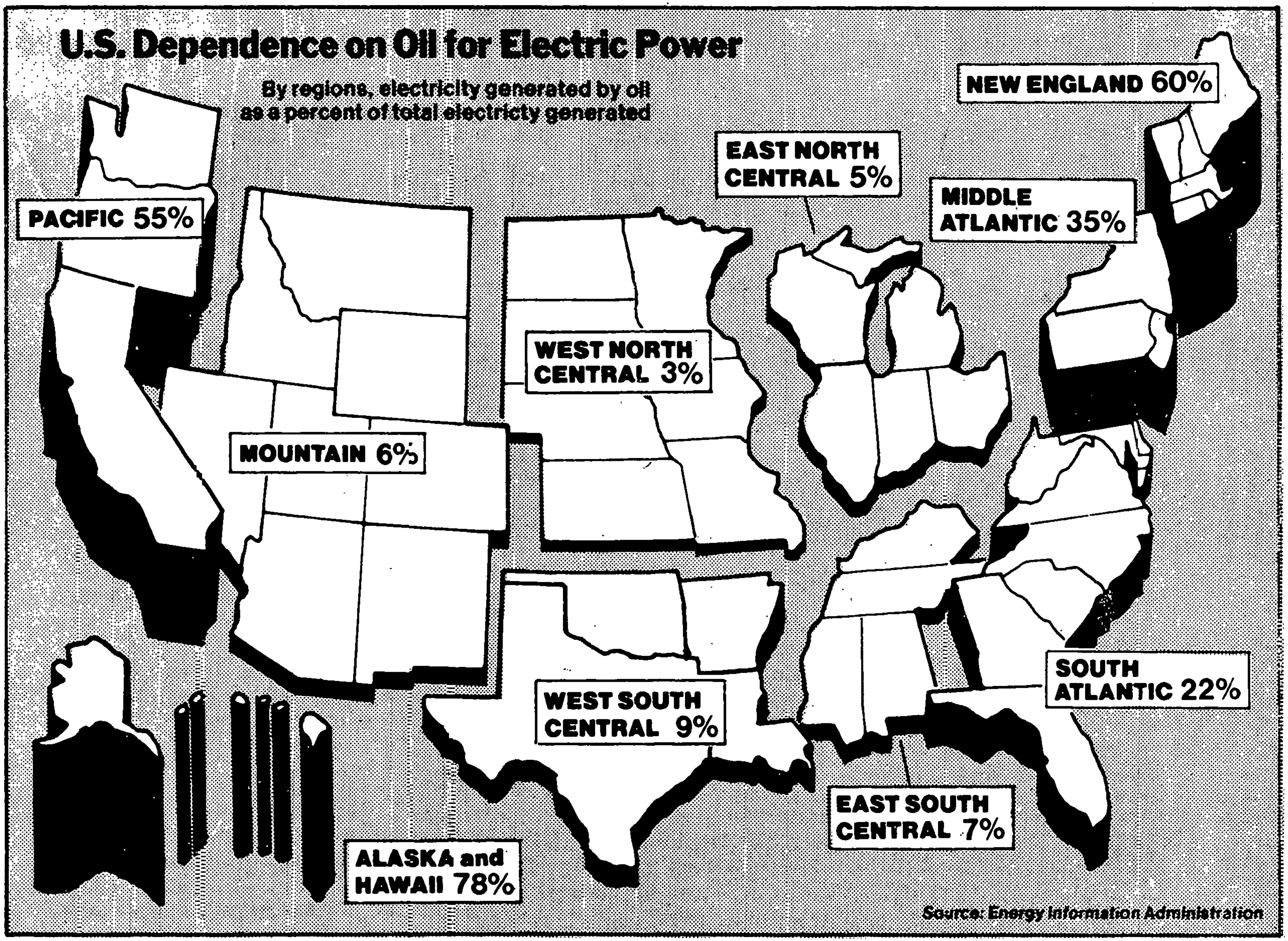
- SYSTEM PREFERENCES
- REAL ESTATE VALUES
- ENERGY CONSERVATION

SYSTEM READINESS EXPERIMENTS

- REGIONAL CLUSTERS
- 100 UNITS CLUSTERED ON SINGLE DISTRIBUTION LINE FROM SUBSTATION
- DESIGNED, ASSEMBLED AND OCCUPANT SELECTED BY INDUSTRY
- IMPACT OF HIGH CAPACITY PENETRATION ON A UTILITY
- PV SYSTEM INSTALLATION, PERFORMANCE, MAINTENANCE AND RELIABILITY
- PUBLIC ACCEPTANCE
- SEED POINT FOR THE GROWTH OF A MARKETPLACE

RESIDENTIAL SYSTEM DEVELOPMENT





U.S. Dependence on Oil for Electric Power

By regions, electricity generated by oil as a percent of total electricty generated

Source: Energy Information Administration

The New York Times / July 18, 1979

BATTERY STORAGE FOR PHOTOVOLTAICS

ROBERT P. CLARK
SANDIA LABORATORIES
ALBUQUERQUE, NEW MEXICO

PRESENTED AT PHOTOVOLTAIC ADVANCED
R & D ANNUAL REVIEW MEETING
SEPTEMBER 17, 1979 - DENVER, COLORADO

BATTERIES FOR SPECIFIC SOLAR APPLICATIONS

1 - BECHTEL - BATTERY/PHOTOVOLTAIC HANDBOOK

2 - HITTMAN - SOLAR DATA BASE AND SYSTEMS STUDY

3 - SANDIA - BATTERY SYSTEMS FOR PHOTOVOLTAIC ENERGY STORAGE

BECHTEL - BATTERY/PHOTOVOLTAIC HANDBOOK

I - OBTAIN BATTERY DATA RELEVANT TO PV SYSTEMS

  A - PRESENT DAY BATTERIES
  B - ADVANCED BATTERIES

II - PUBLISH HANDBOOK

HITTMAN - SOLAR DATA BASE AND SYSTEMS STUDY

I - Develop Data Bases
  A - Batteries
  B - Power Conditioning
  C - PV Arrays

II - Develop End-Use Characteristics

III - Perform Cost Analysis of Battery Systems

IV - Identify Required R&D

BATTERY SYSTEMS FOR PHOTOVOLTAIC ENERGY STORAGE PROGRAM

- BATTERY REQUIREMENTS ANALYSIS
    - LABORATORY EVALUATION
    - PHOTOVOLTAIC ADVANCED SYSTEMS TESTS
    - PHOTOVOLTAIC APPLICATIONS EXPERIMENTS
    - BATTERY RESEARCH AND DEVELOPMENT

PROGRAM STRATEGY

1. CONDUCT SYSTEMS ANALYSES TO DEFINE BATTERY REQUIREMENTS.
2. CONDUCT LABORATORY EVALUATIONS AND SYSTEMS TESTING TO REFINE BATTERY REQUIREMENTS ANALYSIS.
3. IDENTIFY DIFFERENCES BETWEEN BATTERY REQUIREMENTS AND EXISTING TECHNOLOGY.
4. DEFINE AND SUPPORT NECESSARY BATTERY RESEARCH AND DEVELOPMENT.

PV/BATTERY STUDY SCOPE

OPERATIONS MODE

- STAND ALONE
- GRID CONNECTED
  - TOD PRICING
    - OFFPEAK CHARGING
  - SELLBACK

APPLICATION

- RESIDENTIAL
- INTERMEDIATE
  - AGRICULTURAL
  - INDUSTRIAL
  - COMMERCIAL
    - APARTMENT
    - SHOPPING CENTER
    - LIGHT MANUFACTURING

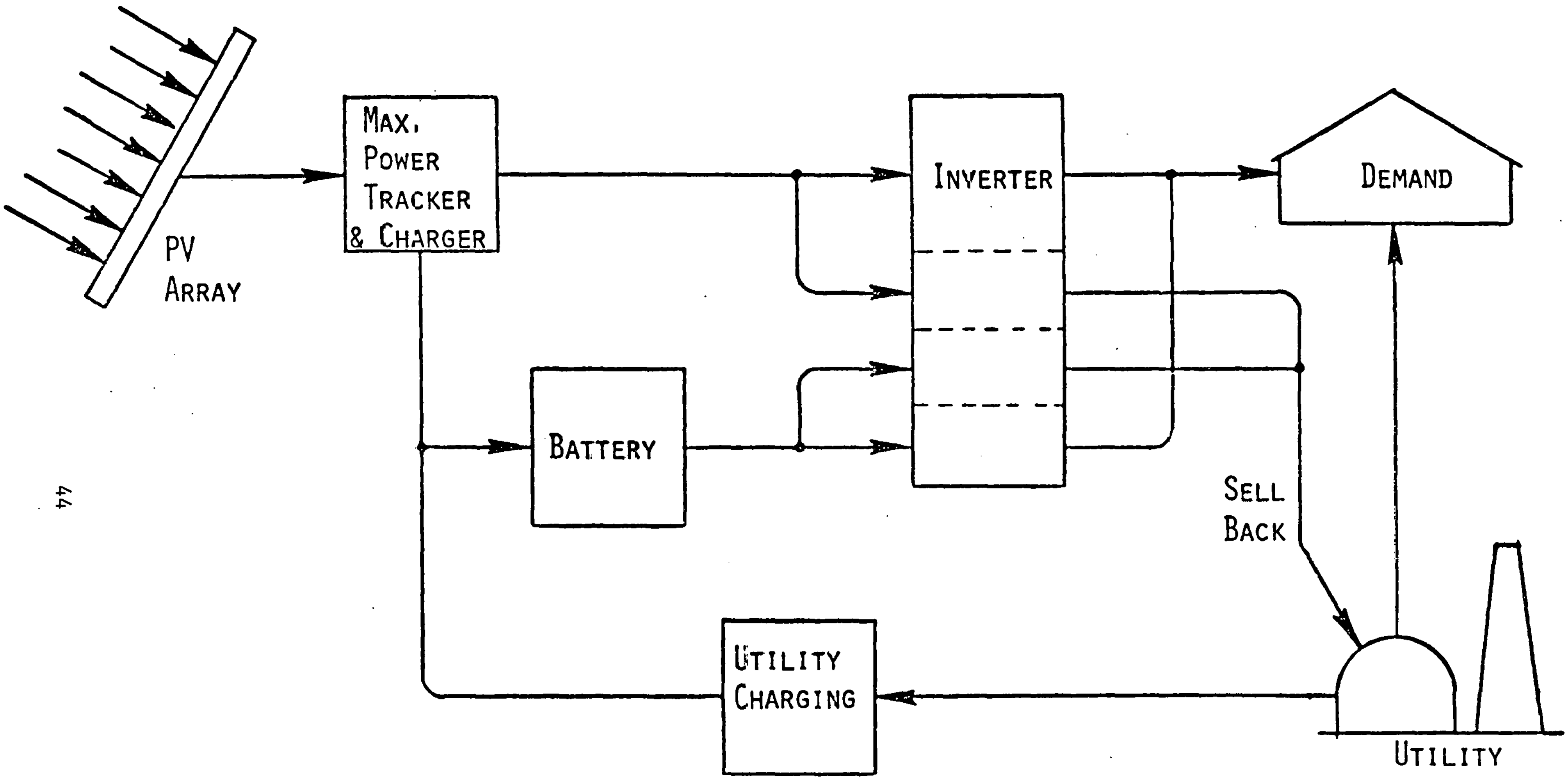


FIGURE 1. SOLSTOR MODEL

RESIDENTIAL PHOTOVOLTAIC SYSTEMS ANALYSIS

Parameters

- Array Cost (70¢/W_p)
- Time of Day Price Ratio (1, 3, 6)
- Sellback Ratio (0, .25, .50, .75)
- Battery Cost ($64/KWH, 91, 163, 270)
- Solar Availability
- Economics-Fuel Escalation (0%, 3, 6)

PV/STORAGE STUDY RESULTS

TOD RATIO		LIFE CYCLE COST RATIO			PV ARRAY SIZE (m^2)			STORAGE SIZE (KWH)			OFF-PEAK CHARGING?		
		1:1	3:1	6:1	1:1	3:1	6:1	1:1	3:1	6:1	1:1	3:1	6:1
SELLBACK RATIO	0.	.82	.74	.63	92	73	58	28	21	16	N	N	Y
	.25	.82	.76	.65	94	70	53	31	20	20	N	N	Y
	.50	.78	.55	.37	150	150	150	0	0	28	-	-	Y
	.75	.52	.22	-.03	150	150	150	0	24	26	-	Y	Y

LOCATION: PHOENIX

3% RATE ESCALATION

$91/KWH STORAGE COST

DATE: 7/19/79

PV/STORAGE STUDY RESULTS

	TOD RATIO	LIFE CYCLE COST RATIO			PV ARRAY SIZE (m^2)			STORAGE SIZE (kWh)			OFF-PEAK CHARGING?		
		1:1	3:1	6:1	1:1	3:1	6:1	1:1	3:1	6:1	1:1	3:1	6:1
SELLBACK RATIO	0.	.68	.62	.51	119	107	55	43	45	43	N	Y	Y
	.25	.67	.59	.43	150	150	150	46	33	36	N	Y	Y
	.50	.60	.36	.09	150	150	150	40	35	50	N	Y	Y
	.75	.42	.06	-.32	150	150	150	-	40	49	-	Y	Y

LOCATION: NEW YORK

3 % RATE ESCALATION

$91/kWh STORAGE COST DATE: 8/1/79

PV/STORAGE STUDY RESULTS

SELLBACK RATIO	TOD RATIO	LIFE CYCLE COST RATIO			PV ARRAY SIZE (m^2)			STORAGE SIZE (kWH)			OFF-PEAK CHARGING?		
		1:1	3:1	6:1	1:1	3:1	6:1	1:1	3:1	6:1	1:1	3:1	6:1
	0.	>1.	1.0	.86	0	34	29	0	0	22	-	-	Y
	.25	>1.	1.0	.76	0	37	0	0	0	44	-	-	Y
	.50	>1.	.98	.75	0	41	0	0	0	45	-	-	Y
	.75	>1.	.83	.64	0	150	150	0	0	20	-	-	Y

LOCATION: COLUMBIA, MO

3% RATE ESCALATION

$91/kWH STORAGE COST

DATE: 8/15/79

PRELIMINARY CONCLUSIONS FOR SINGLE RESIDENCES

- AT A COST OF $100-$150/KWH, BATTERIES BEGIN TO BE ATTRACTIVE FOR RESIDENTIAL PV SYSTEMS

- BATTERIES WILL PROBABLY BECOME INCREASINGLY ATTRACTIVE WITH TIME

- THE USE OF BATTERIES IN A PV SYSTEM GENERALLY INCREASES THE OPTIMUM SIZE OF THE PV ARRAY
  - INCREASES FOSSIL FUEL DISPLACEMENT
  - INCREASES PV ARRAY PRODUCTION RATES

TEST PROGRAM OBJECTIVES

TASK II - LABORATORY EVALUATION

Develop a test laboratory for evaluating small battery systems in simulated photovoltaic energy storage application. (A. E. Verardo)

TASK III - PV ADVANCED SYSTEMS TESTS

Evaluate battery performance in a controlled fullscale PV system environment. (J. L. Chamberlin)

TASK IV - PV APPLICATION EXPERIMENTS

Evaluate battery performance in "real world" PV application experiment environment. (J. B. Allen)

NBTL - Electric Vehicle Applications

1. light weight ⟶ high energy density
2. environment - vibration, vehicle safety, temperature
3. lifetime - 3 to 5 years (500 to 2000 cycles)
4. charge-discharge profile - long charging period (overnight)

Sandia - Solar Applications

1. long life - 20 years (2000 to 5000 cycles)
2. low cost
3. deep discharge perhaps daily
4. erratic charging and high charge rates

BEST - Utility Load Leveling Applications

1. large system capacity - 10 MWHr
2. more controlled charge-discharge cycles
3. shallow depth of discharge
4. low cost and long life

TEST SYSTEM CAPABILITIES

1) PROGRAMMABLE CHARGE RATES - SOLAR CELL - CHARGER SIMULATIONS
2) PROGRAMMABLE DISCHARGE RATES - LOAD SIMULATIONS
3) TEMPERATURE CONTROL - TEMPERATURE CYCLING
4) DATA MONITORING & ACQUISITION - BATTERY VOLTAGE
    - BATTERY CURRENT
    - BATTERY TEMPERATURE
    - STATE OF CHARGE
5) DATA STORAGE
6) DATA PLOTTING
7) EXPANDABLE TO MULTIPLE TEST STATIONS

TASK III - PV ADVANCED SYSTEMS TESTS

GOALS:

- EVALUATE BATTERIES IN FULL PV SYSTEM
- RELATE LABORATORY EVALUATION DATA TO SYSTEM RESULTS
- VERIFY AND/OR MODIFY BATTERY REQUIREMENTS ANALYSIS

EXISTING CAPABILITIES AT PVTF

1. 21 KWHr lead acid battery system
2. AC charger
3. 150 KW AC-DC load bank
4. Programmable 15 KW AC-DC load bank
5. 4 inverter systems (PCU) with utility interface
6. 10 KW Martin Marietta array
7. 10 KW (6 KW) Spectrolab array
8. 2.5 KW JPL flat plate array
9. 75 KW array simulator

DESIRED ENHANCEMENTS TO THE PVTF

1. DC regulator/charger
2. Additional batteries
3. PV array dedicated to battery system testing

TASK IV - PHOTOVOLTAIC APPLICATION EXPERIMENTS

GOALS:

- RELATE LABORATORY EVALUATION AND PV TEST FACILITY RESULTS TO REAL WORLD PERFORMANCE

- VERIFY AND/OR MODIFY BATTERY REQUIREMENTS ANALYSIS

EXISTING PV-BATTERY APPLICATION EXPERIMENTS

Schuchuli Indian Village - NASA Lewis Research Center

Location: Gunsite, Arizona
PV Array Size: 3.5 KW
Battery Size: 200 KWHr
Application: Refrigerators and lights for village

Irrigation Test Site - MIT Lincoln Laboratory

Location: Mead, Nebraska
PV Array Size: 25 KW
Battery Size: 180 KWHr
Application: Pump for irrigation

Natural Bridges - MIT Lincoln Laboratory

Location: Natural Bridges National Monument, Utah
PV Array Size: 100 KW
Battery Size: 600 KWHr
Application: Visitor Center

TASK V - BATTERY RESEARCH AND DEVELOPMENT

- DEFINE DISCREPANCIES BETWEEN BATTERY STATE-OF-ART AND BATTERY SYSTEM REQUIREMENTS FOR PV ENERGY STORAGE APPLICATIONS
- DEFINE GOALS TO ELIMINATE DISCREPANCIES
- OUTLINE AND IMPLEMENT R&D PROGRAM TO ACHIEVE GOALS
  - SUPPLEMENT EV AND LL EFFORTS
  - UTILIZE INDUSTRY, UNIVERSITIES, RESEARCH INSTITUTES, GOVERNMENT
  - MAINTAIN SMALL IN-HOUSE EFFORT

NOTES

Research Program of the SERI Photovoltaics Branch

by

Sigurd Wagner
Solar Energy Research Institute
Golden, Colorado 80401

The purpose of the SERI Photovoltaics Branch is twofold: one, to carry out research in areas critical to the national program; two, to support the SERI Photovoltaic Program Office, the Department of Energy, and other interested parties with independent technical advice.

Nine programs are being set up to address these functions. With the exception of one, the programs are experimental. A reductionist approach to the cost problem in photovoltaics shows that the main cost factor,up to a finished module, lies in device materials preparation and cell fabrication. Therefore, the branch programs are oriented heavily toward electronic materials, and processes.

The nine programs are:

- Solid state theory
- High efficiency cells
- Thin film cells
- Silicon purification
- Silicon crystallization
- Thick film technology
- Device processing
- Surface and interface analysis
- Measurement techniques

With the move to the SERI interim laboratory between April and June, 1979, the branch has entered a phase of laboratory development that is still not complete.

The solid state theory group, with A. Zunger, U. Lindefelt (postdoctoral), and J. Dow (sabbatical) is developing theoretical approaches to the solution of generic problems in photovoltaics. Current work is focusing on (a) the electronic structure of semiconductor surfaces, and of lattice-matched and non-matched interfaces between semiconductors; (b) structure of and carrier kinetics at deep levels, in particular due to transition metal impurities; (c) stability and optical properties of A-B type crystals.

In the high efficiency cell program, with A.E. Blakeslee (sabbatical), M. Kowalchik, and R. Axton, present emphasis lies on construction of apparatus for the multi-layer growth of III-V alloys. Included are liquid phase epitaxy, and a reactor for metal-organic chemical vapor deposition. A molecular beam epitaxy station for III-V work will be employed within the surface and interface analysis program.

With the thin film cell work by R. Kerns and J. Abelson focusing on amorphous silicon-hydrogen alloys, a capacitively-coupled radio frequency plasma reactor is being set up that will permit precise control of major and of dopant constituents. The goal of this program is the improvement of cell performance through correlation of photovoltaic parameters with local electronic structure.

Reduction of SiO_2 and purification to solar grade Si in a single step is the goal of the silicon purification program of J. Olson and N. Meyer. High-temperature electrochemical techniques have been chosen. Initial screening is being carried out on electrolyte composition and temperature, on cathode phase and geometry as well as on rates of transport and deposition.

The silicon crystallization program, with T. Ciszek and J. Hurd, will be dealing primarily with the development of new techniques for sheet growth. Experiments to date have dealt with silicon solidification in porous (carbon foam) or open (perforated carbon sheet) substrates. Currently used equipment is home-made, but commercial crystal growth apparatus is expected to arrive shortly.

Thick film technology will deal with screen printing, spraying, and to some degree, evaporation. This program, carried out by S. Hogan and K. Firor, currently seeks to improve the screen printing and firing process for II-VI compounds, but in the future will also work on metallic and conducting glass contacts. In addition, S. Hogan and K. Firor are responsible for photovoltaic engineering and systems in aspects that usually arise from the branch's support function: advice to program managers, cooperation with standards and performance criteria development, responses to outside inquiries.

A yet unstaffed device processing program will meet two functions: one, to operate a processing laboratory in support of the other branch programs, and two, to carry out research in device processing.

The surface and interface analysis laboratory, with L. Kazmerski, P. Ireland and P. Sheldon uses Auger electron spectroscopy, secondary ion mass spectrometry, and x-ray photoelectron spectroscopy for the determination of chemical composition of grain boundaries and of heterofaces (see article by L. Kazmerski in this volume). Current emphasis is on comparison of grain boundaries with adjacent bulk, on correlation of impurity content of boundaries with solar cell performance, and on chemical composition of tunneling oxides. This program has dealt with the major candidate materials including silicon, cadmium sulfide, gallium arsenide, and indium phosphide.

Two directions have been pursued within the measurements techniques program. One was the set-up, by T. Gilmer, of commercial characterization equipment for the measurement of resistivity, mobility, diffusion length and lifetime. The other direction is that of developing new measurement techniques, exemplified by the demonstration of a microwave interferometer for resistivity determination of thin semiconductor films on metallic substrates, carried out by S. Hogan and S. Wagner in cooperation with F. Barnes of the University of Colorado.

In summary, the branch programs are making satisfactory progress. Although much of the year ahead will be spent on laboratory development, we expect the branch to make valuable contributions to the Photovoltaic Advanced R&D Program.

NOTES

OVERVIEW OF THE SERI PHOTOVOLTAIC PROGRAM OFFICE SUBCONTRACT ACTIVITY

J. R. Burke
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The Photovoltaic Program Office (PVPO) of the Solar Energy Research Institute is responsible for Advanced Research and Development (AR&D) subcontract management to the Department of Energy (DOE) Photovoltaics Systems Branch. In FY79, approximately $17M was authorized to PVPO for subcontracts and management. Figure 1 shows the distribution of annualized dollars among 124 subcontracts.

The subcontract program is divided into four categories:

- Advanced Materials/Cell Research - materials and cells for which the efficiency and cost projections indicate potential for demonstrating technical feasibility of (\$150 - \$400) kW_{ep} by 1986.
- High Risk Research - materials and concepts with potential for improvements on present day photovoltaic device approaches, with emphasis on fundamental investigations to prove this potential.
- Research Support - studies to define the impact of systems and large scale deployment of photovoltaic systems using cells developed by the AR&D program.
- Development Initiatives - exploratory development projects. A material in the Advanced Materials/Cell Research category will enter this phase when reproducible high efficiencies are obtained. The objective is to evaluate the cost and yield of present cell processes and identify the technical feasibility of lowering processing costs to meet the DOE goals.

I. Cu_2S/CdS and Cu Alloy/CdS Cells

Areas of study presently include: 1) Cu_2S/CdS and Cu_2S/CdZnS cells formed by vacuum evaporation of CdS or CdZnS followed by a CdCl ion exchange process in which the cell is formed either by dipping CdS (CdZnS) in chemical solution or by a second evaporation followed by a solid state reaction; 2) Cu_2S/CdS cells by reactive sputtering; 3) Cu_2S/CdS and Cu_2S/CdZnS cells by magnetron sputtering; 4) $CuInSe_2$/

CdS cells by multisource evaporation; 5) Cu Ternary/CdS and Cu Alloy/CdS materials and cells by evaporation; and 6) Cu_2S/CdS cells by chemical spray and screen printing processes.

Cu_2S/CdS cells formed by the dipping process have achieved the highest efficiencies (9.1%). Diffusion/grain boundary effects appear to be a barrier to achieving higher efficiencies. Thus the solid state reaction on both CdS and CdZnS is being pursued. Cu ternary, quaternary and pentenary alloys on CdS offer significant opportunity for increased efficiency because of the feasibility to simultaneously achieve optimum bandgap, and lattice and electron affinity match to CdS. The stability of all CdS based cells requires more systemmatic investigation.

II. Polycrystalline GaAs Cell Research

Areas being studied are: 1) Chemical Vapor Deposition (CVD) and Liquid Phase Epitaxy (LPE) on substrates that are low-cost but offer the potential to achieve the desired grain size and electronic properties; 2) grain boundary passivation approaches; and 3) Molecular Beam Epitaxy (MBE) for fine control of the influence of grain size and grain boundary characteristics on electronic properties.

The performance of thin-film polycrystalline GaAs cells is severely limited by the influence of grain boundaries on open circuit voltage. Better understanding of the limiting mechanisms is needed in order to identify the potential for passivation. A polycrystalline GaAs film on tungsten coated graphite has resulted in the highest efficiency cell (6.7%).

III. Polycrystalline Silicon Cells

Investigations include: 1) the fundamental properties and potential efficiencies of Metal/Insulator/Semiconductor (MIS) and conducting oxide/semiconductor structures; 2) CVD and vacuum evaporation for large grain growth on foreign and epitaxial substrates; 3) purification/recrystallization approaches to metallurgical silicon low-cost substrates for thin-film cells; and 4) fundamental studies of grain boundaries and the potential for chemical passivation.

To date, the use of a partially purified, recrystallized metallurgical silicon substrate is the most cost effective substrate approach to thin-film silicon cells. The highest efficiency achieved thus far (9.8%) was derived from the CVD deposition of a p-n junction on a silicon substrate prepared in this manner.

IV. Amorphous Materials/Cells

The major emphasis is on amorphous silicon. However, the potential of other amorphous materials such as boron, gallium arsenide II-IV-V (pseudo III-V) chalcopyrites and multicomponent chalcogenide glasses, is being investigated. A variety of growth techniques are being employed to investigate the relationship between the technique and the incorporation of the passivant (such as hydrogen) that compensates the defected structure and reduces the number of bandgap recombination states. Small area efficiencies of 5-6% have been achieved from Schottky barrier silicon cells produced by plasma deposition of hydrogenated silicon from SiH_4. Better understanding of the composition of the plasma relative to that of the film is needed.

V. Emerging Materials

Emerging Materials are defined to be new or less developed materials whose intrinsic properties indicate potential for low cost, greater than 10% efficiency cells in thin film form. Presently being studied are: InP/CdS, CdTe, Cu_2O, Polyacetylene, Zn_3P_2, Cu_2Se/CdS, $ZnSiAs_2$, $CdSiAs_2$, and BAs.

VI. Advanced Concentrator Cells and Concepts

Low-cost luminescent and high efficiency (>30%) multijunction concentrators are being investigated. Luminescent concentrators make use of the optical confinement of a transparent plate and organic or inorganic dyes to convert the broad band solar spectrum to a line spectrum matched to the bandgap of a chosen photovoltaic cell. Multijunction concentrators are monolithic or split-spectrum cells using semiconductors with different bandgaps to convert a greater part of the solar spectrum to electrical power.

Luminescent concentrators presently have a useful photon or geometric concentration ratio of 32 and, using GaAlAs cells, efficiencies of 4.8%. Research is centered on degradation mechanisms prevalent in high-conversion efficiency organic dyes and optimization of the conversion efficiency of stable inorganic dyes.

Split-spectrum cells, using a dichroic mirror and Si and GaAlAs cells, have achieved efficiencies of 28%. Monolithic cells presently being studied make use of p-n junctions in GaAlAs, GaInAs or GaAlInAs. Techniques to effect cell integration, such as tunnel junctions and thermal bonding, are also being investigated.

VII. Electrochemical Photovoltaic Cells

Contracts in this area emphasize studies of: 1) the efficiency and stability of a variety of semiconductor photoanodes in single crystal, polycrystalline, and amorphous form; 2) the effect of electrolyte composition (aqueous, non-aqueous, molten salt, and solid) on photoanode stability and junction properties; and 3) the potential of in-situ storage. Photoanode materials being studied include GaAs, Si, CdSe, CdTe, WSe_2 and $CuInSe_2$.

VIII. Innovative Concepts

A program designed to foster new, more efficient, and cost effective approaches to photovoltaic energy conversion. Solicitations are issued twice yearly. Projects are funded up to a level of $100K per year and reporting requirements are minimized. These projects may extend over a two year period depending on the results of the first year. The primary objective of the program is the support of exploratory research to test the feasibility of new ideas.

IX. Technical Support

- Tests and Measurements

  A Photovoltaic Program Office laboratory facility has been established to provide general cell characterization equipment as well as state-of-the-art instrumentation for investigations of specialized material and electro-optical problems. This facility will be made available to contractors not equipped for particular measurements, and also used to evaluate the performance of contractor provided cells.

- Availability of Materials

  Studies to determine AR&D photovoltaic material reserves and resources and the costs for conversion to large scale applications.

- Environmental, Health, and Safety

  Studies and experiments to identify potential problems associated with the development and deployment of AR&D photovoltaic systems.

- Economic and Policy Analysis

  Studies to establish cost effective guidelines for the transfer of research on photovoltaic cells to systems and commercialization.

- Definition of AR&D Systems Requirements

  Studies to define systems requirements generated by new photovoltaic approaches resulting from AR&D.

- Materials Research

  Investigations of materials problems, such as encapsulation and electrical contacts, related to cell and module reliability and lifetime.

X. Development Initiatives

Exploratory development projects that focus on processing technologies for cells that are achieving reliable efficiencies approaching 10%. The cost of the present day processing technology and the technical feasibility of achieving cost goals are evaluated.

Photovoltaic

Research and Development Summary

	No. of Contracts	FY79$
Advanced Material/Cell Research:		
• Cu_2S/CdS and Cu Ternary/Cds cells	13	$3.2M
• Polycrystalline GaAs Cells	5	1.8
• Polycrystalline Silicon Cells	26	4.6
• Amorphous Silicon Materials/Cells	17	2.9
High Risk Research:		
• Emerging Materials	18	2.8M
• Amorphous Materials	4	0.5
• Advanced Concentrator Cells and Concepts	6	1.4
• Electrochemical Photovoltaic Cells	11	1.7
• Innovative Concepts	17	1.5
Technical Support and Fundamental Studies:		
• Tests and Measurements	5	0.8M
• Availability of Materials	2	0.3
• Environmental, Health, and Safety	0	0
• Economic and Policy Analysis	0	0
• Definition of AR&D Systems Requirements	0	0
• Materials Research	0	0
Development Initiatives	0	0
	124	$21.5M

FIGURE 1

SESSION II

PHOTOVOLTAIC PROGRAM OFFICE AMORPHOUS SILICON/MATERIALS PROGRAM OVERVIEWS

Jack Stone, Senior Scientist/Task Manager
Ed Sabisky, Senior Scientist
Harv Mahan, Staff Scientist

The development of hydrogenated amorphous silicon alloys as a practical, low cost, photovoltaic material has followed rapidly since Sterling and his colleagues (1, 2) prepared high resistivity α-si by decomposition of SiH_4 in an RF discharge. Following the demonstration of substitutional doping by Spear and Le Comber (3) and the preparation of a thin film p-n junction by Spear et al (4), Carlson and Wronski were able to demonstrate thin film solar cells of α-Si:H in p-i-n form (5) and as Schottky barriers (6). Although power conversion efficiencies have been limited to less than 6%, primarily by low minority carrier diffusion lengths, the theoretical maximum efficiency, based on the optical band gap, is estimated to be approximately 15% (7). Predicated on these early successes, a massive research effort has been mounted both in the United States and abroad to improve and more fully understand this potentially useful material (8, 9, 10).

The Solar Energy Research Institute (SERI), as a prime contractor to the Department of Energy (DOE) is pursuing a program for the Photovoltaics Branch of the DOE Division of Distributed Solar Technology, of investigations of photovoltaic concepts, materials, and solar cell structures which indicate a significant potential for generating electricity at a cost below that which is projected for diffused p-n junction, single crystal silicon solar cells. In 1978, a Program Research and Development Announcement (PRDA) was issued by the DOE, Division of Solar Technology, to solicit proposals for research on amorphous thin film solar cell materials which show promise of significantly impacting the solar energy program. In particular, goals of producing 10% efficient thin film solar cells by 1980 and demonstrating the feasibility of producing cells for a cost of $0.30/watt or less by 1986 (in 1975 dollars) were established. (11).

This paper reviews in detail the status of the understanding of the basic material properties of α-Si:H, the effects of modifiers added to the material (e.g. fluorine), the effects of fabrication techniques, cell geometries, and other relevant factors related to fabricating solar cells to meet the above mentioned goals. The amorphous silicon projects monitored by SERI for the DOE will also be reviewed.

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(9) Proceedings of the 7th International Conference on Amorphous and Liquid Semiconductors, 1977, edited by W. E. Spear (CICL, University of Edinburgh).

(10) Proceedings of the 8th International Conference on Amorphous and Liquid Semiconductors, 1979, Cambridge, MA., (to be published Journal of Non-Crystalline Solids).

(11) National Photovoltaic Program - Program Plan, DOE Document Number ET-0035 (78), March 1978, U.S. Department of Energy, Division of Solar Technology.

Photovoltaic Program Office
Amorphous Silicon/Materials
Program Overviews

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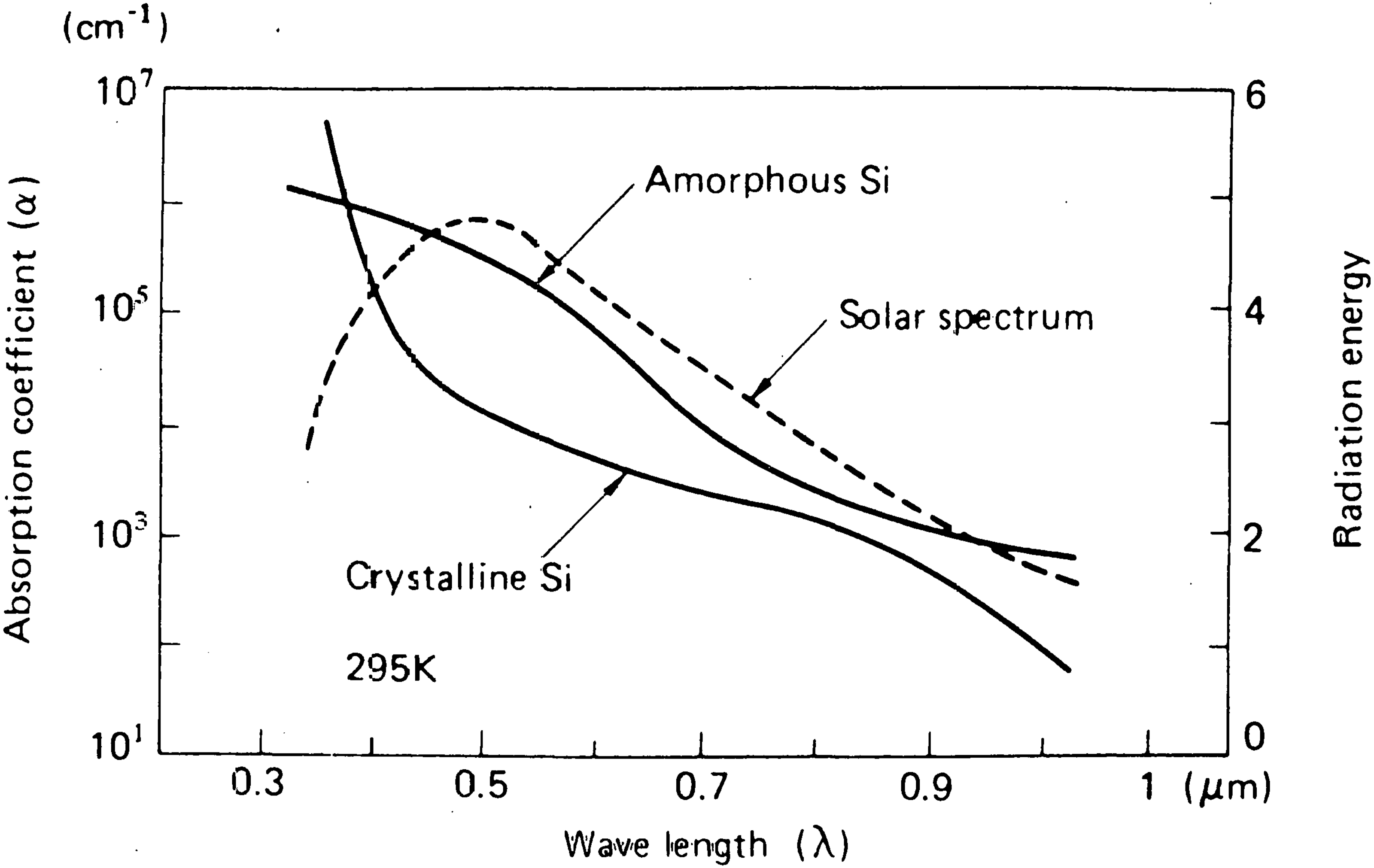
SERI

Absorption coefficient and wave length



ELECTRONIC PROPERTIES OF a-Si

	PURE	HYDROGENATED
Dangling Bonds	5×10^{19}CM^{-3}	$<10^{16}$CM^{-3}
States in the Cap	10^{19}-10^{20}CM^{-3}EV^{-1}	10^{16}-10^{17}CM^{-3}EV^{-1}
Conductivity	Hopping at Fermi Level	Activated to Band or Band Tail
Optical Absorption	Tails into Infra-Red, GAP$\sim$0.6EV 4×10^{4}CM^{-1} at 8870Å	Optical Edge (1.6-1.8EV) 5×10^{5}CM^{-1} at 5000Å
Photoresponse	Very small	Photoluminescent Photoconductive (10^{-4}-10^{-5} Ω^{-1}CM^{-1})
Doping Effects	----------	P- or N-type possible $\sigma\approx10^{-2}$ (ΩCM)$^{-1}$ (using P or B with H) $\sigma\approx5$ (ΩCM)$^{-1}$ (using P or As with F and H)

History of Amorphous Silicon Development

Material Preparation

- 1957 — High Resistivity Silicon Prepared by Glow Discharge Decomposition of SiF_4
- 1969 — High Resistivity Silicon by Glow Discharge Decomposition of SiH_4, Some Characterization
- 1976 — rf Sputtering of Silicon in the Presence of Hydrogen and Argon

Resistivity Control

- 1975 — Substitutional Doping of α-Si:H
- 1977 — Doping of α-Si:H by Ion Implantation

Application to Photovoltaics

- 1976 — Amorphous Silicon p-n Junction Fabricated
- 1976 — p-i-n Amorphous Silicon Solar Cell
- 1977 — Schottky Barrier Solar Cell with α-Si:H
- 1978 — MIS α-Si:H Solar Cell
- 1978 — Large Area, High Voltage Series Connected Cell

State of Knowledge

Amorphous Silicon Can be Made by A Variety of Techniques
The Role of Hydrogen is Reasonably Well Understood
One Micron Thick Film Is Sufficient for Absorbing Most of the Solar Spectrum
Can be Made N- and P-Type
Good Photoconductivity Demonstrated
5.5% Demonstrated for Small Area Cells
3% Demonstrated for Large Area Cells
Strong Photoluminescence
IR and Raman Spectrums Well Understood
Low Density of Paramagnetic States
High Open Circuit Voltage and Short Circuit Current Demonstrated
250° C-400° C Shown To Be Near Optimum For Substrate Temperature
Can Be Deposited on Low Cost Substrates
High Voltage Cell Configurations Are Available
Various Solar Cell Structures Are Possible
Fluorine Has Been Shown To Increase the Photoconductivity in Doped Layers
Glow Discharge Produced Materials Have Achieved Highest Efficiencies

Problem Areas

- Materials (Preparation and Properties)
  - Poor Minority Carrier Transport
  - Difficult to Control Si-H Bonding Types
  - Little Understanding of Gas-Solid Interactions
  - Large Number of Parameters Affecting Material Properties
  - Defect Control is Difficult
  - Role of Impurities Not Understood
  - Role of Modifiers Not Understood
  - Defect Creation By P-Type Dopant Not Understood
  - Area Scale-Up Difficult
  - Growth Kinetics Are Not Well Understood
  - Experimental Geometry Not Optimized

Problem Areas

- Characterization
  - No Theoretical Base
  - Unreliable Determination of the Density of Gap States
  - Unreliable Determination of Hydrogen Content
  - Difficult to Measure Lifetime and Minority Diffusion Lengths
  - Transport Phenomena Not Understood
  - No Relationships Established Between Material Parameters and Photovoltaic Properties
- Cells
  - Low Fill Factor
  - Limited Depletion Region Resulting in Small Drift Component of Current
  - Role of Interfacial Layers and States Unknown
  - Stability Not Studied in Depth

Preparation Techniques

- Glow Discharge
  - DC (Cathodic, Anodic, Proximity)
  - AC (RF Capacitive, Inductive)
- Reactive Sputtering
  - Diode
  - Magnetron
- Electrodeposition
- Ion Plating
- Chemical Vapor Deposition
- Evaporation
  - In Situ Hydrogenation
  - Post Deposition Hydrogenation
- Ion Implantation

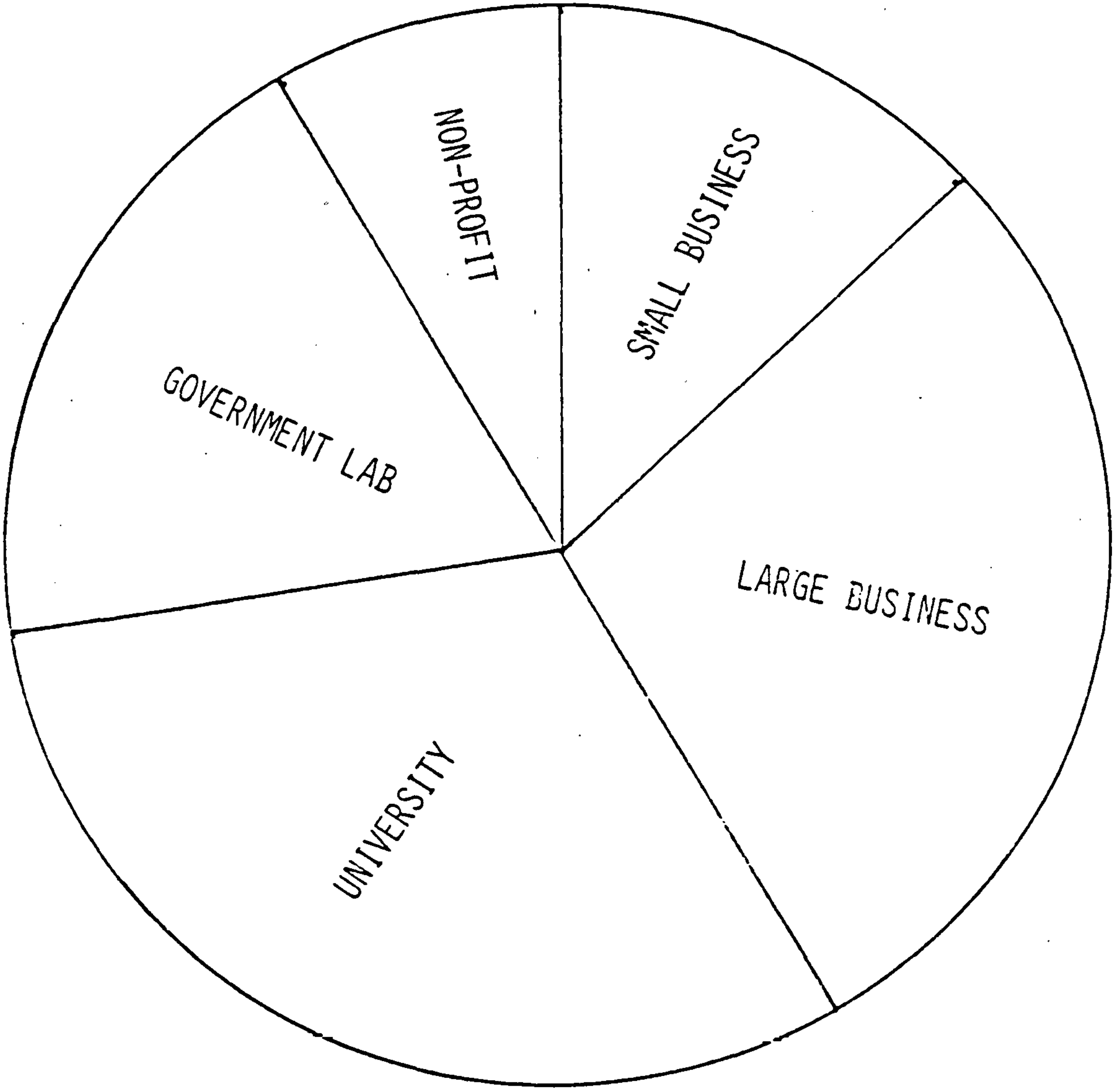
Primary Approaches and Control Parameters

- **Glow Discharge**
  - Substrate Temperature
  - Silane + Dopant + Diluent Pressures
  - Gas Flow Rate
  - Experimental Geometry
  - Glow Control Type
  - Substrate Bias
  - Power Density
  - Impurities
- **RF Sputtering**
  - Substrate Temperature
  - Partial Pressure of Sputtering Gas(es)
  - Experimental Geometry
  - Gas Flow Rate
  - Target Composition
  - Sputtering Type
  - Power Density
  - Background Gases and Pressures
  - Impurities

Characterization

• Structural	SEM TEM (Morphology) SIMS (Trace Impurities) Hydrogen Content (Evolution, SIMS, Nuclear Reactions) Extended X-Ray Absorption Fine Structure Electron Spin Resonance Nuclear Magnetic Resonance Heat of Crystallization X-Ray (Amorphousness) Small Angle X-Ray Scattering
• Optical	IR Vibrational Spectroscopy Raman Spectroscopy Photo-Luminescence Photoacoustic Spectroscopy Optical Absorption Coefficient Optical Bandgap Spectral Response Optical Emission Spectroscopy
• Electronic	Photoconductivity Dark Conductivity Diffusion Length Minority Carrier Lifetime Drift Mobility I-V (Solar Cell Parameters) Density of States in Bandgap (Field Effect, Transient Current Decay, Tunneling) Collection Efficiency Depletion Width Surface States Electron Affinity Thermopower Hall Effect

BUDGET BREAKDOWN



UNIVERSITY	$1,074,000
LARGE BUSINESS	969,000
GOVERNMENT LAB	662,000
SMALL BUSINESS	429,000
NON-PROFIT	298,000
TOTAL	$3,432,000

Organization: Institute of Energy Conversion — University of Delaware, University of Chicago (Subcontractor)

Contract Title: Novel Amorphous Thin Film Solar Cell Structures

Principal Investigator: Vikram L. Dalal

Funding: $257,000

Key Technical Issues:

- Pursue a careful material growth and characterization program using rf capacitive glow discharge.
- Material property characterization to include hydrogen content, hydrogen bond strength, heat of crystallization, defect density, drift mobility, minority carrier lifetime, diffusion length, and photoconductivity.
- Prepare a variety of solar cell structures including pn junctions (including p-i-n), graded base layer cells for field aided transport, Schottky barriers with surface preparation, MIS Schottky, and heterojunction cells with and without I layers.
- Device properties will be analysed according to collection efficiency, Schottky barrier heights, properties of interfacial layers, studies of silicide formation, photoeconomy, resistive losses, electron affinity, interface and surface states, and stability

Significant Accomplishments:

- Deposition conditions under control, making silane deposited films with high photoluminescence, and p-i-n diodes with 755 mV open circuit voltage.
- Detailed device design studies have been completed, realistic design goals of V_{oc} = 1 volt, J_{sc} = 15 mA/cm^2, FF = 72%, η = 11%.
- Light trapping and light reflection can add ~ 1% to the conversion efficiency over that of a simple cell structure.

Organization: Lockheed Missiles and Space Company
Telec Corporation (Subcontactor)

Contract Title: Amorphous Silicon Thin Films Prepared by Reactive Sputtering for Solar Cell Applications

Principal Investigator: Art D. Jonath

Funding: $252,000

Key Technical Issues:

- Deposit a-Si:H films by rf reactive sputtering onto stainless steel or stainless steel coated glass.
- Deposit a-Si:H by dc magnetron sputtering.
- Use ion implantation to introduce various alloy constituents and dopants into a-Si.
- Characterize the deposited films as to structural, optical, and electrical properties.
- Prepare Schottky Barrier solar cells using Pt, HgSe, and $(SN)_x$ as barrier metals.

Significant Accomplishments:

- High conductivity n and p-type a-Si (40 — 100 ohm-cm, $E_A = 0.13$ ev) films are sputter deposited as possible n^+ and p^+ contact material.
- Hydrogenation of films by introducing H_2 during sputtering yields high resistivity material with moderate photoconductivity.
- n- and p-type a-Si and a-Si:H films are consistently produced from n- and p-type sputter targets respectively.
- Dark conductivity of a-Si films is decreased by H^+ implantation and F^+ implantation with subsequent thermal anneal.

Organization: Mobil Tyco Solar Energy Corporation

Contract Title: Amorphous Silicon Thin Film Heterojunction Solar Cells

Principal Investigator: Mary C. Cretella

Funding: $219,000

Key Technical Issues:

- Establish a glow discharge apparatus to reproducibly fabricate doped amorphous silicon films. Substitution of carbon, tin, and germanium for part of the silicon will be used to vary the optical bandgap closer to the maximum absorption region.
- Replace part of the hydrogen with alkali metals to attempt an increase in minority carrier lifetime.
- Prepare heterostructures between a-Si:H and CVD crystalline silicon and β -silicon carbide on quartz substrates.

Significant Accomplishments:

- Small amounts of C, O_2, B but not P, have been shown to introduce a silicon hydrogen stretch mode at 2080 cm^{-1}.
- Stable, non-columnar a-Si:H films produced by glow discharge show a Si-H stretch mode at 2005cm^{-1}.
- The dark conductivity of a-Si_x:C_{1-x}:H films can be varied substantially by boron doping.

Organization: The Pennsylvania State University

Contract Title: Black a-Si:H Sputtered Films for Photovoltaic Solar Cells

Principal Investigators: R.F. Messier
T.S.T. Tsong

Funding: $92,000

Key Technical Issues:

- Surface microstructure of sputtered a-Si:H films can be altered by etching process to achieve total reflectance of < 2% in solar wavelength region.
- Study detailed preparation and characterization of rf-reactively sputtered a-Si:H films

Significant Accomplishments:

- a-Si:H has been prepared by rf sputtering under a range of partial pressures of H_2
- Etched films show a large reduction in reflectivity
- Etching reveals anisotropic microstructure in the films

Organization: RCA Laboratories

Contract Title: Amorphous Silicon Alloys Thin Films for Solar Cell Applications

Principal Investigator: David E. Carlson

Funding: $625,000

Key Technical Issues:

- Develop models of the quantum efficiency of produced free carriers in amorphous silicon alloys, demonstrate the Meyer-Neldel behavior of dark conductivity assuming exponential tail states, and examine a three center bonding defect in a-Si:H.
- Investigate deposition and doping for plasma produced thin films from silane (SiH_4) and fluorine containing compounds (SiF_4 and HF). PH_3 and B_2H_6 are the primary additives used for doping both n- and p-type respectively.
- Develop experimental methods for characterizing amorphous silicon including density of states measurements by transient current decay of pulsed diodes, tunneling in MOS structures and collection efficiency with illumination by below bandgap light. Surface states are measured by surface photovoltage and space charge capacitance and minority carrier diffusion lengths by back illuminating Schottky barrier cells.
- Investigate various solar cell structures of 3 cm^2 and 40 cm^2 active area including inverted p-i-n on glass substrates, MIS, and p-i-n on metal or metallized glass substrates. Various contact and Schottky metals are being investigated.
- Develop automated testing facilities to measure photovoltaic properties of individual cells and two dimensional graded samples containing a matrix of cells. Develop laser scanning techniques to quantitatively measure various solar cell parameters and to provide on-line evaluation of the quality of the amorphous thin films.
- Perform stability studies for various a-Si:H structures with particular attention given to the effects of water vapor. These studies will be combined with accelerated life tests.

Significant Accomplishments:

- Depletion widths of approximately 0.5 μ have been achieved in undoped a-Si:H under AM1 illumination.
- Conversion efficiency of 3.2% achieved in a p^+-i-n^+ device with an area of 1.6 cm^2 and an efficiency collection efficiency of 40%; this data translates into internal efficiency of 8%.
- Minority carrier diffusion lengths are less than 40 nanometers based on analysis of back illuminated cells.
- Collection efficiency measurements for below bandgap light indicate hole transport within deep gap states.
- Tunneling measurements indicate presence of bulk defect level at about 0.45 ev below conduction band.
- Preliminary line of sight mass spectroscopy measurements indicate that $Si:H_3^+$ are the dominant species incident on the substrate in a magnetron discharge system.

Organization: Brookhaven National Laboratory

Contract Title: New Amorphous Hydrogenated Semiconductors by Advanced Glow Discharge Techniques

Principal Investigator: R.W. Griffith

Funding: $100,000

Key Technical Issues:

- Investigate new amorphous semiconductor materials in which recombination centers are passivated using plasma deposition
- Characterize the optoelectronic properties pertaining to both majority and minority carrier transport in as-deposited films and devices.
- Investigate the effects of residual gaseous impurities on the optoelectronic quality of a-Si:H.
- Characterize the plasma by optical emission spectroscopy, molecular absorption spectroscopy, and mass spectroscopy.

Significant Accomplishments:

- Oxygen can be incorporated without a large increase in defect density.
- Electronic properties of plasma deposited a-Si:H films were found to depend on O_2 and N_2 impurities.
- Optical emission spectroscopy was used to identify emitting reactive species in the plasma: Si, SiH, SiH^+, H_2, H, N.
- Observed shift of stretching mode in infrared transmission studies as a function of O_2 bonding in a-Si:H.

Organization: Harvard University (B)

Contract Title: Determination of Pseudogap State Density and Carrier Mobility in RF Sputtered a-Si

Principal Investigator: William Paul

Funding: $97,000

Key Technical Issues:

- Measure independently the two factors comprising the conductivity in rf sputtered a-Si:H.
  - the density of states in the pseudogap using the field effect technique,
  - the carrier mobility using time of flight measurements,

  to obtain a better understanding of transport mechanisms in the pseudogap and in the extended states.
- Identify the nature of recombination through pseudogap states.
- Attempt to reduce the pseudogap state density in order to increase the recombination lifetime and mobility in rf sputtered a-Si:H.

Organization: Lawrence Berkeley Laboratory

Contract Title: Photoacoustic Characterization of Hydrogenated Amorphous Silicon

Principal Investigator: Nabil Amer

Funding: $100,000

Key Technical Issues:

- The absorption edge of a-Si:H prepared under different conditions will be measured by photoacoustical spectroscopy (PAS) allowing measurement of the optical density of states in the gap. Changes in the gap states induced by doping will also be investigated.
- Luminescence measurements will be combined with PAS to fully characterize the de-excitation mechanisms of the a-Si:H samples.

Significant Accomplishments:

- Absorption Coefficient for a-Si:H 1μ thick, measured down to 0.1 wavenumber.

Organization: Naval Research Laboratory

Contract Title: Structural and Electronic Properties of Hydrogenated Silicon for Solar Cell Application

Principal Investigator: Stephen G. Bishop/P. Craig Taylor

Funding: $117,000

Key Technical Issues:

- Produce a-Si:H samples by glow discharge and by rf sputtering in hydrogen atmosphere.
- Study effect of hydrogen in a-Si:H using pulsed and wide-line NMR and small angle x-ray scattering.

Significant Accomplishments:

- The observation of extensive small angle x-ray scattering from hydrogenated a-Si made from silane by glow discharge techniques indicates that the void distribution in this material is very similar to that for evaporated a-Si. The improved electrical properties of hydrogenated material may not be due to this material having a homogeneous structure.

Organization: Naval Weapons Center

Contract Title: Preparation and Characterizaton of Amorphous Silicon

Principal Investigators: T.M. Donovan/D.S. Kyser

Funding $141,000

Key Technical Issues:

- Deposit a-Si by rf magnetron sputtering.
- Determine effect of additives (H) and impurities (O) on electronic properties.
- Prepare doped material using B_2H_6 or PH_3.

Significant Accomplishments:

- Have deposited a-Si:H films by magnetron sputtering with 30-40% hydrogen incorporation.
- IR measurements indicate only Si-H species incorporated into the films.

Organization: Xerox Corporation

Contract Title: Defect States in Plasma Deposited a-Si:H

Principal Investigator: John C. Knights

Funding: $92,000

Key Technical Issues:

- Study localized defect states in plasma deposited amorphous silicon.
- Determine the effect of doping and other plasma parameters on defect incorporation.
- Establish preparation conditions which minimize non-radiative recombination and maximize minority carrier lifetime.
- Determine how defect states determine transport and recombination of electrons and holes.

Significant Accomplishments:

- Electrically active defects have been identified as dangling bonds.
- Defects are associated with structural and compositional inhomogenities.
- Dopants are incorporated into films with different efficiencies; boron content is 2 — 5 times that of the gas concentration, O_2 is greater than 10 times that of gas.
- Luminescence in a defect band in doped a-Si is directly associated with optically induced EPR.

Organization: Battelle Columbus Laboratories

Contract Title: Electrodeposited Amorphous Silicon for Solar Cell Application

Principal Investigators: Al E. Austin

Funding: $298,000

Key Technical Issues:

- Develop semiconducting doping of electrodeposited amorphous silicon with controlled electronic properties on low cost substrates. The dopant will be preferably co-deposited with the silicon. Nonaqueous organic solutions such as $SiHCl_3$ in propylene carbonate with tetraalkylammonium chlorides as supporting electrolytes will be pursued.
- Identify and demonstrate n- and p-type doping using compounds which are reducible at cathode potentials less than silicon.
- Determine physical and electronic properties of the electrodeposited materials. Morphology, phase, dopant concentration and distribution, impurities, and hydrogen content will be emphasized
- Develop Schottky barrier and pn junction cells from electrodeposited amorphous silicon.

Significant Accomplishments:

- Successfully demonstrated electrodeposition of a-Si onto a variety of 2" diam. substrates — Ti, Al, Ti-6Al-4V.
- n- and p-type dopants, Li, B and Ga, can be codeposited with the silicon.
- Dopants can be activated by annealing.
- Hydrogen content is controllable by the temperature of deposition.
- Schottky diodes, p-i-n junctions have been produced.

Organization: Duke University (A)

Contract Title: Prepartion and Characterization of Hydrogenated a-Si Films Produced by Ion Plating Techniques

Principal Investigator: Franklin H. Cocks

Funding: $136,000

Key Technical Issues:

- Ion plating (i.e., evaporation of a metal or semiconductor into a glow discharge) deposition of hydrogenated amorphous silicon.
- Produce amorphous silicon with controllable electronic properties on low cost substrates.
- Characterize the a-Si films and evaluate with appropriate solar cell structure.

Significant Accomplishments:

- Magnetic field confinement has been used to enhance the deposition rate of glow discharge decomposition of silane.

Organization: University of Southern California

Contract Title: Low Cost Solar Cells Based on Amorphous Silicon Electrodeposited from Organic Solvants

Principal Investigator: Ferdinand A. Kroger

Funding: $55,000

Key Technical Issues:

- By cathodic plating techniques, plate a-Si on a conductive base using solutions of $SiCl_4$ or SiF_4 in various solvents.
- Determine the chemical composition, microstructure, and physical properties (amorphousness, resistivity, SiH bonding configurations) of the deposits.
- Determine deposition potentials of donor and acceptor compounds and see which are more or less noble than silicon.
- Demonstrate the co-deposition of dopants and silicon.

Significant Accomplishments:

- Demonstrated thin film silicon plating using a variety of silicon compounds, solvents, and electrolytes.

Organization: Spire Corporation
Contract Title: Amorphous Silicon Solar Cells by Ion Implantation
Principal Investigator: Allan R. Kirkpatrick
Funding: $124,000
Key Technical Issues:

- Deposit CVD thin polycrystalline silicon films and convert to amorphous form by implanting silicon, argon, or hydrogen.
- Develop doping processes for a-Si films by addition of dopant gases to SiH_4 CVD or by ion implantation of boron and phosphorus.
- Establish the Si-H bonding system by hydrogen implantation.
- Investigate the effects of pulsed electron beam heating to improve the properties of the films.
- Characterize the films as to structure, optical, and electronic properties.
- Evaluate the material by preparing Schottky and p-n junction solar cell structures.

Significant Accomplishments:

- Special implantation capabilities have been developed for modification of existing silicon films.
- A thin film cell device structure has been developed for implantation investigations.
- Experiments are in process to identify adequate sets of conditions to produce amorphous silicon cells.
- First test cells with implanted hydrogen exhibit low efficiency.

Organization: Argonne National Laboratory

Contract Title: Computer Modelling of Amorphous Materials for Photovoltaic Conversion

Principal Investigator: Lester Guttman

Funding: $30,000

Key Technical Issues:

- Understand the structure and electronic properties of random networks formed by tetrahedrally bonded semiconductors with emphasis on dangling bonds and the role of the hydrogen additive.
- Construct computer analogs representing the atomic structure of pure amorphous silicon.
- Compute from first principles the electronic wave functions, and energy levels for a-Si containing hydrogen or which is defective in various ways.
- Use the results to help interpret the effects of hydrogen on photoconductivity and electrical resistivity.
- Provide guidance in understanding the relation of the material transport properties to the parameters of the fabrication process.

Significant Accomplishments:

- Construction of realistic computer models for a-Si.
- Computations of accurate ground state wave functions and energies for a-Si.
- Demonstration of the existence of charge fluctuations in a-Si, partial interpretation in terms of atomic geometry.
- Computation of wave functions and energies of "dangling bond" states in a-Si.

Organization: Naval Research Laboratory

Contract Title: Theoretical Study of the Role of Hydrogen in Silicon

Principal Investigator: D. Papaconstantopoulos

Funding: $94,000

Key Technical Issues:

- Develop models to understand the role of hydrogen in a-Si.
- Compute density of states, imaginary part of dielectric constant and absorption coefficient of a-Si:H.

Significant Accomplishments:

- Adopted the tight-binding version of the coherent potential approximation for calculating electronic states for a-Si.
- The following physical quanities are being modeled: hydrogen tying up dangling bonds, randomness, and distorted bonding arising from lattice relaxation around vacancies.
- Cluster and cluster-coherent potential approximations are being developed for a wider variety of Si-H atomic arrangements.

Organization: Duke University (B)

Contract Title: Preparation and Characterization of Hydrogenated Amorphous Boron Films and Solar Cells Produced by Glow Discharge

Principal Investigator: Franklin H. Cocks

Funding: $136,000

Key Technical Issues:

- Glow discharge growth and doping techniques to produce amorphous boron.
- Characterize hydrogenated amorphous boron films by infrared, resistivity, photoconductivity, Hall effect.

Significant Accomplishments:

- Using glow discharge decomposition of diborane (B_2H_6), a-B:H films have been produced with hydrogen concentration varying from 2 to 34% At.
- The optical bandgap varies from0.8 to 2.2 eV, bandgap decreasing with decreasing hydrogen content.
- N-type doping was achieved with carbon and silicon incorporation.

Organization: EIC Corporation

Contract Title: Synthesis, Evaluation, and Defect Compensation of $A_{II}B_{IV}C_{V2}$ Tetrahedral Glasses as Possible Solar Cell Materials

Principal Investigator: David Rauh

Funding: $86,000

Key Technical Issues:

- Prepare $CdM_{IV}P_2$, $ZnM_{IV}P_2$, and $ZnM_{IV}As_2$ whereby M is Ge, Si, Mg, or Sb and characterize the materials in regard to their glassy phases and composition.
- Deposit thin films of selected amorphous $A_{II}B_{IV}C_V$ compounds using rapid quenching through rollers, evaporation, sputtering, and CVD.
- Determine the electrical and optical properties of the produced films.

Significant Accomplishments:

- Synthesized bulk materials of ternary systems, whose phase and composition were analyzed by x-ray analysis and atomic emission measurements.
- Obtained amorphous thin films of $ZnAs_2$ by vapor deposition.

Organization: Harvard University (A)

Contract Title: Production and Evaluation of a-GaAs Solar Cells

Principal Investigator: William Paul

Funding: $143,000

Key Technical Issues:

- Produce thin films of a-GaAs:H of different hydrogen content by rf sputtering in Argon in a variety of deposition conditions.
- Characterize thin films with regard to their structural, electronic and optical properties.
- Fabricate Schottky barriers with suitable metals and measure conventional solar cell parameters.

Organization: Massachusetts Institute of Technology
Contract Title: Chalcogenide Glass Solar Cells
Principal Investigator: David Adler
Funding: $143,000
Key Technical Issues:

- Investigate the introduction of dopants into chalcogenide glass films which enables the production and maintenance of a metastable low resistivity state characterized by extrinsic conductivity.
- Characterize these films in regard to their physical, structural, optical, and electronic transport properties.
- Interpret such results in terms of the theory of glassy thin amorphous films.
- Fabricate solar cells and perform standard characterizations.

INNOVATIVE CONCEPTS

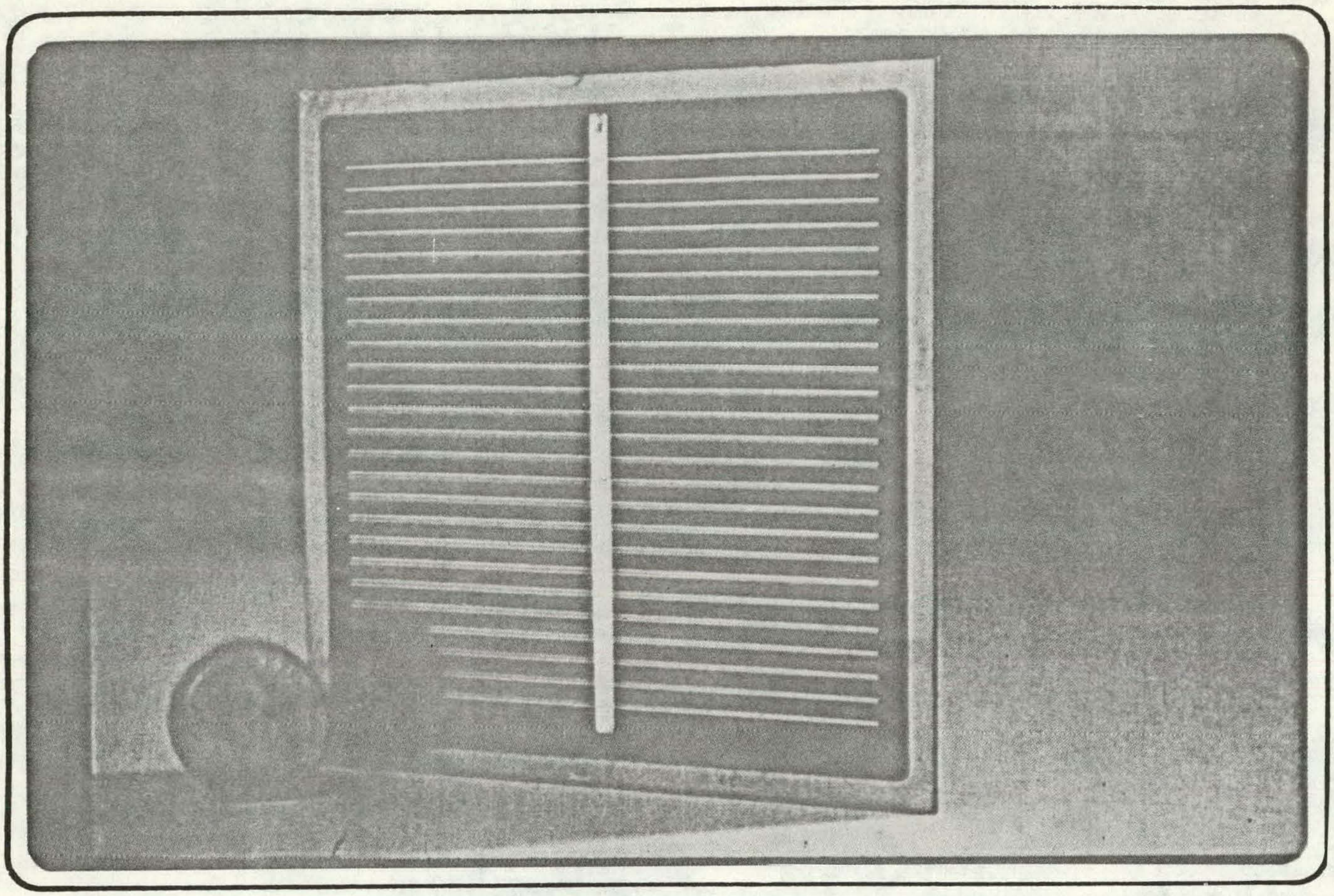
ORGANIZATION	TITLE
AERO CHEM RESEARCH LABS, INC.	MECHANISM OF PREPARATION OF PHOTOVOLTAIC AMORPHOUS SILICON FILMS
PLASMA PHYSICS CORPORATION	PLASMA-ASSISTED CVD OF FLUORINATED, HYDROGENATED A-SI
SUNY AT BUFFALO	FABRICATION AND TESTING OF MIS SOLAR CELLS ON A-SI:F:H
THE UNIVERSITY OF ARIZONA	PHOTOELECTRIC PROPERTIES OF AMORPHOUS SILICON DEPOSITED BY THE PYROLYTIC DECOMPOSITION OF SILANE

Published Solar Cell Status

Company	Cell Type	AR	Voc (mV)	Jsc [mA/cm^2]	n (%)
RCA	SS-n$^+$-i-Pt	Yes	803	12	5.5
Osaka U.	SS-n$^+$-i-p$^+$-ITO	Yes	560	12 (a)	4.5
Sanyo	SS-n$^+$-i-Pt	No	500	9 (15)	2.6 (4.3)
U. of Dundee	SS-Cr-p$^+$-i-n$^+$	No	670	9.3 (13)	3.4 (4.9)
Heriot-Watt U.	SS-n$^+$-i-TiO$_x$-Ni	Yes	630	7.5 (b)	4.8
Present Material Capacity		Yes	800	14.5	7

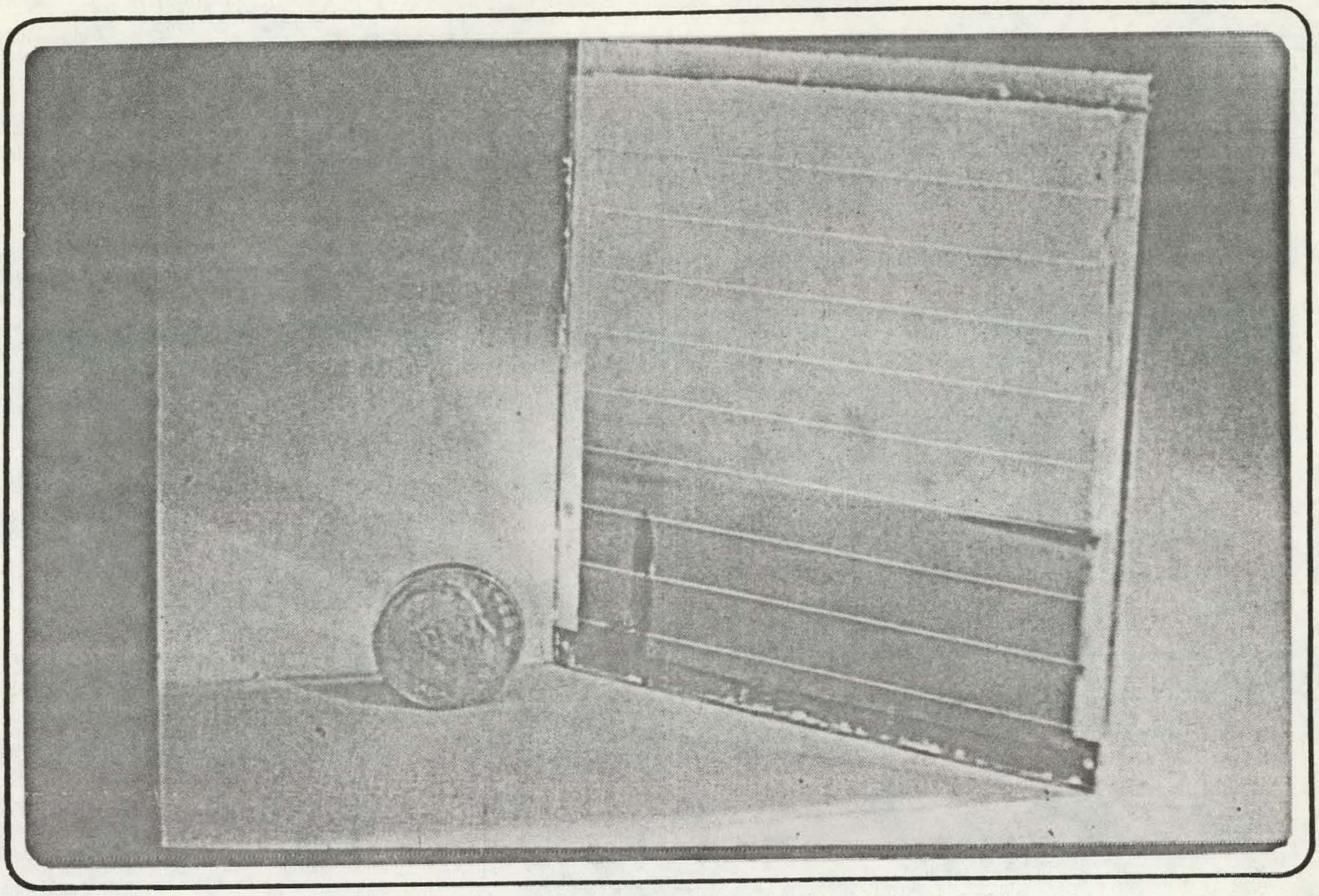
(a) 80 mV/cm^2 Illumination

(b) 60 mV/cm^2 Illumination



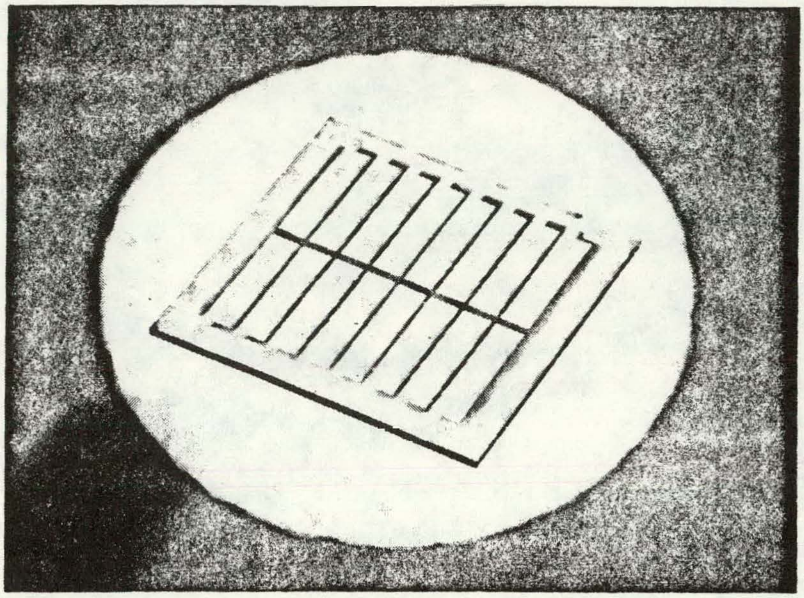
RCA

V_{oc} (volts)	J_{sc} (mA/cm^2)	FF	n (%)	Active Area (cm^2)
0.73	6.5	.36	2.8	25



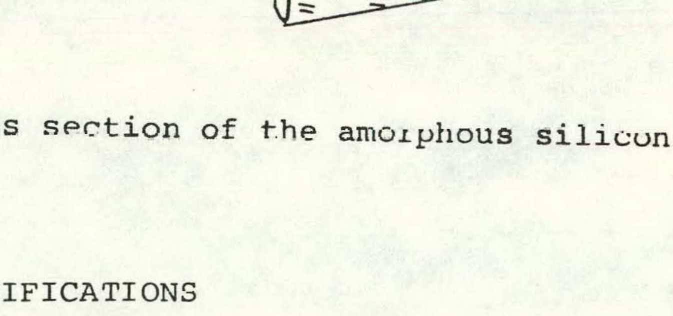
RCA
Series Connected Cell

No. of Cells In Series	Active Area (cm^2)	V_{oc} (volts)	J_{sc} (mA/cm^2)	FF	n (%)
9	37	6.5	5.8	.55	2.6



Amorphous silicon solar battery.

Sanyo Electric Co., Ltd.
Osaka, Japan



Cross section of the amorphous silicon battery.

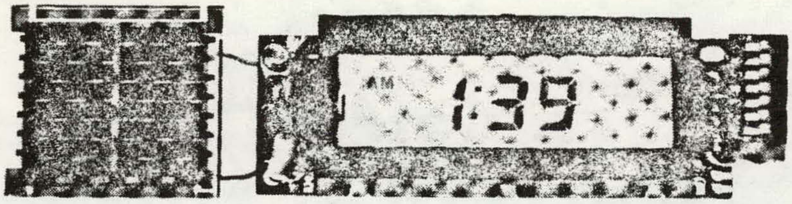
SPECIFICATIONS

1) Open voltage .... 0.6 volts
2) Short circuit current .... 9.2 mA/cm^2
3) Efficiency .... 3.2 %

[in AM-1 sun light (100 mw/cm^2)]

Sanyo Electric Co., Ltd.
Osaka, Japan

Application for a clock

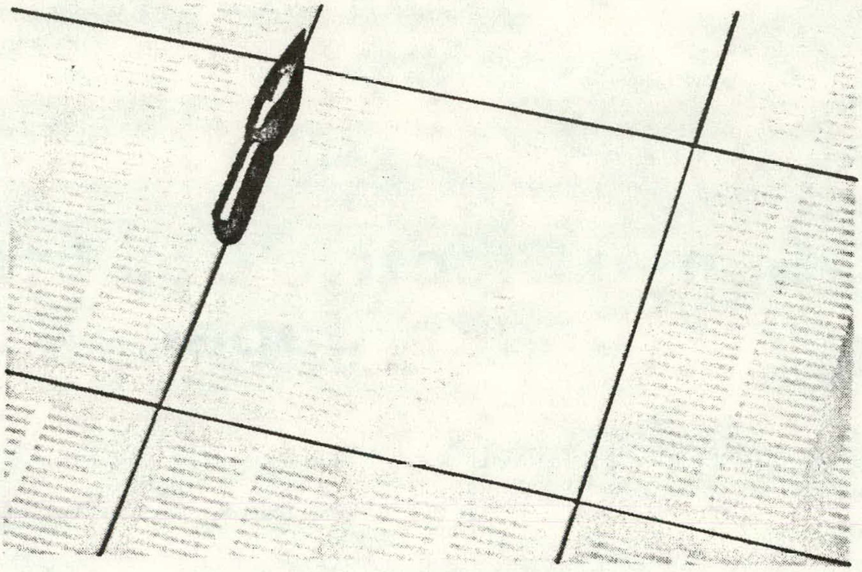


A clock operated by the amorphous silicon solar cell module.

Specifications of solar cell module for consumer applications

1) Open voltage .... 0.5 volts/cell (4V for 8 series)
2) Short circuit current ... 18 microampere/cm^2
3) Maximum power .... 4.5 microwatt/cm^2

[in fluorescent lighting (white color 300 lux)]



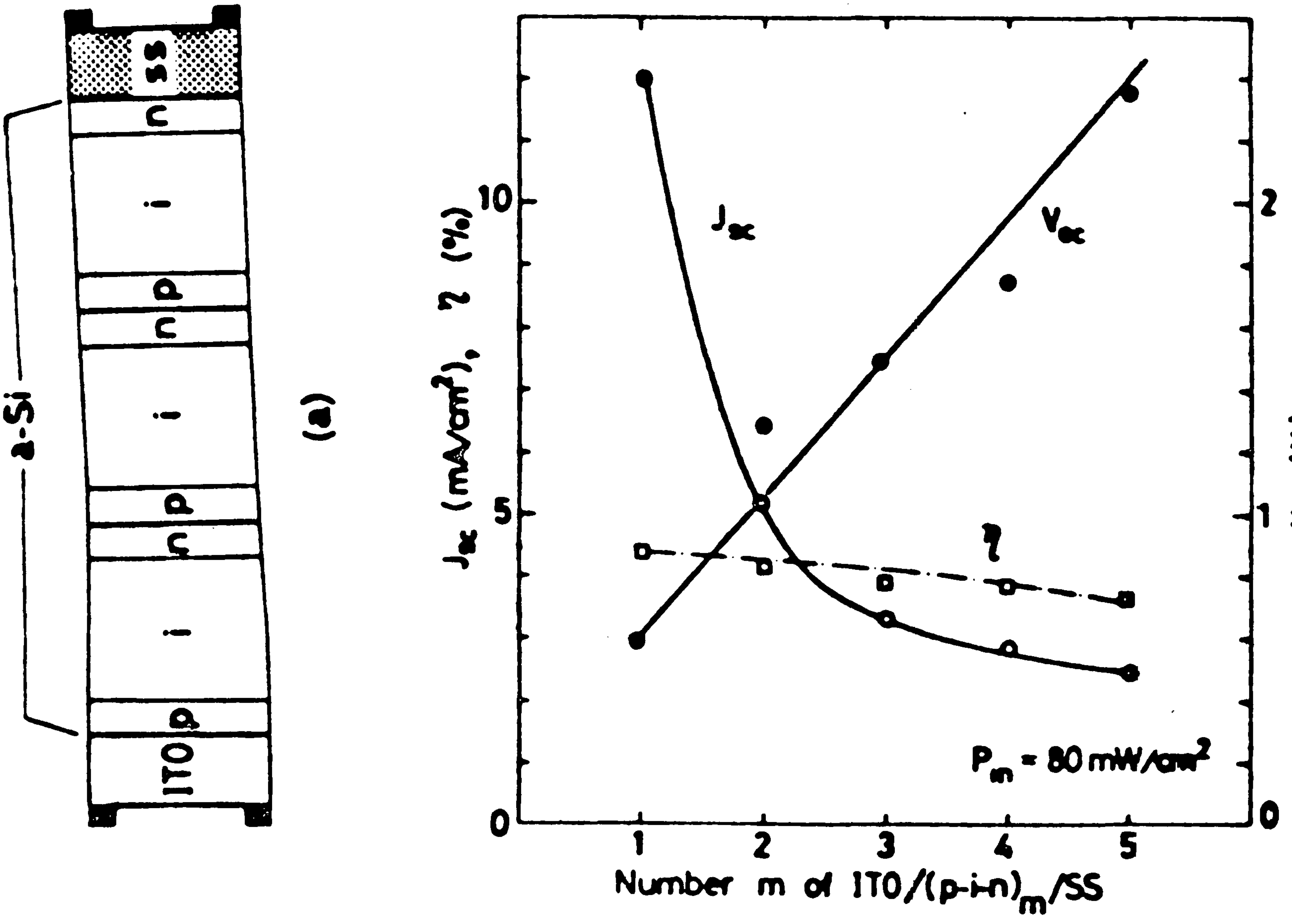
Fuji Electric Co., Ltd.
Yokosuka City, Japan

Specifications:

V_{oc} = 0.6 Volt
J_{sc} = 6 mA/cm^2
FF = 0.513
η = 2.5% Am2

Structure:

Stainless Steel —n+/a-Si:H — i/a-Si:H — Pt — (Ti — Ag) grid — SiO AR


SS
n
i
p
n
i
p
n
i
p
ITO
a-Si
(a)
Jsc (mA/cm²), η (%)
Voc (V)
Jsc
Voc
η
Pin = 80 mW/cm²
Number m of ITO/(p-i-n)m/SS
0
5
10
0
1
2
1
2
3
4
5

Important Research Areas for Future Work

- Reactions at Gas-Solid Interfaces
- Improvement of Limited Lifetimes
- Better Understanding of Structure of Density of States
- Picture of Amorphous Materials on Microscopic Scale
- Nature of Chemical Bonding
- Understanding of Plasma
- Importance of Surface States at Subtrate and Between Various Layers
- Fill Factor Improvement
- Detailed Understanding of the Role of Impurities
- A Better Theoretical Understanding

AMORPHOUS SILICON CELL DEVELOPMENT*

D. E. Carlson
RCA Laboratories
Princeton, NJ 08540

BACKGROUND

The first detailed study of discharge-produced a-Si was published in 1969 [1], and shortly thereafter an extensive research program was started at the University of Dundee [2]. Early field-effect measurements [3] indicated that the density of gap states was several orders of magnitude lower in discharge-produced a-Si than in evaporated a-Si. Moreover, the transport properties were interpreted in terms of conduction in the extended states [2].

The first photovoltaic devices were made in 1974 at RCA Laboratories [4]. In 1975, researchers at the University of Chicago [5] showed that discharge-produced a-Si was actually an amorphous silicon-hydrogen alloy (a-Si:H). At roughly the same time, scientists at Harvard University [6] showed that hydrogen reduced the density of defect states in sputtered a-Ge:H and a-Si:H. The first detailed study of substitutional doping in a-Si:H was published in 1975 by Spear and LeComber [7]. It is now recognized that the incorporation of hydrogen (~5-50 at. %) in a-Si:H is responsible for the low density of gap states that in turn allows the material to be doped either n- or p-type. Recently, new alloys of amorphous silicon have been prepared by adding gases containing carbon [8], fluorine [9] and oxygen [10] to the discharge atmosphere. This research offers new ways to modify the electronic and optical properties of the material.

In the last few years, several investigators [11,12,13,14] have reported conversion efficiencies in the range of 4-6% for a-Si:H solar cells. However, the theoretical limit for the conversion efficiency has been estimated to be ~15% [15]. We will now consider the problem areas that limit the conversion efficiency and discuss future directions to overcome these limitations.

PROBLEM AREAS

Poor minority carrier transport has been recognized as a major limitation to device performance since the early work on solar cells [11]. Recently, the hole diffusion length has been estimated to be ~40 nm for an undoped a-Si:H film produced in an rf capacitive discharge [16]. Thus, essentially all the collected carriers are photogenerated in the depletion region of an a-Si:H solar cell. The lifetime for free holes generated in a quasi-neutral region appears to be on the order of 1 ns.

The conversion efficiencies of early a-Si:H solar cells were also limited by small depletion widths (~0.1-0.3 μm) in AM1 sunlight. Recent optimization work at RCA Laboratories has succeeded in lowering the space-charge density in undoped a-Si:H so that depletion widths of ~0.5 μm have been measured under AM1 illumination. We have obtained conversion efficiencies of ~3.2% in p-i-n cells (area ~1.6 cm^2) with poor optical transmission (~40%) into the depletion region (~8% of the solar radiation transmitted into the depletion region was converted into electric power). Thus, undoped a-Si:H need not possess a large hole diffusion length if a significant fraction of the solar radiation can be absorbed in the depletion width.

The optical properties of a-Si:H depend on deposition conditions as shown in Figure 1. The absorption coefficient curves shown for a-Si:H films deposited at ~ 210°C and ~415°C may be regarded as practical limits for films possessing good electronic properties; i.e., the optical gap falls somewhere between ~1.6 and ~1.8 eV depending on deposition conditions. From the data in Figure 1, we can calculate the limiting short-circuit current density (J_{sc}) as a function of the optical path length assuming an AM1 solar spectrum and no recombination. As shown in Figure 2, the maximum value of J_{sc} should fall in the range of 17.5 to 22 mA/cm^2 for an optical path length of 1.0 μm.

Thus, relatively large currents can be expected from an a-Si:H solar cell with a depletion region of ~0.5 μm if the light can be efficiently transmitted into the undoped layer (the optical path length will be twice the film thickness if the back contact is a reflective surface).

The quality of doped a-Si:H presents some serious limitations to the performance of a-Si:H p-i-n solar cells. In particular, the p-type material has both poor electronic and optical properties for use in a-Si:H solar cells. Figure 3 shows the collection efficiency as a function of photon energy for a relatively good p-i-n device. The poor response at short wavelengths is due to the short recombination lifetimes in the p-layer. Boron doping not only decreases the lifetime, but as shown in Figure 1, it also increases the optical absorption so that a significant fraction of the incident sunlight is absorbed in the dead layer. In present p-i-n cells, ~20-40% of the theoretical current (see Fig. 2) is lost due to the poor quality of the p-layer.

The built-in potential of p-i-n devices is limited to ~1.1-1.2 V by the poor electronic quality of the doped layers; thus, the open-circuit voltages (V_{oc}) is generally less than ~0.85 V. However, values of V_{oc} as large as 1.3 V have been obtained with electrolytic contacts so improving the quality of the p-layer should lead to significantly larger open-circuit voltages.

The built-in potential also depends on the conductivity of the n+ layer as shown in Figure 4. Increasing the PH_3 content of the SiH_4 atmosphere to a ratio of 10^{-2} to 10^{-3} causes the built-in potential (and hence V_{oc}) to increase; the Fermi level of the n+ layer moves closer to the conduction band as the film becomes more conductive. The contact resistance between the doped layers and the contacting electrodes also decreases as the doped layers become more conductive. In present cells, the contact resistance is on the order of 3-10 Ω-cm^2, and the resistance can limit the performance by 5-20%.

FUTURE DIRECTIONS

The performance of a-Si:H solar cells can be improved significantly if a wide bandgap, highly conductive p^+-type layer can be developed. Such a layer should assure both high transmission of light into the depletion region and a large built-in potential. The structure shown in Figure 5 should exhibit a conversion efficiency greater than 10% with such a p^+ layer; the band structure of such a device is shown in Figure 6. A graded n^+ layer may help to extend the electric field over a greater film thickness and thus increase the current. The transparent conductive oxide (TCO) layer serves as both an electrical contact and as an antireflection coating. If the p^+ layer is highly conductive, a tunnel junction should form at the interface with the TCO.

One might expect an open-circuit voltage over 1.1 V for this structure and a short-circuit current density of ~15 mA/cm^2. The conversion efficiency would be ~10% even if the fill factor is only 0.6. This structure employs an improved p+ layer in conjunction with the present quality undoped a-Si:H.

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*Research reported herein was prepared for the Department of Energy, Division of Solar Technology, Under Contract No. ET-78-C-03-2219, and RCA Laboratories, Princeton, NJ 08540.

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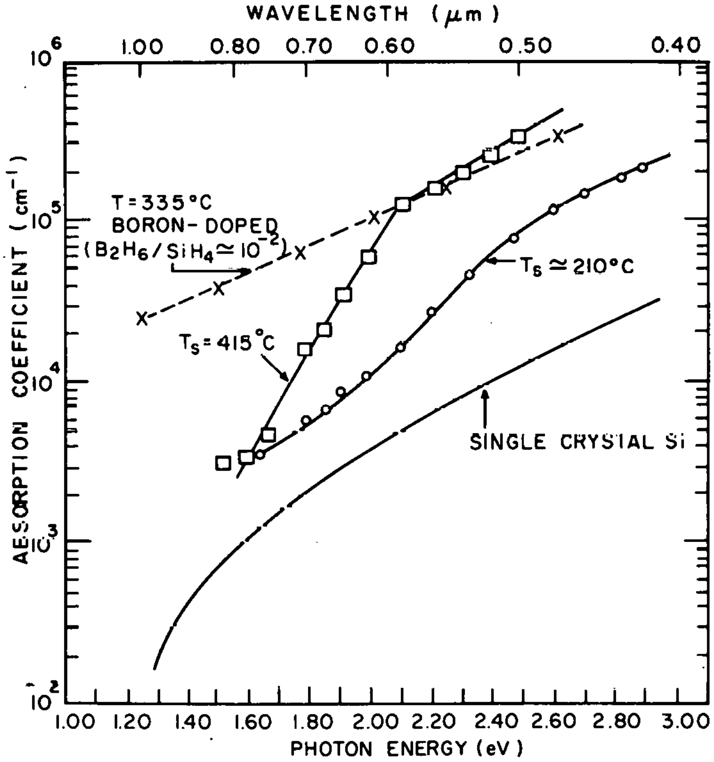

Figure 1. The optical absorption coefficient as a function of photon energy for undoped a-Si:H films deposited at 210 and 415°C and for a boron-doped film deposited at 335°C.

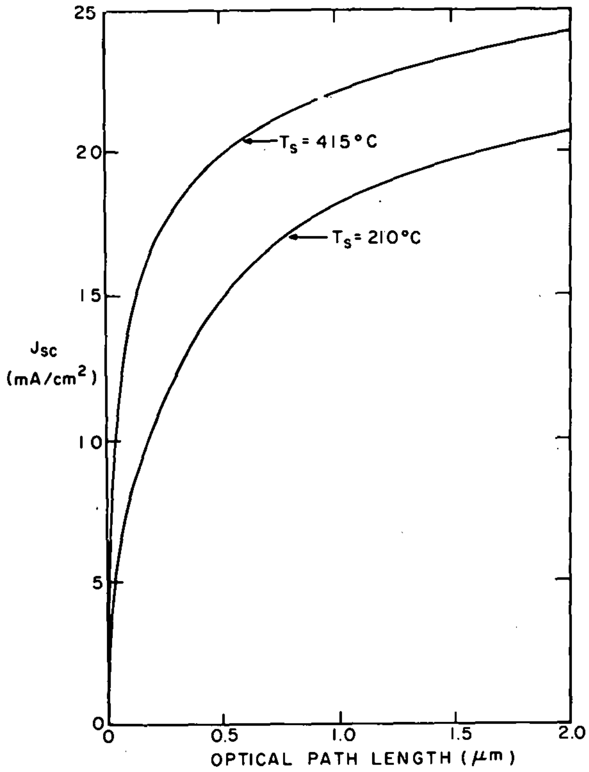

Figure 2. Maximum short-circuit current density (J_{sc} as a function of optical path length for undoped a-Si:H films deposited at 210 and 415°C.

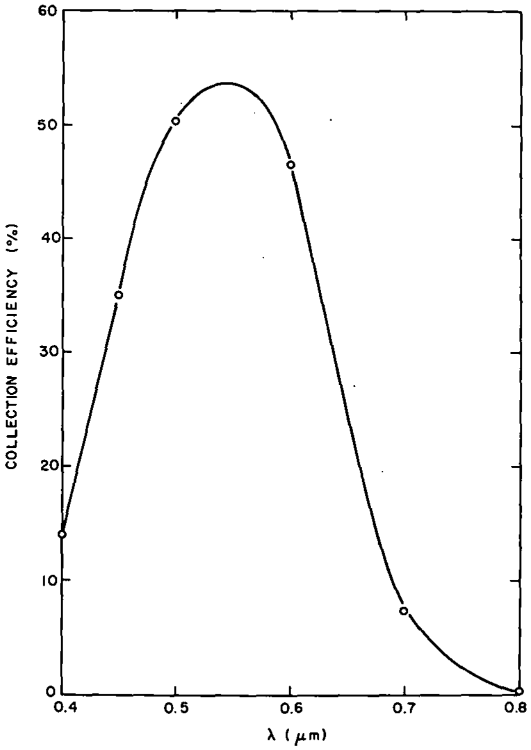

Figure 3. Collection efficiency as a function of wavelength for an a-Si:H p-i-n cell.

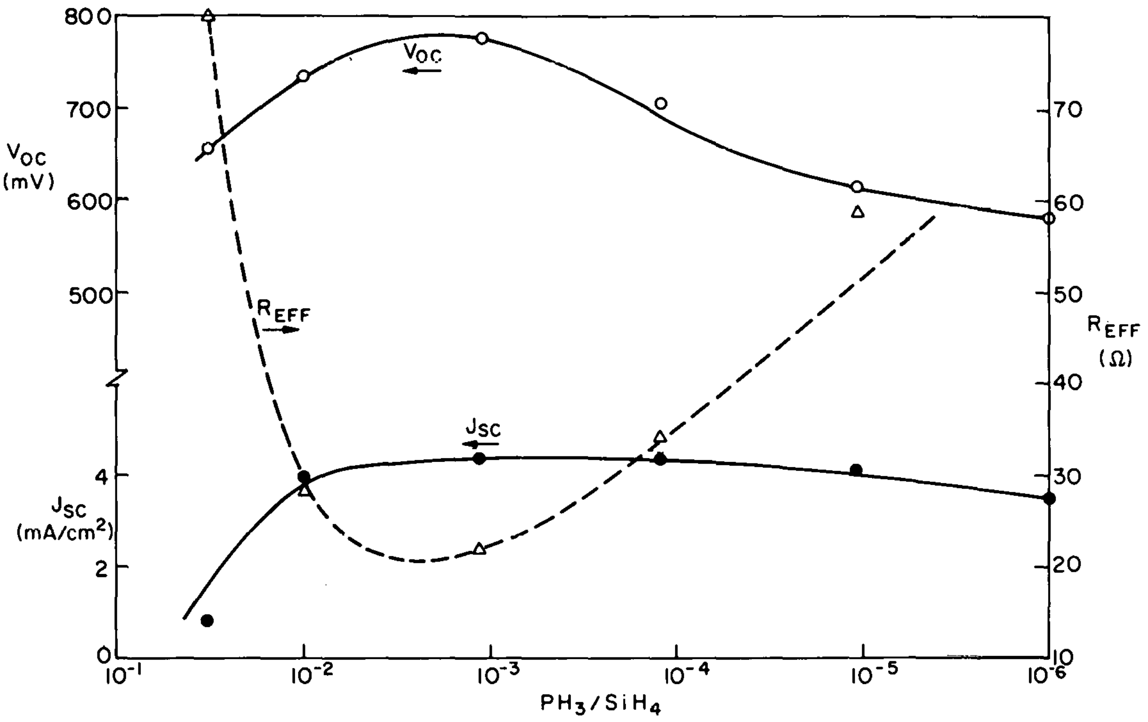

Figure 4. Variation of V_{oc}, J_{sc} and R_{eff} (measured at I = 0) with the doping level of phosphine (PH_3/SiH_4) in the n+ contacting layer of MIS cells.

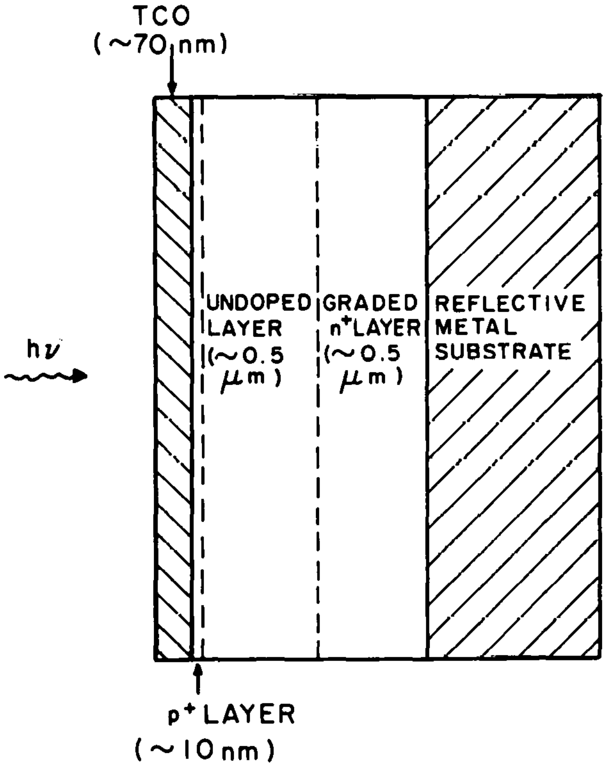

Figure 5. Schematic of an a-Si:H p-i-n cell on a metal substrate.

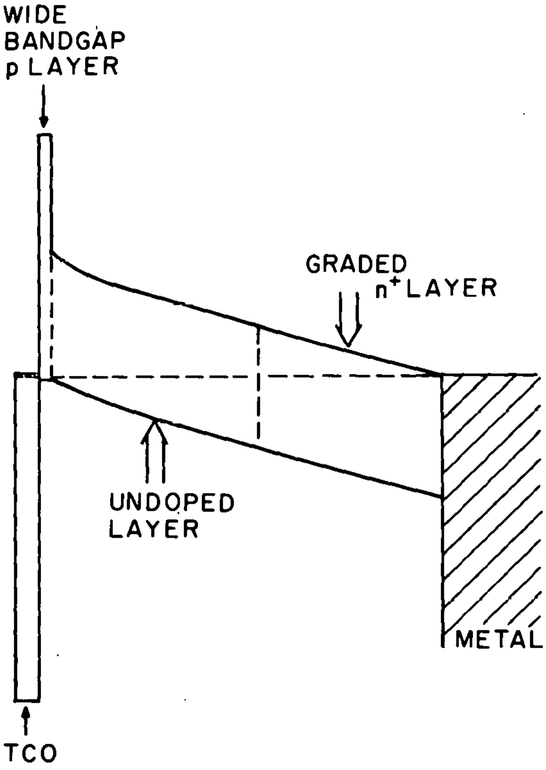

Figure 6. Energy-band diagram of a p-i-n cell with a modified p-layer.

NOTES

THE ELECTROCHEMICAL PHOTOVOLTAIC CELLS

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SERI, Photovoltaic Program Office

Research into four active fields of photoelectrochemistry as potential sources of solar energy conversion technologies is currently being supported by several agencies (National Science Foundation, Office of Naval Research, Department of Defense, Department of Energy, Solar Energy Research Institute) and include:

1. the conversion of light energy into chemical energy in the form of chemical products and fuels in nonregenerative photoelectrosynthetic and photocatalytic cells;

2. the direct conversion of light energy into electrical energy in regenerative electrochemical photovoltaic cells; and

3. the conversion of light energy with electrolyte absorption and photoredox reactions into chemical and/or electrical energy in photogalvanic cells.

Of the first three cell types which involve light absorption in the semiconductor space charge region to produce the highly reactive electron-hole pairs which subsequently undergo redox reactions with electrolytic species, research involving electrochemical photovoltaic cells (EPC) is currently being supported by the Photovoltaic Program Office at SERI. Regenerative operation of electrochemical photovoltaic cells (composition of the electrolyte does not change with time) is accomplished by the oxidation and reduction of the same redox couple which serves the function of completing the cell circuit via the diffusion of reactants and redox products, controlling the maximum open circuit voltage by establishing the equilibrium Fermi level position and magnitude of band bending in the dark, and stabilizing semiconductor photoelectrodes by competing with electron transfer photodecomposition reactions. Electrochemical photovoltaic cells are in principle capable of highly efficient direct conversion of light energy into electrical energy and can be competitive in cost with solid state photovoltaic devices in terms of:

1. technology; e.g., ease in forming the semiconductor electrode-electrolyte junction;

2. the incorporation of low-cost thin-film polycrystalline and amorphous semiconductor materials as photoelectrodes with reduced grain boundary related losses; and

3. the incorporation of in situ storage cability in hybrid systems either by incorporating a third electrode or by connecting redox or fuel cells to photoelectrochemical cells.

The major disadvantage of electrochemical photovoltaic cells is the instability of the semiconductor photoelectrode under illumination (and in some cases, in the dark) which will require extensive research to solve and which may ultimately determine the viability of liquid junction photovoltaic devices.

In the relatively short time period that photoelectrochemical cell research has been persued, impressive gains in efficiency have been attained as shown in Figures 5 and 6. The highest published efficiency to date, 12%, has been obtained for single crystal n-GaAs by workers at Bell Laboratories, who have also obtained efficiencies of 4.8%, and more recently 7.3%, for CVD polycrystalline n-GaAs. In unpublished work by the Rockwell group even higher efficiencies have been obtained for single crystal and polycrystalline n, n^{+-} GaAs. Single crystal and polycrystalline n-CdSe cells have also exhibited high efficiencies, ~ 8% for both, as determined by groups at Bell Laboratories and the Weizmann Institute in Israel. The efficiency status for bulk and thin-film polycrystalline n-CdSe prepared by several techniques is summarized in Figure 6. Published data indicate that stabilities on the order of weeks can now be obtained and longer term stability studies are in progress. Efficiency goals for the PVPO Electrochemical Photovoltaic cell program, Figure 7, are 15% AM1 for single crystal and 10% AM1 for thin-film polycrystalline materials. Considering the rapid rate of progress made in the electrochemical photovoltaic field in the last five years, these goals should be met by groups either in or outside the PVPO supported program.
The remainder of the EPC program goals relate to a fundamental understanding of:

1. semiconductor photoelectrode decomposition mechanisms;

2. the physics and chemistry of the semiconductor electrode-electrolyte interface; and

3. the potential for in situ and ex situ storage systems using electrochemical photovoltaic cells.

The Electrochemical Photovoltaic Cell Program as a whole presently addresses five technology issues, Figure 8, directly related to the goals of the program. In terms of stability six materials having bandgaps in the range 1.1 to 1.7 eV including GaAs, Si, CdSe, CdTe $MoSe_2$, and WSe_2 dominate the program. The latter two materials are relatively new and possess the potential for greater stability due to nonbonding d-d electronic transitions which leave the σ bonding core of the semiconductor lattice intact. The emphasis in the program is on thin-film amorphous and polycrystalline materials and theoretical studies based on concepts derived from treatments applied to heterojunctions and SIS structures as well as calculations based on simple bonding models will be carried out to model the kinetics of electron transfer at the electrode-electrolyte interface and to predict the energies of surface state respectively.

In terms of stability, the present program incorporates all of the techniques which have been previously identified in the literature as possessing potential for stabilizing semiconductor photoelectrodes including:

1. surface modification by chemical bonding or adsorption;

2. incorporating fast one-electron transfer redox couples to compete with lattice photoredox decomposition, Figure 12; and

3. the use of less polar nonaqueous, molten salt and solid electrolytes.

Significant results have already been obtained by the Rockwell, SRI and CSU groups for the stabilization of CdSe and GaAs in nonaqueous, aqueous and molten salt electrolytes respectively using $Fe^{+2/+3}$ complexes, and work is continuing in this direction. As summarized in Figure 13, material technology is being approached from three directions:

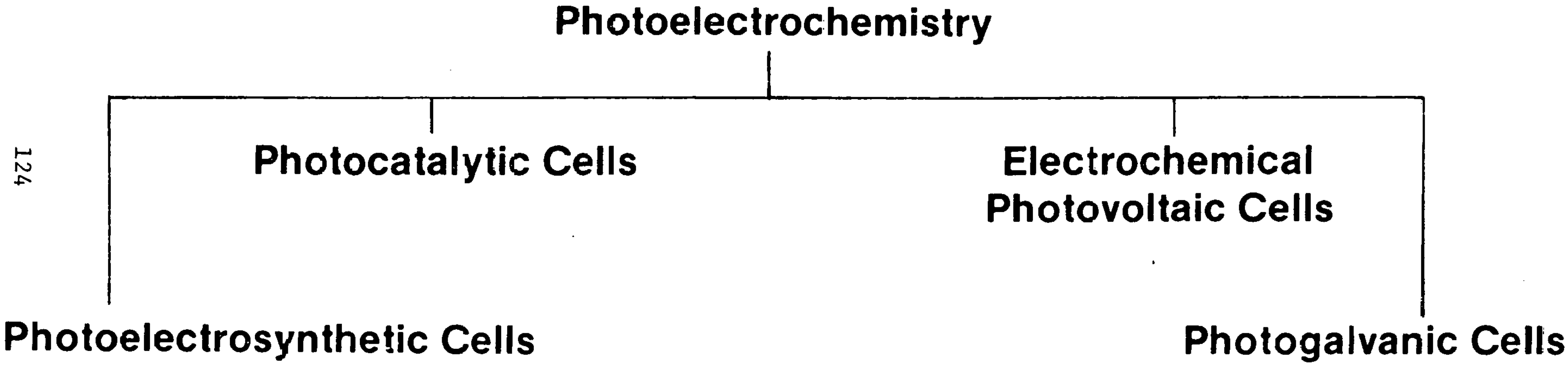
1. the photoelectrode including various thin film preparation techniques using a variety of substrates;

2. the electrolyte, including solvent, redox couple and supporting electrolyte; and

3. the counter electrode, emphasizing the replacement of noble metal materials with low-cost electrodes minimizing polarization and overpotential problems.

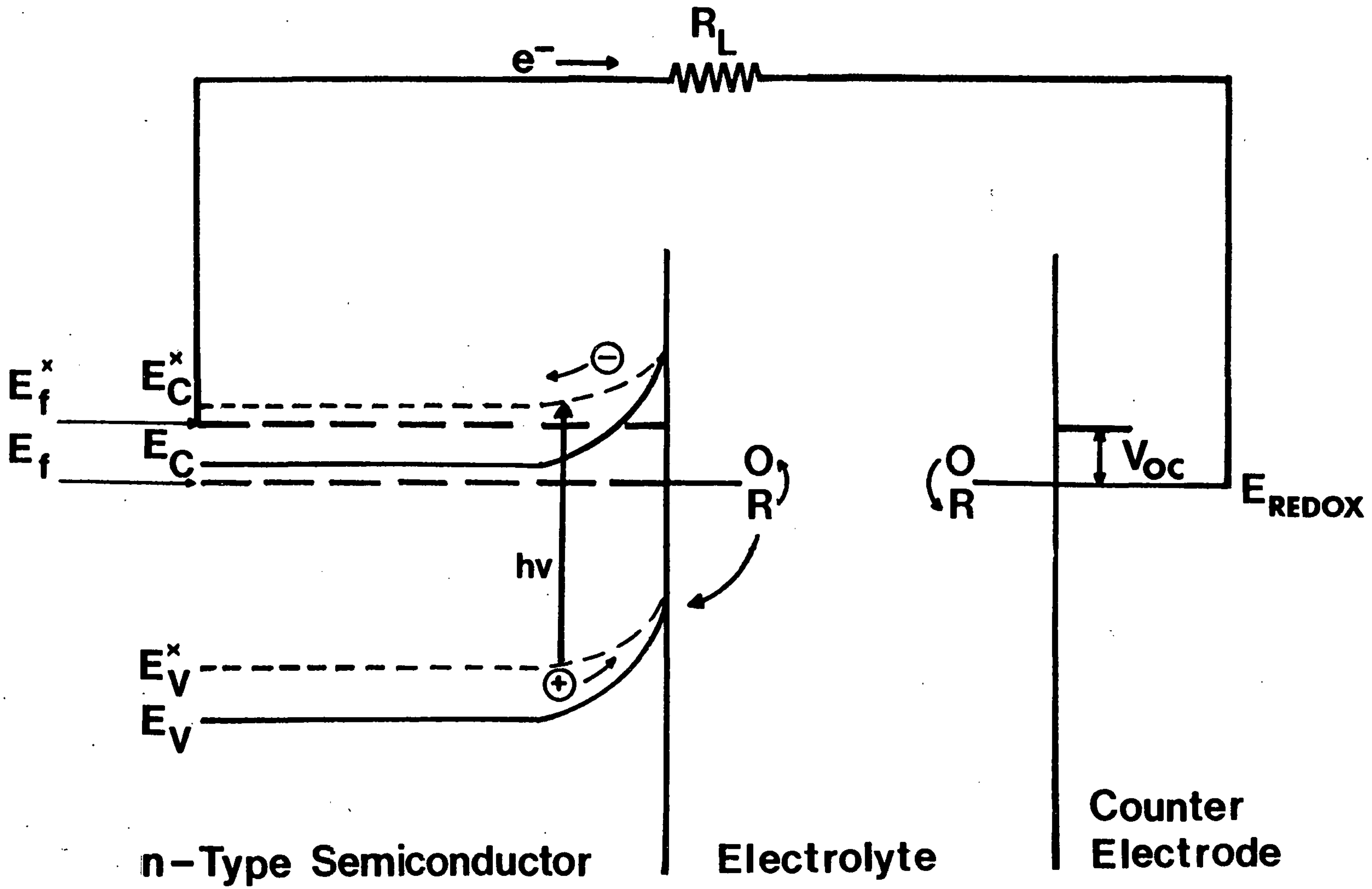
Energy storage studies presently concentrate on three configurations: the three electrode photovoltaic-storage cell (Brooklyn College); the all solid state cell incorporating a solid electrolyte (IGT), and the flow redoxcell-photoelectrochemical cell combination (IGT), which are illustrated in Figures 15-17. Modeling studies will compare both <u>in situ</u> and <u>ex situ</u> storage designs in a preliminary attempt to evaluate the cost effectiveness and economic potential of various storage configurations. In terms of device fabrication prototype storage cells will be developed and analyzed in modeling studies in an attempt to improve device characteristics using a synergistic approach. The individual research program of the fourteen contractors presently in the EPC program is summarized in Figures 19-21. Finally, the major strengths of the present EPC program are summarized in Figure 22, which also identifies those program areas that will receive more attention as the program matures.

Photoelectrochemical Technologies



Photoelectrochemistry

- Photoelectrosynthetic Cells
- Photocatalytic Cells
- Electrochemical Photovoltaic Cells
- Photogalvanic Cells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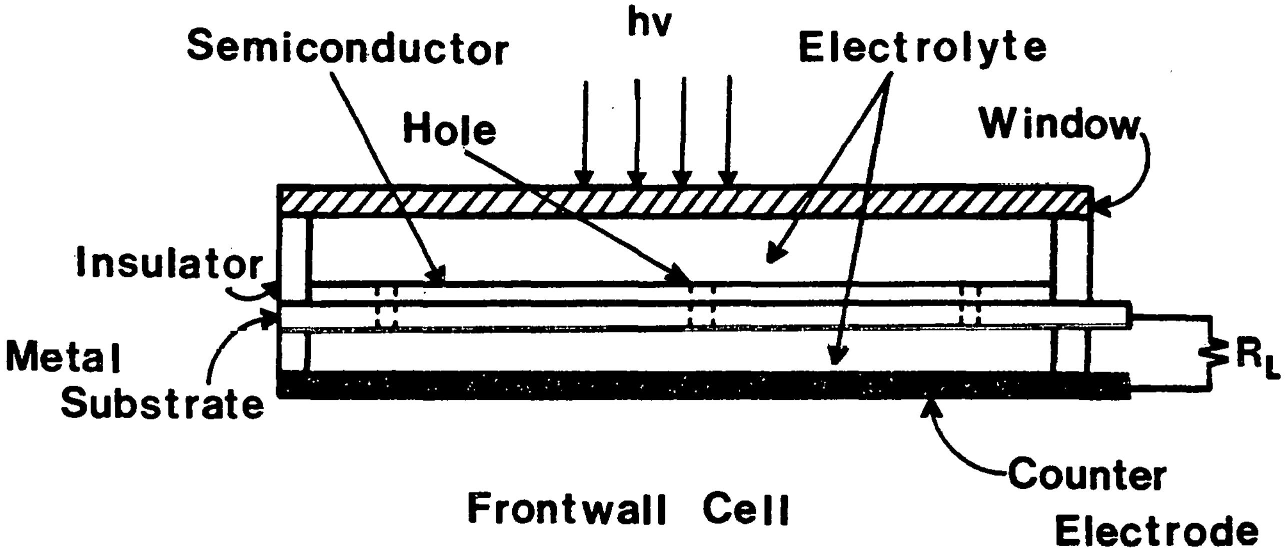
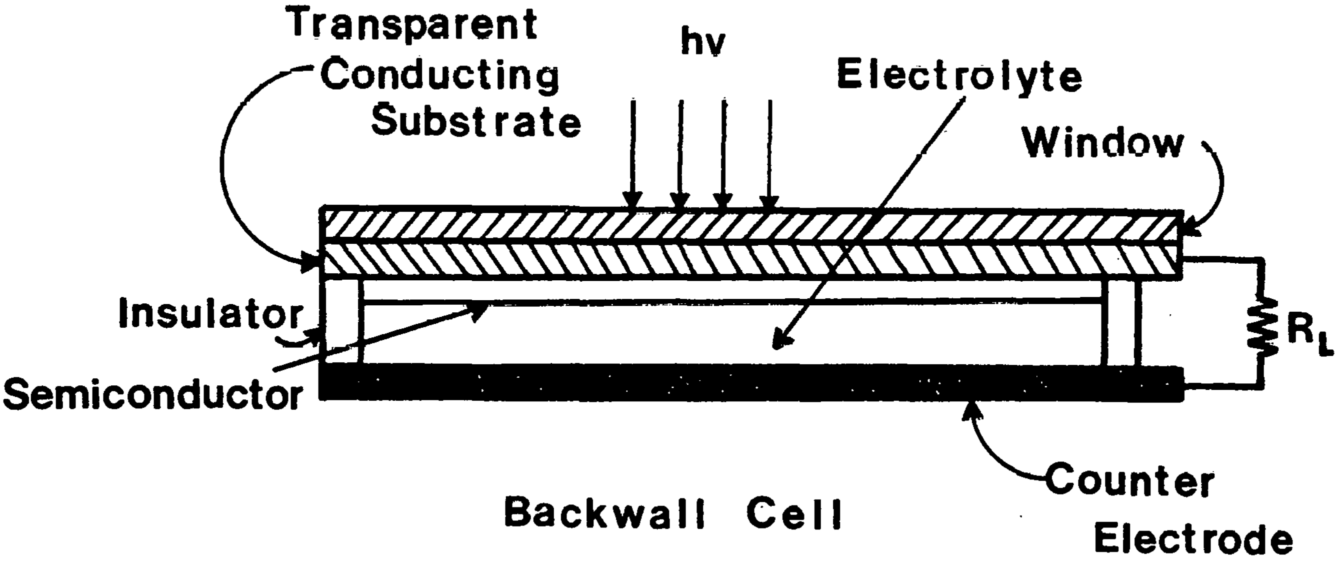
E_V
n-Type Semiconductor
Electrolyte
Counter Electrode



Frontwall Cell



Backwall Cell

Electrochemical Photovoltaic Cell Program

Positive Attributes

- High Efficiency, Competitive Cost , Direct Electrical Conversion
- Ease in Forming the Semiconductor/ Electrolyte Junction
- Incorporation of Low Cost Polycrystalline and Amorphous Semiconductor Electrode Materials
- Rapid Rate of Progress in a Short Time Period (~ 5 Years)
- Capability for In Situ Storage
- Hybrid Systems Possible (Photovoltaic and Thermal)

Negative Attributes

- Instability of Semiconductor Electrodes in Electrolytes
- Need for Rigorously Degassed, Dry Nonaqueous Electrolyte Solutions for Many Systems
- Highly Absorbing Redox Systems

Electrochemical Photovoltaic Cells
Status of Technology

Semiconductor (Morphology) Electrolyte	Preparation Technique	V_{oc} (V)	J_{sc} (mA/cm²)	FF	n (%)	Workers
n-GaAs (SC) $0.8MSe^{-2}$, $0.1MSe_2^{2}$, $1MOH^{-}$		0.72	24	0.70	12	Parkinson, Miller Heller
n-GaAs (P) $0.8MSe^{-2}$, $0.1MSe_2^{-2}$, $1MOH^{-}$	CVD	0.57- 0.62	22	0.42	4.8	Parkinson, Miller Heller, et al
n-CdS(SC) $0.2MFe(CN)_6^{-4}$, $0.1MFe(CN)_6^{-3}$ $0.4MKCl$		0.95	6.2	0.68	5.5	Gerischer, Gobrecht
n-CdTe(SC) $1MSe^{-2}$, $0.1MSe_2^{-2}$, $1MOH$		0.81	18.1	0.4	8.4	Miller, Heller Chang
n-$CuInS_2$ $2MS^{-2}$, 2MS, $2MOH^{-}$					3.5- 4.3	Robbins, et al.

Electrochemical Photovoltaic Cells
Status of Technology

Semiconductor (Morphology) Electrolyte	Presentation Technique	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	n (%)	Workers
n-CdSe(SC) $1MS^{-2}$, 1MS, $1MOH^-$		0.72	14	0.60	8.4	Heller, Miller Chang
n-CdSe(P) $1MS^{-2}$, 1MS, $1MOH^-$	PP	0.67	12	0.45	5.1	Miller, Heller Robbins, et al.
n-CdSe(P) $2.5MS^{-2}$, 1MS, $1MOH^-$	CE	0.51	8.2	0.61	5	Russak, Deb, Chen, et al.
n-CdSe(P) $2MS^{-2}$, 2MS, $1MOH^-$	ED	0.45	5	0.59	2- 2.5	Chen, Kiss
n-CdSf(P) $2MS^{-2}$, 2MS, 1MOH	CSD	0.25- 0.35	4.5	0.41	1- 1.5	Chen, Kiss
n-CdSe(P)	Thin Film				8	Manassen

Electrochemical Photovoltaic Cell Program

Program Goals

- Demonstration of a Stable and High Efficiency (15% AM1) Cell with a Single Crystal Photoelectrode
- Demonstration of a Stable and Moderate Efficiency (10% AM1) Cell with a Polycrystalline or Amorphous Photoelectrode
- Development of a More Fundamental Understanding of Degradation Mechanisms and Identification of Approaches to Minimize or Eliminate Decomposition Processes
- Development of a More Fundamental Understanding of the Physics and Chemistry of the Semiconductor Electrode/Electrolyte Interface: Relate this Knowledge to Device Development and Fabrication
- Demonstration of Electrochemical Photovoltaic Cells with <u>In Situ</u> and <u>Ex Situ</u> Storage Capability: Assessment of the Economic and Technological Advantages/Disadvantages of Various Storage Configurations

Technology Issues Addressed By The Photovoltaic Cell Program

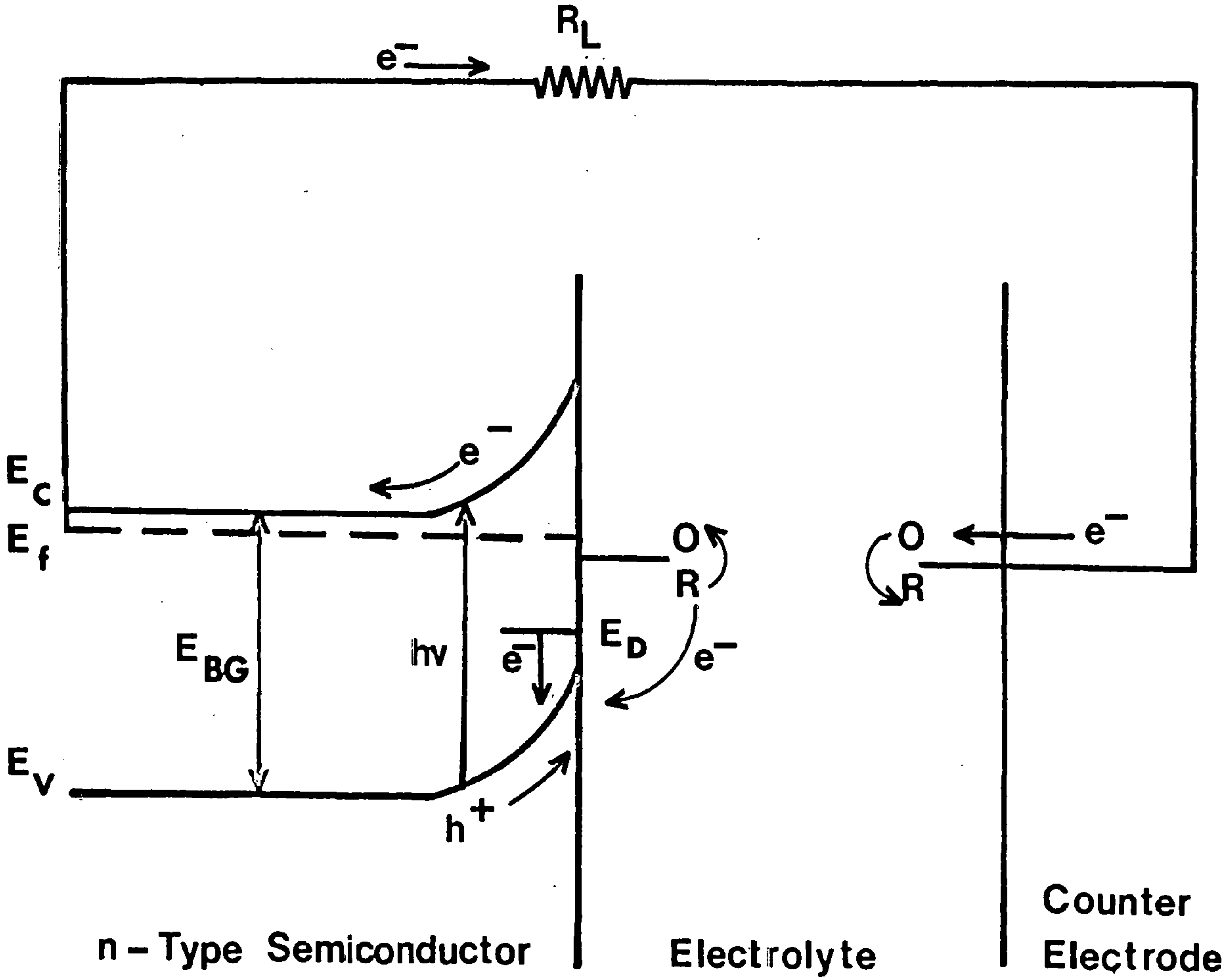
- Efficiency
- Stability
- Material Technology
- Energy Storage
- Device Fabrication

Efficiency

- 1.1 - 2.5 eV Bandgap Semiconductor Material
- New Materials (WS_2(Se_2), MoS_2(Se_2))
- Morphology (Single Crystal, Polycrystalline, Amorphous)
- Modeling (Semiconductor — Electrolyte Interface)

Stability

- Surface Modification (Chemical Modification, Adsorption, Alteration of Surface States)
- Choice of Redox Couples
- Stable Semiconductor Electrode Materials
- Electrolyte Stability
- Nonaqueous Electrolytes
- Molten Salt Electrolytes
- Solid Electrolytes


R_L
e^-
E_c
E_f
e^-
E_{BG}
hν
e^-
E_D
O
R
e^-
E_V
h^+
O
R
e^-
n – Type Semiconductor
Electrolyte
Counter Electrode

Material Technology

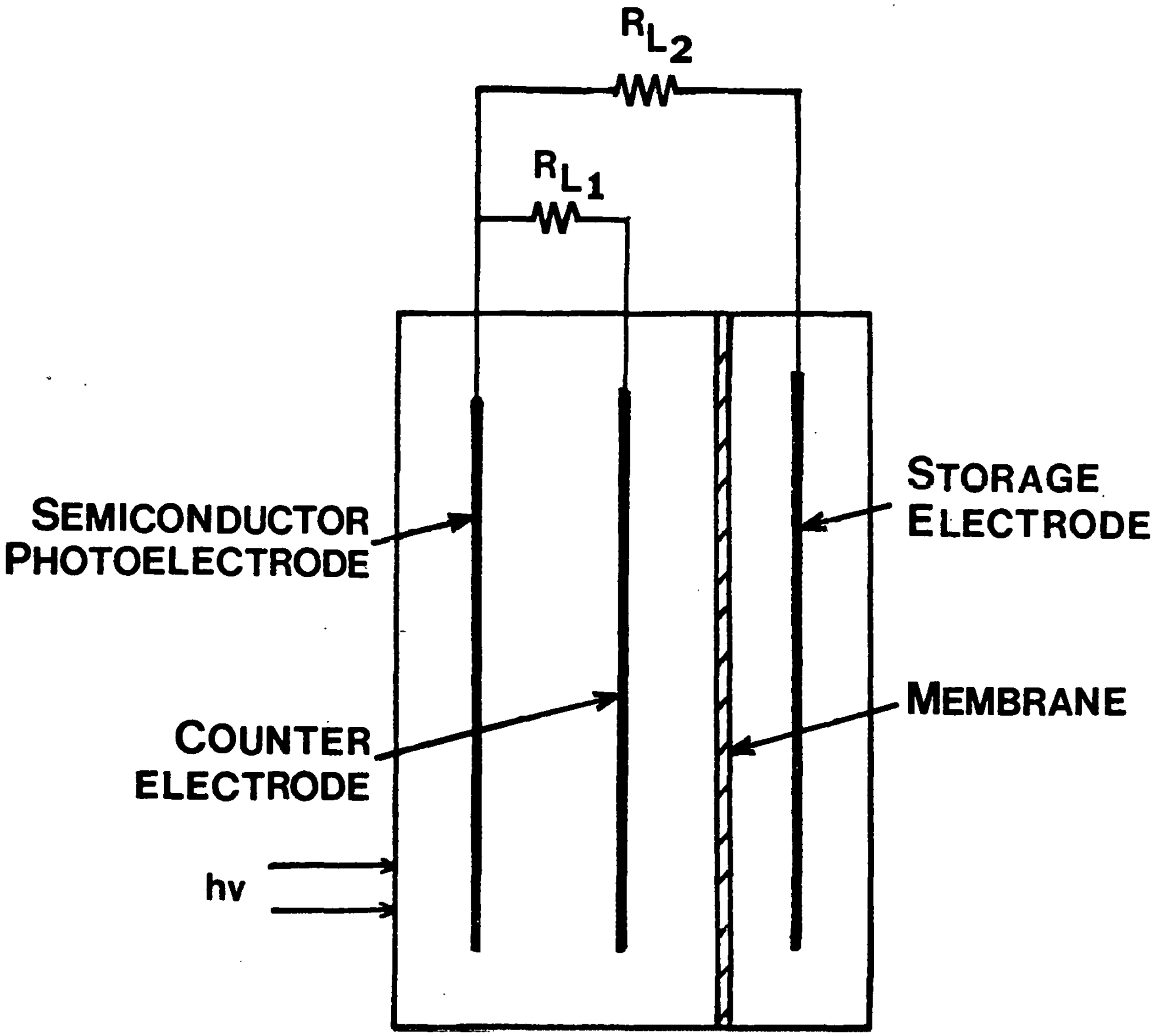
- Thin Films, (ED, CSD, Chemical Vapor Transport, Cleavage of Single Crystals)
- Polycrystalline — Amorphous
- Single Cyrstals
- Counter Electrode Materials
- New Electrolyte Materials

ELECTROCHEMICAL PHOTOVOLTAIC CELLS
POTENTIAL MATERIALS

PHOTOELECTRODE	THIN FILM TECHNOLOGY	ELECTROLYTE			COUNTER ELECTRODE
		SOLVENT	SUPPORTING ELECTROLYTE	REDOX COUPLES	
Semiconductors	Co-Evaporation	Aqueous Nonaqueous		Organic Molecules	
	Sputtering	Acetonitrile			
GaAs		Tetrahydrofuran	TBA ClO_4	TMPD o/+	Pt
Si	Electrodeposition		TBA BF_4	Anthraquinone$^{0/+}$	Co
CdSe	Chemical Spray Deposition	Propylene Carbonate	TBA Cl	Anthracene$^{0/+}$	Ti
CdTe			NaBr	Transition Metal Complexes	PbO_2
WSe_2		Molten Salt	HBr		Ni
$CuInSe_2$		Butylpyridinium Chloride			Fe
Substrates				$Fe(CN)_6{}^{-4/-3}$	PbS
Cu		Aluminum Trichloride		Ferrocene o/+	
Zn				Simple Ions	
Ti				$Fe^{+2/+3}$	
ITO				$Se^{-2}/Se_2{}^{-2}$	
				Se^{-2}/Sn^{-2}	

Energy Storage

- In Situ and Ex Situ
- Three Electrode Liquid Junction Cell
- Solid State Cell
- Flow Cell — Redox Cell
- Modeling Studies



LIGHT

$2Se^{2-} \longrightarrow Se_2^{2-} + 2e^-$ PHOTOANODE

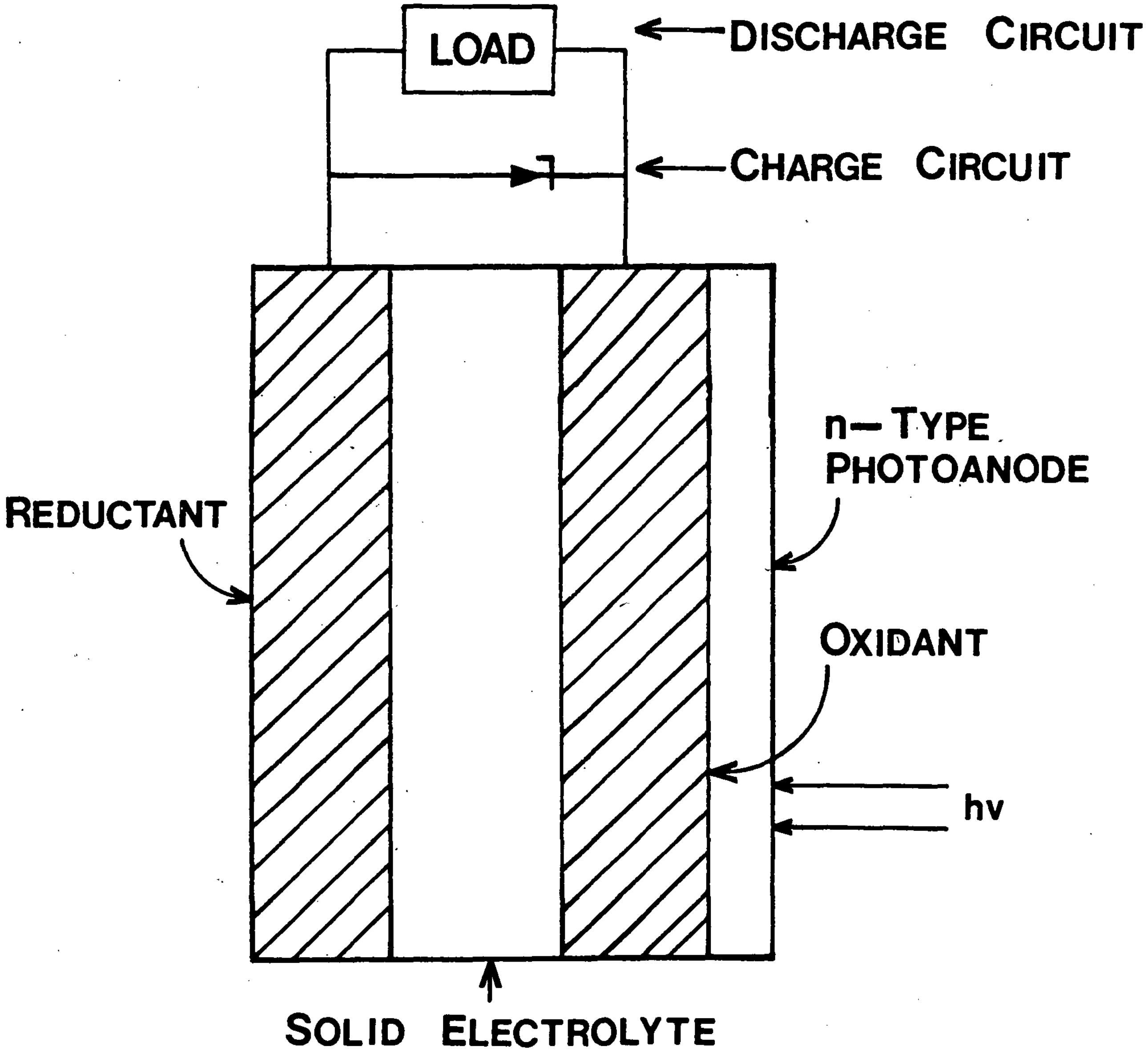
$Se_2^{2-} + 2e^- \longrightarrow 2Se^{2-}$ CATHODE

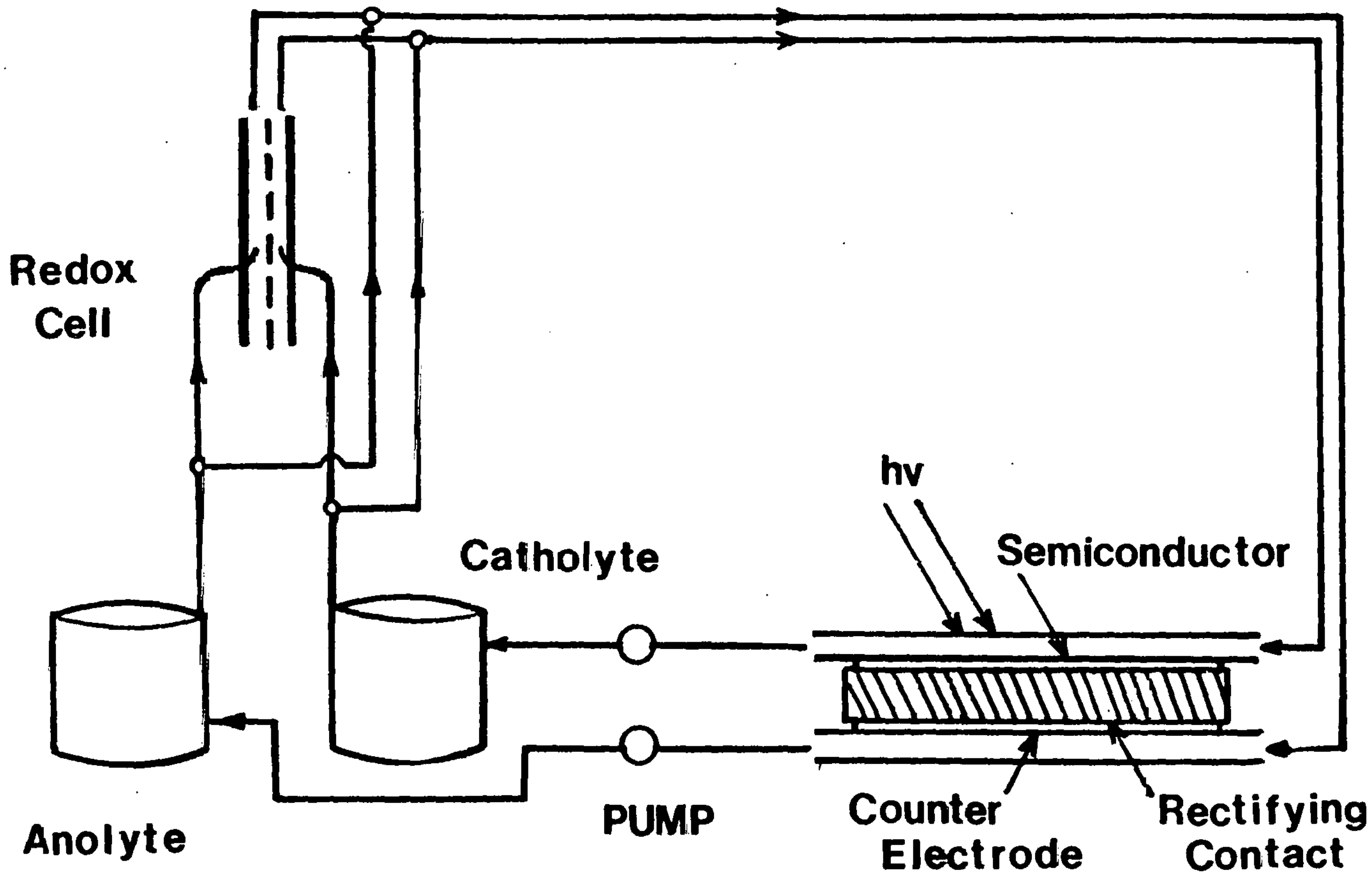
$Ag_2Se + 2e^- \longrightarrow 2Ag + Se^{2-}$ STORAGE

DARK

$Se_2^{2-} + 2e^- \longrightarrow 2Se^{2-}$ CATHODE

$2Ag + Se^{2-} \longrightarrow Ag_2Se + 2e^-$ STORAGE


LOAD
DISCHARGE CIRCUIT
CHARGE CIRCUIT
n– TYPE PHOTOANODE
REDUCTANT
OXIDANT
hv
SOLID ELECTROLYTE



PHOTOELECTROCHEMICAL / REDOX CELL STORAGE SYSTEM

Device Fabrication

- Experimental Cells (Three Electrode Cells for Initial AR&D)
- Complete Phototype Cells
- Storage Cells
- Modeling Studies

Contractor	Program Manager	Descriptive Title	Amount
Ames	Thomas E. Furtak	Photoelectochemical Solar Cells Based on d-Band Electrochemistry at Transition Metal Diselenides	86,000
Battelle	Eric W. Brooman	Efficiency and Stability of Si and GaAs Polycrystalline and Amorphous Thin Film Photoelectrochemical cells	167,000
Chronar	Zoltan Kiss	Efficiency and Stability of Thin Film Cadmium Chalcogenide Photoelectrochemical Cells	137,000
CSU	Joel Dubow	Development and Modeling of Photoelectrochemical Cells Incorporating $MoSe_2$, GaAs, Si, $CuInS_2$ and $CuInSe_2$ Photoanodes and Using Aqueous or Molten Salt Electrolytes	190,000
EIC	R. David Rauh	Efficiency and Stability of GaAs, CdTe, Zn_3P_2 and Chalcopyrite Photoelectochemical Cells in Nonaqueous Eletrolytes	198,000

Contractor	Program Manager	Descriptive Title	Amount
Grumman	Michael Russak	Modeling and Optimization of Thin Film CdSe and $CuInS_2$ Photoelecrochemical Cells Incorporating Sulfide (Selenide) Polysulfide Electrolytes	211,000
IGT	Anthony Sammells	Photoelectrochemical Cells Incorporating GaAs, CdSe, $MoSe_2$, and MoS_2 Photoelectrodes in Liquid Junction Cells: Investigation of In Situ and Ex Situ (Liquid Junction and Solid State) Storage Configurations	138,000
Penn State	Stephen Fonash	Theoretical Studies of the Semiconductor Electrode-Electrolyte Interface and Development of Photoelectrochemical Cells Incorporating Fe_2O_3, CdTe, CdSe, Si, and InP Photoanodes in Aqueous and Nonaqueous Solvents	154,000
Rockwell	Dennis Tench	Stabilization of II-VI Semiconductor Photoelectrochemical Cells Using Novel Electrolytes, Nonaqueous Solvents, and Chemical Modification of the Electrode Surface	199,000
SRI	Karl Frese	Experimental and Theoretical Studies Involving GaAs, CdSe, CdTe, and Si Photoelectrode Corrosion in Photoelectrochemical Cells	117,000

Contractor	Program Manager	Descriptive Title	Amount
Sum X	David DeBerry	Stabilization and Optimization of Nonqueous Regenerative Photoelectrochemical Cells	136,000
CUNY	Micha Tomkiewicz	Stabilization and Characterization of the Electrodeposited CdSe Photoelectrochemical Cell	(150,000)
IGT	Anthony Sammells	Photoreducing Membranes for Solar Energy Conversion	(82,000)
Gould	H. Frank Gibbard	Electrochemical Photovoltaic Cells Incorporting Molten Salt Electrolytes	(116,000)

CONCLUSION

MAJOR STRENGTHS

- MAJOR EMPHASIS IN PROGRAM ON SEMICONDUCTOR ELECTRODE STABILIZATION
- STRONG EMPHASIS ON POLYCRYSTALLINE AND AMORPHOUS THIN FILM SEMICONDUCTOR ELECTRODES
- FUNDAMENTAL STUDIES IN SUPPORT OF ENHANCED STABILITY AND EFFICIENCY: DEGRADATION MECHANISMS, ELECTRON TRANSFER KINETICS, PHYSICS AND CHEMISTRY AT THE ELECTRODE/ELECTROLYTE INTERFACE
- COMPREHENSIVE DEVICE STUDIES
- MODELING STUDIES IN SUPPORT OF DEVICE OPTIMIZATION
- MODELING STUDIES COMPARING IN SITU AND EX SITU STORAGE CONFIGURATIONS

PROGRAM AREAS NEEDING MORE EMPHASIS

- TECHNIQUES FOR MEASURING LONG TERM STABILITY; UNIFORM STABILITY MEASUREMENT PROCEDURES
- INCREASING EMPHASIS ON DEVICE FABRICATION AS PROGRAM MATURES
- MORE FUNDAMENTAL STUDIES
- INCREASED STUDY OF IN SITU STORAGE OPTIONS

NOTES

STATE OF THE ART GaAs PHOTOELECTROCHEMICAL SOLAR CELLS

B. A. Parkinson, Ames Laboratory

A photoelectrochemical cell consists of a semiconducting photoelectrode, a redox couple solution and a "dark" counterelectrode, e.g. carbon. The photoactive junction is spontaneously formed upon immersion of the semiconductor in the electrolyte solution (Fig. 1). In the last year considerable improvement in the stability and conversion efficiencies of photoelectrochemical solar cells has been achieved by workers at Bell Laboratories. n-GaAs $|$ $.8MK_2Se - .1MK_2Se_2$ - 1MKOH $|$C solar cells are presently the most efficient light to electrical energy converters of this type for photoelectrodes of both single crystal and small grain polycrystalline materials.

The redox couple (Se^{-2}/Se_2^{-2}) effectively competes with detrimental photocorrosion processes for photogenerated carriers at the semiconductor surface. The dissolution of the semiconductor has been effectively eliminated for the equivalent of up to three months of solar illumination before failure of the encapsulation.

Anti-reflection coatings are impractical on liquid junction photoelectrodes due to the difficulty of achieving effective charge transfer through such a coating. To reduce reflective losses a surface texturizing etch has been developed which creates hillocks of about 1 micron dimension on GaAs (100) single crystal surfaces (Fig. 2). The "matte" surface results in a 50% increase in short circuit current over a "shiny" etched surface. The many fold increase in the microscopic surface area also results in lower local current densities and thus further suppresses corrosion.

The adsorption of metal ions on the gallium arsenide surface resulted in increases or decreases in cell performance. Adsorption of ruthenium results in a persistant improvement of the fill factor and open circuit voltage of single crystal

GaAs cells. The improvement is attributed to the reduction of surface recombination by interaction of ruthenium with surface states on the semiconductor surface.

A combination of surface texturization and ruthenium treatment resulted in improvements depicted in Fig. 3 which resulted in a 12% solar to electrical conversion efficiency in 95 mW/cm^2 sunlight.

The solar cell performance of chemical vapor deposited thin films is dramatically improved by treatment of the surface with a solution containing Ru(III) (Fig. 4). Charge collection scanning electron microscopy of a gold Schottky barrier deposited over the ruthenium treated surface revealed that ruthenium increases the overall charge collection efficiency by both increasing the number of active crystallites and decreasing the propensity of grain boundaries to act as recombination centers.

Polycrystalline material grown by S. Chu et al. at S.M.U. has resulted in cells of about 7% efficiency after ruthenium treatment, however the long term stability of the polycrystalline films is still not as good as the single crystal devices.

References

1. B. A. Parkinson, A. Heller and B. Miller, Appl. Phys. Lett., 33(6) 521 (1978).
2. B. A. Parkinson, A. Heller and B. Miller, J. Electrochem. Soc., 125(6)954 (1979).
3. W. D. Johnston, H. J. Leamy, B. A. Parkinson, A. Heller and B. Miller, J. Electrochem. Soc., in press.
4. R. J. Nelson, J. S. Williams, H. J. Leamy, B. Miller, H. C. Casey, Jr., B. A. Parkinson and A. Heller, Appl. Phys., in press.
5. S. Chu, T. L. Lee, B. Miller and A. Heller, in preparation.

Figure Captions

Fig. 1. Schematic diagram of photoelectrochemical solar cell.

Fig. 2. SEM photograph of "matte" etched surface.

Fig. 3. Effect of ruthenium treatment and "matte" etch on current voltage characteristics of single crystal GaAs photoanade. Curves 1 and 2 are "shiny" electrodes; Curves 3 and 4 are "matte electrodes; Curves 1 and 3 untreated electrodes; Curves 2 and 4 ruthenium treated electrodes.

Fig. 4. Current voltage curve for CVD GaAs photoelectrode as a function of surface treatment

1. virgin electrode
2. short etch
3. ruthenium treated electrode

Fig. 5. Average scan current, I_c, normalized by electron beam current, I_b, plotted vrs. electron beam energy for CCSEM as a function of GaAs treatment prior to gold metalization

● untreated

□ etched

△ etched + selenide

o etched + selenide + ruthenium

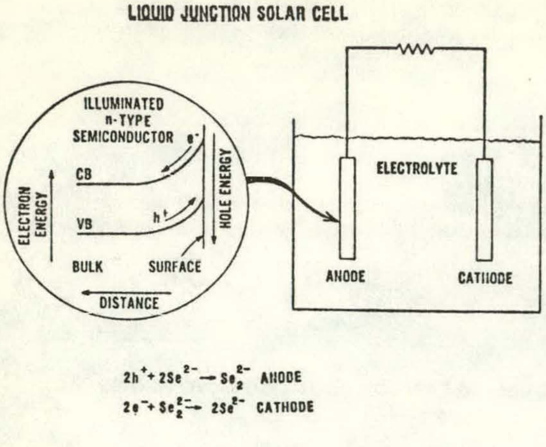


Fig. 1

Fig. 2

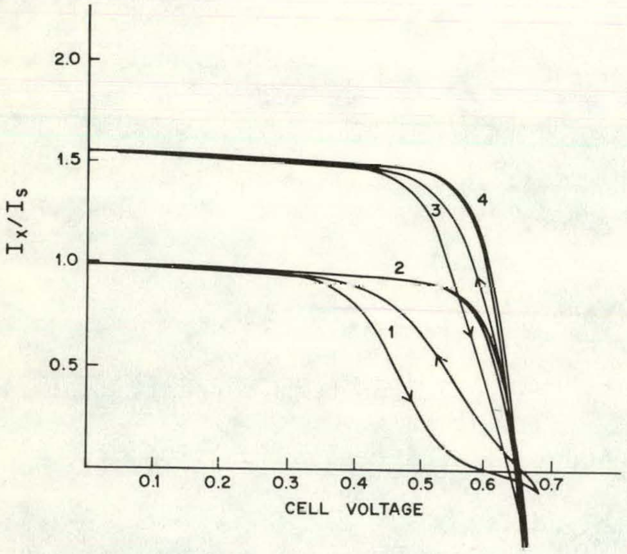


Fig. 3

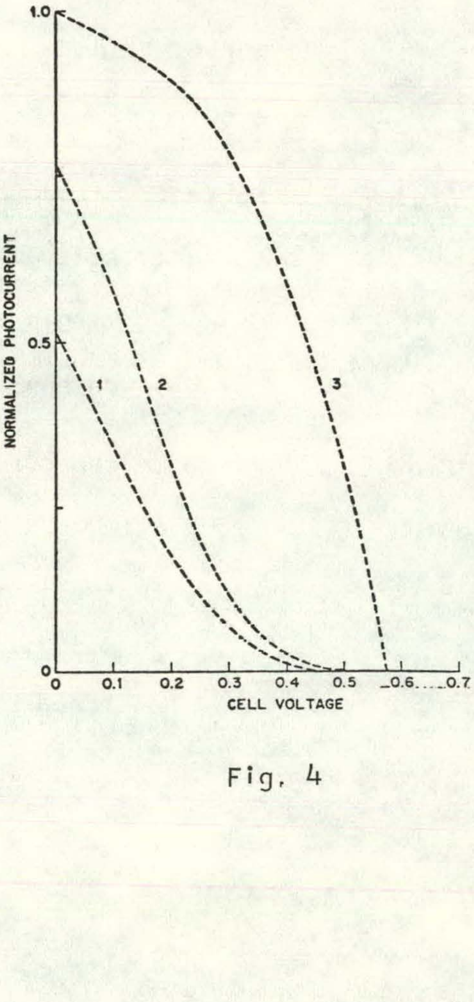


Fig. 4

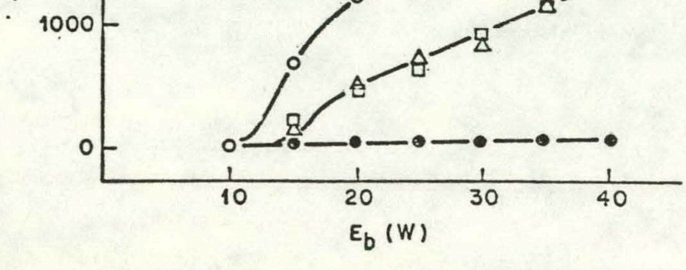


Fig. 5

MATERIAL RESOURCES AND ENVIRONMENTAL STUDIES

S. Nagy, SERI, Photovoltaics Program Office

INTRODUCTION

Material Resources and Environmental Studies serve as "early warning" activities in support of mainstream R&D. They are designed to outline the nature and extent of certain barriers to commercialization of PV material technologies under consideration at SERI. Information on these barriers and recommendations for dealing with them can effect changes in research emphasis within a material area and can also be directed toward technology development, where efforts will focus on removing barriers by engineering the material technology. These activities are also "early warning" in the sense that a high degree of uncertainty in technology characterizations will usually not allow definitive assessments in these areas. For this last reason, work in materials availability and environmental effects is limited to the advanced materials part of the AR&D program.

MATERIAL RESOURCES

Concern has been voiced about the availability and price of many materials used in technologies presently in R&D. As noted in Figure 5, Battelle Pacific Northwest recently conducted a cursory investigation of thirteen cell types (1), and found several materials which have potential supply constraints. The magnitude of the problems with gallium and indium were such that even this preliminary work justified concern about their future supply at a reasonable price. The milestone in Figure 2 reflects this. Other material problems were not severe enough, more uncertain, or involved technologies in the high risk categories such that further research is not warranted at present.

Figure 3 outlines the two-level approach to materials availability problems. If potentially severe problems have been identified in the screening described by the first bullet, further studies are initiated along the lines of the second bullet. The three general strategies are listed in order of importance. Early consideration of material conservation in the PV technology lessens the need for materials, impacts device cost, and allows conservation techniques to be incorporated into the processing concept instead of adding them onto a well-developed technology. The other two strategies involve the materials mining and extraction industries, and can require effort and money beyond the promise of the PV technology involved.

The program has two contractors, as shown in Figure 4. Figures 5-10 describe the Battelle effort. The screening requires characterizations of the cell fabrication process, as exemplified in Figure 8. Because materials requirements cannot be precisely specified in R&D, sensitivity analysis over different amounts and kinds of materials is necessary. Also important are feedstock availability and process efficiencies, the latter because they greatly affect feedstock requirements. Materials requirements are calculated and then screened using different availability and cost criteria. Problem areas which arise undergo out-of-computer analysis to assess their severity (see (1) for criteria examples and methodology). The five technologies being reviewed are polycrystalline thin-film silicon, copper sulfide/cadmium sulfide, amorphous silicon, polycrystalline gallium arsenide, and gallium arsenide vertical multi-junction advanced concentrators. The CRA effort (Figure 11) will study gallium supply using econometric forecasting techniques.

ENVIRONMENTAL STUDIES

In this activity, environmental, health and safety risks are examined throughout the life-cycle of all advanced material technologies. There are two reasons for the milestones shown in Figure 12. First, there is already a large EH&S data base for silicon-based technologies from the semiconductor industry. Second, cadmium sulfide and gallium arsenide technologies are broadly perceived as having potential major risks because of the large quantities of cadmium and arsenic compounds required. SERI's efforts will focus on the first two bullets in Figure 13. In-depth research (toxicology studies, worker exposures, emissions, etc.) will be conducted by Brookhaven National Lab, the DOE PV EH&S research lead laboratory. Environmental control technology development is the domain of the TD&A Lead Center.

The early assessments mentioned in Figure 14 are pioneering attempts at identifying PV risks. Because of the difficulties in defining immature technologies, these assessments are of limited use. The PV Programmatic EA is presently being completed by DOE, and the industrial hygiene study is listed as reference (2). The infrastructure among JPL, SERI and BNL has been set up, and the SERI task in this area is scheduled to begin in October, 1979.

References

1. Watts, R. L., et al., Some Potential Material Supply Constraints in the Deployment of Photovoltaic Electric Systems, PNL-2971, Battelle Pacific Northwest Laboratory, Richland, Washington, September, 1978.

2. Briggs, T.M., Owens, T.W., Industrial Hygiene Characterization of the Photovoltaic Solar Cell Industry, PEDCo Environmental, Inc., Cincinnati, Ohio, and NIOSH, Division of Surveillance, Hazard Evaluation and Field Studies, Cincinnati, Ohio, August, 1979.

PV Advanced R&D Annual Review
September 17-19, 1979

Material Resources and Environmental Studies

- Objectives
- Milestones
- Approach
- Status

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FTS 327-1392

Figure 1

Material Resources: Objective and Milestone

Objective: Assure a sufficient supply and price of materials used in advanced, low-cost PV technologies.

Milestone: Complete resource availability and cost study of indium and gallium in FY 80.

Figure 2

Material Resources: Approach

- Determine the nature and extent of material supply problems singularly associated with the large-scale deployment of PV technologies in advanced R&D.
- Identify mitigating strategies and implement.
    - Emphasize material conservaton in cell fabrication technologies.
    - Optimize present extraction processes.
    - Investigate alternative sources and extraction processes.

Figure 3

Material Resources: Status

- "Evaluation of Critical Materials for PV Cells," Battelle Pacific Northwest Laboratories, $194K
- "Future Supply of Gallium," Charles River Associates Inc., $61K

Figure 4

HISTORY OF CRITICAL MATERIALS ASSESSMENT PROGRAM (CMAP)

- FY 77-78 — CMAP METHODOLOGY DEVELOPED (PNL 2711)
- FY 78 — ANALYZED 12 SHACOB AND AIPH SYSTEMS (PNL 2972)
- FY 78 — ANALYZED 13 PHOTOVOLTAIC CELLS IN 15 SYSTEMS (PNL 2971)
  — GALLIUM AND INDIUM IDENTIFIED AS BEING IN SHORT SUPPLY

Figure 5

HISTORY OF CRITICAL MATERIALS ASSESSMENT PROGRAM (CMAP) - CON'T

- FY 79 — CMAP FURTHER DEVELOPED AND APPLIED TO SPS PROGRAM BY BCL
- FY 79-80 — PHOTOVOLTAIC MATERIALS AVAILABILITY PHASE II STARTED JUNE '79 DUE TO BE COMPLETED MARCH '80. COOPERATIVE PNL, BCL

Figure 6

TASK I

OBJECTIVE: CHARACTERIZE 5 CELLS INCLUDING PROCESS EFFICIENCIES

STATUS: VIRTUALLY COMPLETED

Figure 7

a-Si SOLAR CELL

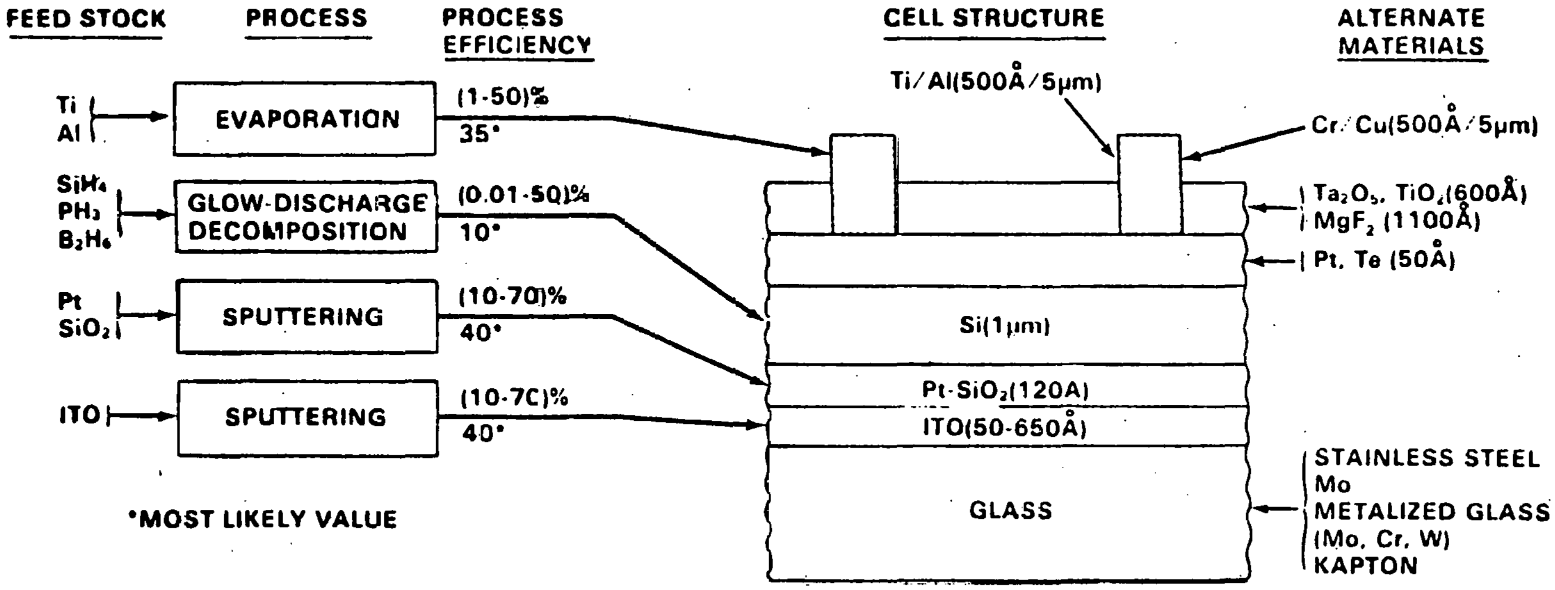


Figure 8

TASK II

OBJECTIVE: MODIFY CMAP TO HANDLE PRODUCTION PROCESS, CARRY OUT COMPUTER (CMAP) SCREENING OF 5 CELLS, REVIEW RESULTS, CARRY OUT SENSITIVITY ANALYSIS ON KEY PARAMETERS

STATUS: CMAP MODIFIED

Figure 9

TASK III

OBJECTIVE: INVESTIGATE THE PROBABLE FUTURE AVAILABILITY OF GALLIUM & INDIUM, EMPHASIZING THE ECONOMICS OF GALLIUM FROM COAL; DEVELOP STRATEGY OPTIONS AND RECOMMENDATIONS FOR DEALING WITH POTENTIAL GALLIUM & INDIUM SHORTAGES

STATUS: A NUMBER OF INDUSTRY VISITS TO GALLIUM AND INDIUM PRODUCERS. COAL PROCESSING TECHNOLOGIES REVIEWED

Figure 10

“Future Supply of Gallium,” Charles River Associates Inc.

Objective: Assess the supply price of gallium as a function of demand scenarios and rates of introduction of GaAs PV systems.

- Delimit Ga supply.
- Evaluate recovery processes.
  - Technology assessments
  - Process flow sheets
  - Production cost estimates
- Economic analysis
  - Recovery processes
  - Non-PV Ga demands
  - Potential co-products of Ga recovery
  - Industry infrastructure
  - Potential bottlenecks, constraints and disruptions (EH&S regulations, cartels, etc.)

Status: Program initiated September 1979

Figure 11

Environmental Studies: Objective and Milestones

Objective:	Provide for the environmental acceptability of advanced PV technologies throughout their life-cycle.
Milestones:	Complete environmental assessments of cell technologies using cadmium, arsenic and their compounds by the end of FY81 (Cd) and FY82 (As).

Figure 12

Environmental Studies: Approach

- Identify the potential environmental risks of the manufacture, deployment, and decommissioning of advanced PV materials.
- Identify environmental and occupational health and safety regulations and exposure/emission guidelines applicable to the manufacture, deployment, and decommissioning of advanced PV technologies.
- Provide technical input on environmental, health, and safety (EH&S) risks of advanced PV technologies to the JPL Technology Development and Applications Lead Center and the DOE PV EH&S research lead laboratory.

Figure 13

Environmental Studies: Status

- EH&S research compiled
  - Early assessments (EPA, DOE, et al.)
  - PV Programmatic Environmental Assessment (EA)
  - Industrial hygiene characterization of the PV solar cell industry

- Liaisons established with the JPL Lead Center and Brookhaven NL, the PV EH&S research lead laboratory

- SERI Institutional and Environmental Assessment Branch to address risks and regulations beginning in FY80

Figure 14

CADMIUM SULFIDE BASED SOLAR CELLS

S. Deb and W. Haines
SERI, Photovoltaic Program Office

Summary

The objective of this program is to carry out research and development on CdS-based thin-film heterojunction photovoltaic devices to obtain energy conversion efficiencies greater than 10% with long-term stability to meet DOE's cost objective of \$0.15-0.50/peak We. To meet these objectives the SERI Program Office is currently managing 18 contracts in a comprehensive program on cell fabrication, material and device optimization and characterization, identification of stability problems and degradation mechanisms, basic understanding of device physics and low-cost process development.

For CdS/Cu_2S solar cells the effort is concentrated on two types of devices--the textured cell and the planar cell. The textured cell is formed by etching the CdS base layer and subsequent formation of a Cu_2S layer by dipping in a Cu_2Cl_2 solution. By appropriate loss minimization, the efficiency of this cell has been raised to $\sim$ 9.2% which is near the upper limit for this technology. However, with a planar configuration, where the Cu_2S layer is formed by a solid state reaction between thin films of CdS and Cu_2Cl_2, the problems associated with the intrusion of Cu_2S into CdS are minimized and this approach may boost the efficiency over 10%. Significant progress has increased the efficiency of the planar cell from $\sim$ 6% to 8.1% during the current contracting period. The major problem associated with the planar cell is the ineffective light trapping and the approaches now being taken to solve this problem consist of (i) textured front surface, (ii) textured substrate, (iii) textured CdS surface and (iv) suitable AR-coating. The successful solution of the light trapping should lead to a planar cell with efficiency over 11%.

Another interesting avenue towards obtaining a high efficiency ($\eta \simeq 16\%$) cell that is being pursued by several contractors consist of replacing CdS films by (Cd, Zn)S which should result in higher open circuit voltage while maintaining the J_{sc} and FF of the CdS based cell. Controlled film deposition, appropriate post-deposition treatment and better understanding of the junction function properties have led to the development of 8.2% efficient textured cell. Recent improvement in cell performance has been achieved by combining the results of the (Cd, Zn)S material analysis with the knowledge gained from the textured CdS/Cu_2S cell optimization program. The technology base for this type of a device still needs considerable improvement before the full potential of this material is realized. The high efficiency cells obtained thus far have been fabricated on CdS films prepared by thermal evaporation. Alternative methods for CdS and (Cd, Zn)S film deposition, such as reactive sputtering, Magnetron sputtering, spray and screen printing, are being explored to fabricate high efficiency cells thus far with not too encouraging results.

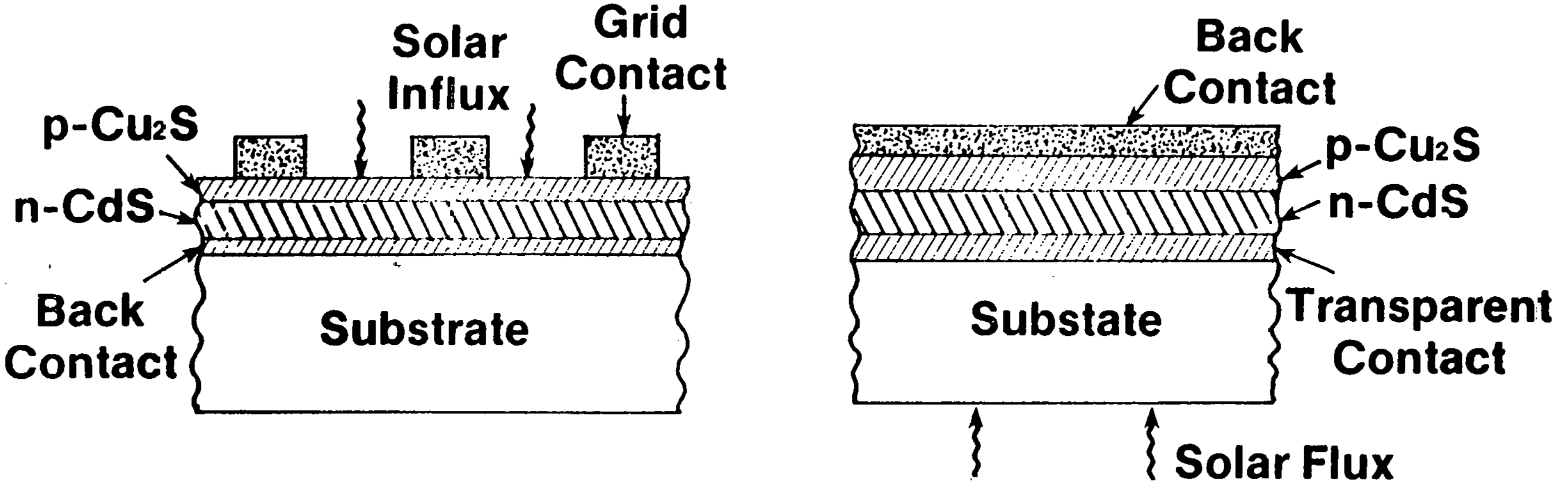
A small effort has been devoted to the development of thin film glass encapsulant and to stability and degradation studies of these cells. Some preliminary results on the stability studies on cells, which are not hermetically sealed, show considerable deterioration over a period of several months. However, it is interesting to note that the initial cell efficiency can be restored by suitable heat treatment.

Significant progress has been made on the successful fabrication of a thin-film CdS/Cu-ternary (alloy) cell. By controlled deposition of stoichiometric CuInSe$_2$ film on CdS has led to the development of cells with 5.7% efficiency. The interesting aspect of this type of cell is the achievement of rather high short circuit current (I_{sc} = 31 ma/cm^2) and better stability under ambient condition. The V_{oc} and FF still remaining very poor (V_{oc} = 0.36V and FF = 0.54). Several ternary alloy have been synthesized to achieve better lattice - match with CdS and hence improved efficiency. A small area cell fabricated from evaporated CdS film on sintered CuIn$_{0.3}$ Ga$_{0.7}$ Se$_{1.2}$ Te$_{0.8}$ has shown 13% conversion efficiency. The effort is now concentrated on the fabrication of a thin film and polycrystalline cell consisting of this type of material.

Some preliminary cost estimates have been made on a CdS/Cu$_2$S cell based on state-of-the-art processing steps which show that the DOE cost objective can be met with this type of device. Cost minimization of some processing steps have been identified. Our new effort to develop spray and screen print cells is an attempt toward minimizing the fabrication cost.

In conclusion, the methodology used in the current program should continue to give systematic improvement in energy conversion efficiency to make it more cost effective. The deficiencies in the cell fabrication program lie in the areas of reliability of large area cells, device stability and identification and solution of degradation processes. Attempts are being made to address these critical issues.

General Configurations of the CdS/Cu_2S Solar Cells



A. Frontwall Configuration

B. Backwall Configuration

Historical Development

1954	**Discovery of CdS photovoltaic solar cell by Reynolds**
1963	**Cusano suggests that Cu_2S may form CdS**
1967	**Photoresponse is assigned to Cu_2S**
1973	**Band diagram established by Fahrenbruch**
1976	**7.8% efficient cell reported**
1978	**9.2% efficient cell reported**

CdS, (Cd, Zn)S/Cu_2S Thin Film PV-Cells

Contractor, Principal Investigator	Project Description	($K) Amount (Approx.)
1. IEC, Delaware Dr. J.D. Meakin	Fabrication & Characterization of High Efficiency Solar Cells	713
2. Lawrence Berkeley Lab Dr. J. Washburn	Defect Characterization	23
3. Lawrence Livermore Lab Dr. A. Armantrout	Optimization of Reactively Sputtered Cells	175
4. Lockheed Corporation Dr. W. Anderson	Characterization of Cells Fabricated by Mangetron Sputtering	160
5. Telic Corporation Dr. J. Thornton	Cell Fabrication by Magnetron Sputtering	150
6. Westinghouse Corp. Dr. J. Szedon	Fabrication and Characterization of High Efficiency Cells	285
	Total	1506K

CdS, (Cd, Zn)S/Cu-Ternary (Alloys) PV-Cells

Contractor, Principal Investigator	Project Description	($K) Amount (Approx.)
1. Boeing Corp. Dr. R. Mickelsen	Development of Efficient Thin Film Cellls by Co-Evaporation Method	186
2. Brown University Prof. J.J. Loferski	Fabrication of Efficient Solar Cells Using Cu-Ternary and Alloys	240
3. Sperry Univac D.L. Fleming	Fabricaton of Solar Cells by Flash Evaporation	201
4. University of Maine Prof. A.H. Clark	Deposition of $CuInSe_2$ Films by MBE Techniques	55
	Total	$682K

Basic Mechanisms of CdS/Cu_2S Solar Cells*

Contractor, Principal Investigator	Project Description	($K) Amount (Approx.)
1. Clarkson College of Technology Dr. R.A. Serway Dr. N.K. Annamalai	Study of Efficiency Loss Mechanism	99
2. University of Delaware Prof. J. Eddington	Grain Boundary Effect in PV Cells	66
3. University of Delaware Prof. K.W. Boer	Photovoltaic Mechanism in Polycrystalline Solar Cells	52
4. IEC, Delaware Dr. J.D. Meakin	Critical Studies in Material & Durability	194
	Total	$411K

* Most programs started toward the end of FY79.

Active Contracts

Contractor	Work Title	Amount ($K)	Start Date
Spray/Screen Print (S/S)			
Exxon H.P. Maruska	Chemical Spray/ Ion Exchange CdS/Cu_2S	191K	9/1/79
Globe Union G. Goodman	Screen Print SdS/CdT Cells	154K	9/15/79
RAD Mont Devices G. Entine	Spray Deposition of CdS, CdZnS/ CdTe/CuTe	165K	9/15/79
SRI Int'l J. Mooney	Spray Screen Print $CdS/CdTe/Cu_2Te$ $CdS/CuInSe_2$	173K	9/1/79
	Total	683K	

Theoretical and Practical Efficiencies of Solar Cells

CdS/Cu_2S Cells

Frontwall	Backwall
J_{sc} (max) 35 mA/cm^2	26 mA/cm^2
J_{sc} (act) 25 mA/cm^2	17 mA/cm^2
V_{oc} (act) 0.57 Volts	0.57 Volts
Efficiency 16.1% Theoretical	12.0%
Efficiency 10.4% Practical	7.8%

$Zn_xCd_{1-x}S$ Cells

J_{sc} (max) 35 mA/cm2	31 mA/cm^2
V_{oc} 0.74 Volts	0.74 Volts
Efficiency 26% Theoretical	23%
Efficiency 16% Practical	14%

Significant Accomplishments of Different Contractors

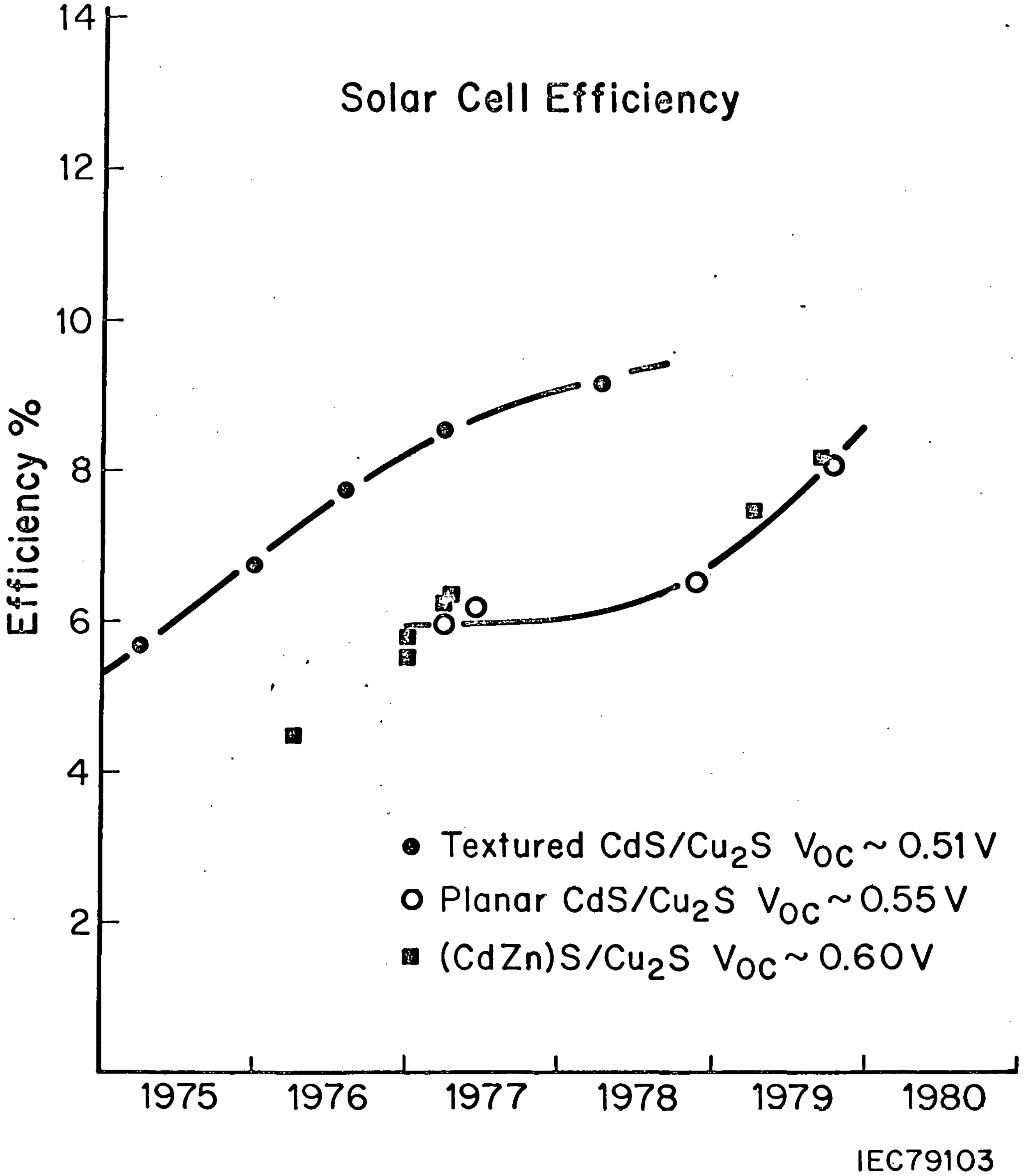
(A) CdS, (Cd, Zn) S/Cu_2S Program Area

Contractor **Accomplishments**

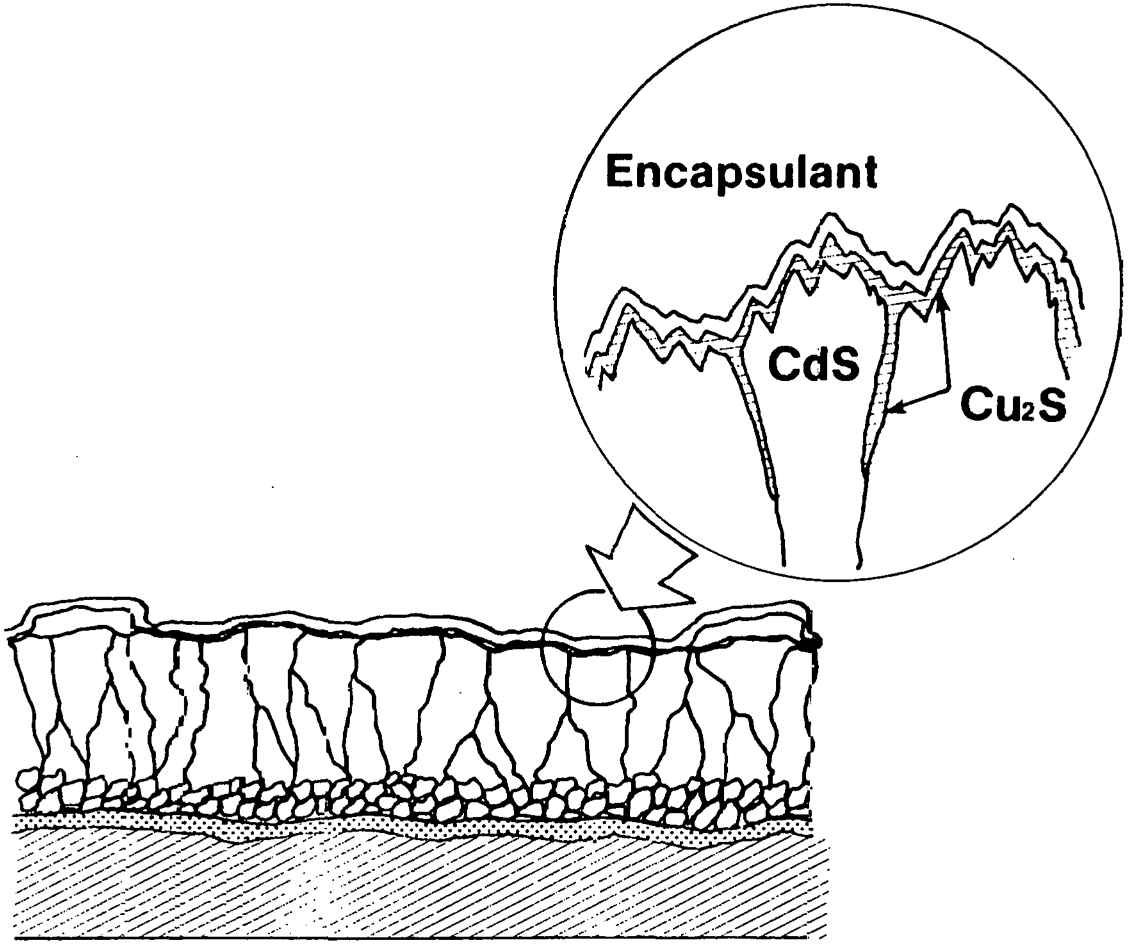
IEC, University of Delaware

- CdS/Cu_2S Textured Cell - ($\eta = 9.15\%$, $V_{oc} = 0.51V$, $J_{sc} = 24.8$ mA/cm^2 $FF = .71$
- CdS/Cu_2S Planar Cell - ($\eta > 8\%$, $V_{oc} = 0.5V$, $J_{sc} > 23$ mA/cm^2 $FF = .72$)

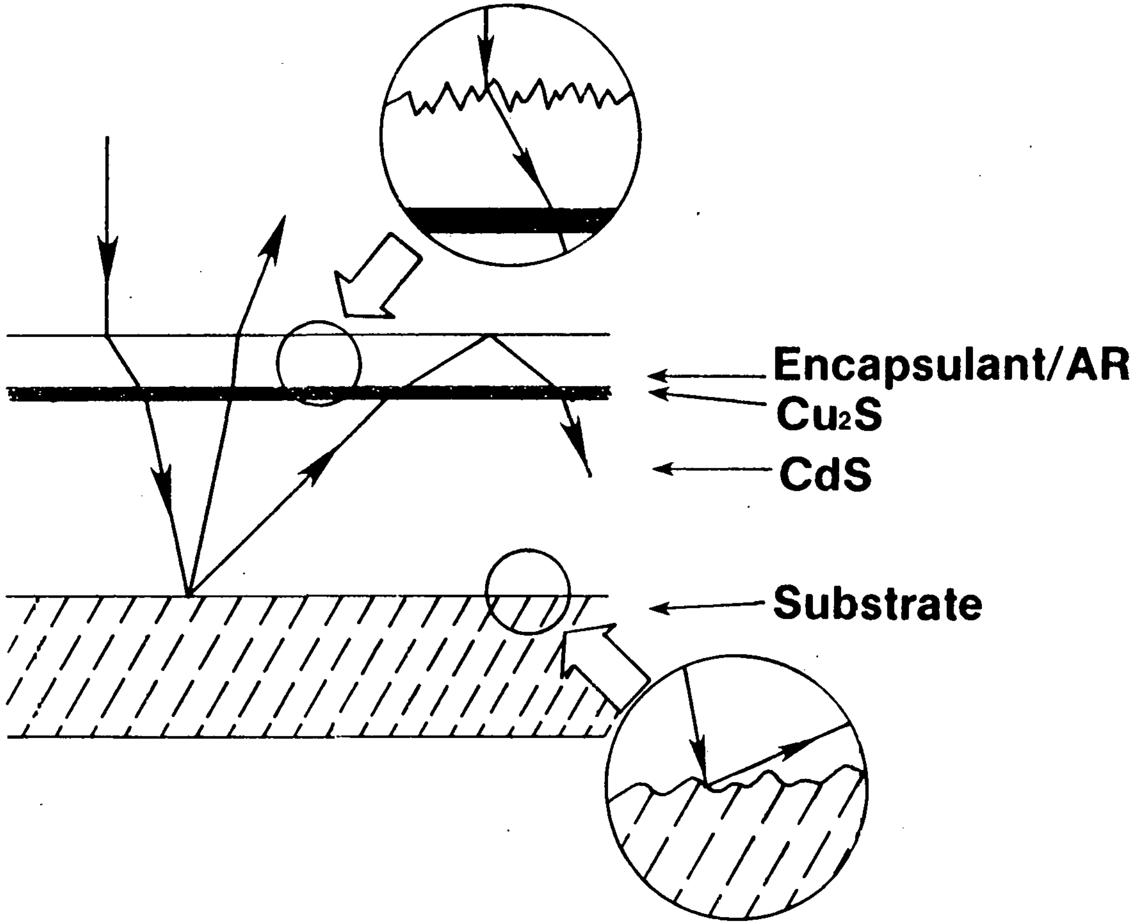
- $(Cd, Zn)S/Cu_2S$ Textured Cell ($\eta = 8.7\%$, $V_{oc} = 0.58V$, $J_{sc} = 21$ mA/cm^2)
- Lowering of (Cd, Zn)S film resistivity
- Identification of Cu_2S Morphology in (Cd, Zn)S structure
- Map Junction Field & quantity junction recombination
- Reversibility of atmospheric degradation
- Electronic Compatibility of glass film Encapsulants

Solar Cell Efficiency
Efficiency %
14
12
10
8
6
4
2
1975
1976
1977
1978
1979
1980
● Textured CdS/Cu2S Voc ~ 0.51 V
○ Planar CdS/Cu2S Voc ~ 0.55 V
■ (CdZn)S/Cu2S Voc ~ 0.60 V
IEC79103

SiO	0.07 µm
Au	12x2 µm
Cu_2S	1-0.3 µm
CdS	8-3.0 µm
Zinc	0.5 µm
Copper	30-40 µm



Cross-section of a Textured CdS/Cu_2S Solar Cell



Cell Texturing for Improved Light Trapping

(A) CdS, (Cd, Zn)S/Cu_2S Program Area (continued)

Contractor **Accomplishments:**

Westinghouse Corporation

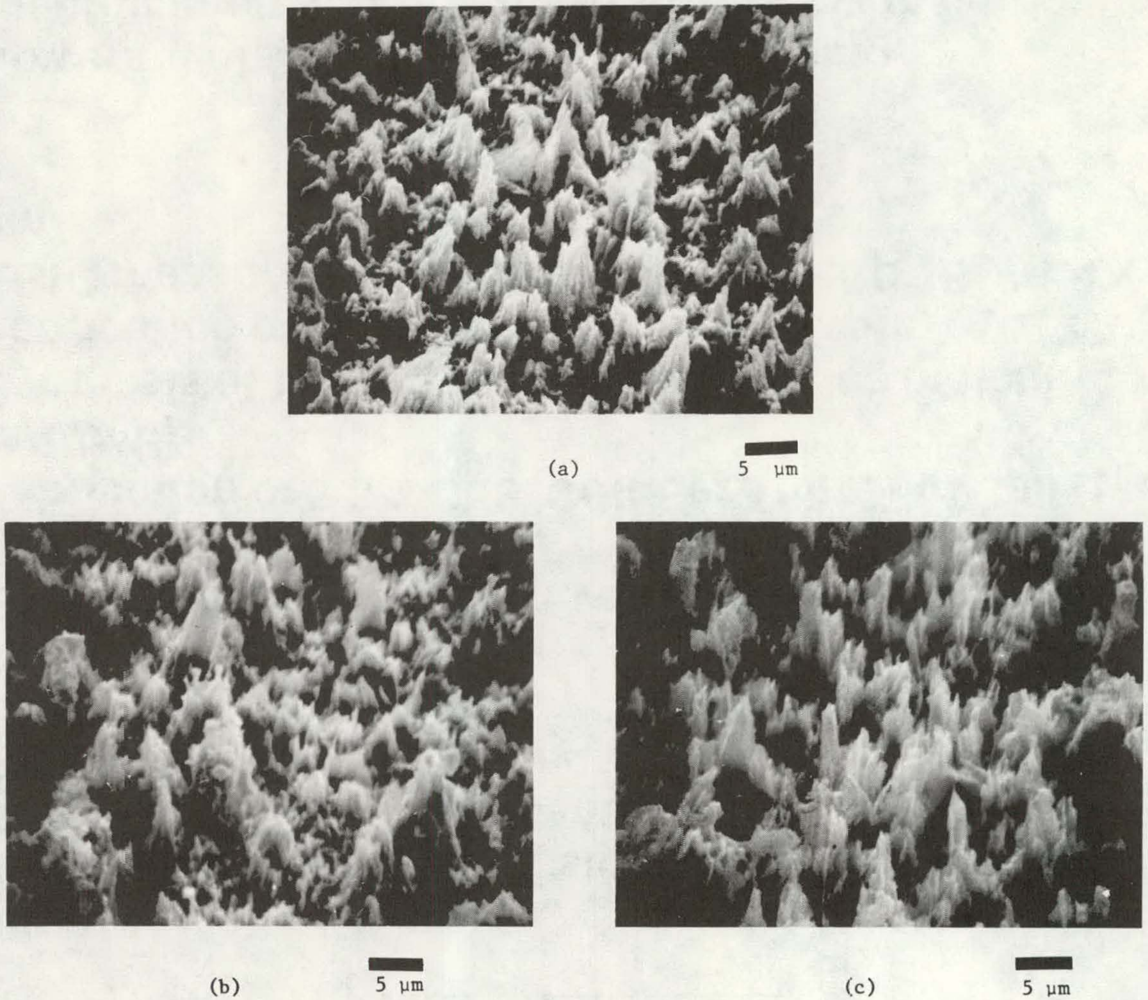
- CdS/Cu_2S Textured Cell ($\eta = 6\%$, $V_{oc} = .48V$, $J_{sc} = 20\ mA/mc^2$ $FF = .63$, $A = 4cm^2$)
- Replica Technique for Cu_2S intrusion in CdS
- Evaluation of diffusion length and surface recomb. velocity
- Effect of grain size on Photoresponse

Lockheed/Telic Corporation

- Improved efficiency of sputtered cell efficiency from .03% to .4%
- Role of substrate emissivity on growth of thin films

Lawrence Livermore Laboratory

- Measure of Diffusion Length by EBIC Measurements
- Demonstrated 4% efficient cell using sputtered Cu_2S
- SCL studies show role of traps in I-V characteristics



Free-standing Cu_2S Films from cells of various output levels, as viewed from CdS side of interface. (a) J_{SC} = 8.0 mA/cm^2, η = 2.2% [Cell #585-6]. (b) J_{SC} = 11.8 mA/cm^2, η = 3.4% [Cell #585-5). (c) J_{SC} = 16.5 mA/cm^2, η = 5.0% [Cell #594-8].

Significant Accomplishments of Different Contractors

(B) CdS/Cu-Ternary (Alloys) Area

Contractor	Accomplishments

Boeing Corporation

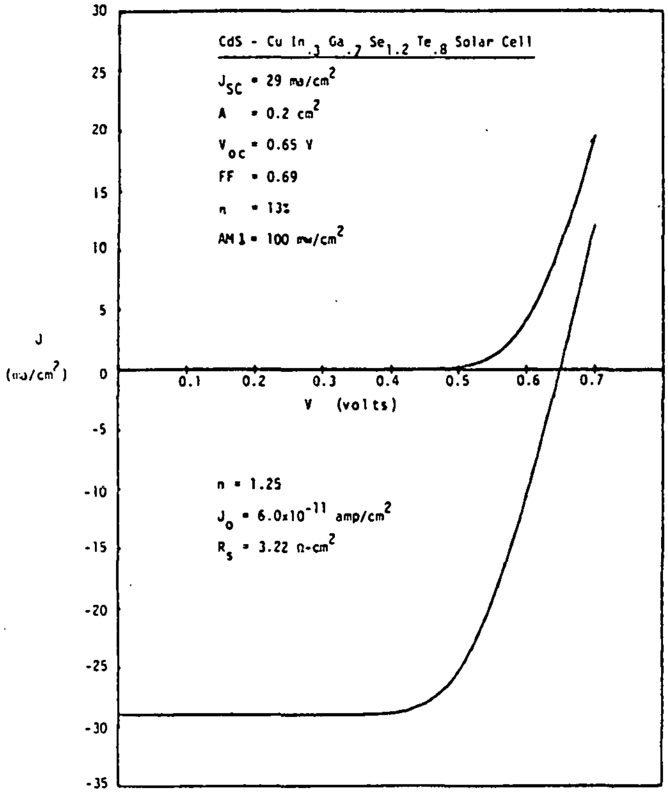
- Controlled Deposition of stoichiometric $CuInSe_2$ Film
- Fabrication of 5.7% efficient cell - ($V_{oc} = .34V$, $I_{sc} = 31\ mA/cm^2$, $FF = .54$)

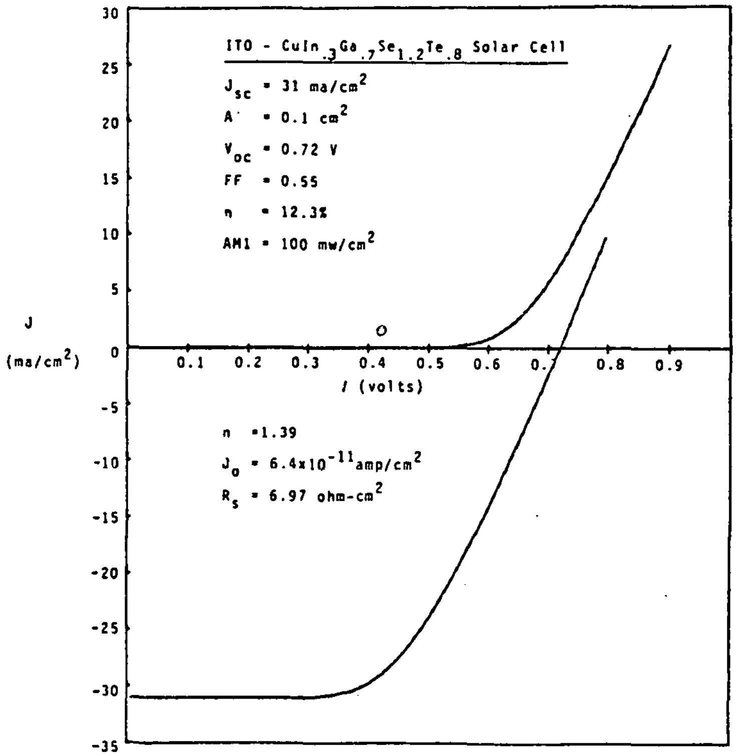
Brown University

- Fabrication of 13% CdS (Evap)$CuGa_yIn_{1-y}Te_{2z(1-z)}$ (sintered) cell
- Fabrication of 5.3% $CdS/CuInSe_2$ Thin Film Cell ($I_{max} = 33\ mA/cm^2$)
- Synthesis of ternary alloys having lattice matching with CdS
- Fabrication of ITO/ternary alloy cells with 12%
- EBIC measurements - L_d in $CuInSe_2$ 2.5 μ , $S_r = 1.4 \times 10^6$ cm/sec.

Sperry Univac

- Lowering of CdS resistivity by Al-doping
- Identification of problems associated with fabrication of stoichiometric films





PERFORMANCE NUMBERS

CDS SYSTEM

		PREV. REPT.
CDS-CUINSE$_2$	J_{SC} = 22 MA/CM^2	
	A = 0.2 CM^2	
	V_{OC} = 0.45 V	
	FF = 0.51	
	η = 5.1%	
CDS-CUINSE$_{1.8}$TE$_2$	J_{SC} = 28 MA/CM^2	27
	A = 0.2 CM^2	.04 CM^2
	V_{OC} = 0.53 V	0.49
	FF = 0.68	0.69
	η = 10.1%	9.1
CDS-CUIN$_{.3}$GA$_{.7}$SE$_{1.2}$TE$_{.8}$	J_{SC} = 29 MA/CM^2	
	A = 0.2 CM^2	
	V_{OC} = 0.65 V	
	FF = 0.69	
	η = 13.0%	

AM1 ILLUMINATION (100 MW/CM^2)

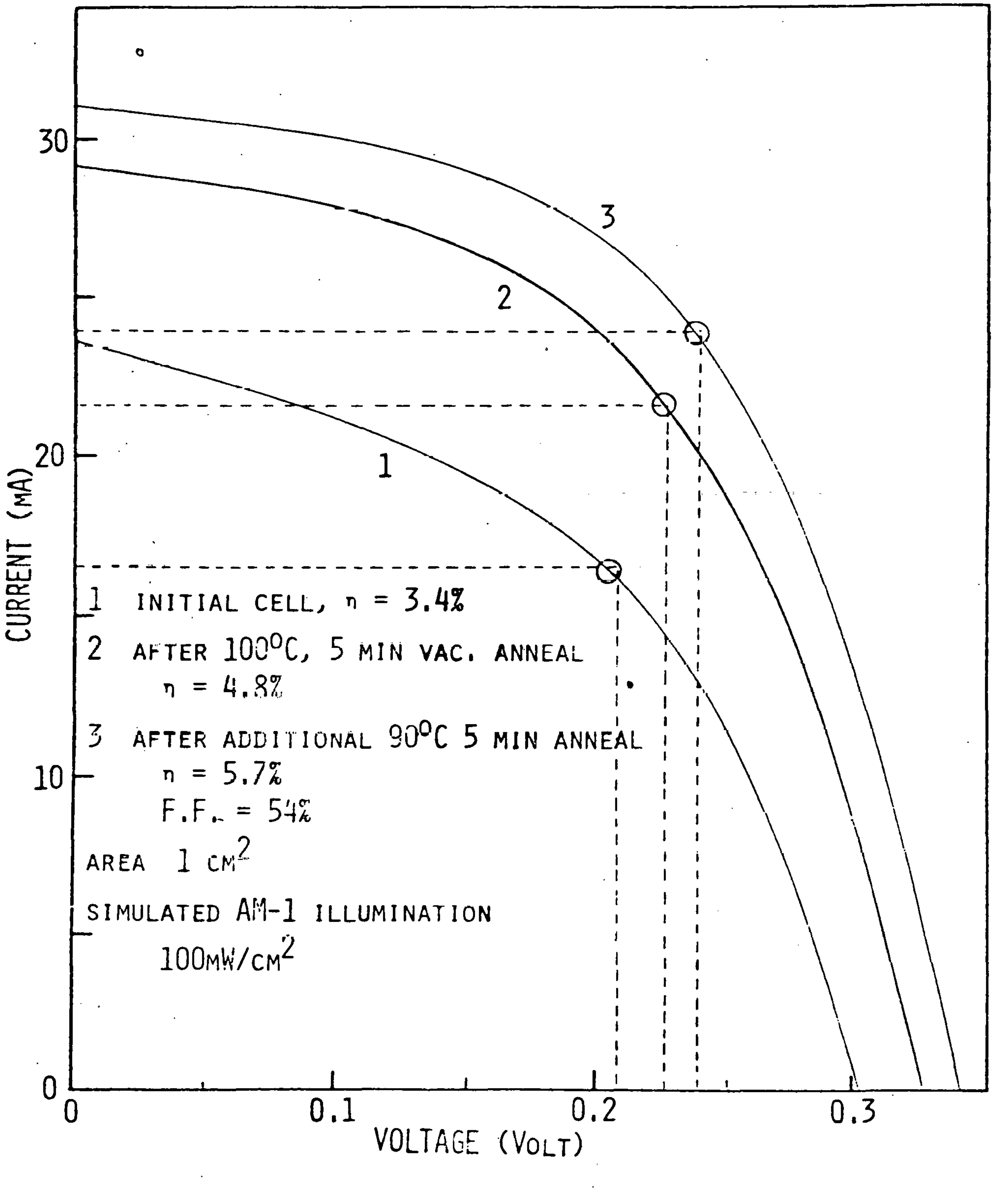
PERFORMANCE NUMBERS

ITO SYSTEM

ITO-CUINSE$_2$	J_{SC} = 24 MA/CM^2
	A = 0.1 CM^2
	V_{OC} = 0.49 V
	FF = 0.47
	η = 5.5%
ITO-CUINSE$_{1.8}$TE$_{.2}$	J_{SC} =/30 MA/CM^2
	A = 0.1 CM^2
	V_{OC} = 0.51V
	FF = 0.54
	η = 8.3%
ITO-CUIN$_{.3}$GA$_{.7}$SE$_{1.2}$TE$_{.8}$	J_{SC} = 31 MA/CM^2
	A = 0.1 CM^2
	V_{OC} = .72 V
	FF = 0.55
	η = 12.3%

AM1 ILLUMINATION (100 MW/CM^2)

LIGHT CHARACTERISTICS OF HIGHEST EFFICIENCY
CdS/CuInSe$_2$ THIN-FILM CELL
BOEING



Technology Issues Being Addressed

- Materials
- Device Fabrication
- Material and Device Characterization
- Degradation Processes
- Cost Analysis

Materials Problem

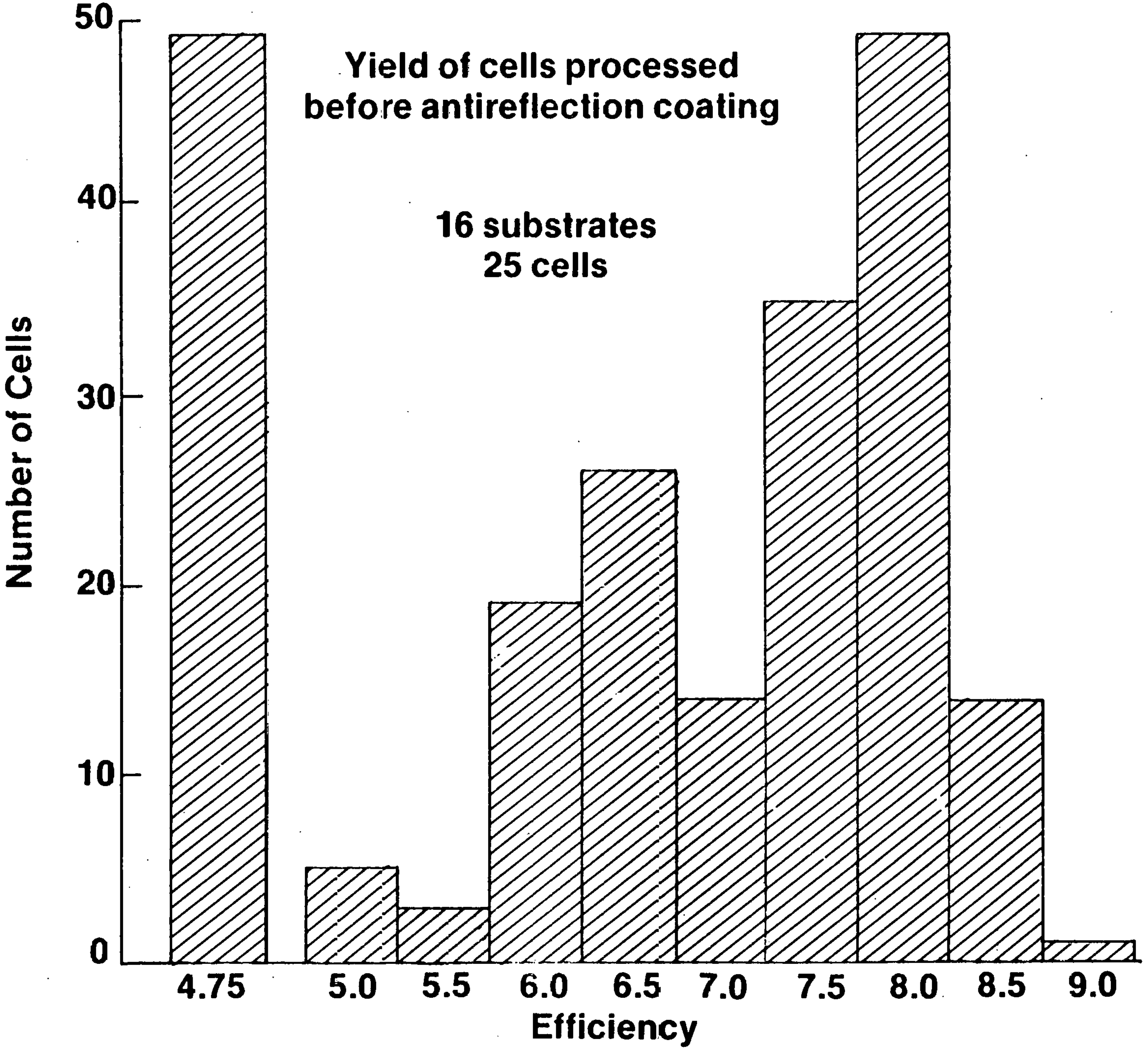
1. Substrates
   - Device configuration (front wall and back wall)
   - Ohmic contacts (Cu-Zn), transparent conductor
2. CdS Layer
   - Role of traps
   - Resistivity (controlled by doping, heat treatment and preparation methods)
   - Lower than optimum V
   - Cost effective method of film deposition
   - Large electron affinity and lattice mismatch with Cu_2S
3. (Cd, Zn)S Layer
   - Bandgap (adjustable, higher than CdS)
   - Resistivity (bigger problem)
   - Problems with junction formation
   - Higher V_{oc} and I_{sc}
4. Cu_2S Layer
   - Bandgap dependence on stoichiometry and crystal structure
   - Controlling optimum p-type conductivity
   - Structure sensitive opt. and elec. properties
   - Low carrier lifetime
   - Ionic conductor
5. Cu-Ternaries and Mixed Ternaries
   - Dependence of Bandgap on composition
   - Structure sensitive opt. and elec. properties
   - Electron affinity and lattice mismatched with CdS small and adjustable ($\Delta a = 0$)
   - More difficult to fabricate this film
6. Grid Materials
   - Optimum material Au
   - Disadvantage high cost
7. AR-Coating
   - Single layer (SiO) in textured cell
   - Multilayer (ZnS + MgF_2 in Planar cell)
8. Encapsulants
   - Rigid glass
   - EB evaporated glass, hermaticity unknown
   - Polymeric material — permeability problems

Material & Device Fabrication

1. Materials — Thin Film & Polycrystalline

- Thin Film Deposition Techniques
  - — Thermal Evaportion (IEC, Delaware)
  - — Reactive Sputtering (Telic/Lockheed, LLL, Brown U.) Diode and Magnetron
  - — Co-evaporation (Sperry Univac)
  - — Spray Deposition (Exxon, SRI, Radiation Monitoring)
  - — Screen Printing (Globe Union, SRI)
  - — Polycrystalline (Brown U.)

2. Devices
  - — Textured Cell (Evaporation and Chemical Reaction)
  - — Planar Cell (Evaporation)
  - — Spray Deposition
  - — Screen Printing



Histogram of the Efficiency of 215 Cells Produced from 16 CdS Substrates

Materials & Device Characterization

1. Opto-Electronic Properties

- Optical absorption
- Photoluminescence
- Photocapacitance
- EBIC measurements
- Electrical conductivity
- Hall effect
- Spectral response
- Collection efficiency
- Cell parameters (V_{oc}, F.F., I_{sc}, R_s, R_{sh}) as a function of intensity, temperature, and spectral content
- Localized distributon of I_{ph}

2. Structural

- Stoichiometry
- Phase transition
- Morphology
- Grain boundary and grain size
- Auger and SIMS

3. Post Deposition Heat Treatment

- Cu^+ ion diffusion in CdS
- Cu_2S stoichiometry
- Modification of surface and recombination centers

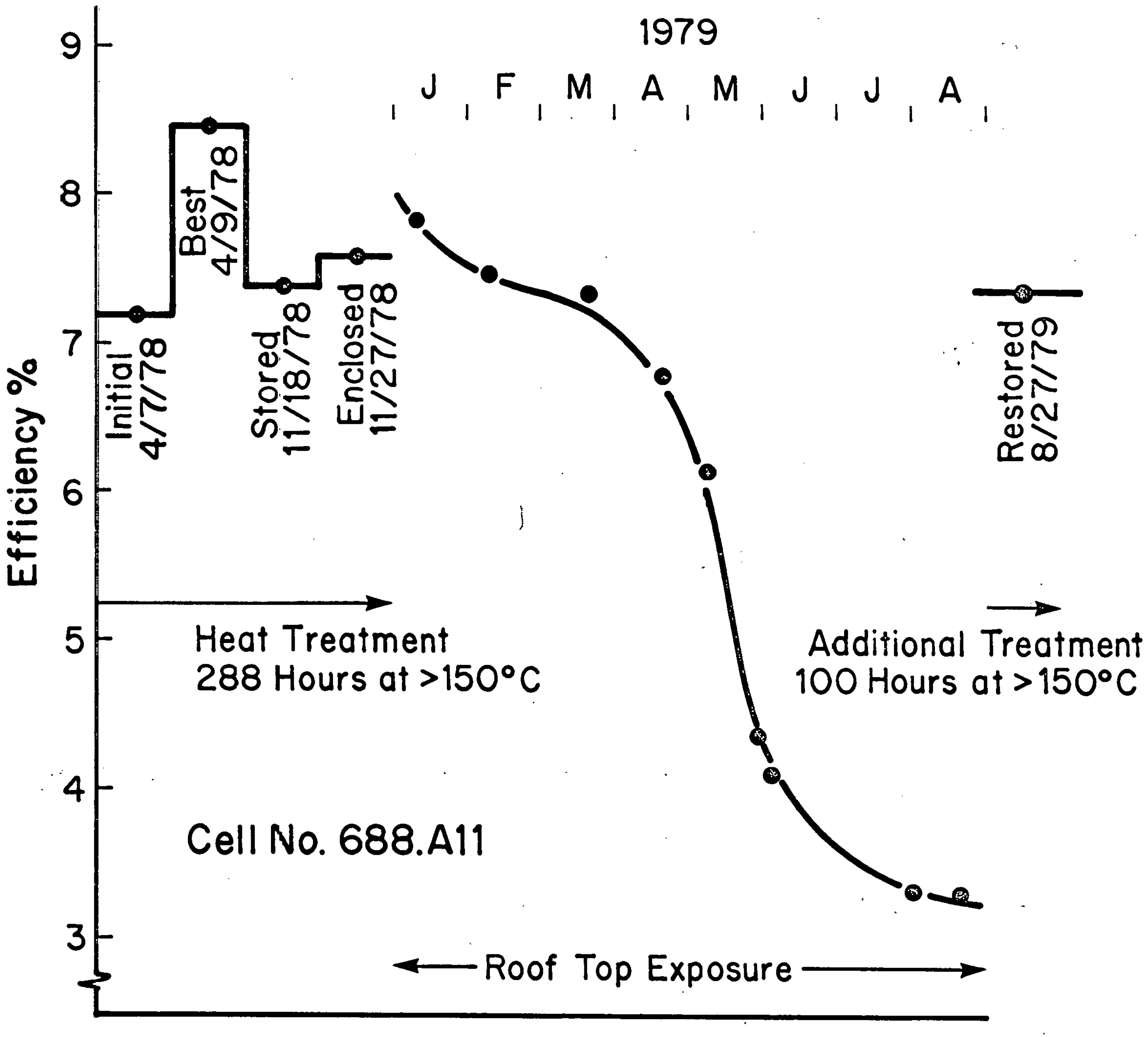
4. Theoretical Modeling

- Mechanism of current transport
- Optimization of material and device parameters

Degradation Problems

Cause of Degradation	Parameters Effects	Solution
Exposed to high humidity	I_{sc} (collection efficiency due to creation of traps)	Recovered by heating in vacuum at 180° C Hermetic sealing
Heating in air above 60° C (oxidation of Cu_2S)	I_{sc}	Hermetic sealing
Heating in air over 60° C under illumination (photo induced phase change of Cu_2S $Cu_{2.n}S$)	I_{sc}	Evaporation of 100A° Cu on Cu_2S
Temperature cycling (-150° to + 60° C) (Delamination increased series resistance)	I_{sc}	Effect is minimum for terrestrial application

Reversable Decay of CdS/Cu_2S Cell Output



IEC79099

Process Sequence for Fabricating Free Standing Cu_2/CdS Thin Film Solar Cell Modules

Process Step	Input/Output Produce
	Copper Foil
1. Substrate Preparation	
	Zinc-Plate Copper Foil Sheet
2. Cds Deposition	
	CdS on Substrate
3. Barrier Formation	
	Cu_2S/CdS Film Structure
4. Photolithography	
	Patterned Resist Coating of Film Structure
5. Gold Evaporation	
	Thin Gold (0.1 μm) Coated Structure
6. Electroplating	
	Fully Electroded Cell
7. Sealing	
	Completed Module, Laminated to Glass Cover

Cost Analysis (Westinghouse)

Contributions to Array Selling Price Assuming 100% Yield for 200 MW Production.

Cost Items	Total Cost ($\$10^6$ 1986)
• Direct Material	143.0
• Equipment	11.2
• Electricity	8.1
• Floor Space	2.2
• Direct Labor	7.2
Total	\$171.7

1986: $$\frac{\$171.7 \times 10^6}{200 \times 10^6 \text{ watts}} = \$0.86/\text{watt}$$

1975: $\$0.86/1.9 \text{ watt}^{-1} = \$0.45/\text{watt}$

After Probable Cost Reduction

1975: \$0.38/watt

Array Efficiency 8% Module Size - 2′ x 8′

Conclusion

Major Strengths:

- Demonstrated high efficiency (9.2%) thin film cell
- Studies on new materials and devices to achieve efficiency higher than 10%
- Multiplicity of approaches to material and device fabrication
- Optimization and characterization of materials and device parameters
- Process development for low cost devices
- Basic research to support technology
- Strong parallel effort in private sector for cell commercialization

Program Areas that Need More Emphasis:

- Reliability of cell fabrication and device stability
- Identification and solution of degradation processes
- Large area cell fabrication
- Cost effectiveness of material and device fabrication
- Encapsulation
- More fundamental research

CRITICAL PROPERTIES OF THE
Cu_2S/CdS Interface

B. Haines, SERI

Although the CdS/Cu_2S cell has been studied for 25 years, many questions concerning its photovoltaic properties remain unanswered. The processing of CdS/Cu_2S cells has seemed like a "black art", with various heat treatments and processing steps quoted as being essential to producing good cells. Recent investigations have begun to probe the nature of the Cu_2S/CdS interface and show promise for understanding the details of photovoltaic operation for these devices. Three areas that need better understanding are (1) the sensitivity of the cell to the spectral content of light, (2) the effects of heat treatment on the photovoltaic response, and (3) the mechanisms responsible for degradation of the cell. When unusual phenomena are found in photovoltaic systems, they provide a means for studying the system. The large capacitance changes observed with the Cu_2S/CdS cell indicate that capacitance measurements should lead to a better understanding of cell performance.

The spectral sensitivity of the junction was used as a probe to determine the nature of charge transport at the interface. Two beam experiments were used to determine the spectral response of the quenching of photocapacitance, and to investigate the variation of J_o and α_i. Figure 1 indicates the spectral response of quenching of photocapacitance and of open-circuit voltage. A decrease in junction capacitance is accompanied by an increase in open-circuit voltage. The onset of quenching processes occurs at 1160 µm (1.06 eV) and at 1630 µm (0.76 eV) while maximum quenching occurs at 900 µm (1.36 eV) and at 1360 µm (0.91 eV). At low temperatures, the low energy quenching peak disappears and excitation of photocapacitance occurs. Figure 2 indicates the response of V_{oc} to short-wavelength light. For light energies greater than the CdS (516 µm) bandgap there is a sharp drop in V_{oc} accompanied by an increase in junction capacitance.

The sensitivity of the junction to "blue" ($\lambda < 516$ µm) and "red" ($\lambda > 700$ µm) light was used to measure J_o and α. Figure 3 shows J_{sc} - V_{oc} plots obtained by using a solar simulator plus a bias light source. Each line corresponds to a fixed intensity of bias light, while the points on the line are obtained by using neutral density filters with the solar simulator. The interception of the lines with the current axis is J_o, while the slope provides α_i. This measurement was performed on a variety of cells, and the results are shown in Figure 4 where ln J_o is plotted versus α_i. The data indicates that there is a relationship between J_o and α given by:

$$\ln J_o - -0.44\ \alpha_i q + C \qquad (1)$$

A derivation of the probability of tunneling between a deep donor-like level in the CdS and the Cu_2S indicates that for low temperatures and/or for narrow barriers the J_{sc} - V_{oc} characteristics are described by the equation:

$$J_{sc} = J_{oo} \exp\left(\alpha_i \left(E_I - \Phi_{T_o}\right)\right) \{\exp\left(\alpha_i q\ V_{oc}\right) - 1\} \qquad (2)$$

where J_{oo} is the current pre-exponential factor, Φ_{T_o} is the zero-bias barrier height in the CdS, E_I is the ionization energy of the deep donor, and α_i is a tunneling factor dependent on the net positive charge density in the CdS near the interface, N_{Deff}, and is given by:

$$\alpha_i = \frac{2(m^*\varepsilon\varepsilon_o)^{\frac{1}{2}}}{h\ (qN_{Deff})^{\frac{1}{2}}} = \frac{4.527 \times 10^{10}}{N_{Deff}^{\frac{1}{2}}} \quad eV^{-1} \qquad (3)$$

where N_{Deff} is expressed in cm^{-3}, $m^* = 0.2m_o$ and $\varepsilon = 8.8$.

By combining the tunneling model and the results from the photocapacitance measurements, a band diagram for the CdS/Cu_2S junction is drawn in Figure 5. This diagram shows the energy levels attributed to the deep donor and copper acceptor levels. The acceptor levels are in good agreement with previous work of CdS, and the deep donor level is consistent with earlier work on CdS photoconductros by Bube. Recent measurements by Livermore and Lockheed also indicate a dominant 0.45 eV level. The spectral sensitivity of the cell is due to trapping a detrapping of holes by the copper acceptors. Bandgap light excites holes which are trapped by the copper acceptors while red light optically frees the trapped holes.

The behavior that this model predicts is that with heat treatment copper diffuses into the CdS and compensates the deep donors. This widens the depletion segion reducing the tunneling current and causing V_{oc} to increase. However, the deep donor level also acts as an interface recombination center. With heat treatment, the field at the interface is reduced and greater interface recombination occurs. This reduces J_{sc} and explains why increasing V_{oc} is accompanied by decreasing J_{sc}. The spectral content of the light determines the extent of compensation at the interface and directly effects V_{oc} and J_{sc}.

The observed behavior for the Cu_2S/CdS junction is more complex than described in the previous paragraph. Table 1 indicates the effects of heat treatment and subsequent storage in air on V_{oc} and J_{sc} for a single crystal cell. Heat treatment in Argon caused a reduction in both V_{oc} and J_{sc}, while heat treatment in H_2 caused J_{sc} to increase and V_{oc} to decrease. With exposure to air V_{oc} increased to its original value. This data appears to be in conflict with the model proposed, which would predict V_{oc} increasing with heat treatment. However, two additional factors: the change in stoichiometry of the Cu_2S with heat treatment; and the nature of the deep donor levels, can account for this discrepancy.

Oxidation of Cu_2S causes the film to become copper deficient. This is accompanied by a decrease in diffusion length and a reduction in short-circuit current. This is closely tied to the Cu_2S resistivity, the resistivity decreasing as the material becomes copper deficient. The effect of heat treatment in hydrogen on the conductivity of a Cu_2S film (on single-crystal CdS) is shown in Figure 6. Above $105^{o}C$ Cu_2S becomes an ionic conductor, and reactions which occur at the surface effect the stoichiometry of the entire film. H_2 heat treatments increase the copper content of the film by (1) reducing any Cu_2O on the surface with Cu diffusion into the film or (2) removal of S from the film. The change in resistivity is related to the short-circuit current as is shown in

Figure 7. Path 1 indicates the short-circuit current as a function of temperature in H_2, while path 2 indicates J_{sc} in air.

Reduction of both J_{sc} and V_{oc} is explainable by oxidaton of Cu_2S. This may occur even in a vacuum heat treatment if there is chemiabsorbed oxygen or water on the surface, but the results of H_2 heat treatment show J_{sc} increasing and V_{oc} decreasing. Subsequent exposure to air causes V_{oc} to increase with little change in J_{sc}. This effect may be explained by considering the nature of the deep donor level. A likely candidate for the deep donor level is a sulfur vacancy. Oxygen could annilate the sulfur vacancy by sitting on its site. Heat treatment in H_2 would remove oxygen from these sites increasing the deep donor density, increasing J_o and reducing V_{oc}. H_2 heat treatment might also remove S creating more deep donors. Upon exposure to air, oxygen would diffuse to the interface, and annilate some of the deep donor levels.

This analysis explains why heat treatment in air might help some cells and hurt others. Oxidation of Cu_2S will decrease V_{oc} and J_{sc}, but oxygen on sulfur vacancy sites at the interface would increase V_{oc} and J_{sc}. These two mechanisms are competitive and depend sensitively on film structure and morphology. Cu_2S films produced by the dry process on single crystal CdS were quite stable in air, with no siqnificant decrease in J_{sc} for 9 months exposure to air, while Cu_2S films produced by an identical process on thin-film CdS showed significant degradation overnight.

The CdS/Cu_2S system is sufficiently complex that no set prescription describes the behavior of all cells. An understanding of the processes which occur at the interface, however, provides a means for modeling and analysis of the device. The performance and long-range stability of this type of cell depends critically on the interface properties. Detailed capacitance and J_o and α measurements provides a way to probe the interface and determine its condition. In this way the degradation mechanisms can be studied, and steps can be taken to stabilize the cell under operation.

References

W. G. Haines, PARAMETERS CONTROLLING THE PHOTOVOLTAIC PROPERTIES OF THE COPPER SULFIDE/CADMIUM SULFIDE HETEROJUNCTION, PhD Thesis, Stanford University, June 1979

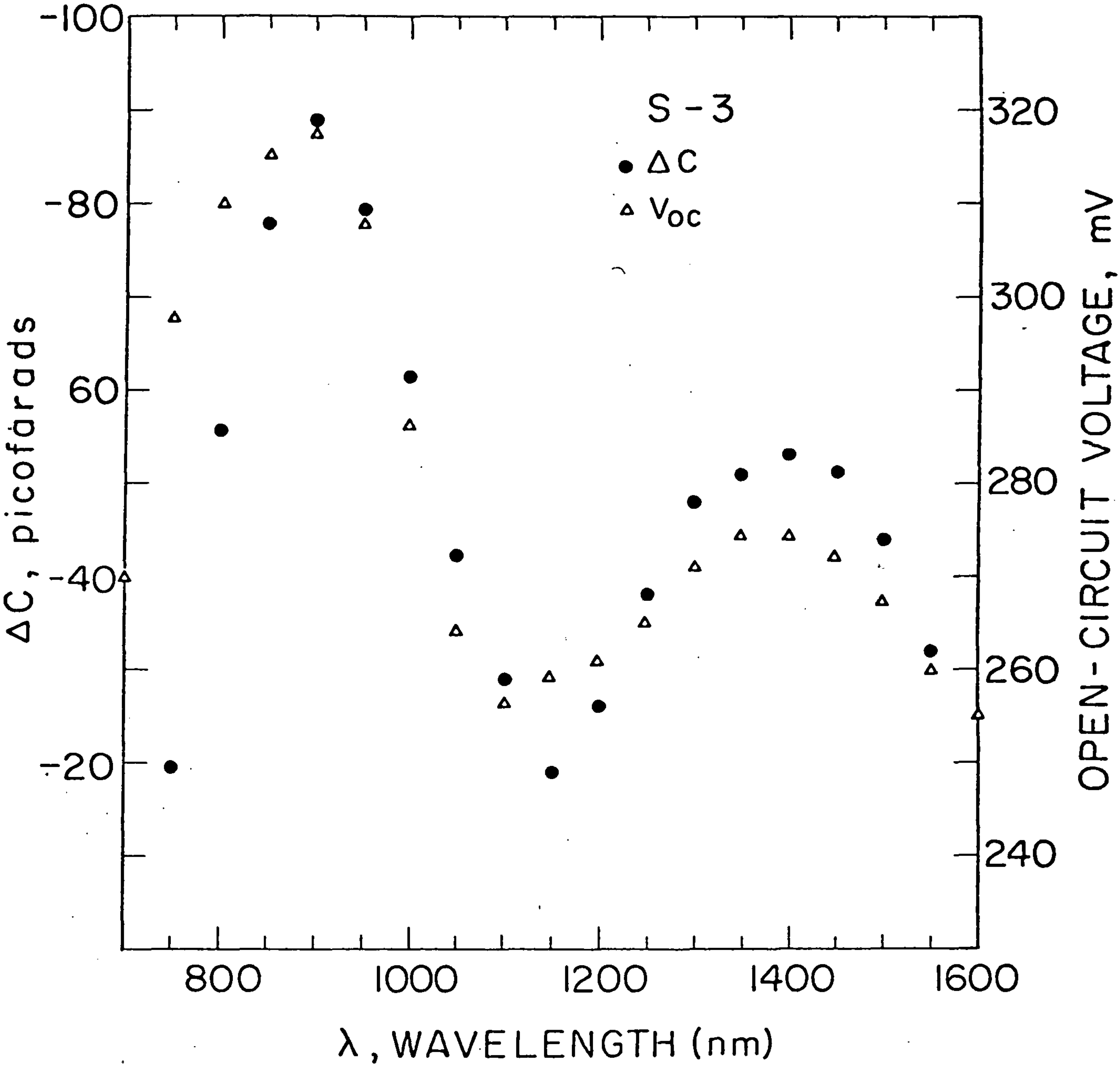
W. G. Haines and R. H. Bube, "Tunneling currents in the Copper Sulfide/Cadmium Sulfide Heterojunction", submitted to IEEE Transactions on Electron Devices Vol. ED-27 Number 4 April 1980

TABLE 1

Effects of Heat Treatment and Recovery in Air for a Single Crystal Cell

Treatment	V_{oc}, V	J_{sc}, mA/cm^2	C_{light}, nf[a]	C_{dark}, nf[a]
Initial	0.396	11.1	1.70	1.44
5 min at 180°C in Ar	0.359	5.1	2.36	1.44
5 min at 200°C in H_2	0.347	8.0	1.68	1.32
5 min at 220°C in H_2	0.320	9.6	1.24	0.965
Dark for 24 hr	0.393	9.4	1.43	1.11
Dark for 72 hr	0.394	9.0	1.31	1.11

[a] Measured at 1 MH_z



S - 3
● ΔC
△ V_{oc}
-100
-80
60
-40
-20
320
300
280
260
240
800
1000
1200
1400
1600
ΔC, picofarads
OPEN-CIRCUIT VOLTAGE, mV
λ, WAVELENGTH (nm)

FIGURE 1

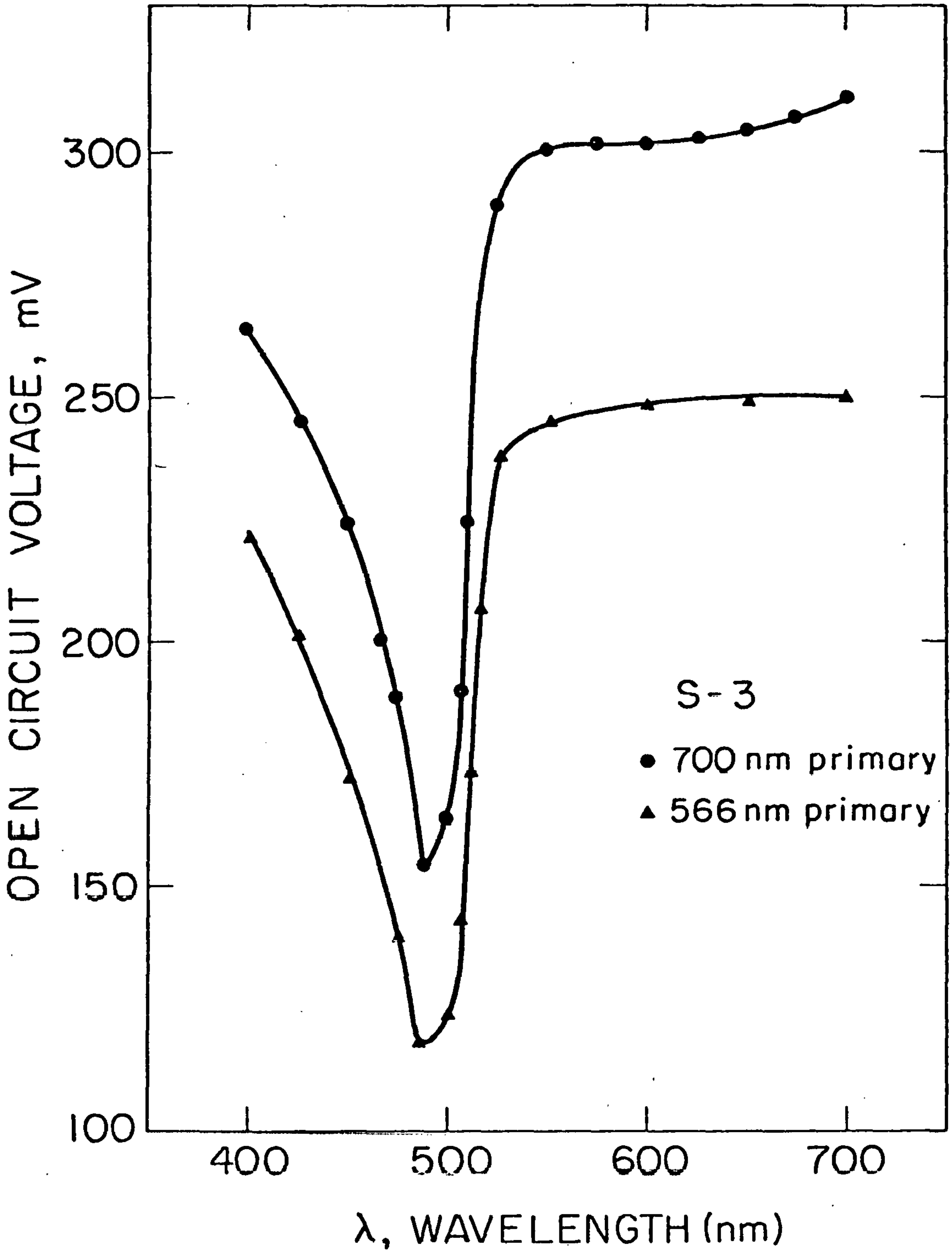

OPEN CIRCUIT VOLTAGE, mV
300
250
200
150
100
400
500
600
700
λ, WAVELENGTH (nm)
S-3
● 700 nm primary
▲ 566 nm primary

FIGURE 2

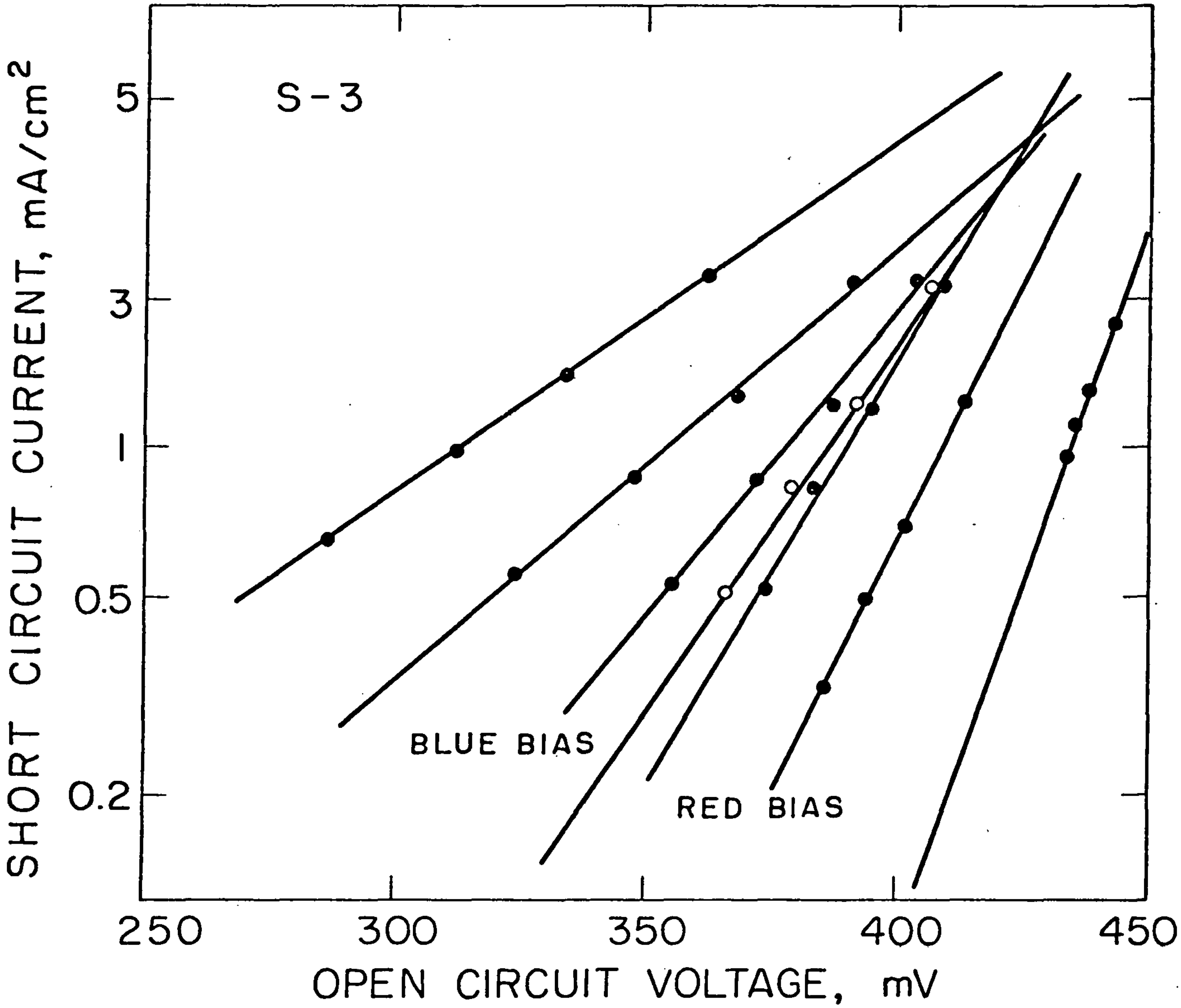

S-3
SHORT CIRCUIT CURRENT, mA/cm^2
5
3
1
0.5
0.2
BLUE BIAS
RED BIAS
250
300
350
400
450
OPEN CIRCUIT VOLTAGE, mV

FIGURE 3

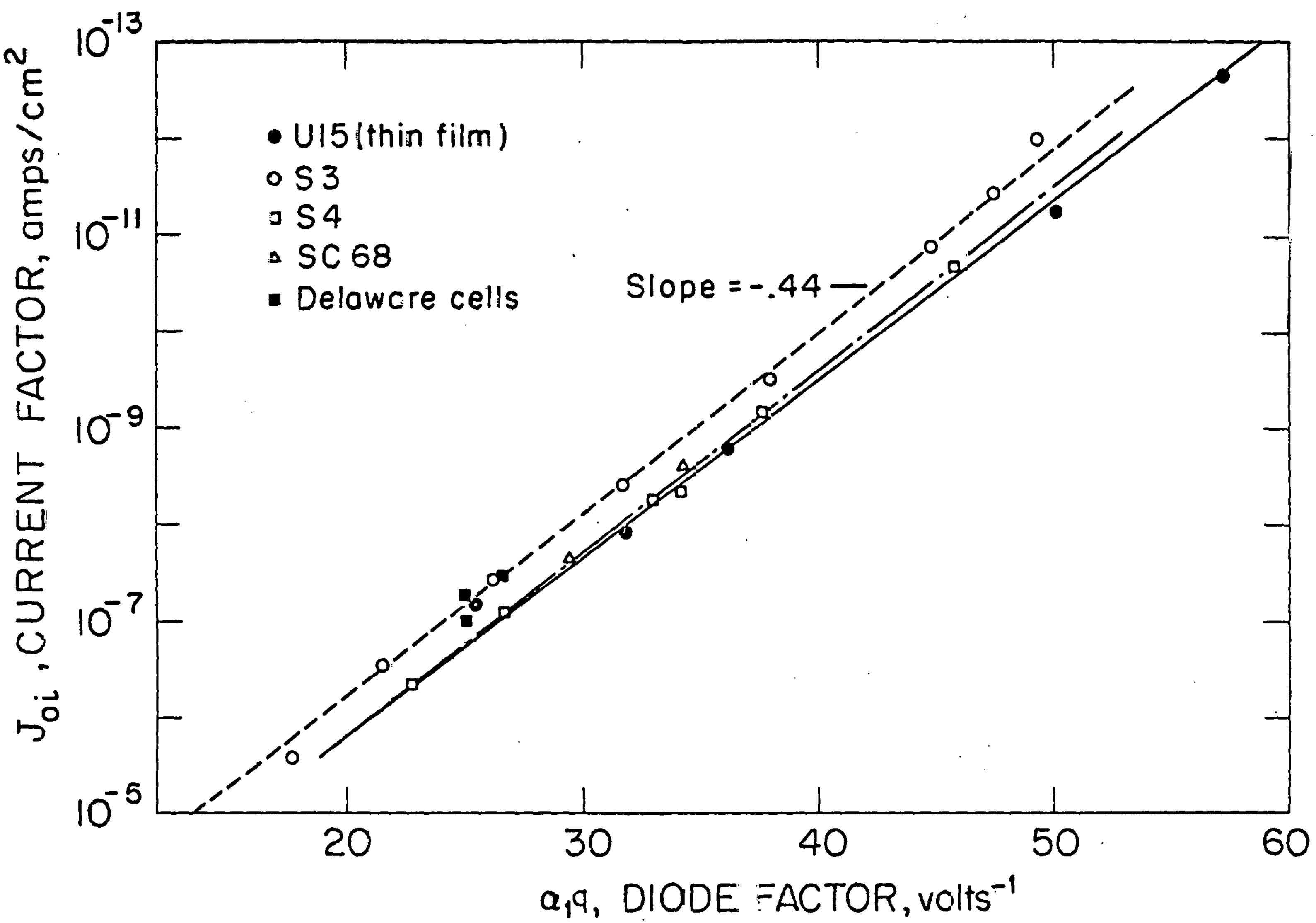

10^-13
10^-11
10^-9
10^-7
10^-5
20
30
40
50
60
J_{oi}, CURRENT FACTOR, amps/cm²
$\alpha_1 q$, DIODE FACTOR, volts⁻¹
● U15 (thin film)
○ S3
□ S4
△ SC 68
■ Delaware cells
Slope = -.44

FIGURE 4

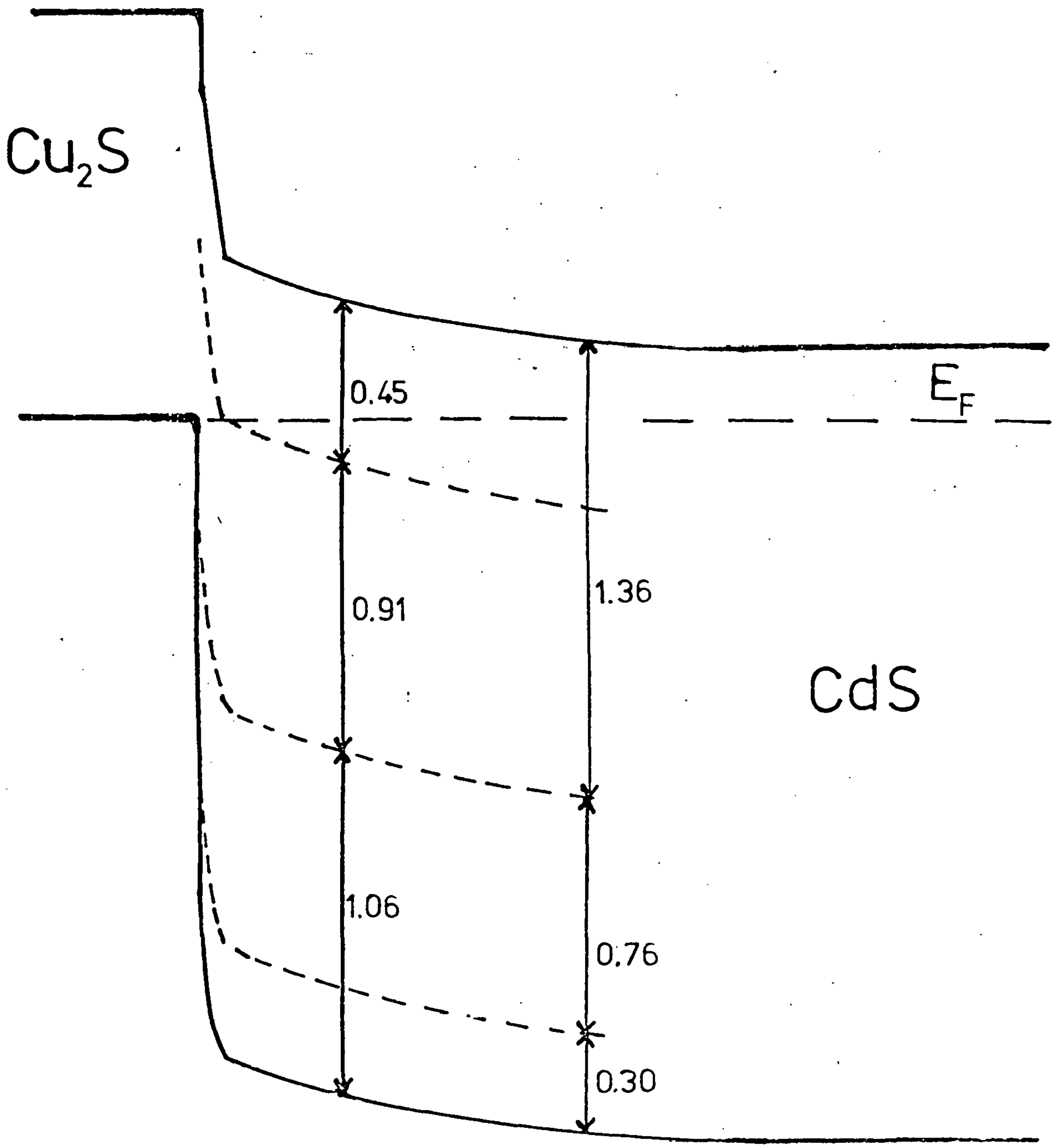


FIGURE 5

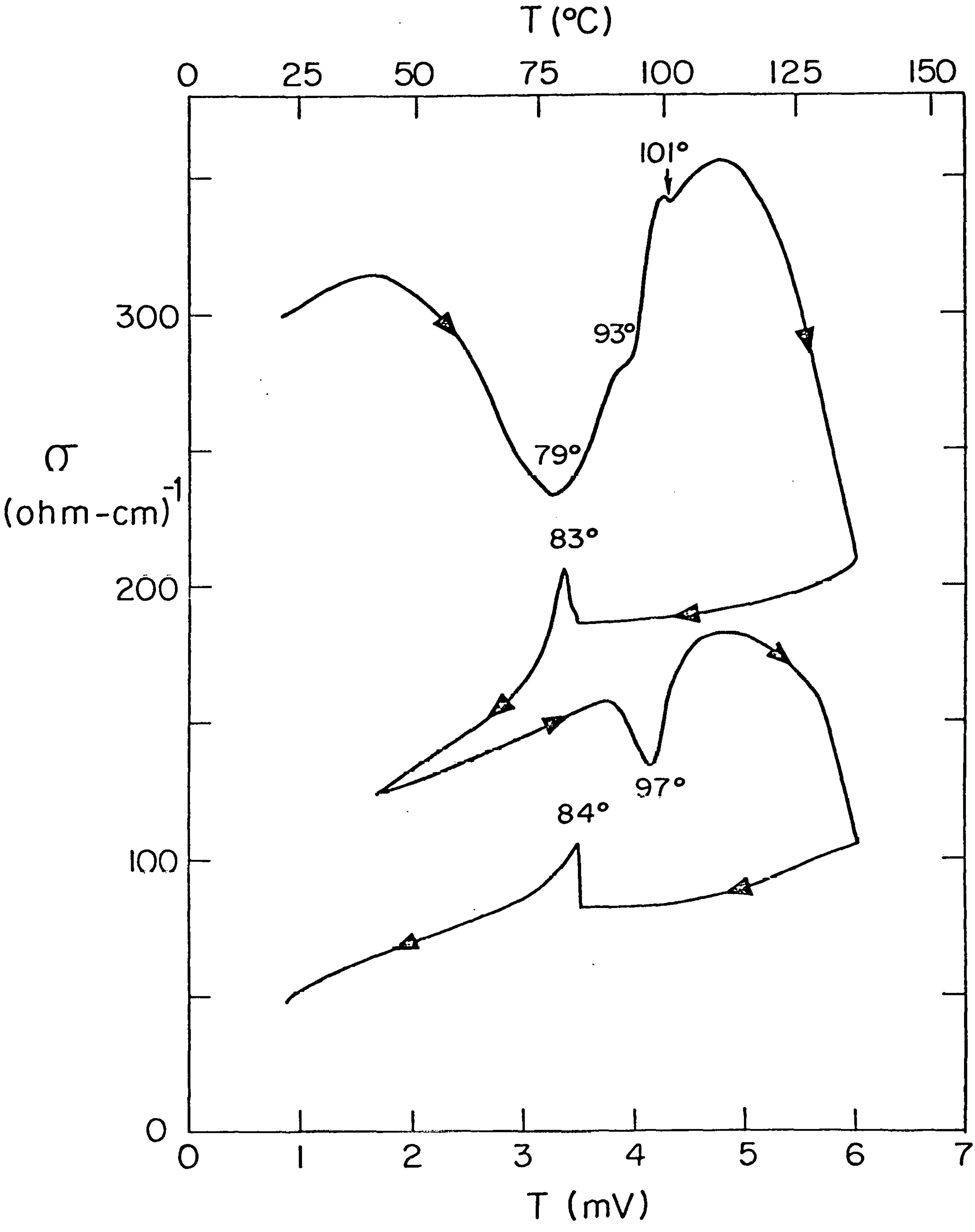

T (°C)
0
25
50
75
100
125
150
101°
93°
79°
83°
97°
84°
σ
(ohm-cm)$^{-1}$
300
200
100
0
0
1
2
3
4
5
6
7
T (mV)

FIGURE 6

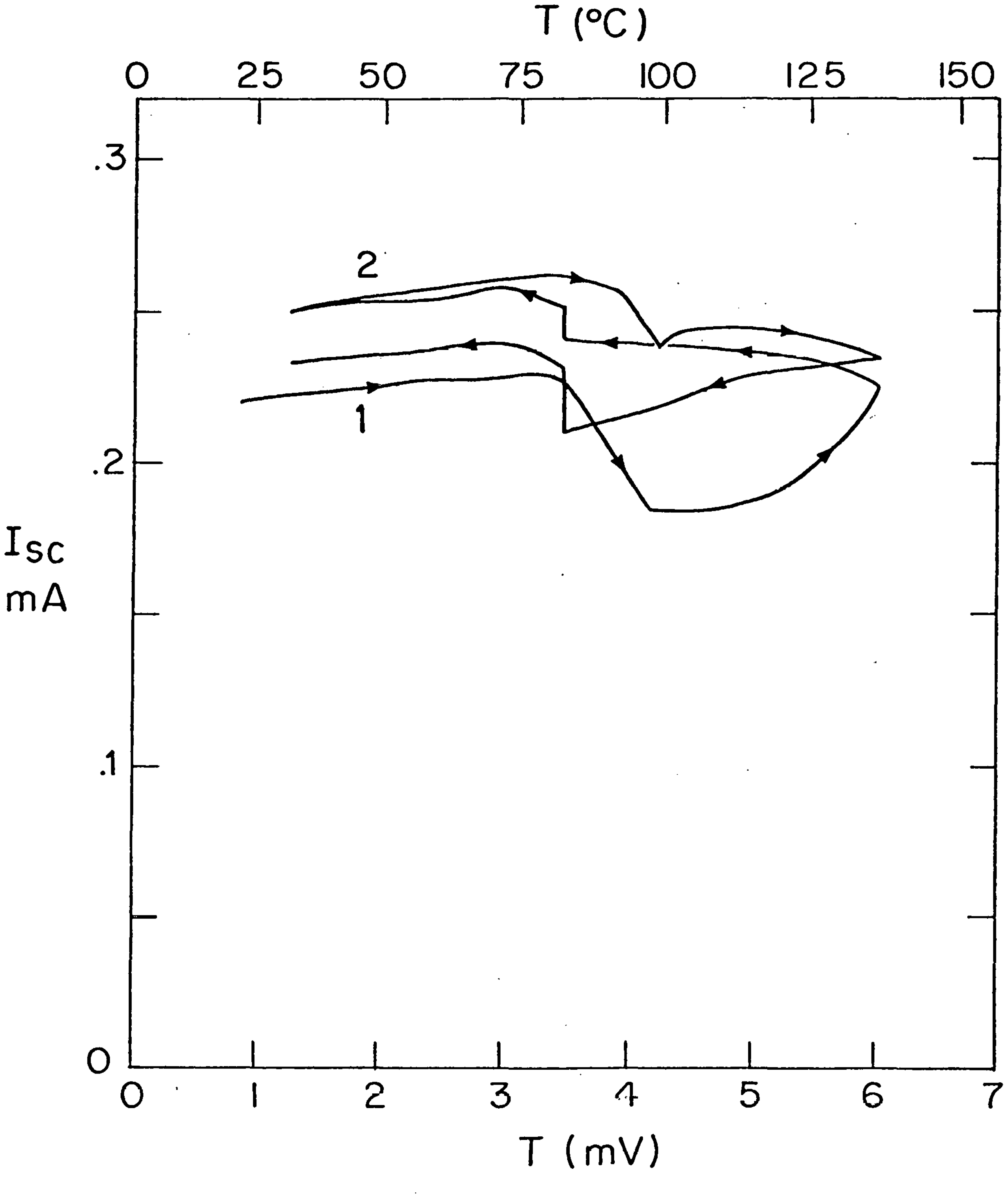


FIGURE 7

NOTES

SESSION III

SERI ANNUAL R&D REVIEW

LSA PROJECT ACTIVITIES PRESENTATION

ABSTRACT

William T. Callaghan*
Jet Propulsion Laboratory

The intent of this presentation is to highlight recent progress and near-term plans of the Low-Cost Solar Array (LSA) Project. A few words regarding the goals of the Project and the process by which these goals are being approached may help in placing the progress and plans in context.

Two principal goals have been established for the Project. The first is the achievement of Technical Readiness by the end of FY82 of a \$0.70/W_p (1980\$) module technology. This milestone requires the demonstration of silicon material Experimental Process Systems Development Units (EPSDUs) in the production of material at the appropriate purity and throughput rates that, if scaled to commercial size, could sell for \$14/Kg (1980\$) or less by 1986. In addition, Technical Readiness requires the demonstration of Large Area Sheet Experimental Growth Units (EGUs) that provide the appropriate throughput rates for quality sheet formation within the allocated added price for the particular sheet technology being demonstrated; and lastly that automated process sequencing of the sheet material into cells and finally into modules is also accomplished.

The second principal goal calls for Commercial Readiness of a \$0.70/W_p (1980\$) module technology by 1986. The LSA Project's role in Commercial Readiness is defined as: encouraging private investment in the photovoltaic (PV) supply industry through technology transfer to interested firms of information resulting from the PV Program; assisting in the development of industry standards and user requirements; and demonstrating that the economics of scale have been realized through the emplacement of sufficient production capacity to meet the \$0.70/W_p module goal. It is currently estimated that approximately 30 MW_p/year in a single automated plant is the necessary throughput rate to demonstrate the goal.

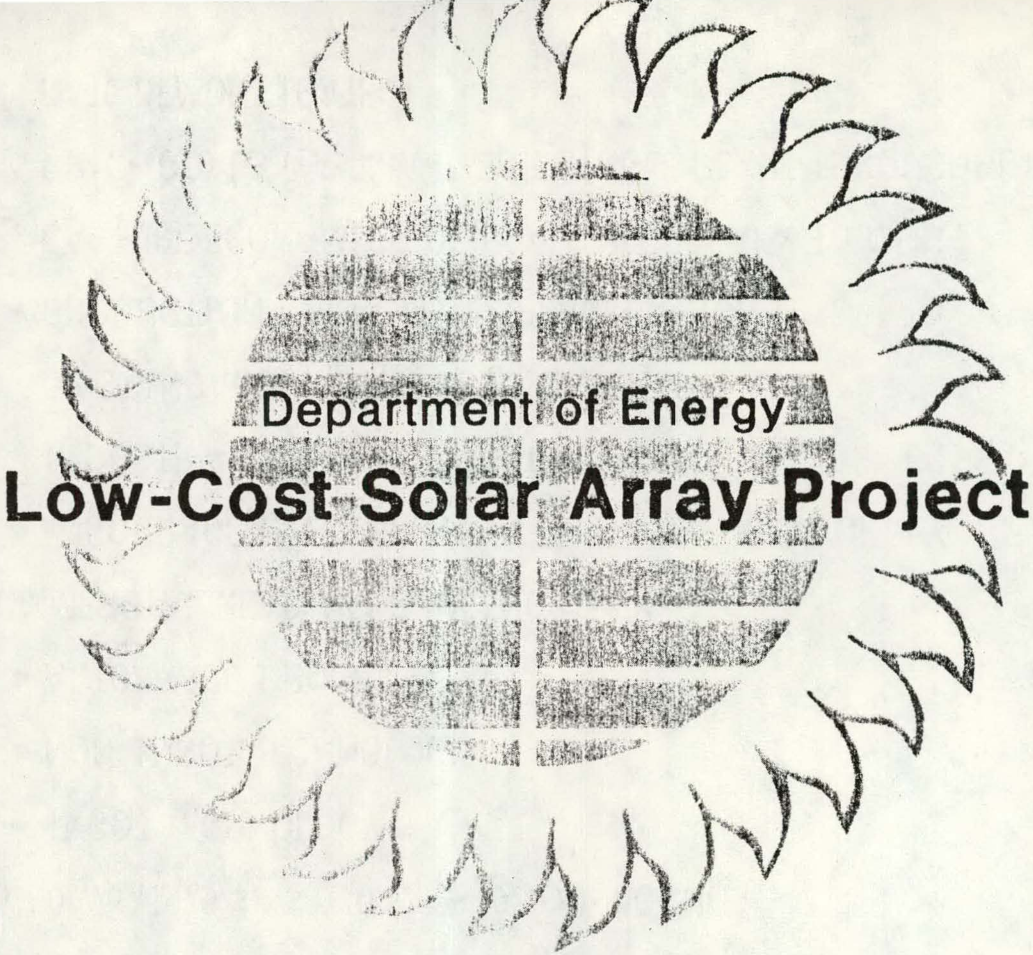
The basic process by which these goals are pursued is techno-economic in character. That is, the price goal sought (\$0.70/W_p module - 1980\$) is one in which competing technical processes vie for Project funding and continuation. Thus, a price goal allocation process is used to negotiate a technical sub-task share of the price goal (i.e., large area sheet formation may be allocated \$0.14/W_p of the \$0.70 available). This negotiating process occurs as necessary depending on the relative successes of the sub-tasks. The attempt is made to invoke "equal pain" on all sub-task efforts and avoid allegiance to an unnecessarily harsh or lenient allocation.

Another facet of the technical and economic activity is the necessity to resolve competing claims as to which technical advance offers the

*Presented by Larry Dumas

least added cost. Sensitivity trade-offs are also required to determine the optimum mix of elements in a given module technology manufacturing process sequence. These problems are solved using a modeling technique wherein detailed technical information regarding a specific process sequence; equipment requirements; manpower requirements; financial and capital information are input and manufacturing costs, selling price and supporting information are output. The Solar Array Manufacturing Industry Costing Standards (SAMICS) model was developed by the LSA Project and was critiqued by industry participants and modified until a high degree of maturity was achieved. SAMICS is now routinely used in technical and economics data/information generation.

The progress and plans of each LSA Project Task is presented on the viewgraph material that follows. This material formed the basis for the LSA Project Activities presentation on Tuesday, 18 September 1979.



Department of Energy
Low-Cost Solar Array Project

Dr. William T. Callaghan
Manager

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

LOW-COST SOLAR ARRAY PROJECT

GOALS

- TECHNICAL READINESS BY END OF FY82

  $0.50/Wp (1975 $) ($0.70/Wp - 1980 $) MODULE

  - INGOT TECHNOLOGY
  - NON-INGOT TECHNOLOGY
  - AUTOMATED PROCESS
- COMMERCIAL READINESS BY END OF FY86
  - ENCOURAGE INVESTMENT IN PHOTOVOLTAIC SUPPLY INDUSTRY BY TECHNOLOGY TRANSFER, DEVELOPMENT OF STANDARDS, USER REQUIREMENTS
  - PRODUCTION CAPACITY EMPLACED - SUFFICIENT TO CAPTURE ECONOMICS OF SCALE NECESSARY TO MEET PRICE GOALS (~30MWe/YEAR SINGLE PLANT THROUGHPUT RATE DEMONSTRATED)

WTC

LOW–COST SOLAR ARRAY PROJECT

TECHNICAL READINESS DEFINITION

- OPERATE SILICON EPSDUs - DEMONSTRATE SILICON MATERIAL THROUGHPUT RATES AND PRICE GOALS
- OPERATE LARGE AREA SHEET EGUs - DEMONSTRATE THROUGHPUT RATES AND PRICE GOALS
- DEMONSTRATE AUTOMATED MANUFACTURABILITY OF PV MODULES AT \$0.50/Wp (1975 \$) (\$0.70/Wp - 1980 \$)

WTC
6/28/79

LOW-COST SOLAR ARRAY PROJECT

TECHNO-ECONOMIC PROCESS

- PRICE GOAL ALLOCATION PROCESS
  - NEGOTIATED TASK SHARE OF PRICE GOAL
  - AIDS RESOURCE ALLOCATION TO TASK
  - DYNAMIC OVER TIME

- COST/PRICE STANDARDIZATION
  - MULTIPLE CONTRACTORS
  - ASSESSING PRICE ACHIEVEMENTS
  - SAMICS METHODOLOGY

WTC
6/28/79

LOW-COST SOLAR ARRAY PROJECT

SILICON MATERIAL TASK

PROGRESS

UNION CARBIDE CORP (SILANE/SILICON)

- STARTED DETAILED DESIGN OF 100-MT/yr EPSDU
- R&D SUPPORT PROGRAM
    - FSR REDESIGNED AND FABRICATION STARTED
    - POTENTIAL FOR CAPACITIVE HEATING OF FBR SHOWN
    - RFP PREPARED FOR Si POWDER MELTER DEVELOPMENT SUBCONTRACT

BATTELLE COLUMBUS LABS (Zn REDUCTION OF $SiCL_4$)

- PROCESS DEVELOPMENT UNIT UNDER CONSTRUCTION
- EFFICIENT $ZnCl_2$ RECOVERY DEMONSTRATED

WESTINGHOUSE (Na REDUCTION OF $SiCl_4$)

- OPERATED PROCESS DEMONSTRATION SYSTEM IN GAS-ONLY TESTS
- BROUGHT SYSTEM TO STATE OF NEAR COMPLETION (98%)

LOW-COST SOLAR ARRAY PROJECT
SILICON MATERIAL TASK

PROGRESS (Contd)

SRI INTL (Na REDUCTION OF SiF_4)

- CONDUCTED THREEFOLD REACTOR SCALE-UP

WESTINGHOUSE (IMPURITY EFFECTS STUDY)

- ELECTRICALLY ACTIVE CONCENTRATIONS SHOWN TO BE LINEAR WITH TOTAL CONCENTRATIONS FOR Ti, Cr, V, Mo

IN-HOUSE STUDIES

- INCREASED CONVERSION EFFICIENCY AND PRODUCT SIZE/DENSITY IN FSR
- BED CLOGGING REDUCED BY SLUGGING OPERATION IN FBR

SILICON MATERIAL TASK

PLANS

UCC

- EPSDU PHASE NEGOTIATED BEGINNING OF FY80
- CONTINUE EPSDU DETAILED ENGINEERING DESIGN
- CONTINUE R&D SUPPORT

BCL

- COMPLETE PDU INSTALLATION AND START OPERATION IN OCTOBER

WESTINGHOUSE (SILICON PROCESS)

- COMPLETE PROCESS DEMONSTRATION BY END OF DECEMBER
- CONDUCT CRITICAL DESIGN REVIEW

HEMLOCK SEMICONDUCTOR CORPORATION (MODIFIED SIEMENS PROCESS)

- CONTRACT START MID-SEPTEMBER

SRI INTL

- CONTINUE DEVELOPMENT EFFORT FOR Si SEPARATION AND PURITY DETERMINATION CRITICAL DESIGN REVIEW MID-SEPTEMBER

LOW-COST SOLAR ARRAY PROJECT

LARGE AREA SILICON SHEET TASK

PROGRESS

ADVANCED CZOCHRALSKI

HAMCO

- ACHIEVED 108 kg GROWTH/CRUCIBLE (84% SINGLE CRYSTAL, 13 cm DIA)

SILTEC

- ACHIEVED 15 cm DIA INGOT GROWTH FROM CLF FURNACE

INGOT CASTING

CSI

- CAST SHAPED INGOTS (15 cm CUBE, 8 kg) BY HEAT EXCHANGE METHOD

ADVANCED WAFERING

SILTEC

- SLICED 10 cm DIA INGOT AT 22 WAFERS/cm; 15 cm DIA INGOT AT 15 WAFERS/cm (ADVANCED ID WAVERING)

CSI

- DEMONSTRATED 0.15 mm/min CUTTING RATE (EQUIVALENT OF 1.4 WAFERS/min) ON 10 cm DIA INGOT (MULTI-WIRE WAFERING)

LOW-COST SOLAR ARRAY PROJECT

LARGE AREA SILICON SHEET TASK

PROGRESS (Contd)

SHAPED RIBBON:

MOBIL TYCO (EFG)

- DEMONSTRATED SEPARATELY:
  - 15 HOURS OPERATION OF 5 RIBBON STATION
  - 10 cm WIDE RIBBON GROWTH
  - 11% AM1 CELL EFFICIENCY (5 cm x 10 cm CELL)
  - LARGER GRAIN STRUCTURE (1 cm x 10 cm)

WESTINGHOUSE (WEB)

- DEMONSTRATED 27.1 cm^2/min GROWTH RATE
- PRODUCED 12% AM1 CELL FROM WEB RIBBON GROWN FROM SILICON MATERIAL TASK'S BATTELLE SILICON MATERIAL

ENERGY MATERIALS (LAR)

- GROWTH DEMONSTRATION OF LOW-ANGLE RIBBON (LAR) (1 cm WIDE BY 20 cm LONG BY 0.8 mm THICK, 14 cm^2/min)

SUPPORTED FILM:

HONEYWELL (SOC)

- DEMONSTRATED SILICON-ON-CERAMIC COATING ON 5 cm x 40 cm CERAMIC SUBSTRATE BY THE SCIM TECHNIQUE

LOW-COST SOLAR ARRAY PROJECT

LARGE AREA SILICON SHEET TASK

PLANS

ADVANCED CZOCHRALSKI

- DEMONSTRATE 100 kg GROWTH/CRUCIBLE IN SILTEC'S CLF FURNACE
- ACHIEVE GROWTH THROUGHPUT (>2 kg/hr)

INGOT CASTING

- CAST SHAPED INGOT OF 20 cm CUBE SIZE (18 kg) BY HEM METHOD

ADVANCED WAFERING

- DEMONSTRATE 25 WAFERS/cm SLICING ON 10 cm DIA INGOT
- DEMONSTRATE PRECISION SLICING OF 15 cm DIA INGOT

SHAPED RIBBON

- DEMONSTRATE MULTIPLE GROWTH OF 10 cm WIDE EFG RIBBONS
- ACHIEVE 12% AM1 EFFICIENT EFG SOLAR CELLS
- DEMONSTRATE CLOSED-LOOP CONTROL OF WEB RIBBON GROWTH
- ROUTINE GROWTH OF WEB RIBBONS AT 25 cm^2/min RATE
- SELECTION OF DIE MATERIAL FOR ARCO SOLAR'S VACUUM DIE-CAST SHEET

SUPPORTED FILM

- ACHIEVE 11% AM1 EFFICIENT SOC SOLAR CELLS

ENCAPSULATION TASK

PROGRESS

- ENCAPSULATION SYSTEMS WHICH MEET 1986 COST GOALS (10¢-14¢/W) HAVE BEEN INCORPORATED INTO LSA BLOCK IV MODULES
- POLY-N-BUTYLACRYLATE (PNBA) HAS BEEN DEVELOPED AS A SOLVENT FREE CASTABLE POTTANT
- MINIMODULES (12 in x 16 in) ARE BEING FABRICATED OF 1986 CANDIDATE MATERIAL SYSTEMS (SUBSTRATE AND SUPERSTRATE DESIGNS) FOR FIELD TESTING AND LIFE VALIDATION
- SOLAR MODULE AND MATERIAL DEGRADATION MODELS ARE BEING FORMULATED FOR PHOTODEGRADATION, THERMO-MECHANICAL STRESS, AND CORROSION

LOW-COST SOLAR ARRAY PROJECT

ENCAPSULATION TASK

PLANS

- DESIGN, ANALYSIS, AND TEST VERIFICATION OF 1986 DESIGNS FOR OPTICAL, THERMAL, ELECTRICAL, AND STRUCTURAL PERFORMANCE
- FIELD TESTS STARTED ON 1986 MINIMODULE ENCAPSULATION SYSTEMS
- FEASIBILITY DEMONSTRATION OF LARGE SCALE LOW-COST ELECTROSTATIC BONDING OF SILICON TO GLASS SHEET
- FABRICATION AND QUALIFICATION TESTING OF THE PNBA ENCAPSULANT
- COMMENCE EVALUATION OF UV SCREENING FILMS FOR LOW COST POTTANTS

LOW-COST SOLAR ARRAY PROJECT

PRODUCTION PROCESS AND EQUIPMENT AREA

PROGRESS

METALLIZATION

- MOLYBDENUM OXIDE - TIN SYSTEM BEING IMPROVED
- COMPLETED EVALUATION OF FRITLESS THICK FILM CANDIDATES; BEGAN 2nd GENERATION SILVER AND NICKEL PASTES
- INITIATED CONTRACT UTILIZING "MIDFILM®" PROCESS FOR FINE LINES

JUNCTION FORMATION

- BEGAN WORKING WITH PROCESS INTERDEPENDENCE OF MATERIAL SURFACE, THICK FILM METALLIZATION, AND ION IMPLANTATION

ASSEMBLY

- CONTRACTORS WORKING ON NEAR-TERM GOALS HAVE HAD TO MODIFY ORIGINAL DESIGNS

IN-HOUSE EFFORTS

- MOVED TO NEW FACILITIES
- LAB EQUIPMENT 90% INSTALLED
- LONG-LIFE HOLLOW CATHODE ION IMPLANTATION SOURCE SUCCESSFULLY OPERATED
- INITIATED PHASE III PROCUREMENT PACKAGE FOR AUTOMATED PROCESS SEQUENCING EQUIPMENT

LOW-COST SOLAR ARRAY PROJECT

PRODUCTION PROCESS AND EQUIPMENT AREA

PLANS

- DEVELOP NEW METALLIZATION SYSTEMS RECENTLY SHOWN TO BE PROMISING USING COMMERCIAL METALS
- ADVANCE ION IMPLANTATION IN COMBINATION WITH PULSED ELECTRON BEAM ANNEALING INTO MACHINE DEVELOPMENT STAGE
- ISSUE RFP TO INDUSTRY FOR PHASE III (DESIGN OF EQUIPMENT AND FACILITIES)
- BEGIN PROCESS VERIFICATIONS IN PP&E LABORATORY

LOW-COST SOLAR ARRAY PROJECT
ENGINEERING AREA
PROGRESS

COMPLETED ACTIVITIES

- RESIDENTIAL BUILDING CODE STUDY (BURT-HILL)
- CELL FRACTURE TESTING (JPL)
- WIND LOAD ANALYSIS - PHASE I (BOEING)
- SOLAR CELL RELIABILITY TESTING - PHASE I (CLEMSON)
- GLASS STRUCTURAL SIZING ANALYSIS (JPL)
- CURVED GLASS MODULE ANALYSIS (BECHTEL)
- MODULE INTERCONNECT FATIGUE LOADING (JPL)
- MODULE HOT SPOT STRESS ANALYSIS (JPL)

LOW-COST SOLAR ARRAY PROJECT
ENGINEERING AREA
PROGRESS (Contd)

CONTINUED ACTIVITIES

- ELECTRICAL INSULATION STUDY (BECHTEL)
- SERIES/PARALLEL ANALYSIS (JPL)
- MODULE SOILING STUDIES (JPL)
- MODULE UV-EXPOSURE TESTING (DSET)
- SERI STANDARDS SUPPORT (JPL)

INITIATED ACTIVITIES

- ELECTRICAL TERMINATION STUDY (MOTOROLA/CANON)
- SAFETY REQUIREMENTS STUDY (UL)

LOW-COST SOLAR ARRAY PROJECT

ENGINEERING AREA

PLANS

ACTIVITIES TO BE COMPLETED

- ELECTRICAL TERMINATION STUDY (MOTOROLA)
- MODULE SAFETY REQUIREMENTS – PHASE I (UL)
- SERIES/PARALLEL STUDY – PHASE I (JPL)
- SOILING STUDY – PHASE I (JPL)

CONTINUED ACTIVITIES

- ACCELERATED UV WEATHERING (DSET)
- CELL RELIABILITY TESTING (CLEMSON)
- MODULE SOILING SUTDIES (JPL)
- WIND LOAD TESTING (BOEING)
- SAFETY REQUIREMENTS (UL)
- SERIES/PARALLEL STUDIES (JPL)
- SERI STANDARDS SUPPORT (JPL)

ACTIVITIES TO BE INITIATED

- COMMERCIAL BUILDING CODE STUDY (BURT-HILL)
- RESIDENTIAL O & M COST STUDY (BURT-HILL)
- INTEGRATED RESIDENTIAL ARRAY DESIGN STUDIES (RFP)
- LOW-COST STRUCTURAL ELEMENTS DEVELOPMENT (RFP)

PV-T MODULE ENGINEERING (JPL/RFP)

LOW-COST SOLAR ARRAY PROJECT
OPERATIONS AREA
PROGRESS

- BLOCK III DELIVERIES 95% COMPLETED (375 kW OF BLOCK PROCUREMENT MODULES TO DATE)
- BLOCK IV DESIGN AND TEST CONTRACTS AWARDED; PRELIMINARY DESIGN REVIEWS COMPLETED
- BLOCK III QUAL TESTING COMPLETED; EXPLORATORY (MARGIN) TESTING INITIATED
- PRDA-38 (FLAT-PANEL PV EXPERIMENTS) MODULE QUAL TESTING AND PERFORMANCE EVALUATION COMPLETED
- SECOND LARGE-AREA PULSED SOLAR SIMULATOR (LAPSS) INSTALLED AND CHECKED OUT
- FIELD TESTS OF MODULES ONGOING AT 16 SITES
- OVER 500 MODULE PROBLEM/FAILURE REPORTS PROCESSED TO DATE

LOW-COST SOLAR ARRAY PROJECT
OPERATIONS AREA
PLANS

- COMPLETE BLOCK IV DESIGN, TEST, PRICE ANALYSIS, AND PRODUCTION
- COMPLETE BLOCK III EXPLORATORY AND BLOCK IV QUALIFICATION TESTS
- DEPLOY BLOCK IV MODULES TO FIELD TESTS AND APPLICATIONS
- REPORT PROBLEM/FAILURE ANALYSIS, ENVIRONMENTAL AND FIELD TEST RESULTS

LOW-COST SOLAR ARRAY PROJECT

PROJECT ANALYSIS AND INTEGRATION AREA

PROGRESS

- ANALYZED FIRST CANDIDATE FACTORY FOR MEETING PROJECT GOALS
- ALLOCATED GOALS TO PROJECT ELEMENTS TO MEET PROJECT OBJECTIVES
- CONCLUDED 3 MAJOR VALIDATION REVIEWS OF SAMIS COSTING METHODOLOGY
- ASSESSED NEAR-TERM AND LONG-TERM (FY 2000) POTENTIAL PRICES OF SILICON FLAT-PLATE PV
- INITIATED ANALYSIS OF NEW CANDIDATE FACTORIES; 4 SHEET AND 4 CELL PROCESSING SEQUENCES HAVE BEEN EXAMINED

LOW-COST SOLAR ARRAY PROJECT
PROJECT ANALYSIS AND INTEGRATION AREA
PLANS

- CONTINUE DEVELOPMENT OF CANDIDATE FACTORIES, INCLUDING REVIEW AND PUBLICATION OF RESULTS
- DOCUMENT COMPLETED WORK ON SAMIS VALIDATION/MODIFICATION
- DEVELOP IPEG TO MORE CLOSELY COMPLEMENT SAMIS

LOW-COST SOLAR ARRAY PROJECT

ADVANCED PHOTOVOLTAICS TASK

CHARTER FOR THE TASK

- IDENTIFY, DEVELOP AND DEMONSTRATE MATERIALS AND PROCESSING TECHNOLOGY LEADING TO SOLAR CELL MODULES MEETING COST GOALS FOR TECHNICAL READINESS BEYOND 1986
- INTERFACE BETWEEN SERI/PVPO AND JPL/LSA FOR ADVANCED PHOTOVOLTAICS
- IN-HOUSE DEVICE AND MATERIAL CHARACTERIZATION FACILITY SUPPORTING ALL ELEMENTS OF THE LSA PROJECT

POLYCRYSTALLINE SILICON SOLAR CELLS

T. Surek
Photovoltaic Program Office
Solar Energy Research Institute
Golden, Colorado 80401

The objective of this program is to identify and develop methods for fabricating polycrystalline silicon solar cells with photovoltaic conversion efficiencies of 10% or greater by 1980, and to demonstrate a cost feasibility of less than $500/peak kWe (in 1980 $) by 1986.

The thirty-one (31) participants on the program have resulted from various DOE and SERI solicitations and from SERI's unsolicited proposals program. Nine contracts have resulted from the PRDA on "Thin Film Polycrystalline Silicon Solar Cells" (DOE/San Francisco, 1978), while seven of the awards on the PRDA on "Photovoltaic Mechanisms in Polycrystalline Thin-Film Solar Cells" (DOE/Washington, 1978) were in the area of polycrystalline silicon solar cells. SERI subcontracts have been awarded as a result of unsolicited proposals (six programs), the Innovative Concepts Program (five programs) and the SERI RFP on "Low-Cost Substrates for Polycrystalline Silicon Solar Cells" (four programs). The participating organizations are identified in the accompanying figures.

The research effort in polycrystalline silicon solar cells can be divided into the areas of: (i) Materials development; (ii) Cell development; and (iii) Basic studies. In the accompanying figures, the research issues which are being addressed in each of these areas are identified, followed by a brief outline of the approaches and a listing of the major accomplishments of the participating organizations. It should be recognized that many of the organizations are performing research which addresses more than one of the above research areas; the assignment to one area was made based on what is believed to be the primary effort in each program. The varying start dates of the programs, indicated in the figures, should also be noted.

Efforts in materials development center on the purification of metallurgical grade silicon and the development of techniques for producing low-cost polycrystalline silicon substrates using low-cost silicon feedstock. In addition, significant part of the program involves the evaluation of various thin-film growth techniques for producing large grain-size films on low-cost foreign substrates.

Noteworthy developments include the demonstration of 9.75% efficient cells (9 cm^2 area) on the Southern Methodist University program and 10.1% efficient cells (2 cm^2 area) on the Motorola program. It should be noted that many of the materials development programs are just now being initiated.

Cell development research is concerned mainly with the development of various solar cell structures (MIS/SIS, heterojunction, homojunction) which are compatible with the polycrystalline structure to give high conversion efficiency. The development of epitaxial growth techniques for fabricating high efficiency cells on low-cost polycrystalline silicon substrates is another important part of the program. Notable results include, in addition to the p-n junction results stated above, the demonstration of greater than 10% efficient cells for ITO or SnO_2 on n-type Wacker polycrystalline silicon by spray technology (Exxon) and 9.6% efficient cells for the ITO/p-type Wacker polycrystalline silicon structure (Brown University). Theoretical modelling at Exxon predicts that grain sizes in excess of 150 μm will be required to achieve solar cell efficiencies greater than 10%, AM1.

Programs under basic studies address one or more of the following problem areas: (i) characterization of the structural, compositional, electrical and optical properties of polycrystalline silicon and correlation to cell performance; (ii) theoretical modelling of photovoltaic mechanisms in various solar cell structures in polycrystalline silicon; and (iii) development of techniques for reducing or eliminating the deleterious effects of grain boundaries. Notable achievements include the development of various experimental techniques to characterize the effects of grain boundaries (RCA), the theoretical demonstration that small areal inhomogeneities can cause severe degradation in solar cell performance (University of Florida) and the demonstration of grain boundary passivation by H-plasma treatment (Sandia Laboratories). A more detailed discussion of the latter results is given in the paper by D. S. Ginley in these Proceedings.

Problem areas for further study in the areas of materials development, cell development and basic studies are listed in a later figure. To some extent, the items indicate areas where further research is needed; more importantly, they point out areas of concern in the ongoing research programs and the questions which need to be answered. A breakdown of the funding into the various research areas is also shown; for this figure, the appropriate fraction of each program in the various research tasks was estimated.

In summary, the current status of the polycrystalline silicon solar cell technology is that greater than 10% efficient "thin-film" cells of a large area have been fabricated, and, at least for the p-n junction structure, cell stability has been sufficiently demonstrated. Several approaches to thin-film polycrystalline silicon solar cells appear, therefore, to be ready for a comprehensive exploratory development to examine: (i) scale-up potential; (ii) reproducibility and yield of large-area, high efficiency cells; and (iii) detailed analyses of the cost potentials of the techniques.

POLYCRYSTALLINE SILICON SOLAR CELLS

T. SUREK

G. C. CHEEK

A. ARIOTEDJO

PHOTOVOLTAICS ADVANCED R&D ANNUAL REVIEW

DENVER, COLORADO

SEPTEMBER 17-19, 1979

POLYCRYSTALLINE SILICON SOLAR CELLS PROGRAMS

- POLYCRYSTALLINE SILICON FY78 PRDA

  (Columbia U., EIC, Exxon, JHU/APL, Motorola, Poly Solar/SMU, RCA, Rockwell, SUNY) - \$1.9M

- PHOTOVOLTAIC MECHANISMS FY78 PRDA

  (U. Florida, Motorola, RCA, Sandia, Solarex, SRI, Westinghouse) - \$0.9M

- UNSOLICITED PROPOSALS

  (Brown U., Colorado State U., EMC, RCA, Solarex, J. C. Schumacher) - \$1.1M

- INNOVATIVE CONCEPTS PROGRAM

  (EMC, Phrasor Tech., Semix, Sensor Tech., Siltec) - \$0.5M

- LOW-COST SUBSTRATE RFP

  (Crystal Systems, Honeywell, Motorola, Westinghouse) - \$0.75M

POLYCRYSTALLINE SILICON SOLAR CELLS:
RESEARCH AREAS

- MATERIALS DEVELOPMENT
- CELL DEVELOPMENT
- BASIC STUDIES
  - Research Areas Addressed
  - Approaches/Accomplishments
  - Problem Areas For Study

POLYCRYSTALLINE SILICON SOLAR CELLS: MATERIALS DEVELOPMENT RESEARCH AREAS

- PURIFICATION OF METALLURGICAL-GRADE SILICON FOR USE AS FEEDSTOCK TO FILM OR SUBSTRATE GROWTH.
- EVALUATION OF THE POTENTIAL OF VARIOUS THIN-FILM GROWTH TECHNIQUES FOR PRODUCING LARGE GRAIN-SIZE FILMS ON LOW-COST SUBSTRATES, OR FOR PRODUCING SELF-SUPPORTING FILMS.
- DEVELOPMENT OF FILM GROWTH TECHNIQUES WHICH RESULT IN IMPROVED GRAIN BOUNDARY PROPERTIES.
- IDENTIFICATION AND DEVELOPMENT OF TECHNIQUES FOR PRODUCING LOW-COST POLYCRYSTALLINE SILICON SUBSTRATES.
- EVALUATION OF SCALE-UP AND COST POTENTIALS OF TECHNIQUES.

ORGANIZATION; J. C. SCHUMACHER COMPANY

PRINCIPAL INVESTIGATOR: E. B. MOORE

CONTRACT AMOUNT: $210K DURATION: 6/1/79 - 5/30/80

APPROACH: DEVELOPMENT OF A CLOSED-LOOP, ZERO EFFLUENT PROCESS BASED ON METALLURGICAL GRADE SILICON AND TRIBROMOSILANE TO PRODUCE LOW-COST SOLAR-GRADE SILICON.

ACCOMPLISHMENTS:

- DEMONSTRATED EFFICIENT THERMAL DECOMPOSITION AND HYDROGEN REDUCTION PROCESSES FOR TRIBROMOSILANE (JPL/LSA).
- DEMONSTRATED SYNTHESIS OF TRIBROMOSILANE IN THE PACKED BED REACTOR USING BROMINE AND HYDROGEN. BEST YIELD 42%.
- SYNTHESIZED TRIBROMOSILANE WITH BROMINE AND HYDROGEN FIRST REACTED IN A PLATINUM-CATALYZED REACTOR. BEST YIELD 85%.
- IDENTIFIED DECANE AS A SOLVENT IN GAS CHROMATOGRAPHY ANALYSIS OF TRIBROMOSILANE MIXTURES.
- COMPLETED PRELIMINARY PROCESS DESIGN OF THE MINI-PLANT.

ORGANIZATION: SOUTHERN METHODIST UNIVERSITY

PRINCIPAL INVESTIGATOR: T. L. CHU

CONTRACT AMOUNT: $378K DURATION: 9/1/76 - 9/30/79

APPROACH: DEPOSITION OF SILICON P-N JUNCTION STRUCTURE ON PARTIALLY PURIFIED METALLURGICAL GRADE SILICON SUBSTRATE.

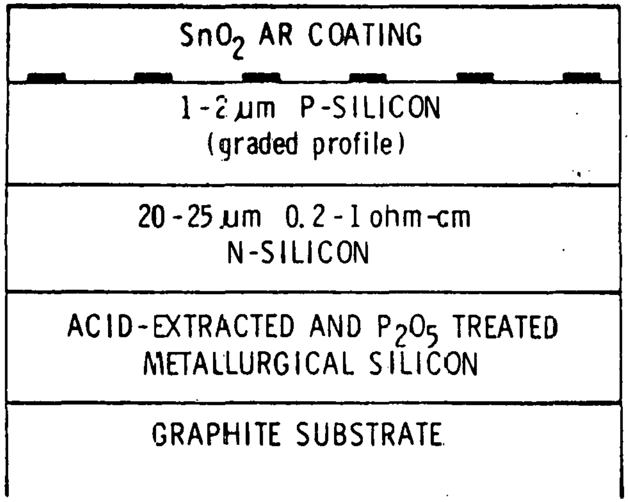
ACCOMPLISHMENTS:

- METALLURGICAL GRADE SILICON PURIFIED BY ACID EXTRACTION AND PHOSPHORUS PENTOXIDE TREATMENT.
- CONDITIONS ESTABLISHED FOR PRODUCING PLANAR AND NON-PLANAR SURFACES DURING UNIDIRECTIONAL SOLIDIFICATION OF METALLURGICAL SILICON ON GRAPHITE.
- EBIC STUDIES OF GRAIN BOUNDARIES IN THIN-FILM CELLS; HEAT TREATMENT REDUCES EFFECTS OF GRAIN BOUNDARIES.
- AM1 SOLAR CELL EFFICIENCY = 9.75% (9 CM^2 AREA).

SILICON SOLAR CELLS ON PLANAR METALLURGICAL SILICON SUBSTRATES

TING L. CHU, SOUTHERN METHODIST UNIVERSITY

- CONFIGURATION



SnO_2 AR COATING

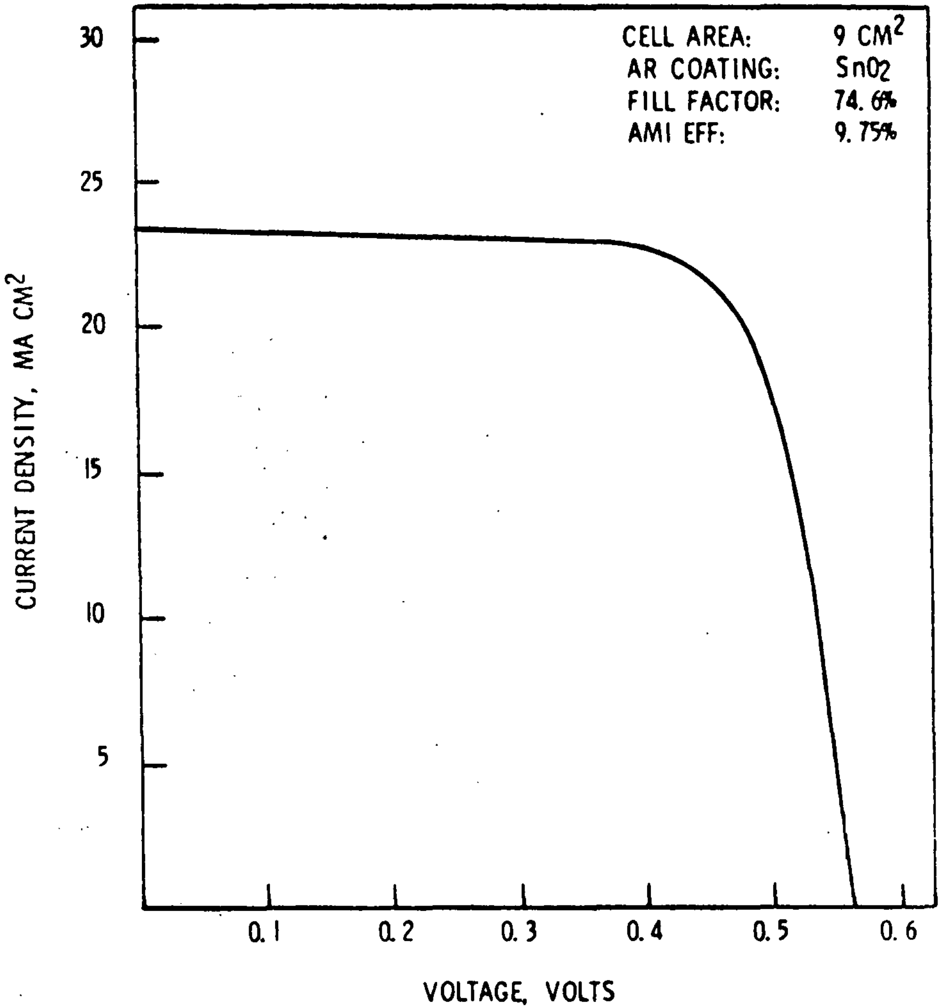
1-2 µm P-SILICON (graded profile)

20-25 µm 0.2-1 ohm-cm N-SILICON

ACID-EXTRACTED AND P_2O_5 TREATED METALLURGICAL SILICON

GRAPHITE SUBSTRATE

- CHARACTERISTICS UNDER ILLUMINATION AT 100 MW / CM^2



CELL AREA: 9 CM^2
AR COATING: SnO_2
FILL FACTOR: 74.6%
AMI EFF: 9.75%

ORGANIZATION: POLY SOLAR, INC.

PRINCIPAL INVESTIGATOR: G. A. VAN DER LEEDEN

CONTRACT AMOUNT: $237K DURATION: 3/15/79 - 3/14/80

APPROACH: EXTENSION OF THE TECHNOLOGY DEVELOPED AT SOUTHERN METHODIST UNIVERSITY; EXAMINATION OF SCALE-UP POTENTIAL, REPRODUCIBILITY AND YIELD OF LARGE AREA, HIGH EFFICIENCY SOLAR CELLS.

ACCOMPLISHMENTS:

- SET UP EQUIPMENT FOR METALLURGICAL GRADE SILICON PURIFICATION, SILICON-ON-GRAPHITE RECRYSTALLIZATION, AND EPITAXIAL DEPOSITION BY CVD.
- INITIAL BATCH OF METALLURGICAL SILICON PURIFIED.
- STUDIED RECRYSTALLIZATION OF LARGE AREA (7.5 CM X 28 CM) SAMPLES USING MOVING-COIL ZONE-MELTING APPARATUS.

ORGANIZATION: MOTOROLA, INC.

PRINCIPAL INVESTIGATOR: K. R. SARMA

CONTRACT AMOUNT: $290K DURATION: 9/25/78 - 9/24/79

APPROACH: ENERGY-BEAM DEPOSITION OF THIN POLYCRYSTALLINE SILICON FILMS ON REUSABLE SUBSTRATES; RIBBON-TO-RIBBON RECRYSTALLIZATION.

ACCOMPLISHMENTS:

- SUBSTRATE SYSTEM STUDIES
  - SHEAR SEPARATION IN SI NEAR $Si-MoSi_2$ INTERFACE
  - THIN SiO_2 LAYER EFFECTIVE BARRIER TO MO DIFFUSION
  - POTENTIALLY LOW-COST COMPOSITE SUBSTRATE: Mo (THICK) / SiO_2 (0.6µM) / Mo (0.5µM)
- ENERGY-BEAM DEPOSITION (EBD)
  - LARGE AREA (1 1/2 IN. X 18 IN.) MICRORIBBONS IN BATCH SYSTEM
  - ROTATING NOZZLE MINIMIZES PLASMA BEAM ARCING
  - SILICON DEPOSITION EFFICIENCY EXCEEDS CONVENTIONAL CVD
  - CONTINUOUS EBD SYSTEM DESIGNED AND BUILT: 1 7/8 IN. X 12 IN. X 7 MILS RIBBONS PRODUCED (CVD MODE)
- RTR RECRYSTALLIZATION AND SOLAR CELL FABRICATION
  - ETCHING OF MO-CONTAMINATED REGION (2-3µM) REQUIRED
  - DOUBLE-SIDED P DIFFUSION IMPROVES DIFFUSION LENGTH
  - AM1 SOLAR CELL EFFICIENCY = 10.1% (~2CM²) V_{OC} = .54V, J_{SC} = 29.5 MA/CM², FF = 63%.

ORGANIZATION: JOHNS HOPKINS UNIVERSITY/APPLIED PHYSICS LAB.

PRINCIPAL INVESTIGATOR: C. FELDMAN

CONTRACT AMOUNT: $174K DURATION: 9/29/78 - 9/28/79

APPROACH: FABRICATION OF THIN-FILM POLYCRYSTALLINE SILICON SOLAR CELLS BY VACUUM EVAPORATION TECHNIQUES.

ACCOMPLISHMENTS:

- DEVELOPMENT OF TiB_2/ALUMINA AS A SATISFACTORY, POTENTIALLY LOW-COST BACK ELECTRODE/SUBSTRATE.
- OBSERVATION OF LARGE (30μM) SILICON CRYSTALLITE FORMATION ON TiB_2-COATED ALUMINA SUBSTRATES, AND SOME PROGRESS MADE IN UNDERSTANDING CONDITIONS FOR THIS GROWTH.
- FABRICATION OF VACUUM-DEPOSITED SOLAR CELLS CONSISTING OF AG/TI TOP ELECTRODE, POLYCRYSTALLINE SILICON, TiB_2 BOTTOM ELECTRODE AND ALUMINA SUBSTRATE.

ORGANIZATION: EIC CORPORATION

PRINCIPAL INVESTIGATOR: R. D. RAUH

CONTRACT AMOUNT: $188K DURATION: 6/11/79 - 6/10/80

APPROACH: ELECTROCHEMICAL DEPOSITION OF THIN POLYCRYSTALLINE AND AMORPHOUS SILICON FILMS USING ORGANIC AND MOLTEN SALT ELECTROLYTES.

ACCOMPLISHMENTS:

- DESIGN AND FABRICATION OF HIGH TEMPERATURE (UP TO 1000°C) ELECTRODEPOSITION CELL.
- DESIGN, FABRICATION AND TESTING OF LOW TEMPERATURE GLASS CELL FOR ELECTRODEPOSITION FROM ORGANIC SOLVENTS.
- CYCLYC VOLTAMMETRY MEASUREMENTS IN PROPYLENE CARBONATE USING POLISHED NICKEL AS WORKING ELECTRODE. SILICON PRECURSORS WERE $SiHCl_3$ AT 80°C AND $(CH_3)_3SiCl$ AT 25°C. BOTH REDUCTION AND OXIDATION WAVES OBSERVED, BUT EVIDENCE FOR DEPOSITION OF SI AS YET INCONCLUSIVE.

ORGANIZATION: ROCKWELL INTERNATIONAL

PRINCIPAL INVESTIGATOR: R. P. RUTH

CONTRACT AMOUNT: $237K DURATION: 7/23/79 - 7/23/80

APPROACH: CHEMICAL VAPOR DEPOSITION OF THIN FILM POLYCRYSTALLINE SILICON ON LOW-COST FOREIGN SUBSTRATES.

ACCOMPLISHMENTS:

- POLYCRYSTALLINE ALUMINA AND GLASS SUBSTRATES PROCURED.
- REACTOR MODIFIED AND READIED FOR INITIAL RUN.

ORGANIZATION: ENERGY MATERIALS CORPORATION

PRINCIPAL INVESTIGATOR: D. N. JEWETT

CONTRACT AMOUNT: $25K DURATION: 8/15/79 - 12/15/79

APPROACH: INVESTIGATION OF TIN AND OTHER LIQUID-SUPPORTED HORIZONTAL GROWTH OF SILICON RIBBON.

ACCOMPLISHMENTS:

- TIN IS NOT PRACTICABLE BECAUSE OF MISCIBILITY OF LIQUIDS AND RAPID DISSOLUTION OF SOLID SI IN TIN.
- INITIAL RESULTS ON SI/PB/SN SOLUTION ARE DISCOURAGING.
- MOLTEN SALTS BEING INVESTIGATED; INITIAL RESULTS ARE PROMISING.

NEW PROGRAMS IN POLYCRYSTALLINE SILICON MATERIALS DEVELOPMENT (EST. START DATE 10/1/79)

- SOLAREX CORPORATION: G. STORTI

  EVALUATION OF THE SENSITIVITY OF CAST POLYCRYSTALLINE SILICON MATERIAL TO IMPURE SILICON FEEDSTOCK OVER A RANGE OF THERMAL CASTING CONDITIONS AND A RANGE OF IMPURITY LEVELS.

- ENERGY MATERIALS CORPORATION: D. N. JEWETT

  DEVELOPMENT OF A SHALLOW TROUGH FOR HORIZONTAL GROWTH OF SILICON RIBBON.

- PHRASOR TECHNOLOGY: J. R. MAHONEY

  DEVELOPMENT OF THE ELECTROHYDRODYNAMIC PROCESS FOR PRODUCING LARGE AREA POLYCRYSTALLINE SILICON SHEET.

- SEMIX, INC.: W. REGNAULT

  DEVELOPMENT OF A DIRECT SHEET CASTING TECHNIQUE FOR PRODUCING POLYCRYSTALLINE SILICON SHEET.

- AWARDS ON RFP FOR "LOW-COST SUBSTRATES FOR POLYCRYSTALLINE SILICON SOLAR CELLS".

LOW-COST SUBSTRATES FOR POLYCRYSTALLINE SILICON SOLAR CELLS (SERI RFP NO. RS-9-8119)

- RFP ISSUE DATE: MARCH 28, 1979
- RESPONSE DUE DATE: APRIL 30, 1979
- RESEARCH TASKS:
  - LOW-COST METHODS FOR PURIFYING METALLURGICAL GRADE SILICON
  - LOW-COST METHODS FOR FABRICATING POLYCRYSTALLINE SILICON SUBSTRATES
  - MATERIAL CHARACTERIZATION
  - SOLAR CELL FABRICATION
- RESPONSES RECEIVED: 24
- AWARDS: 4 AMOUNT: $750K (APPROX.)

LOW-COST SUBSTRATES FOR POLYCRYSTALLINE SILICON SOLAR CELLS-AWARDS

- **CRYSTAL SYSTEMS, INC.: C. P. KHATTAK**

  DIRECTIONAL SOLIDIFICATION OF SILICON INGOTS USING THE HEAT EXCHANGER METHOD (HEM); USE OF METALLURGICAL GRADE SILICON FEEDSTOCK WITH PRIOR AND IN SITU PURIFICATIONS.

- **HONEYWELL: J. D. HEAPS**

  SUPPORTED GROWTH OF POLYCRYSTALLINE SILICON SHEETS ON LOW-COST CERAMIC AND CARBON SUBSTRATES AND ON REUSABLE SUBSTRATES.

- **MOTOROLA, INC.: H. M. LIAW**

  DEVELOPMENT OF DIRECT PURIFICATION TECHNIQUES FOR METALLURGICAL GRADE SILICON AND OF LOW-COST INGOT PULLING TECHNIQUES FOR SUBSTRATE FABRICATION.

- **WESTINGHOUSE: W. R. GASS**

  PRODUCTION OF THIN-FILM POLYCRYSTALLINE SILICON SHEET FROM METALLURGICAL GRADE SILICON AND SILICA SOURCES BY MOLTEN SALT ELECTROPLATING TECHNIQUES.

POLYCRYSTALLINE SILICON SOLAR CELLS: CELL DEVELOPMENT RESEARCH AREAS

- DEVELOPMENT OF SOLAR CELL STRUCTURES (MIS/SIS, HETEROJUNCTION, HOMOJUNCTION) WHICH ARE COMPATIBLE WITH THE POLYCRYSTALLINE STRUCTURE TO GIVE HIGH CONVERSION EFFICIENCY.
- DEVELOPMENT OF EPITAXIAL GROWTH TECHNIQUE FOR FABRICATING HIGH EFFICIENCY CELLS ON LOW-COST POLYCRYSTALLINE SILICON SUBSTRATES.
- OPTIMIZATION OF THE CHEMICAL, STRUCTURAL AND ELECTRICAL PROPERTIES OF THE INSULATING LAYER IN MIS, MOS AND SIS CELLS.
- DETERMINATION OF THE LIMITATIONS TO SOLAR CELL PERFORMANCE.
- DETERMINATION OF THE DEGRADATION MECHANISMS AND LONG-TERM STABILITY OF POLYCRYSTALLINE SILICON CELL STRUCTURES.
- EVALUATION OF SCALE-UP AND COST POTENTIALS OF THE TECHNIQUES.

ORGANIZATION: EXXON RESEARCH AND ENGINEERING

PRINCIPAL INVESTIGATOR: A. K. GHOSH

CONTRACT AMOUNT: \$272K DURATION: 1/1/79 - 12/31/79

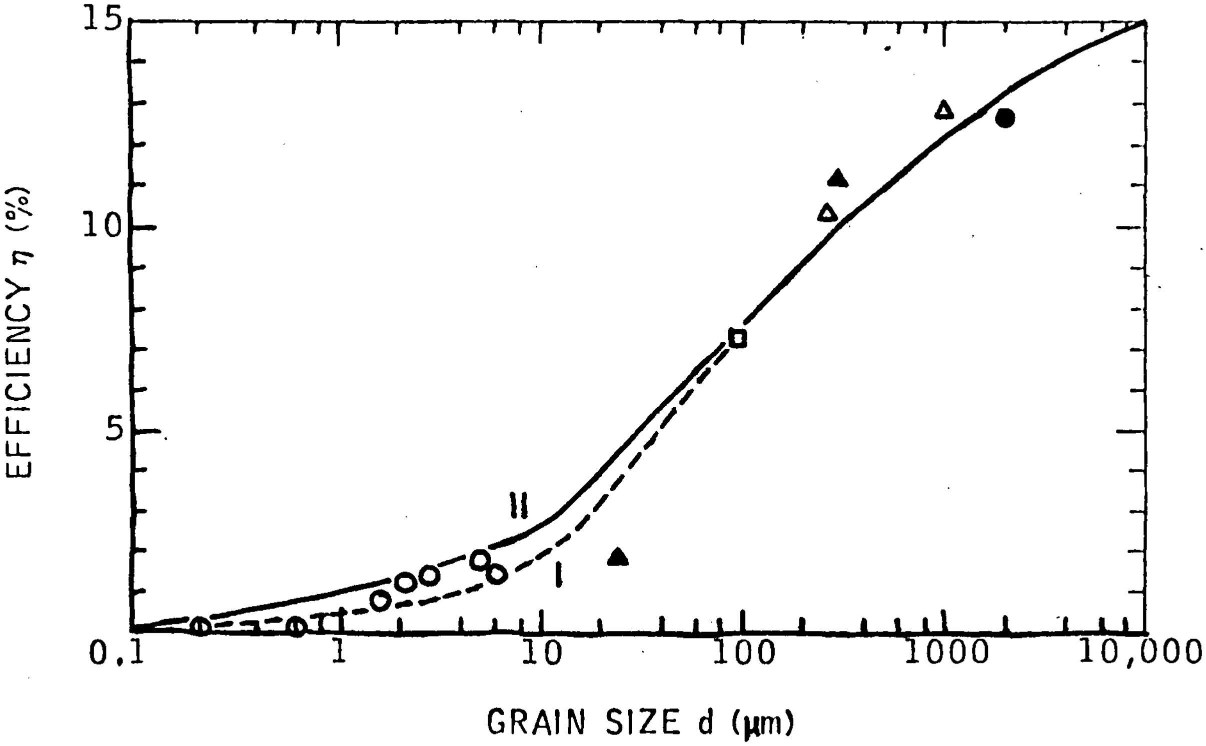
APPROACH: FABRICATION OF VARIOUS SOLAR CELL STRUCTURES (MIS, HETEROJUNCTION, HOMOJUNCTION) ON POLYCRYSTALLINE SILICON; STUDIES OF LONG TERM STABILITY AND DEGRADATION MECHANISMS, AND OF EFFECTS OF GRAIN SIZE ON CELL PERFORMANCE.

ACCOMPLISHMENTS:

- SPRAYED SnO_2 (1000 Å) N-SINGLE CRYSTAL SILICON CELL EFFICIENCY 12.2%, AM1 (V_{OC} = .615V, J_{SC} = 29.1 MA/CM^2, FF = 68%, 3.8 CM^2 AREA).
- SPRAYED ITO (1000 Å) / N-SINGLE CRYSTAL SILICON CELL EFFICIENCY 11.1%, AM1 (V_{OC} = .590V, J_{SC} = 28.3 MA/CM^2, FF = 66%, 3.9 CM^2 AREA).
- ITO AND SnO_2 BY SPRAY TECHNOLOGY ON N-TYPE POLYCRYSTALLINE (WACKER) SILICON GREATER THAN 10% EFFICIENT, 4 CM^2 AREA.
- 10.3% EFFICIENT DIFFUSED-JUNCTION (P ON N) CELL IN WACKER POLYCRYSTALLINE SILICON.
- DEVELOPED THEORETICAL MODEL TO EXPLAIN AND PREDICT PERFORMANCE OF POLYCRYSTALLINE SILICON SOLAR CELLS (MIS, HETERO OR P/N JUNCTION). RESULTS INCLUDE CELL PARAMETERS (V_{OC}, J_{SC}, FF, EFFICIENCY) AS FUNCTION OF GRAIN SIZE.

EXXON RESEARCH AND ENGINEERING COMPANY

PRINCIPAL INVESTIGATOR: AMAL K. GHOSH



THEORETICAL MODEL OF EFFICIENCY AS A FUNCTION OF GRAIN SIZE WITH (I) AND WITHOUT (II) BARRIER SHRINKAGE AT GRAIN BOUNDARIES IN POLYCRYSTALLINE SILICON SOLAR CELLS. EXPERIMENTAL DATA POINTS ARE ALSO SHOWN.

ORGANIZATION: BROWN UNIVERSITY

PRINCIPAL INVESTIGATOR: J. SHEWCHUN

CONTRACT AMOUNT: ~$110K DURATION: 10/1/78 - 1/31/80

APPROACH: INVESTIGATION OF ITO/SILICON SIS SOLAR CELLS; MODELLING, ANALYSES OF LOSS MECHANISMS AND CELL FABRICATION.

ACCOMPLISHMENTS:

- ITO/SINGLE CRYSTAL SI CELL EFFICIENCY 14%, AM1 (V_{OC} = .581V, J_{SC} = 32.2 MA/CM^2, FF = 74.5%, 1.36 CM^2 AREA).
- ITO/WACKER POLYCRYSTALLINE SI CELL EFFICIENCY 9.6%, AM1 (V_{OC} = .542V, J_{SC} = 24.9 MA/CM^2, FF = 71%, 2.6 CM^2 AREA).
- BETTER CONTROL OVER ION BEAM DEPOSITION OF ITO FILMS; REPRODUCIBLE RESULTS.
- LOSS MECHANISM APPROACH TO OPTIMIZE PERFORMANCE HAS SIGNIFICANTLY INCREASED THE VALUE OF V_{OC}.
- INVESTIGATED OTHER OXIDES SUCH AS Cd_2SnO_4.

ORGANIZATION: COLORADO STATE UNIVERSITY

PRINCIPAL INVESTIGATOR: J. DUBOW

CONTRACT AMOUNT: ~$270K DURATION: 10/1/78 - 1/31/80

APPROACH: FABRICATION AND CHARACTERIZATION OF ITO/SILICON SIS SOLAR CELLS.

ACCOMPLISHMENTS:

- ITO/SINGLE CRYSTAL SI CELL EFFICIENCY 9.7%, AM1 (2.2 CM^2 AREA).
- ITO/MONSANTO POLYCRYSTALLINE SI CELL EFFICIENCY 6.8%, AM1 (3.5 CM^2 AREA).
- ANGLE OF INCIDENCE EFFECTS OBSERVED IN ION BEAM DEPOSITION OF ITO FILMS.
- DETECTION AND EVALUATION OF INTERFACE LAYER; UNDULATED OXIDE 12 TO 20 Å.
- DEVELOPED AUTOMATED NETWORK ANALYSIS TECHNIQUE TO EVALUATE EFFECTS OF SURFACE STATES.
- BEST RESULTS OBTAINED WITH NICKEL ELECTROPLATED METALLIZATION.
- MgF_2 AR-COATING INCREASES J_{SC} BY 5%.
- MoO_3 CELLS FABRICATED ON SINGLE CRYSTAL SILICON; 1.7% EFFICIENCY, .079 CM^2 AREA.
- EVALUATED THERMAL DEGRADATION OF ITO/SI CELLS.

ORGANIZATION: SUNY AT BUFFALO

PRINCIPAL INVESTIGATOR: W. A. ANDERSON

CONTRACT AMOUNT: $60K DURATION: 1/1/79 - 12/31/79

APPROACH: DEVELOPMENT OF CR/P-SILICON MIS SOLAR CELLS ON SINGLE CRYSTAL, POLYCRYSTAL AND ELECTRON-BEAM DEPOSITED SILICON.

ACCOMPLISHMENTS:

- SINGLE CRYSTAL SILICON EFFICIENCY 11.9%, AM1 (V_{OC} = .570V, J_{SC} = 30.7 MA/CM^2, FF = 68%, 2.2CM^2 AREA).
- POLYCRYSTALLINE SILICON (WACKER) EFFICIENCY 8.0%, AM1 (V_{OC} = .500V, J_{SC} = 22 MA/CM^2, FF = 73%, 2.2CM^2 AREA).
- THEORETICAL ANALYSIS USED TO IDENTIFY MAJOR LOSS MECHANISMS IN MIS. EFFICIENCY SENSITIVE FUNCTION OF DOPING DENSITY, TRANSMISSION, REFLECTION, INTERFACE AND SURFACE STATES, AND GRAIN SIZE.
- ELECTRON-BEAM DEPOSITED 20-30 μM POLYCRYSTALLINE FILMS ON METAL SUBSTRATES; V_{OC} = 0.1V AND J_{SC} < 1.5 MA/CM^2 ON MIS CELLS.

NEW PROGRAMS IN POLYCRYSTALLINE SILICON CELL DEVELOPMENT (EST. START DATE 10/1/79)

- SENSOR TECHNOLOGY: S. CHITRE

  EXPERIMENTAL INVESTIGATION OF MICROWAVE HEATING IN SOLAR CELL FABRICATION (JUNCTION FORMATION, BSF FORMATION AND METALLIZATION).

- SILTEC CORPORATION: A. C. BONORA

  DEVELOPMENT OF MICROWAVE THERMAL PROCESSING TECHNOLOGY FOR FABRICATION OF SOLAR CELLS (JUNCTION FORMATION AND METALLIZATION).

- RCA LABORATORIES: R. V. D'AIELLO

  INVESTIGATION OF EPITAXIAL GROWTH PROCESSES AND STRUCTURES ON VARIOUS LOW-COST POLYCRYSTALLINE SILICON SUBSTRATES TO PRODUCE HIGH EFFICIENCY, LOW-COST SOLAR CELLS.

BEST EPITAXIAL CELL RESULTS USING UPGRADED METALLURGICAL GRADE SILICON SUBSTRATES

RCA Laboratories; R. V. D'Aiello, P. H. Robinson

Substrate	Base Thickness (μm)	X_J (μm)	J_{SC} (mA/cm^2)	V_{OC} (mV)	FF	Efficiency AM1(%)
Single Crystal Control	15	0.3	26.1	605	0.81	12.7
Dow Corning Metallurgical	15	0.3	25.8	602	0.80	12.4
Dow Corning Metallurgical	15	0.3	25.3	610	0.80	12.4
Single Crystal Control	20	0.3	26.2	598	0.80	12.6
Dow Corning Metallurgical	20	0.3	26.2	605	0.81	12.8
Dow Corning Metallurgical	20	0.3	25.3	610	0.81	12.6
Single Crystal Control	50	0.3	28.0	595	0.79	13.2
Dow Corning Metallurgical	50	0.3	27.1	592	0.80	12.9
Dow Corning Metallurgical	50	0.3	27.0	598	0.81	12.9

POLYCRYSTALLINE SILICON SOLAR CELLS:
BASIC STUDIES RESEARCH AREAS

- DEVELOPMENT OF MEASUREMENT TECHNIQUES TO CHARACTERIZE THE STRUCTURAL, COMPOSITIONAL, ELECTRICAL AND OPTICAL PROPERTIES OF POLYCRYSTALLINE SILICON, AND CORRELATION TO CELL PERFORMANCE.

- DEVELOPMENT OF THEORETICAL PHYSICAL MODELS TO DESCRIBE THE FUNDAMENTAL PHOTOVOLTAIC MECHANISMS WHICH GOVERN AND LIMIT THE CONVERSION EFFICIENCY.

- DETERMINATION OF THE EFFECTS OF GRAIN BOUNDARIES ON THE ELECTRONIC TRANSPORT PROCESSES; MEASUREMENTS AND MODELLING OF GRAIN BOUNDARY EFFECTS.

- DEVELOPMENT OF TECHNIQUES FOR REDUCING OR ELIMINATING THE DELETERIOUS EFFECTS OF GRAIN BOUNDARIES.

ORGANIZATION: RCA LABORATORIES

PRINCIPAL INVESTIGATOR: B. W. FAUGHNAN

CONTRACT AMOUNT: $174K DURATION: 9/11/78 - 9/10/79

APPROACH: DEVELOPMENT OF MEASUREMENT TECHNIQUES TO CHARACTERIZE THE STRUCTURAL, COMPOSITIONAL, ELECTRICAL AND OPTICAL PROPERTIES OF POLYCRYSTALLINE SILICON, AND CORRELATION TO CELL PERFORMANCE.

ACCOMPLISHMENTS:

- TECHNIQUES DEVELOPED FOR ANALYSIS OF GRAIN BOUNDARY EFFECTS (ELECTRON CHANNELLING, DLTS, SPV, QUANTUM EFFICIENCY, 1.15μM LASER SCAN).
- QUANTITATIVE ESTIMATE OF GRAIN BOUNDARY EFFECT IN WACKER MATERIAL DUE TO DECREASE IN L_D (8% LOSS IN J_{SC} DUE TO BULK, 7% LOSS DUE TO GRAIN BOUNDARIES).
- COMPARISON OF LASER SCAN (0.633μM) WITH OPTICAL PHOTOS INDICATES MANY GRAIN BOUNDARIES ARE ELECTRICALLY INACTIVE.
- 1.15μM LASER SCAN SUITABLE FOR DETAILED STUDIES OF PHOTORESPONSE AT GRAIN BOUNDARIES.
- ION-IMPLANTED CELLS FABRICATED WITH EFFICIENCIES AS HIGH AS DIFFUSED CELLS (10.8% SINGLE CRYSTAL, 8.9% WACKER POLY; 4.8 CM^2 AREA, NO AR).
- PHOSPHORUS DIFFUSION AT GRAIN BOUNDARY SLOWER THAN IN SINGLE GRAIN (SIMS ANALYSIS).
- BI-CRYSTALS GROWN BY CZOCHRALSKI TECHNIQUE.

ORGANIZATION: SOLAREX CORPORATION/U. MARYLAND

PRINCIPAL INVESTIGATOR: G. STORTI

CONTRACT AMOUNT: $149K DURATION: 10/1/78 - 9/30/79

APPROACH: THEORETICAL MODELLING AND EXPERIMENTAL INVESTIGATIONS OF GRAIN BOUNDARY EFFECTS IN POLYCRYSTALLINE SILICON SOLAR CELLS TO IDENTIFY LIMITATIONS TO EFFICIENCY.

ACCOMPLISHMENTS:

- THEORETICAL MODELLING SHOWS THAT, FOR GRAIN RADII EXCEEDING A FEW TENTHS OF MM, THE MINORITY CARRIER LIFETIME IN GRAIN DETERMINES J_{SC}.
- LASER AND FINE LIGHT SPOT SCANS SHOW BOTH INCREASES AND DECREASES IN J_{SC} AT GRAIN BOUNDARIES.
- DARK CURRENT OF 10-12% EFFICIENT POLYSILICON CELLS IS DOMINATED BY SPACE CHARGE REGION WHICH LOWERS THE FF AND V_{OC}.
- DARK CURRENT OF 15% EFFICIENT POLYSILICON CELLS IS DOMINATED BY QUASI-NEUTRAL REGIONS.
- OHMIC SHUNTS ARE BELIEVED TO BE CAUSED BY DOPANT PENETRATION ALONG GRAIN BOUNDARIES TO THE BACK CONTACT.
- ORIGIN OF "SINUOUS" GRAIN BOUNDARIES IS ATTRIBUTED TO THE INCORPORATION OF SOLUTE INTO SUCH BOUNDARIES DURING SOLIDIFICATION.
- X-RAY DIFFRACTION AND ELECTRON CHANNELLING USED TO DETERMINE RELATIVE ORIENTATIONS OF ADJACENT GRAINS; <110> COMMON GROWTH DIRECTION.

ORGANIZATION: SRI INTERNATIONAL

PRINCIPAL INVESTIGATOR: S. R. MORRISON

CONTRACT AMOUNT: $98K DURATION: 7/7/79 - 7/6/80

APPROACH: DEVELOPMENT OF ELECTROCHEMICAL TECHNIQUES TO EVALUATE THE PROPERTIES OF POLYCRYSTALLINE SILICON.

ACCOMPLISHMENTS:

- PROGRAM IS IN INITIAL PHASE.
- STUDIES OF C-V AND I-V IN HF ELECTROLYTES ARE IN PROGRESS.
- STUDIES OF SURFACE DAMAGE EFFECTS ARE UNDERWAY.

ORGANIZATION: MOTOROLA, INC.

PRINCIPAL INVESTIGATOR: B. L. SOPORI

CONTRACT AMOUNT: $134K DURATION: 7/30/79 - 7/29/80

APPROACH: CHARACTERIZATION OF STRUCTURAL, COMPOSITIONAL, ELECTRICAL AND OPTICAL PROPERTIES OF POLYCRYSTALLINE SILICON SOLAR CELLS, AND CORRELATION TO CELL PERFORMANCE; DETERMINATION OF EFFECTS OF SPECIFIC PROCESS STEPS ON GRAIN BOUNDARY PARAMETERS.

ORGANIZATION: WESTINGHOUSE/PENN STATE

PRINCIPAL INVESTIGATORS: J. R. SZEDON/S. J. FONASH

CONTRACT AMOUNT: $182K DURATION: 8/1/79 - 7/31/80

APPROACH: THEORETICAL MODELLING OF GRAIN BOUNDARY EFFECTS ON CELL PERFORMANCE; DEVELOPMENT OF OPTICS/ELECTRONICS AND CONTACTING SCHEME FOR LATERAL PHOTORESPONSE CHARACTERIZATION OF POLYCRYSTALLINE SILICON; CHARACTERIZATION AND MODIFICATION OF MINORITY CARRIER LOSSES AT GRAIN BOUNDARIES USING A MATRIX APPROACH TO SEPARATE INTRINSIC AND INTERACTIVE EFFECTS.

ORGANIZATION: UNIVERSITY OF FLORIDA

PRINCIPAL INVESTIGATOR: F. A. LINDHOLM

CONTRACT AMOUNT: $130K DURATION: 9/18/78 - 9/17/79

APPROACH: IDENTIFICATION AND CHARACTERIZATION OF PHOTOVOLTAIC MECHANISMS WHICH GOVERN CONVERSION EFFICIENCY IN POLYSILICON CELLS; BASIC DEVICE PHYSICS AND EXPERIMENTAL ANALYSIS.

ACCOMPLISHMENTS:

- DEVELOPED THEORY OF INFLUENCE OF GRAIN BOUNDARY AND INTRAGRAIN RECOMBINATION CURRENTS ON CELL PERFORMANCE; SUPPORTED BY EXPERIMENT.
- DESCRIBED DEGRADATION OF CELL PERFORMANCE BY AREAL INHOMOGENEITY.
- EXPERIMENTALLY DEMONSTRATED IMPORTANCE OF SURFACE RECOMBINATION VELOCITY AND BANDGAP NARROWING IN EMITTER (HEAVILY-DOPED) REGION OF CELLS.
- MEASURED EFFECTIVE BANDGAP NARROWING FOR DOPING LEVELS UP TO 10^{21} CM^{-3}.
- DEVELOPED SIMPLE ANALYTIC MODELS FOR INCLUDING EFFECTS OF HEAVY DOPING; CAN APPLY NOW TO PHOSPHORUS-PASSIVATED GRAIN BOUNDARIES.

ORGANIZATION: RCA LABORATORIES

PRINCIPAL INVESTIGATOR: D. REDFIELD

CONTRACT AMOUNT: $142K DURATION: 5/31/79 - 5/30/81

APPROACH: THEORETICAL MODELLING OF THE EFFECTS ON SOLAR CELL PERFORMANCE CAUSED BY HEAVY DOPING AND DOPING GRADIENTS, SUCH AS OCCUR NEAR JUNCTIONS AND GRAIN BOUNDARIES; OPTIMIZATION OF SOLAR CELL DESIGN.

ACCOMPLISHMENTS:

- AUGER RECOMBINATION FUNDAMENTALLY CHANGES THE FORM OF THE EQUATION FOR THE SATURATION CURRENT DENSITY; FUNDAMENTAL LOWER LIMIT ON J_0 AS FUNCTION OF DOPING, HENCE AN UPPER LIMIT ON V_{OC}.
- DOPING GRADIENTS IN DIFFUSED REGION DRASTICALLY CHANGE THE ELECTRIC FIELD DISTRIBUTION FROM THAT OF CONVENTIONAL MODELS OF P-N JUNCTIONS; MAJOR EFFECTS ON TRANSPORT PROPERTIES OF MINORITY CARRIERS.

ORGANIZATION: COLUMBIA UNIVERSITY

PRINCIPAL INVESTIGATORS: E. S. YANG, H. C. CARD

CONTRACT AMOUNT: $232K DURATION: 1/1/79 - 6/30/80

APPROACH: THEORETICAL MODELLING OF CARRIER RECOMBINATION AND CARRIER TRANSPORT IN THE VICINITY OF GRAIN BOUNDARIES IN MS AND MIS SOLAR CELLS.

ACCOMPLISHMENTS:

- MAJORITY CARRIER TRANSPORT CHANGES FROM THERMIONIC EMMISSION TO BULK LIMITED CONDUCTION IN AN IDEAL SCHOTTKY BARRIER WITH DECREASING BARRIER HEIGHT AND GRAIN SIZE AND INCREASING GRAIN BOUNDARY MISMATCH ANGLE.
- MINORITY CARRIER INJECTION DOMINATES DARK CURRENT FOR SMALL GRAIN SIZE AND LARGE MISMATCH ANGLES.
- EXPERIMENTS ON AL/P-SI (WACKER) SCHOTTKY BARRIERS SHOWED THAT BOTH DARK AND ILLUMINATED ELECTRICAL CHARACTERISTICS ARE SENSITIVE TO MISMATCH ANGLE.
- MINORITY CARRIER MIS CELLS EXHIBIT SLIGHTLY HIGHER CONVERSION EFFICIENCY THAN MAJORITY CARRIER MIS CELLS WHEN SiO_2 LAYERS ARE FABRICATED UNDER IDENTICAL CONDITIONS. EXACT VALUE OF SiO_2 THICKNESS NOT AS CRITICAL FOR OPTIMUM RESPONSE OF MAJORITY CARRIER CELLS.

ORGANIZATION: SANDIA LABORATORIES

PRINCIPAL INVESTIGATORS: D. S. GINLEY, C. H. SEAGER

CONTRACT AMOUNT: $150K DURATION: 1/1/79 - 12/31/79

APPROACH: FUNDAMENTAL STUDIES OF GRAIN BOUNDARY PASSIVATION IN POLYCRYSTALLINE SILICON.

ACCOMPLISHMENTS:

- GRAIN BOUNDARY CONDUCTION HAS BEEN DESCRIBED IN TERMS OF A THERMAL EMISSION MODEL; THIS HAS ALLOWED FOR DETERMINATION OF THE DENSITY OF DEFECT STATES.
- GRAIN BOUNDARY PASSIVATION HAS BEEN DEMONSTRATED (H-PLASMA, 10^{-1} TORR, 300°C TO 650°C, 3 TO 10 HOURS); GRAIN BOUNDARY CONDUCTANCE INCREASED BY FACTOR OF 10^5.
- SOME IMPROVEMENT IN SOLAR CELL EFFICIENCY AND IN MINORITY CARRIER LIFETIME IN DIFFUSED-JUNCTION NTD POLYSILICON AFTER PASSIVATION.
- DENSITY OF DEFECT STATES SHOWN TO DECREASE AFTER PASSIVATION (5×10^{16} TO $5 \times 10^{14}/M^2$ eV).

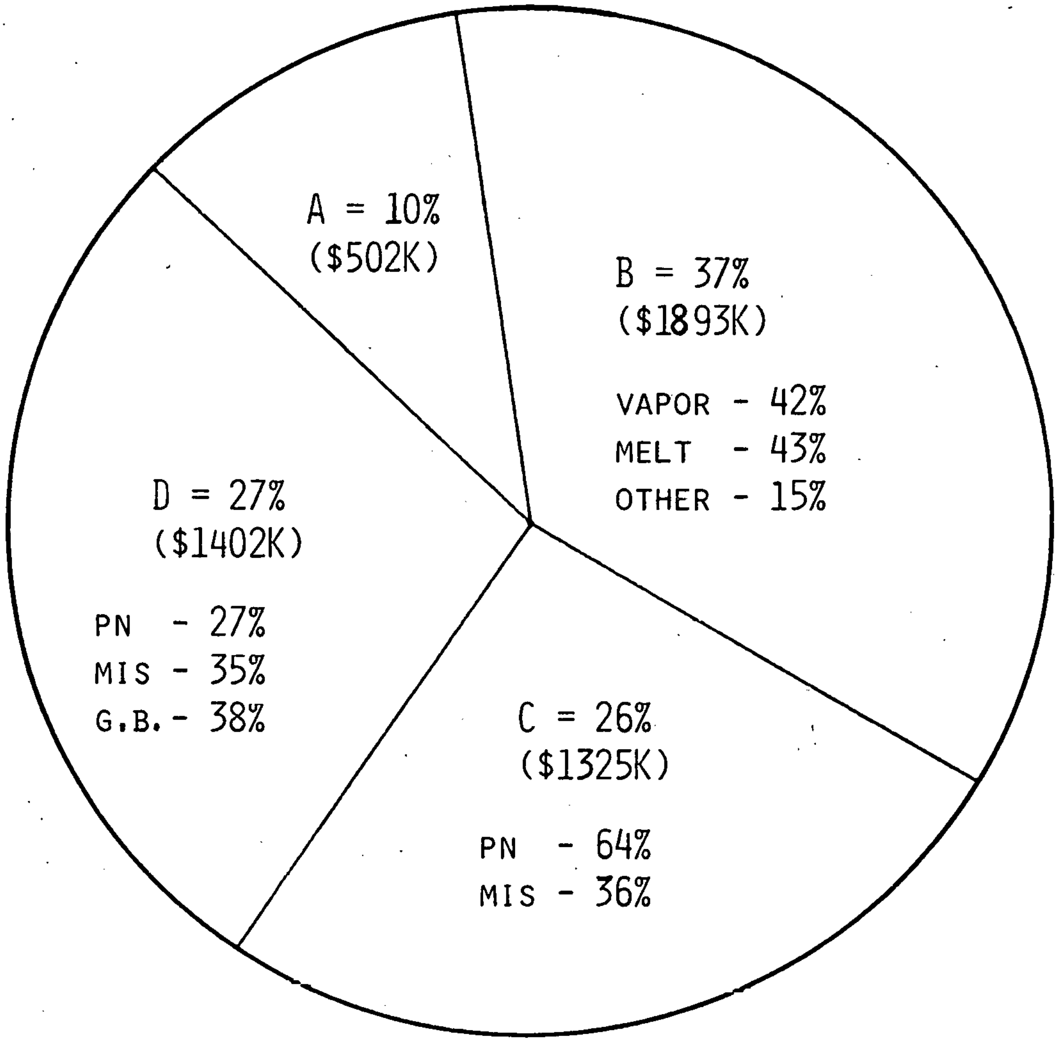
PROBLEM AREAS FOR STUDY

- MATERIALS DEVELOPMENT
  - SMALL GRAIN SIZE IN CVD, PVD AND ELECTRODEPOSITION.
  - RECRYSTALLIZATION OF SMALL GRAIN SIZE FILMS.
  - GRAIN BOUNDARY PASSIVATION DURING OR AFTER FILM GROWTH.
  - DIRECT PURIFICATION OF METALLURGICAL GRADE SILICON.
  - SCALE-UP AND COST POTENTIALS OF TECHNIQUES.

- CELL DEVELOPMENT
  - MUCH OF RESEARCH NOT ON LOW-COST POLYSILICON.
  - ADAPTABILITY OF LOW-COST CELL FABRICATION TECHNIQUES TO THIN POLYCRYSTALLINE FILMS.
  - NOVEL LOW-COST CELL FABRICATION TECHNIQUES.
  - STABILITY/DEGRADATION STUDIES IN POLYCRYSTALLINE CELLS.
  - SCALE-UP AND COST POTENTIALS OF TECHNIQUES.
  - MIS/SIS: LOWER EFFICIENCIES THAN P/N, STABILITY/DEGRADATION, DEVICE PHYSICS, SURFACE AND INTERFACIAL ANALYSIS, SCALE-UP AND COST POTENTIALS.

- BASIC STUDIES
  - RELATION OF STUDIES TO EVENTUAL LOW-COST MATERIALS.
  - STUDIES OF DEFECT/IMPURITY COMPLEXES AND CONTROL OF DEFECT STRUCTURES.
  - AVAILABILITY OF POLYCRYSTALLINE SILICON MATERIALS.
  - INTERACTION AMONG MATERIALS AND BASIC STUDIES GROUPS.

FUNDING BREAKDOWN BY RESEARCH AREA



A = MG-SILICON PURIFICATION
B = GROWTH OF POLY-SI FILMS
C = CELL FABRICATION
D = BASIC STUDIES (G.B. = GRAIN BOUNDARY)

STATUS OF POLYCRYSTALLINE SILICON SOLAR CELL TECHNOLOGY

- CELL EFFICIENCY GREATER THAN 10% DEMONSTRATED IN "THIN-FILM" CELLS.
- LARGE AREA (~10 CM^2) CELLS FABRICATED.
- CELL STABILITY SUFFICIENTLY DEMONSTRATED.
- THEORETICAL PRINCIPLES GOVERNING TECHNOLOGY ARE UNDERSTOOD.
- MATERIAL SYSTEM APPEARS AMENABLE TO LOW-COST TECHNOLOGY.

  - SEVERAL APPROACHES TO THIN-FILM POLYCRYSTALLINE SILICON SOLAR CELLS APPEAR TO BE READY FOR A COMPREHENSIVE EXPLORATORY DEVELOPMENT TO EXAMINE: SCALE-UP POTENTIAL, REPRODUCIBILITY AND YIELD OF LARGE-AREA, HIGH EFFICIENCY CELLS, AND ANALYSIS OF COST POTENTIAL OF TECHNIQUES.

CHARACTERIZATION OF GRAIN BOUNDARIES IN SOLAR CELL MATERIALS

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ABSTRACT

Grain boundaries in multigrained Si and polycrystalline GaAs are characterized using surface analytical techniques. Complementary Auger electron spectroscopy (AES), secondary ion mass spectroscopy (SIMS) and X-ray photoelectron spectroscopy (XPS) are used in conjunction with in-situ, ultrahigh vacuum fracturing to examine the chemistry of the grain boundaries. Scanning Auger microprobe (SAM) and electron beam induced current (EBIC) techniques are used to electrically analyze the same regions characterized compositionally by the surface analysis methods. These results are correlated, and indications of the importance of grain boundary chemistry on solar cell performance are provided.

1. Introduction

Grain boundaries are perceived to be important in determining the performance of polycrystalline solar cells. However, very little is yet known about the properties of individual grain boundaries in a given material. Although the basic mechanisms affecting carrier transport at grain boundaries in polycrystalline semiconductors is currently receiving necessary and increased emphasis, very little of this work is concerned with the correlation of the chemistry, impurity and phase composition of the grain boundary with the resulting electrical activity of that region. In fact, most studies assume that the grain boundary is only a transition region from one crystallite to another, characterized completely by some mismatch in crystal orientation with accompanying misfit dislocations. This paper examines the physical composition of grain boundaries in multigrained Si and polycrystalline GaAs, and correlates these properties with in-situ electrical measurements on the same grain boundaries. The methods used for physical and chemical characterization are:

- Auger electron spectroscopy (AES)
  (electrons in - electrons out)
- Secondary ion mass spectroscopy (SIMS)
  (ions in - ions out)
- X-ray photoelectron spectroscopy (XPS)
  (X-rays in - electrons out)

Complementing these surface analysis techniques, electrical characterization is accomplished using

- Scanning Auger microprobe (SAM)
- Electron beam induced current (EBIC)

By careful control and tracking, selected grain boundaries can be electrically evaluated using the techniques mentioned above. Thereafter, in the same analysis system, the interior of the polycrystalline samples can be exposed using in-situ ultrahigh vacuum fracturing. Thus, the selected grain boundary (under fortunate conditions) can be physically and chemically examined by one or more of the surface techniques. In most cases, grain and grain boundary regions can be analyzed under identical, side-by-side conditions.

2. Multigrained Silicon[1]

The methods summarized in the previous section have been used successfully in characterizing grain boundaries in Si[1]. The methods have been used to provide the first direct physical evidence' for the non-uniform localization of impurities at the grain boundaries in silicon grown by the casting and directional solidification techniques. The multigrained silicon samples used in this study were obtained from three different sources. Two of these were produced by a "conventional" casting process in which the silicon was molten when poured into the shaping crucible held slightly below the melting point of the silicon. The third sample type was produced by the directional solidification process. This differs from casting in that solid silicon was initially loaded into the crucible and subsequently heated into the molten phase. In either case, the cooling and cooling rate were precisely controlled to provide optimum grain size and structure.

Auger mapping of a grain boundary area has been utilized to investigate impurity localization along the grain boundary.[1] The Auger maps of this region do give evidence to impurity concentrations, Ni, Al and C, in these areas with oxygen prevalent throughout. It should be emphasized that the Auger maps here indicate build-up of the impurities, which can be remnants due to fracturing, and lower concentrations of each are detectable throughout the grain boundary regions. No impurities are found in the grain interior. The grain boundary localization of the Ni and Al (in the form of NiO and Al_2O_3, probably from the crucible) is verified by the depth-compositional profiles. The chemical composition of these species is verified from AES peak positions and peak shapes. SIMS analysis is used to provide trace analysis information, both on the fractured grain and grain boundary. A controlled oxygen leak (10^{-7} torr) is used to enhance secondary ion yields. The SIMS spectrum indicates primarily the presence of Si; the only impurity is the intentional dopant, B. The oxides result from the oxygen leak, and Na and K result from the inevitable inclusion of the top and/or bottom surfaces of the thin samples (previously exposed to the atmosphere) in the SIMS analysis. In contrast, many impurities are observed in fractures at the grain boundary.

In addition to the C, O, Al and Ni, trace impurities including O, B, Mg, Ti, Cr, Fe, Co, Cu, An and Sb are detected. None of these appear in the corresponding analysis performed on the grain region. SIMS profiles do confirm that the impurities are localized at the boundary and do not significantly penetrate the grain itself. Typical thicknesses of these impurity localizations are 20-80Å. Bulk analysis by spark souce mass spectroscopy shows the concentrations of these impurities to be in the 10^{11} - 10^{14}/cm^3 range. Quantitative interpretation of the SIMS data indicates that as much as 20% of the grain boundary atomic composition is non-silicon'. Typical comparative SIMS spectra of grain and grain boundary regions are shown in Fig. 1.

The electrical properties of selected grain boundary regions are investigated using high resolution SAM and EBIC techniques. Conductivity data correlating the electrical behavior of grain boundaries with specific grain boundary compositions are measured. Direct evidence is reported which indicates that the electrical activity of the grain boundaries differ considerably in a given sample and depend on the localization of impurities in that region. Fig. 2 presents such a comparison, using the SAM technique reported by Cohen et al.[3] In this, the C_{271} signal from the residual carbon on the sample surface is monitored while stepping the incident electron beam across the surface. When the sample is biased, the Auger spectrum is shifted by an energy which is proportional to the applied bias voltage. This arrangement is shown in the insert of Fig. 2. Thus, the observed shift indicates the electrical activity of the region and the method provides a contactless voltmeter with spatial resolution. The dashed line in Fig. 2 (labelled (a)) indicates the expected ohmic behavior across a grain. The corresponding response across a low impurity content (essentially impurity free) and a high impurity content grain boundary are give by curves (b) and (c) respectively. Comparing these data, the potential drop across the low impurity boundary is greater than the high impurity content boundary ($V_b > V_c$). In addition, the effective depletion region d_b is greater than d_c. Thus, both a higher diffusion potential and greater depletion region is experienced by minority carriers in the vicinity of the cleaner grain boundary. The effect of the impurity carriers in the vicinity of the cleaner grain boundary. The effect of the impurity segregation is to passivate these regions for minority carrier flow. EBIC measurements verify these observations.

Electrical characterization of grain boundaries has also been accomplished using EBIC. Fig. 3 presents results on three grain boundaries of differing electrical activity and chemical composition. The boundary at (a) (Fig. 3a) shows some EBIC response (Fig. 3b and c), but the grain boundary at (b), almost none. A SIMS analysis after fracture of those same two regions showed that boundary (a) was "cleaner" than (b). In fact, Fig. 3d and e show a boundary which is almost impurity free, but its EBIC response (under the same conditions as (a) and (b)) is much more apparent. These preliminary results suggest that the cleaner grain boundaries are more electrically-active, and these with larger impurity concentrations, passivated to some degree.

3. Gallium Arsenide[2]

The basis for this investigation results from an experimental artifact. Schottky barrier solar cells were fabricated from MBE and LPE polycrystalline n-type material which had the same electrical ($n \sim 10^{16}/cm^3$, $\rho \sim 0.1$ Ω-cm) and physical (3-5μm grain size, (100)-orientation) properties. However, although the MBE material was expected to be of higher quality due to the cleaner and better controlled growth conditions, solar cells fabricated from the LPE GaAs consistently had better characteristics. Au-Schottky barrier devices fabricated simultaneously from these two materials differed significantly, with $\eta \sim 1$-2% typical for MBE and ~5% (AM1) for LPE poly-GaAs.

The surfaces of these films were examined by AES in order to find some possible impurity difference between the MBE and LPE GaAs.[2] The AES surveys, shown in Fig. 4 (MBE) and Fig. 5 (LPE), do not, however, indicate any residual impurity content within the detection limits of the technique. However, a closer examination of these spectra, taken under the same operating conditions, shows some noticeable differences in the peak shapes and positions, especially for the Ga peaks in the 990-1050eV range. These differences are more readily discernible in the expanded spectra presented in Figs. 6 and 7. A shift of 3eV in the Ga_{MNN} major peak, as well as shifts in other Ga peaks, are apparent between the two materials. In addition, the expected 1017, 1028 and 1051eV Ga peaks are more pronounced in the MBE GaAs.

Since no other impurities were detected and since the orientations, physical and electrical properties were approximately the same, and the fact that the AES data were reproducible from sample-to-sample, it was first assumed that the spectral differences were due to some basic, inherent material differences between MBE and LPE produced GaAs. However, a SIMS analysis, shown in Fig. 8, provided one basic correlation factor. The LPE material consistently showed the presence of oxygen in the SIMS spectra, while the MBE GaAs did not. The oxygen, although below the detectability limit of AES, did apparently provide the peak shape and energy position differences between the materials. The origin of the oxygen was subsequently determined to be from the residual LPE reactor condicions which provided a limited residual O_2 partial pressure during film growth.

Samples of each type were fractured in UHV so that the interior regions of the films could be examined. Using a focused AES beam, certain regions of the LPE films did show significant oxygen concentrations, while none was detected in any of the MBE layers. Fig. 9 shows a spectrum taken in the upper portion of the LPE film, about 1μm below the surface. The AES spectrum indicates that this portion is primarily Ga_2O_3. XPS data taken selectively on this region are shown in the insert of Fig. 6 and confirm by the 0.9eV shift in the 3d Ga peak that the phase is Ga_2O_3. The localization of this oxide is confirmed by the AES depth compositional profile of Fig. 10. The oxide layer is approximated to be 25Å thick from the calibrated sputtering rate for Ga_2O_3. Through a careful and tedious correlation of the location of these oxidized regions with the topography of the film provided by a secondary electron detection image, the regions were confirmed to be grain boundaries.

4. Summary

- Grain boundaries differ from material to material, as well as within a given material. Their contributions to the determination of solar cell performance differ.

- Grain boundary chemistry is important.

- In silicon, the impurities are localized on the grain boundaries in cast and directionally-solidified material. This can lead to interface state density differences and non-uniform electrical activity. (Problems for modeling).

- The impurity segregation can provide grain boundary passivation.

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[3] M.J. Cohen, J.S. Harris and J.R. Waldrop, Institute of Phys. Conf. Series, Vol.45 (Institute of Physics, London; 1979) pp.263-269.

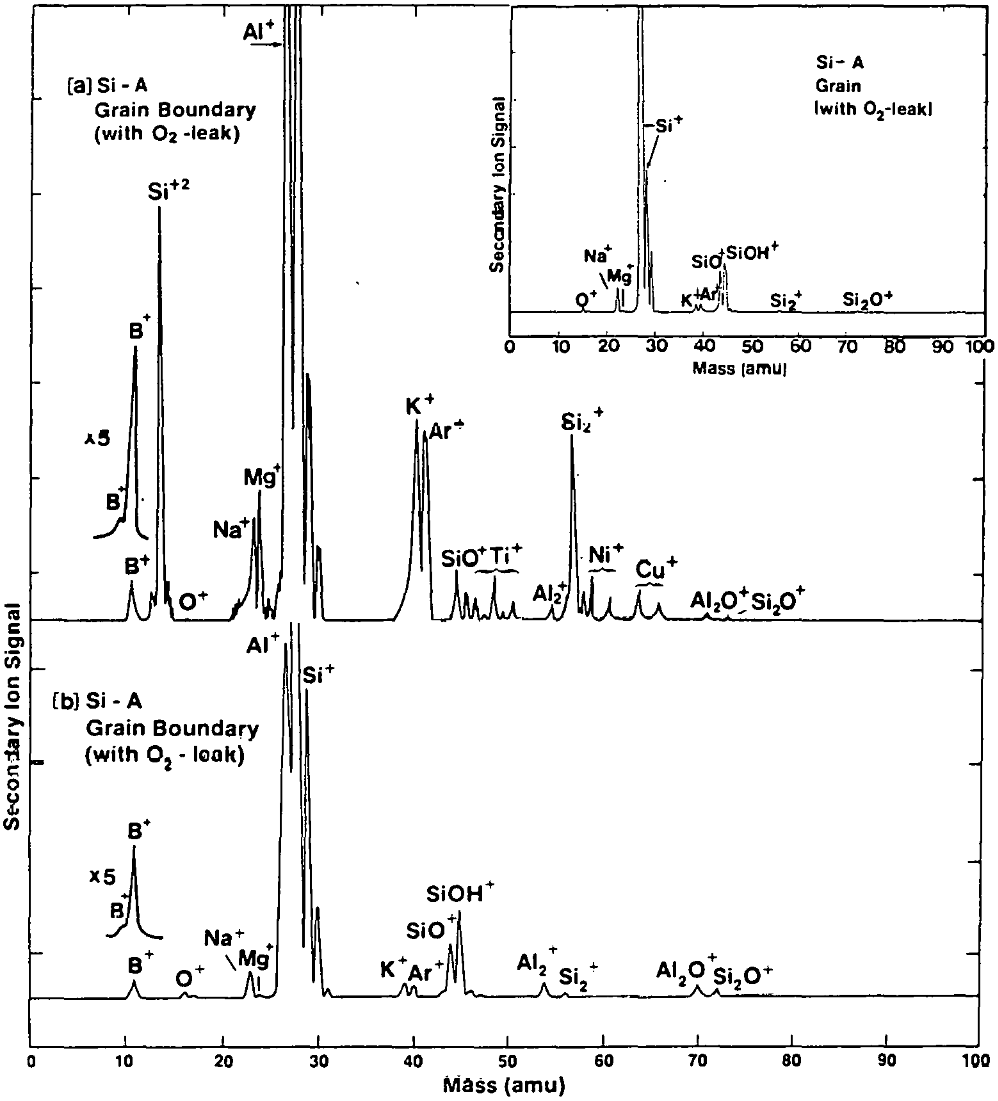

Fig. 1. Positive SIMS Spectra, Multigrained Si. Insert shows grain region. (a) Grain Boundary; (b) Grain Boundary, 3 mm from (a).

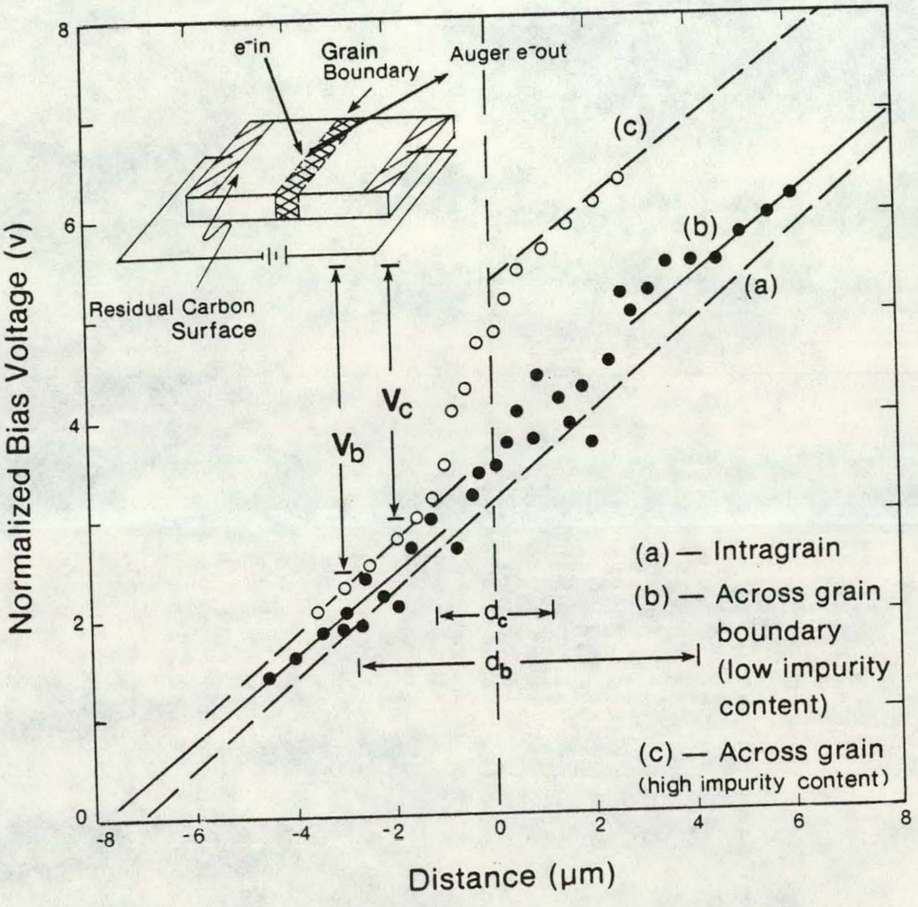

Fig. 2. SAM electrical characterization of grain boundaries.

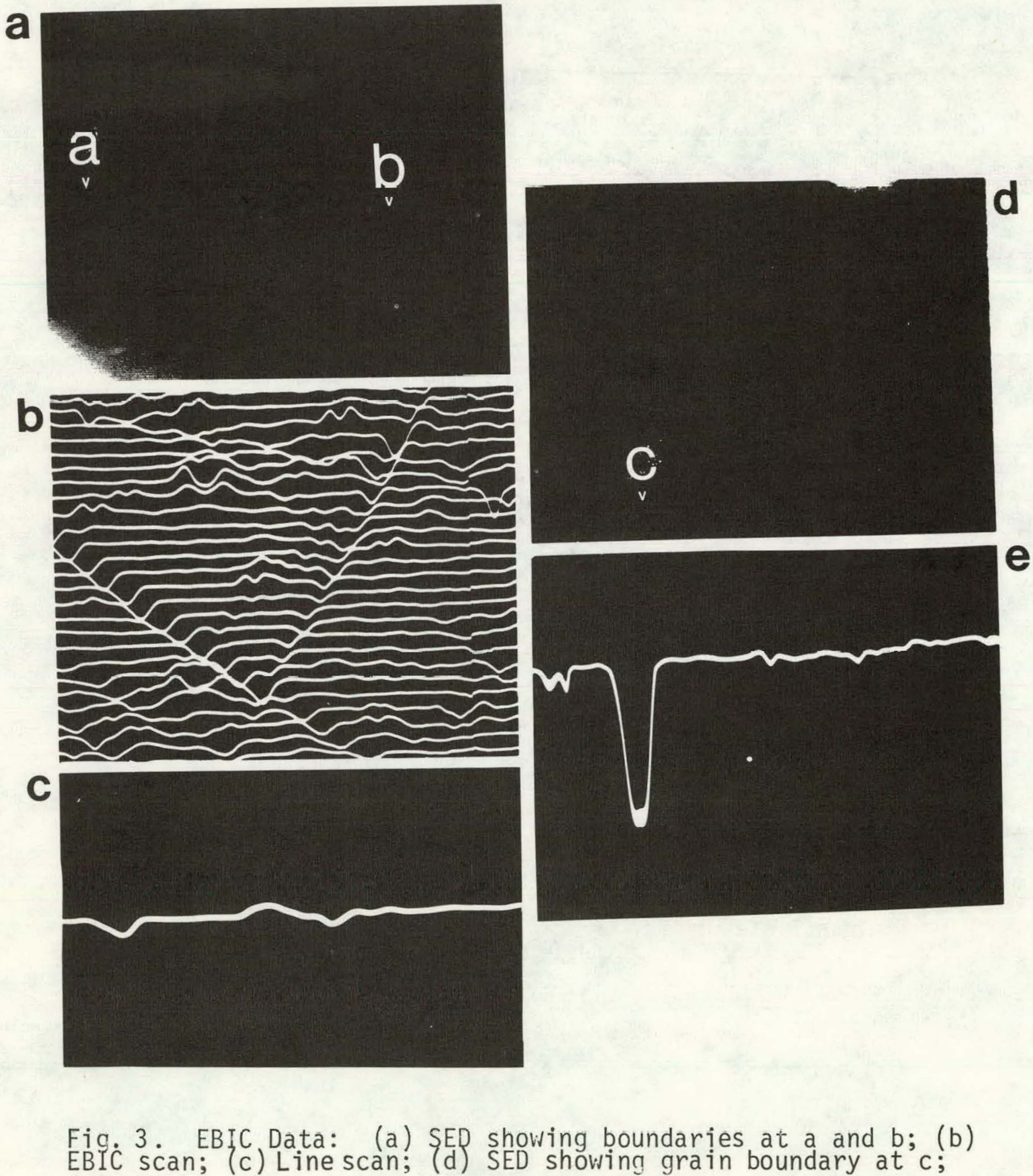

Fig. 3. EBIC Data: (a) SED showing boundaries at a and b; (b) EBIC scan; (c) Line scan; (d) SED showing grain boundary at c; (e) EBIC Response.

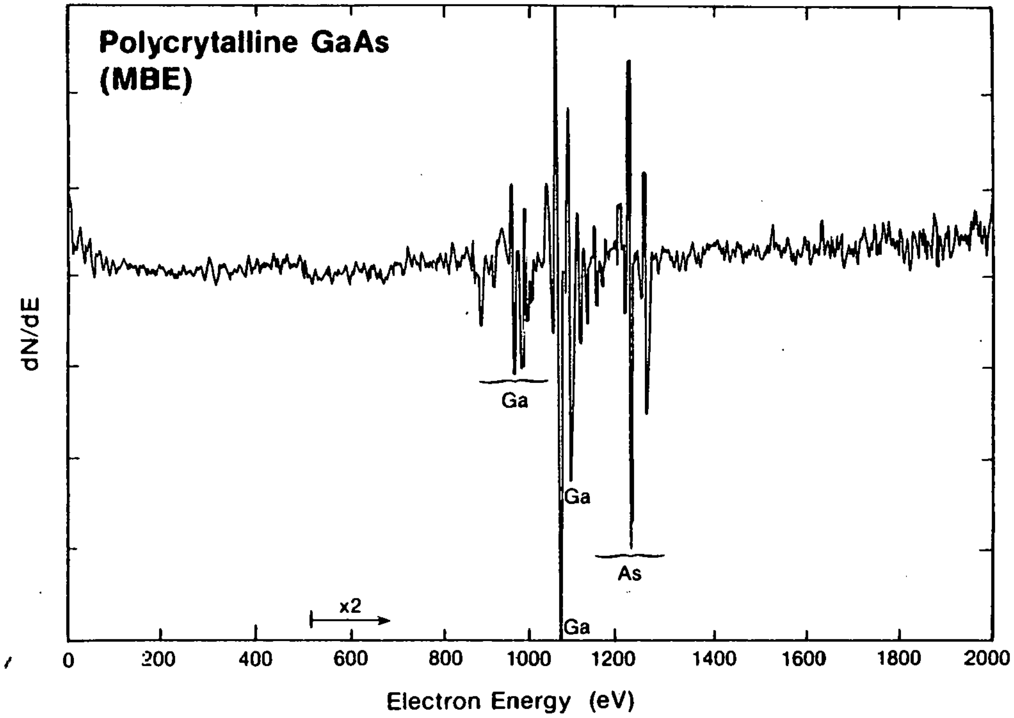

Fig. 4. AES spectrum of polycrystalline GaAs grown by MBE. E_p=5kV, I_p=0.15μA.

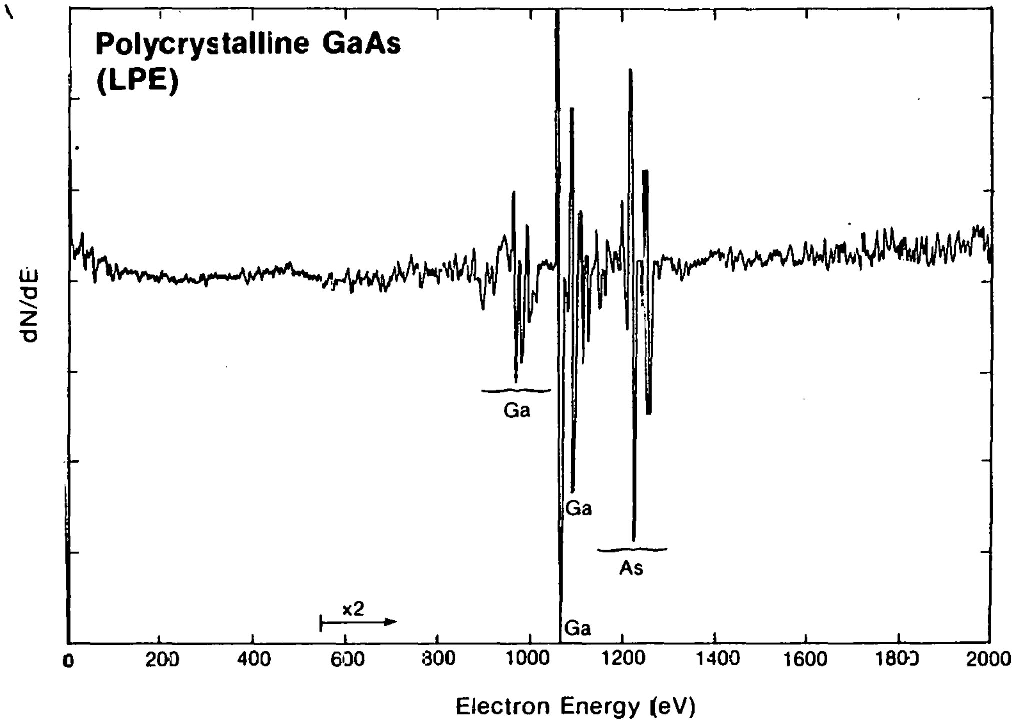

Fig. 5. AES spectrum of polycrystalline GaAs grown by LPE, taken under same conditions as data in Fig. 4.

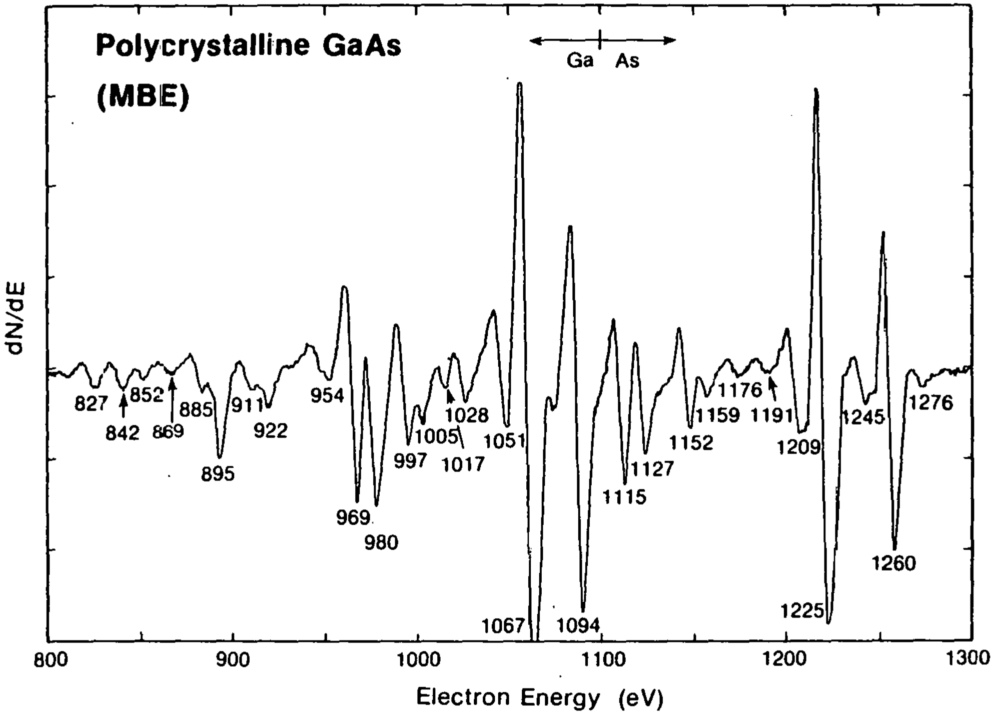

Fig. 6. Expanded AES spectrum showing 800-1300eV range for polycrystalline GaAs (MBE) from Fig. 4. Note positions and shapes of 1005, 1017, 1028 and 1051eV peaks.

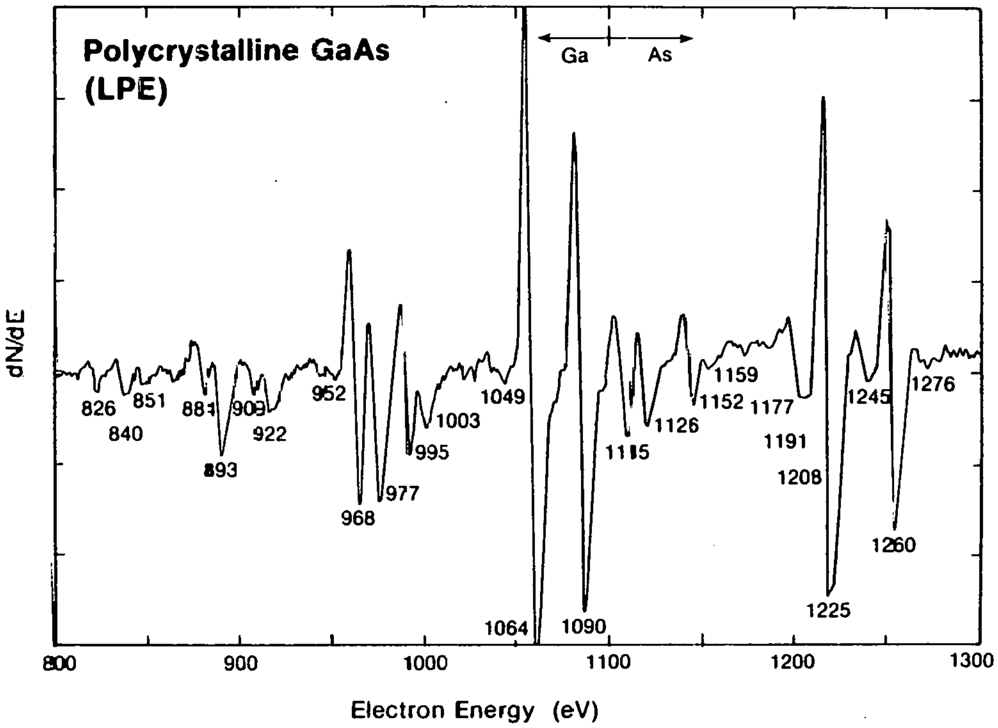

Fig. 7. Expanded AES spectrum showing 800-1300eV range for polycrystalline GaAs (LPE) from Fig. 5. Compare 1003-1049eV range to that in Fig. 6.

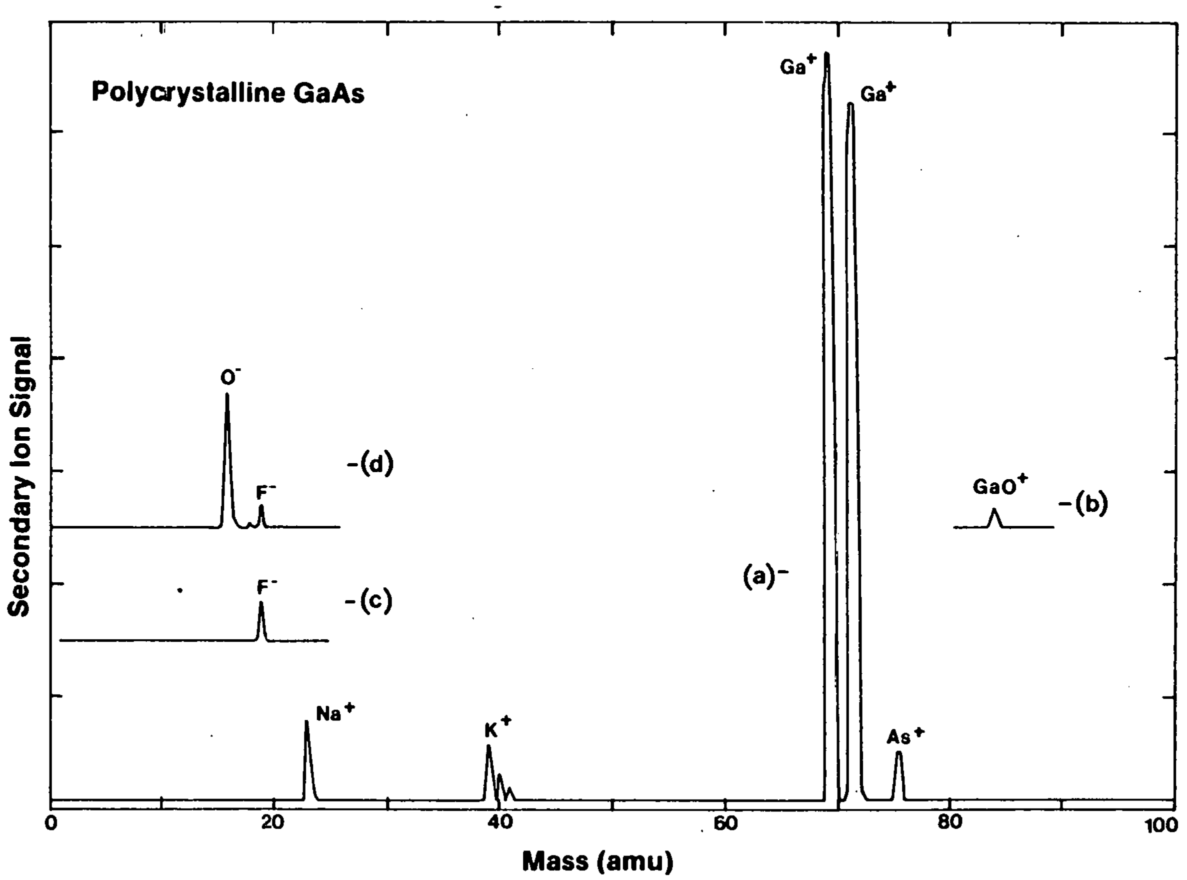

Fig. 8. SIMS spectra from LPE and MBE polycrystalline GaAs surfaces. a) Total positive SIMS spectrum of MBE sample; (b) Portion of positive SIMS spectrum of LPE sample showing presence of oxide species; (c) Negative SIMS spectrum of MBE GaAs (no oxygen present); and (d) Negative SIMS spectrum of LPE material indicating presence of oxygen in film.

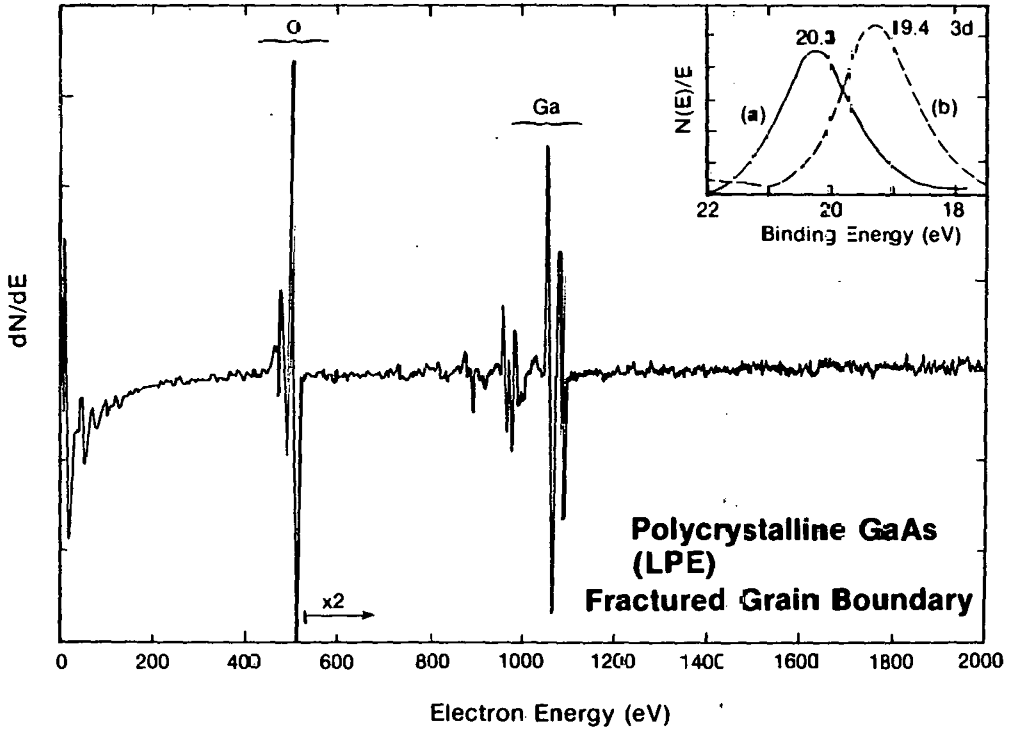

Fig. 9. AES spectrum of LPE polycrystalline GaAs fractured to expose grain boundary. Data are taken approximately 1.0μm below upper film surface. (Minimum beam diameter conditions). Insert shows XPS data: (a) this region, indicating presence of Ga_2O_3; (b) reference signal for Ga 3d peak from GaAs.

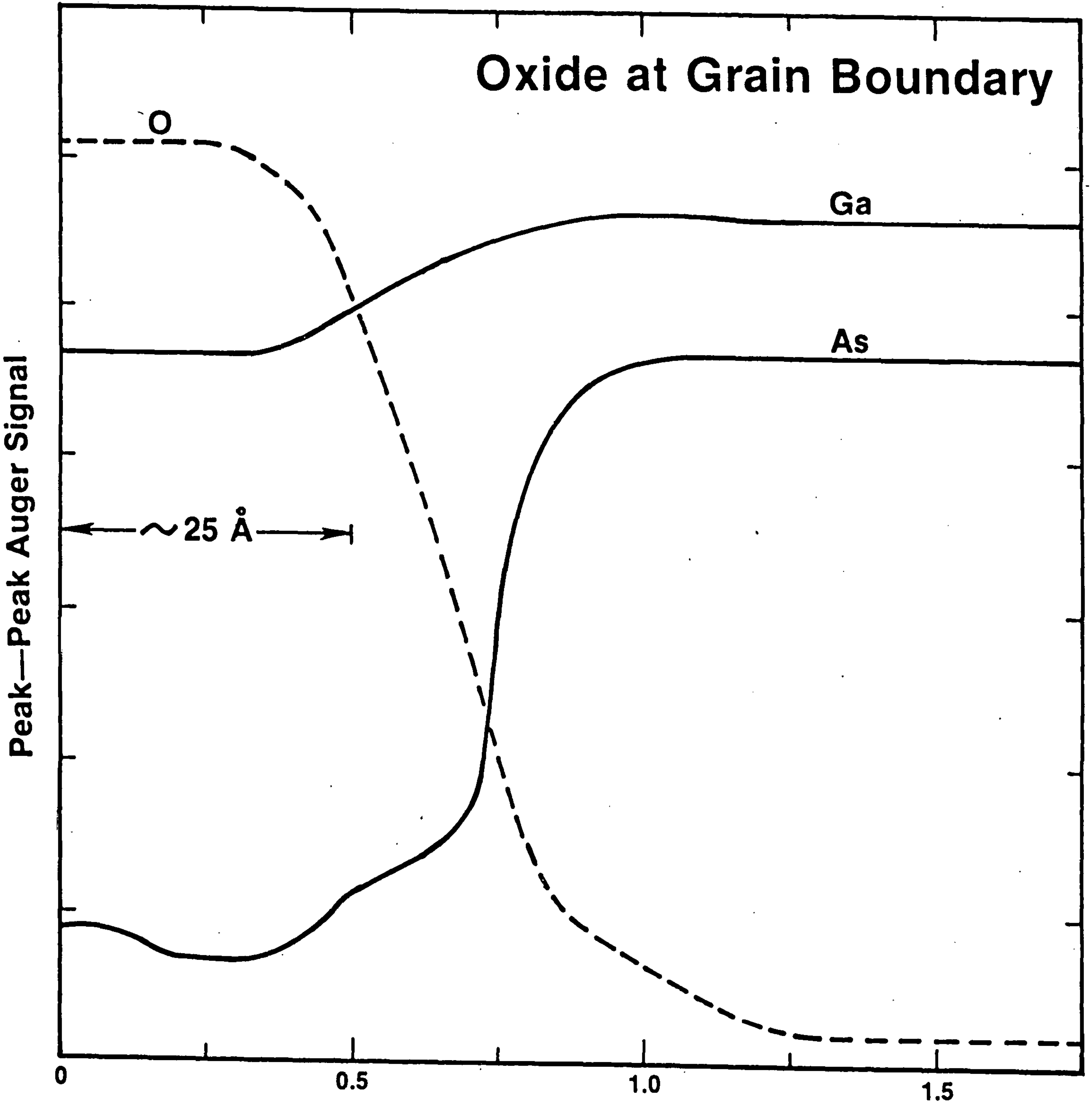
Oxide at Grain Boundary
O
Ga
As
~25 Å
Peak—Peak Auger Signal
0
0.5
1.0
1.5
Sputtering Time (min)

Fig. 10.

NOTES

GRAIN BOUNDARY PASSIVATION AND SOLAR CELL IMPROVEMENT IN POLYCRYSTALLINE SILICON*

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Flat-plate silicon solar cells offer the potential for inexpensive, maintenance-free electrical power production. For that potential to be realized, the cost of the cells must be reduced and their efficiency increased. Thin film polycrystalline solar cells appear to be economically feasible to produce, but have substantially reduced efficiencies when compared to single crystal cells. We will discuss the possible applications of recently discovered (1,2) grain boundary chemical passivation treatments (utilizing monatomic hydrogen) for polycrystalline silicon. We will also present evidence indicating that it may be possible to substantially increase solar cell efficiencies by this technique.

One of the commonly proposed electronic energy diagrams of the grain boundary region is illustrated in Fig. 1.(3) Part A schematically shows the two grains and the region at their boundary if all three were physically isolated. Part B shows the band bending in the grains and the increase in the Fermi level in the boundary which occurs after joining (at zero bias). The defect states at the boundary responsible for the generation of these double depletion layers are most probably "dangling" silicon bonds and/or oxygen or other impurity levels. These recombination centers and the attractive field which exists in the depletion regions effectively trap photogenerated minority carriers and thus substantially reduce polycrystalline solar cell short-circuit currents. Grain boundaries can also act as shunts across a p-n junction, substantially lowering device fill factors and open-circuit voltages. Recently, it has been shown that the flow of current across silicon grain boundaries can be effectively described in terms of thermal emission theory.(4,5) The density of states from direct measurements of charge emission from silicon grain-boundary defect states is in excellent agreement with values obtained by the deconvolution of current-voltage I-V data. Thus, it is possible to directly examine the passivation process by looking at the change in the density of states.

In general, the effectiveness of the passivation process can be probed by examining the grain boundary conductance in a simple four probe fashion. Fig. 2 illustrates two potential vs. distance traces for a slice of p-type polysilicon with approximately 100 micron grains. The upper portion of the curve is for the virgin slice, the vertical steps are the voltage drops across individual grain boundaries. The lower curve is for the same sample, exposed to a 500 millitorr hydrogen plasma for 14 hours at 400°C (note the increased current). Significant increases in grain boundary conductance are seen and the overall sample conductance approaches that of the bulk.

Having established that the passivation process is quite effective at altering grain boundary conductances, we have begun to perform experiments to understand and optimize the process. The rest of the discussion will deal with the observations we have obtained to date.

Fig. 3 illustrates the effect of a series of treatments on the zero-bias conductance, G_o, of an individual grain boundary in a sample of neutron transmutation doped polysilicon. Treatments a, c, f, i and k are hydrogen plasma treatments of various durations at temperatures between 330 and 400°C and pressures of 60 - 100 millitorr. In each case substantial increases in G_o are observed. Treatments b, d and g are vacuum anneals carried out at 1×10^{-6} torr at 620°C. At this temperature a complete return to virgin conductance levels is observed. Treatment e was performed under identical conditions to the hydrogen plasma treatments except for the absence of the electrical discharge. The conductance actually decreases somewhat which may indicate the absorption of impurities in the grain boundary. From this observation, it is clear that the atomic hydrogen generated in the plasma is essential to the process effectiveness. Treatment h is at very low hydrogen pressure (10^{-2} torr); this is apparently below the optimum pressure range for passivation (~100 - 500 millitorr). Treatment j is an anneal in a low-partial pressure of oxygen 5×10^{-4} torr at 625°C. This illustrates that the incorporation of impurity atoms can reduce the grain boundary conductance to values significantly below virgin levels. This effect can be enhanced by higher pressures and has been observed for O_2, SF_6 and N_2.

The zero-bias conductance of two different grain-boundary potential barriers in neutron-transmutation doped polycrystalline silicon are illustrated in Fig. 4. The solid curves show the virgin conductance values, the dashed curves the results after hydrogenation at 400°C for ≈5 hr. In addition to marked increases in barrier conductance, hydrogenation weakens the temperature variation of the barrier conductance; in the case of 10^{16} p/cm^3 sample the observed temperature dependence loses its activated character and takes on an opposite, but weak, variation, characteristic of the conversion of the grain boundary to a simple scattering center for majority carriers. A closer examination of the temperature dependence of the conductance of a virgin and treated sample is illustrated in Fig. 5. The activation energy for conductance in the virgin state is approximately .62 eV while that in the hydrogenated sample is 0.035 eV. This is indicative of a substantial reduction in the number of trap states in the boundary and consequent reduction of barrier height and ease of emission over the barriers. This is further illustrated in Fig. 6, where for the same sample we plot directly the effective density of grain boundary states N_t^* versus energy (in eV) with the zero of energy being the valence band maximum.

The data is obtained by deconvoluting current-voltage data according to the Seager-Pike deconvolution scheme.(4) A substantial reduction in the density of states is observed as expected from the temperature dependence of G_0. Thus, the hydrogen plasma treatment seems to drastically reduce the density of states in the grain boundary region, giving rise to significant reductions in the double depletion layers and consequent increases in conductance.

To evaluate the effective penetration depth of the treatment, a series of etching steps are performed on a sample while monitoring the grain boundary conductance. The results are illustrated in Fig. 7. The effectiveness of the treatment, 417°C for four hours at 500 millitorr, tails off rapidly after below 100 microns with the conductance of the grain boundary near the center of the sample finally approaching that of the virgin state (dashed curve). Some of our treatment effectiveness vs. penetration depth information is summarized in Fig. 8. Plotted is the zero-bias conductance per unit area for various boundaries vs. penetration depth. The 400°C runs are quite effective near the surface, but the conductance rapidly decreases to virgin values at depths greater than 60 μm. The 550°C process seems to passivate boundaries more uniformly throughout the sample, with increased conductances observed in the center of even 500 micron thick samples; however, near the surface boundaries are less affected than at 400°C. These observations most probably reflect the competition of the relative rates for diffusion and binding of the hydrogen.

The fact that grain boundary impedances can essentially be eliminated to depths of up to 100 μm indicates that the passivation process should be very effective on thin films. Fig. 9 illustrates that this is indeed the case. Here we plot the ratio of the zero-bias conductance after treatment to the virgin conductance for variously doped 5 μm thick CVD polysilicon films. The horizontal axis is a rough indication of doping level with PSN1 being lightly phosphorous doped and WNA being degenerate. The passivation process works in dramatic fashion in these diffusion doped thin-film samples with observed treated-to-virgin conductance ratios of up to 10^5. The decreases seen for the heaviest doping level are apparently due to the bonded hydrogen acting essentially as a scattering center in the boundaries.

Having established the viability of the passivation process for bulk and thin-film polycrystalline silicon, we turned our attention to some exploratory experiments on solar cells. The utilization of solar cells allows a direct probing of minority carrier lifetimes and a tentative evaluation of the ability of the process to increase efficiencies. Fig. 10 illustrates typical I-V curves for two cells before and after treatment. Overall efficiencies are low because the neutron transmutation doped (NTD) polysilicon employed suffers from a very low bulk lifetime. The upper set of curves are for a boron diffused solar cell fabricated from NTD (phosphorous) doped polysilicon (200 micron grains). The dashed curves represent the light and dark traces for the virgin cell; the solid lines are the curves for the plasma treated cell. The efficiency increase (AM1) of a factor of ~26 is due to two distinct factors. One is an increase in the short-circuit current ostensibly due to improved transport of minority carriers across grain boundaries.

The other is a substantial improvement in the open-circuit voltage due to an elimination of the shunting nature of the grain boundaries. The lower half of Fig. 10 shows three illuminated I-V curves for a boron ion implanted bulk NTD phosphorous doped polysilicon solar cell. The 1000°C H_2 anneal is an attempt to remove some of the ion implantation defects. Curve 3 again shows that the hydrogen plasma treated cell increases in efficiency as a consequence of improvements in both the short-circuit current and open-circuit voltage in the cell.

The lifetime of the minority carriers and the spectral response of some of the ion implanted cells has been probed more directly as is shown in Fig. 11. The lower curve and number refer to the virgin sample, the upper set are after hydrogen plasma treatment. The lifetimes were determined by watching the short-circuit current decay after a 5 nsec x-ray pulse. The data indicates that there is substantial increase in bulk minority carrier lifetime after plasma treatment. This is substantiated by an examination of the spectral response curves for the cell. There is a large increase in the quantum efficiency of the long wavelength tail where the photons are adsorbed well below the junction.

In conclusion, a process has been developed which can readily modify the density of states in the grain boundary region in polysilicon. Preliminary results indicate that passivation of the grain boundaries in polysilicon solar cells may result in substantial efficiency increases.

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† A U. S. Department of Energy facility.

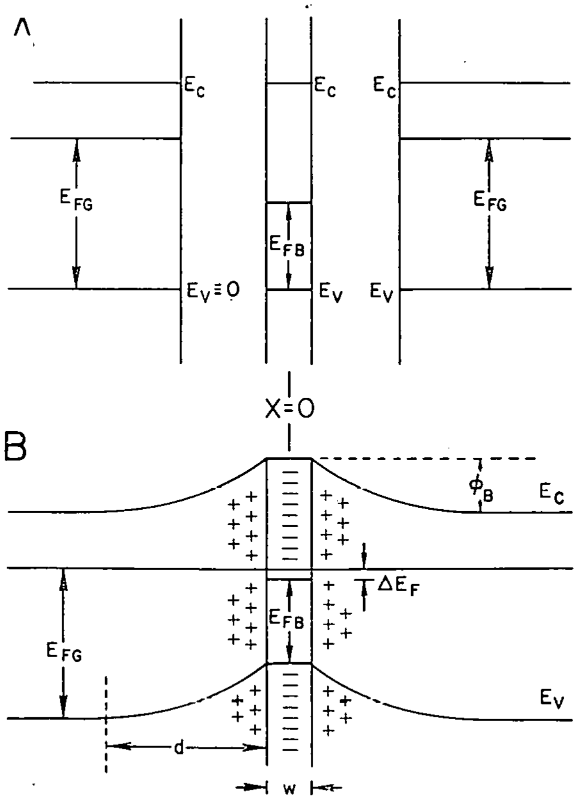

Fig. 1

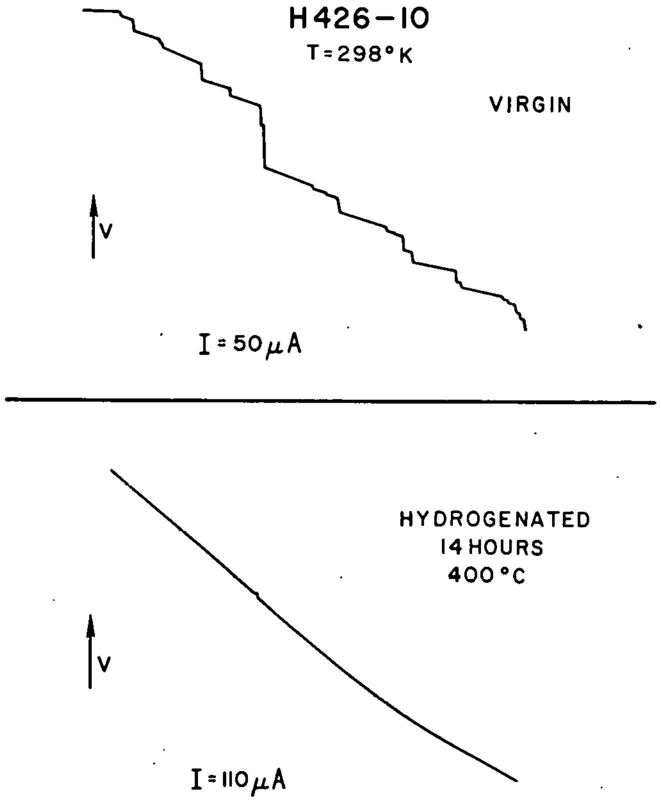

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Fig. 2

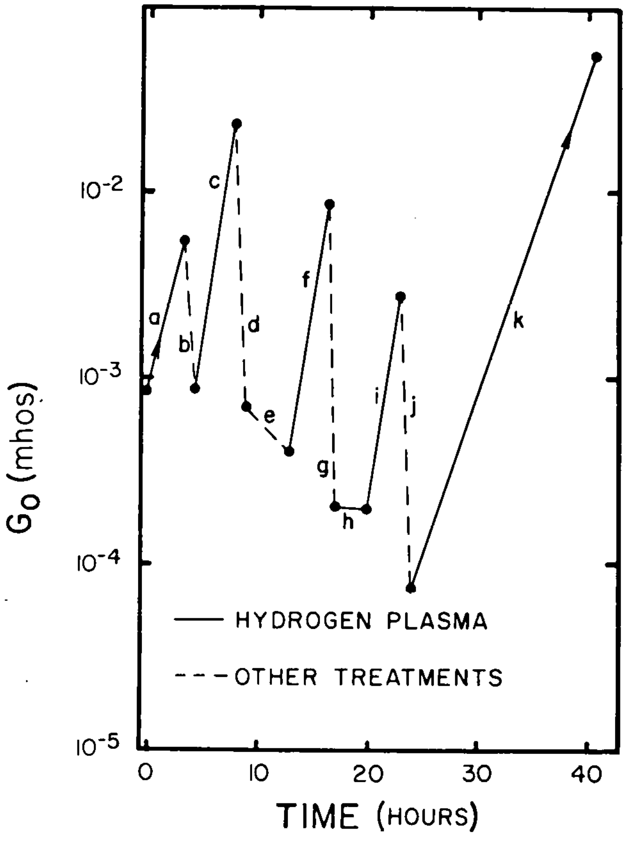


Fig. 3

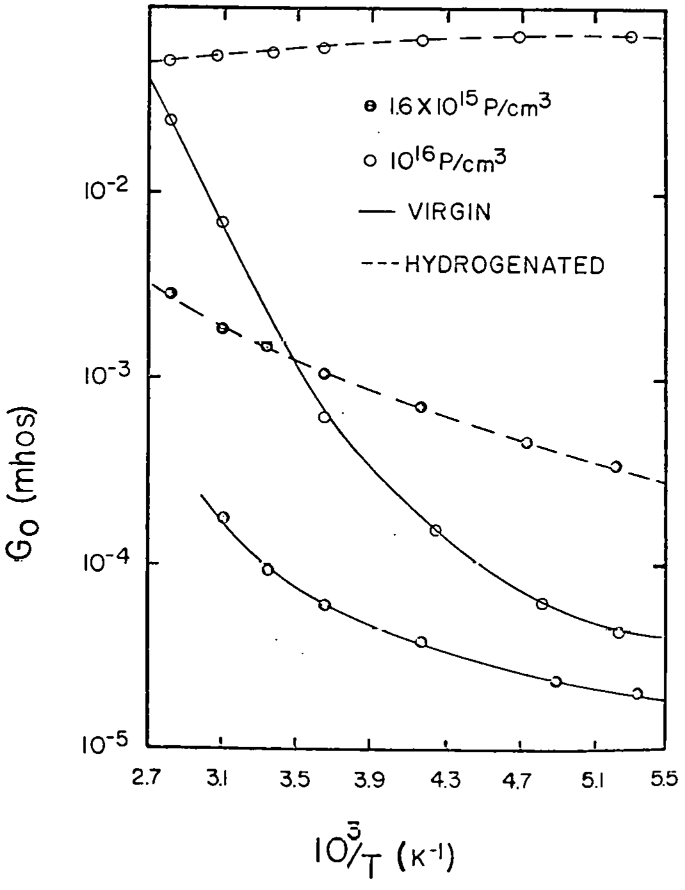


Fig. 4

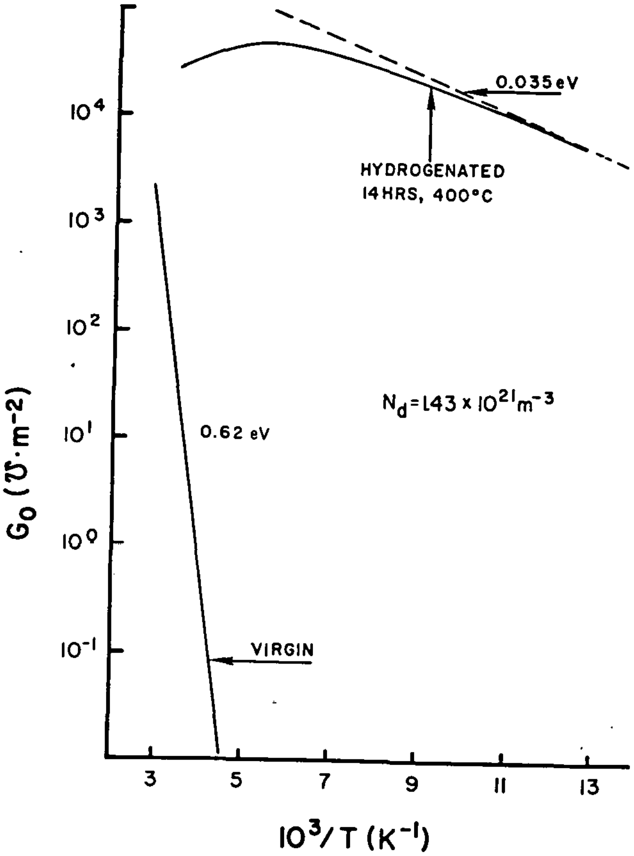


Fig. 5

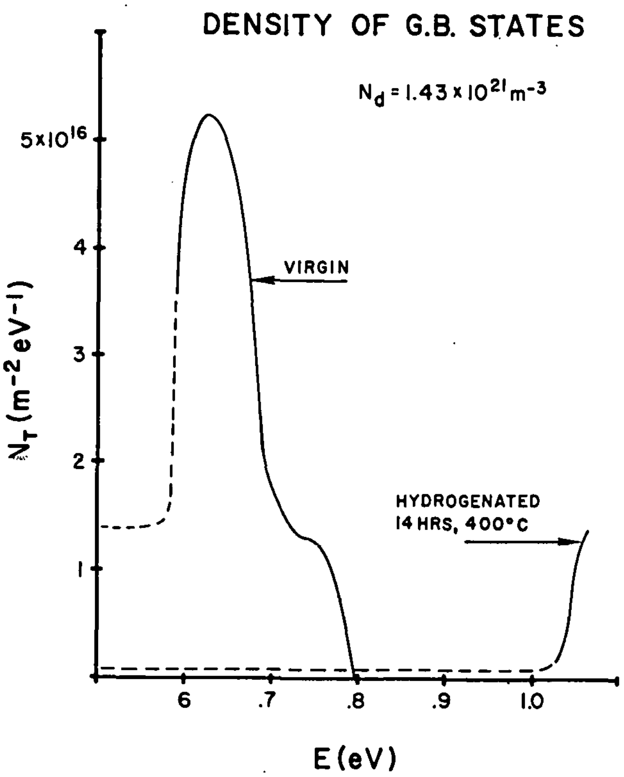


Fig. 6

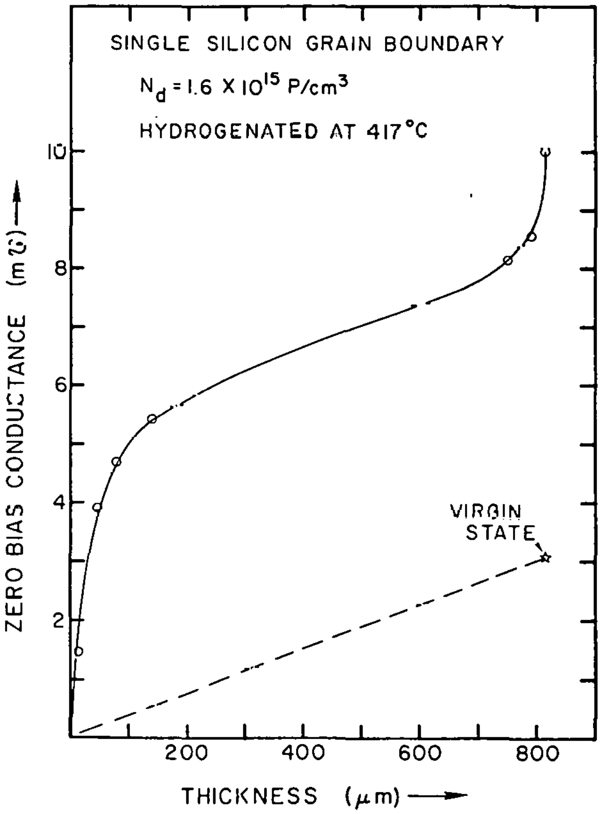


Fig. 7

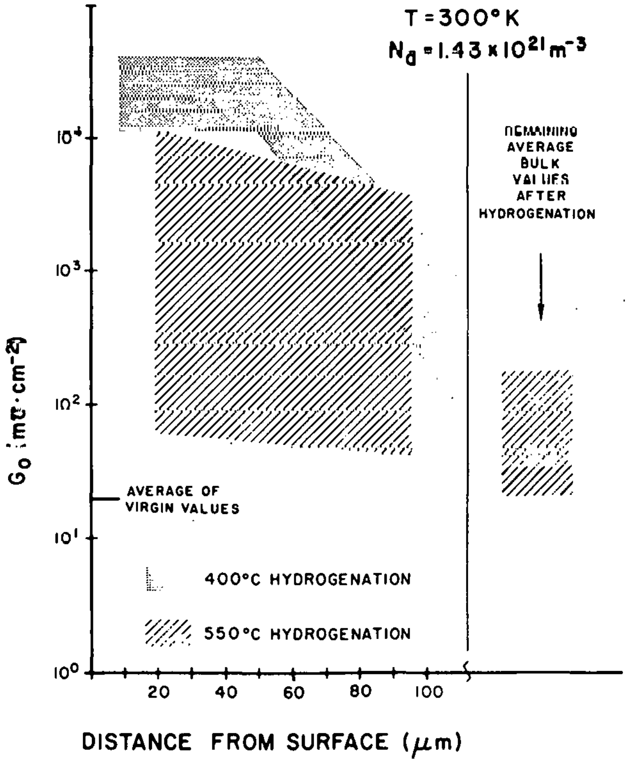


Fig. 8

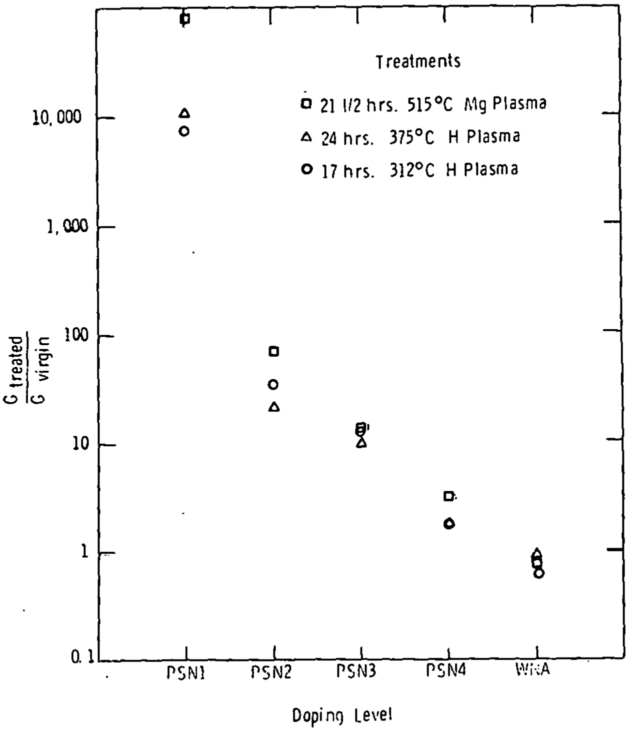


Fig. 9

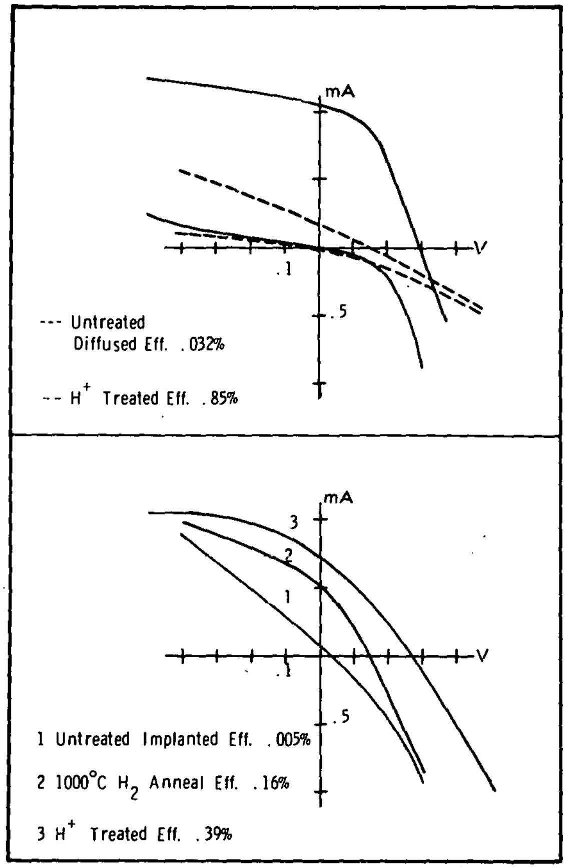


Fig. 10

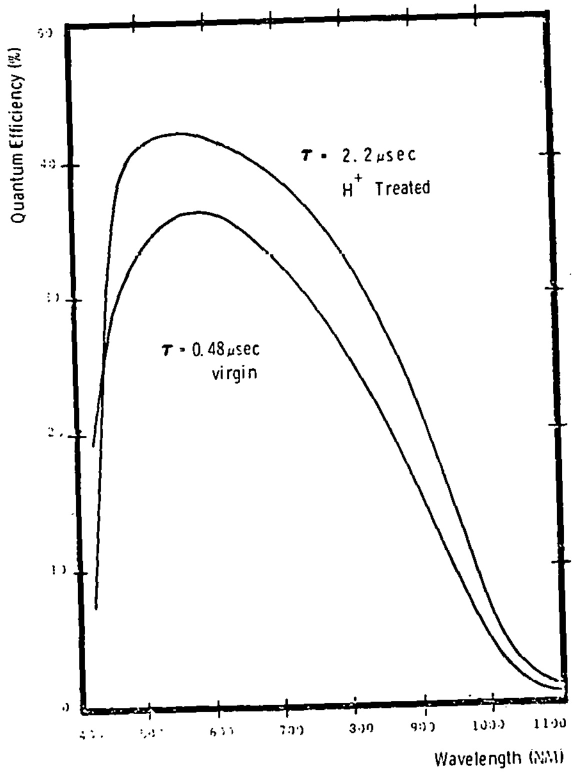


Fig. 11

NOTES

THIN FILM GALLIUM ARSENIDE SOLAR CELLS

J. Benner
Photovoltaic Program Office
Solar Energy Research Institute
Golden, Colorado 80401

The objective of this program is to identify and develop methods for fabricating thin film GaAs solar cells with photovoltaic conversion efficiencies of 10% or greater in 1980, and to demonstrate a cost feasibility of less than $500/peak kWe (in 1980$) by 1986.

Presently the program includes five contractors. Two basic approaches to fabrication of thin film GaAs solar cells are addressed. The first utilizes GaAs films deposited on foreign substrates which do not yield epitaxial growth. The resulting films exhibit grain sizes comparable to the film thickness. The current collection in the best of these films is good, but cell performance is limited by low open circuit voltage and high series resistance due to grain boundary properties. Considerable effort is directed toward development of techniques for grain boundary passivation. The other approach relies on substrates that provide large grain epitaxial growth of the GaAs. A thin layer of germanium is deposited on a low cost substrate and recrystallized to obtain large grains. GaAs has been shown to grow epitaxially upon Ge. Thus, this second approach potentially reduces problems associated with grain boundaries by producing larger grains.

The majority of the program for 1980 will be selected from competition solicited by the Request For Proposals (RFP) released September 7, 1979. The intent of the RFP is to stimulate new interest in GaAs solar cell research and to expand the program to include additional approaches to thin film GaAs solar cell development. Although this solicitation includes elements similar to those contained in an ERDA RFP issued in 1976, the scope has been expanded and the emphasis adjusted to reflect the improved understanding of the problems.

As research progresses toward thinner films even greater emphasis must be placed on development of the materials technology. Techniques for nucleation and growth of GaAs films must be developed to yield grains of good electrical quality with lateral dimensions greater than the film thickness. This may require pre-growth preparation of substrates to promote larger grains through surface seeding of nucleation sites by chemical or mechanical processing or development of substrates yielding epitaxial growth. Technique for control of the grain boundary properties must be developed. These may include means of chemically altering the grain boundary such as by selectively etching, anodizing, alloying or doping. A third area for increased research is development of techniques for fabrication of p-n junctions in thin polycrystalline GaAs films.

The author acknowledges the preparation and contribution of viewgraphs by the participants in this program.

Thin-Film Gallium Arsenide Solar Cells

T. Surek
J.P. Benner

Photovoltaics Advanced R&D Annual Review
Denver, Colorado
September 17-19, 1979

Polycrystalline GaAs Solar Cells Contractors

Organization (P.I.)	Contract Amount	Duration
Jet Propulsion Laboratory (R.J. Stirn)	$258K	6/22/79-8/21/80
Rensselaer Polytechnic Institute (J.M. Borrego, S.K. Ghandi)	$360K	10/01/78-1/10/80
Southern Methodist University (S.S. Chu)	$186K	12/01/78-11/30/79
Rockwell Science Center (J.S. Harris)	$867K	1/15/79-1/14/80
Cornell University (J. Ballantyne)		
Howard University (A.F. Hoyte)		
NCA&T State University (E. Stefanakos)		
Stanford University (G.L. Pearson)	$ 84K	3/19/79-3/18/81

Thin Film Gallium Arsenide Solar Cell Research

- RFP Issue Date: September 7, 1979
- Response Due Date: October 31, 1979
- Multiple Awards: 5 — 8
- Pending FY80 Funds: $1,200,000

Technical Barriers

- Grain Boundaries
    - — low open-circuit voltage
- Small Grain Size in Thin Films on Foreign Substrates
    - — diameter is approximately equal to the film thickness
    - — gallium availability requires thinner films
- Intra-Grain Properties
- MIS Stability
- p-n Junction Fabrication

ERDA RFP No. E(04-3) — 1202; 1976

1. Selection of appropriate low-cost substrates
2. Film deposition
3. Characterization of the film
    - quantitative physical parameters
4. Improvement of film-substrate properties

Heterostructure GaAs Solar Cells

Rensselaer Polytechnic Institute — J.M. Borrego, S.K. Ghandhi

Grain-Boundary Passivation

- The grain boundary acts as a top-to-bottom short, shunting the active solar cells
- Selective anodization is used to 'open' this short
- Leakage current is reduced by 5 — 6 decades in this manner
- Cells made by this method have the following parameters:

Substrate	Molybdenum
Layer Thickness	9 μm
Cell Diameter	3.2mm
Conditions	AM1(ELH) with no AR Coating
V_{oc}	0.5V
J_{sc}	20 mA/cm^2
FF	0.57
n	5.7%

Heterostructure GaAs Solar Cells

Rensselaer Polytechnic Institute — J.M. Borrego, S.K. Ghandhi

The Effect of HCL Treatment on Completed Cells

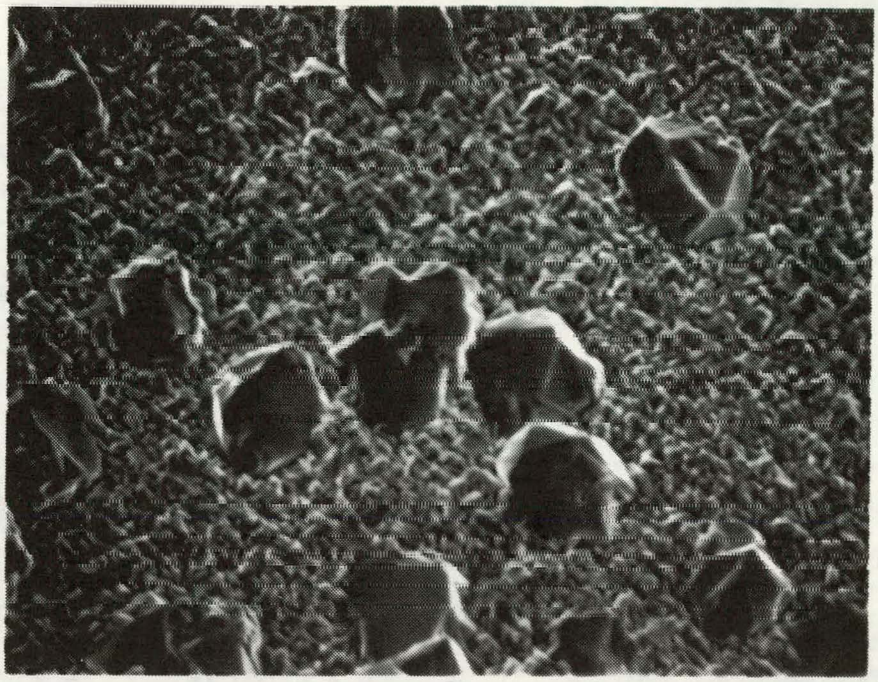
- The presence of an oxide over the grain results in current suppression.
- HCl treatment on a completed cell of this type results in rapid improvement within 3 minutes.
- HCl treatment on completed cells with no oxide on the grain results only in long term changes over a 3 hour period.
- This process allows anodization technique to be made uniform over large areas of slice surface.

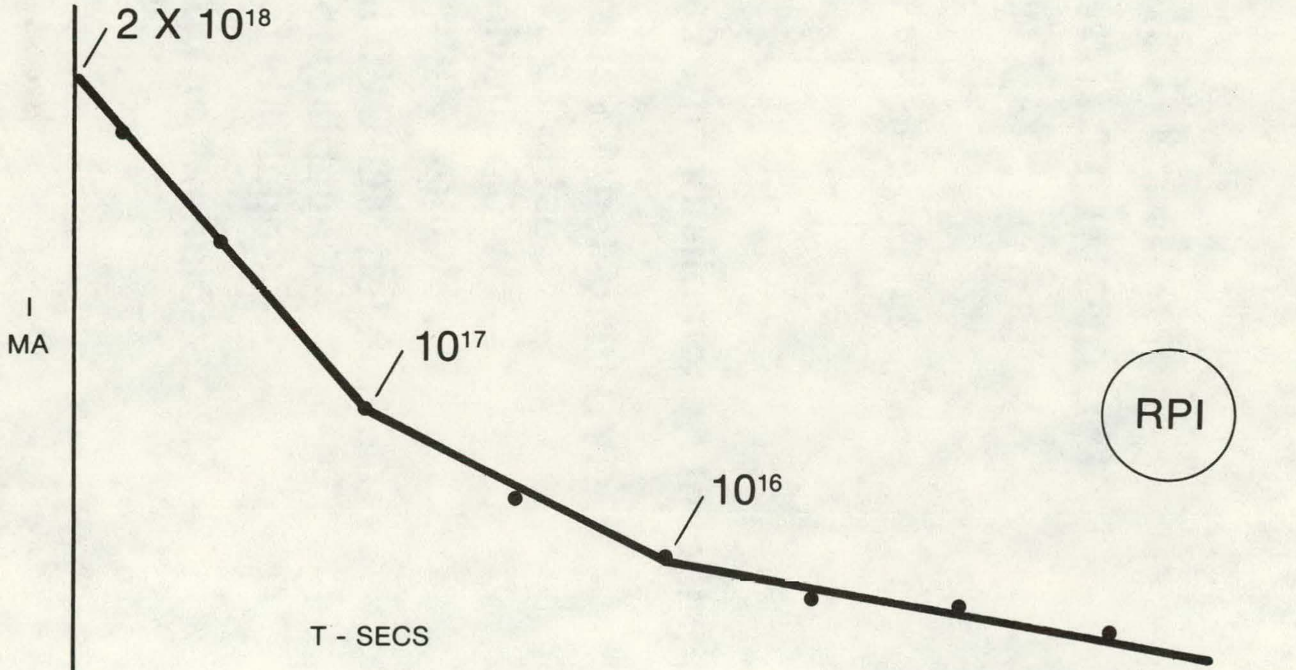
Heterostructure GaAs Solar Cells

Rensselaer Polytechnic Institute — J.M. Borrego, S.K. Ghandhi

Anodization as a Diagnostic Technique for Polycrystalline N-GaAs

- The anodic process creates a negative surface charge with a resulting depletion layer in the n-GaAs.
- Anodization proceeds with breakdown of the GaAs.
- Low BV regions are first affected until there is a sufficient thickness of oxide layer over them. Higher BV regions are affected successively.
- AGW anodic solution (2 parts propylene glycol, 1 part 0.2 M tartaric acid with ph = 6 adjusted by NH_4OH) is being used. Dissolution rate of oxide = 4.2 x 10^{-2} A°/sec for this solution.
- Anodization results are affected by secondary factors (double layer formation, surface preparation, etc.).




2 X 10^18
10^17
10^16
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RPI
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20
40
60
80
100
120

High Efficiency Amos and Homojunction GaAs Solar Cells by MO—CVD

Jet Propulsion Laboratory — R.J Stirn

Significant Accomplishments Past 12 Months (six month hiatus in program):

- CVD tungsten/1% carbon barrier layer to iron
    - Cost (\$0.50/ft^2) too much — substitute Mo for W
    - W/Ge alloying a problem — requires lower temperature at interface
- Completed MO-CVD facility
    - Capability for P on N and N on P GaAs
    - Capability for Ge or Si growth
- AMOS solar cell on poly Ge wafer substrate
    - % AM1 efficiency, 1 cm^2

High Efficiency Amos and Homojunction GaAs Solar Cells by MO-CVD

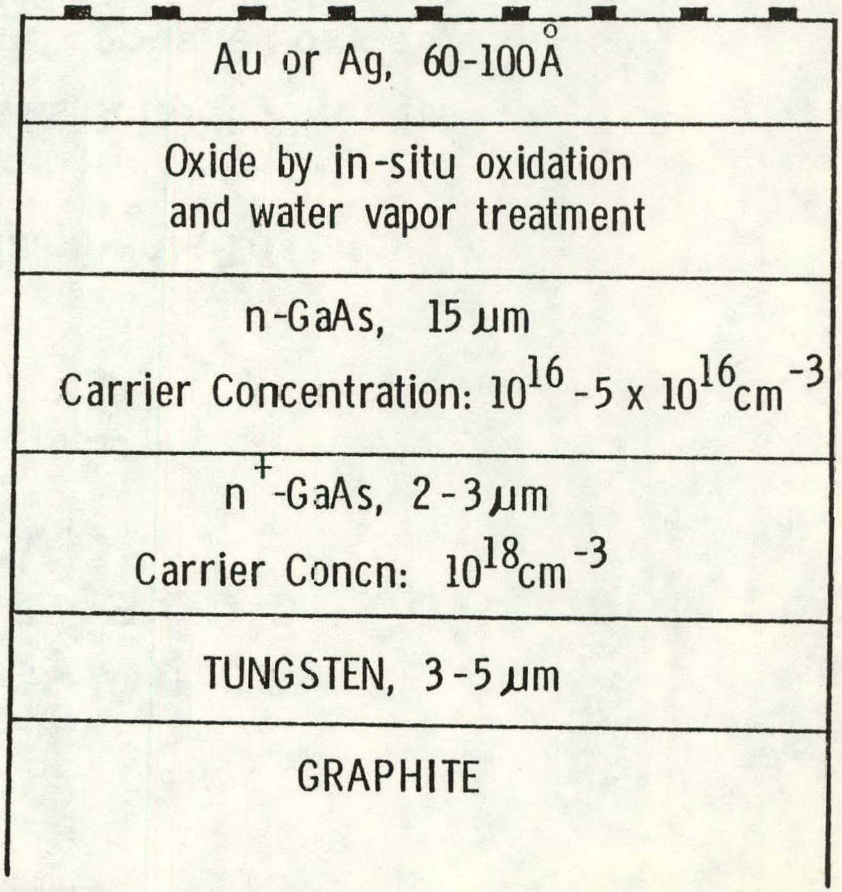
Jet Propulsion Laboratory — R.J. Stirn

Most Significant Accomplishments To Date:

- Innovation in enhanced GaAs Schottky barriers
- AMOS solar cells (native and deposited oxides)
  - — single crystal efficiency 17.3% (1 cm^2)
  - — polycrystal wafer efficiency 14.5% (1 cm^2)
- Double-layer Schottky barrier concept
  $Al_xGa_{1-x}As/GaAs$, $x = 0.40$, $t < 500°$

THIN FILM GALLIUM ARSENIDE SOLAR CELLS ON LOW COST SUBSTRATES
PREPARED UNDER SERI SUBCONTRACT XI-9-8007-I
SOUTHERN METHODIST UNIVERSITY - SHIRLEY S. CHU

- APPROACHES: Preparation of MOS solar cells from gallium arsenide thin films on low cost substrates.
  - The deposition of gallium arsenide films of controlled dopant concentration and distribution on tungsten/graphite substrates by the reaction of gallium, hydrogen chloride, and arsine.
  - The incorporation of a thin layer of gallium arsenide phosphide (or gallium aluminum arsenide) to the surface of gallium arsenide films.
  - The in-situ oxidation of gallium arsenide films.
  - The formation of MOS structures by vacuum evaporation.
  - Solar cell configuration



Au or Ag, 60-100 Å

Oxide by in-situ oxidation and water vapor treatment

n-GaAs, 15 μm

Carrier Concentration: 10^{16} - 5 x 10^{16} cm^{-3}

n^{+}-GaAs, 2-3 μm

Carrier Concn: 10^{18} cm^{-3}

TUNGSTEN, 3-5 μm

GRAPHITE

THIN FILM GALLIUM ARSENIDE SOLAR CELLS ON LOW COST SUBSTRATES
PREPARED UNDER SERI SUBCONTRACT XI-9-8007-1
SOUTHERN METHODIST UNIVERSITY - SHIRLEY S. CHU

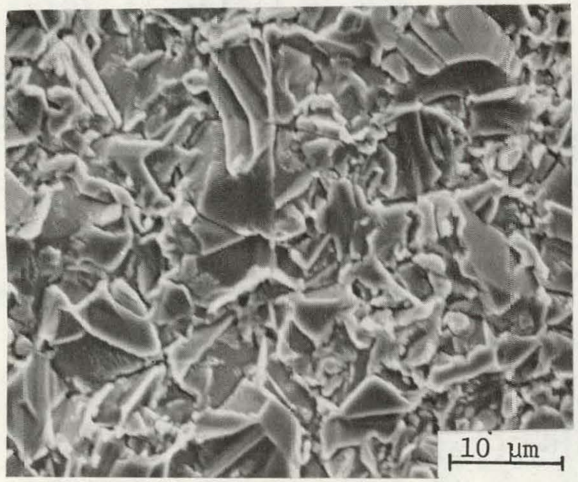
- Significant accomplishments: Chemical reversibility of the halide process has been shown to be essential for obtaining gallium arsenide films of good microstructures.

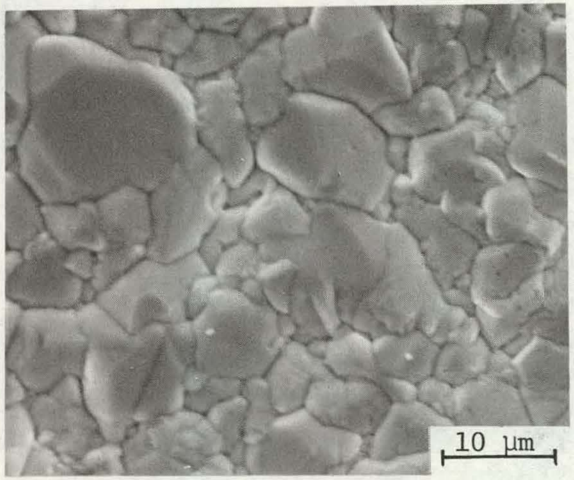
- As-deposited surface without $HC\ell$ to reactant mixture

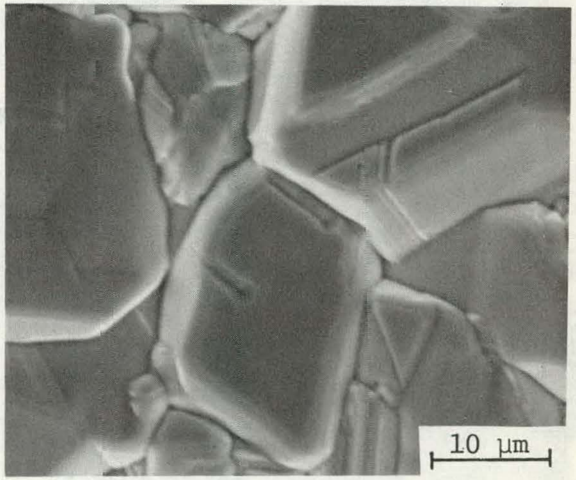
- As-deposited surface with $HC\ell$ to reactant mixture

$GaC\ell/HC\ell$ molar ratio: 8

$GaC\ell/HC\ell$ molar ratio: 3





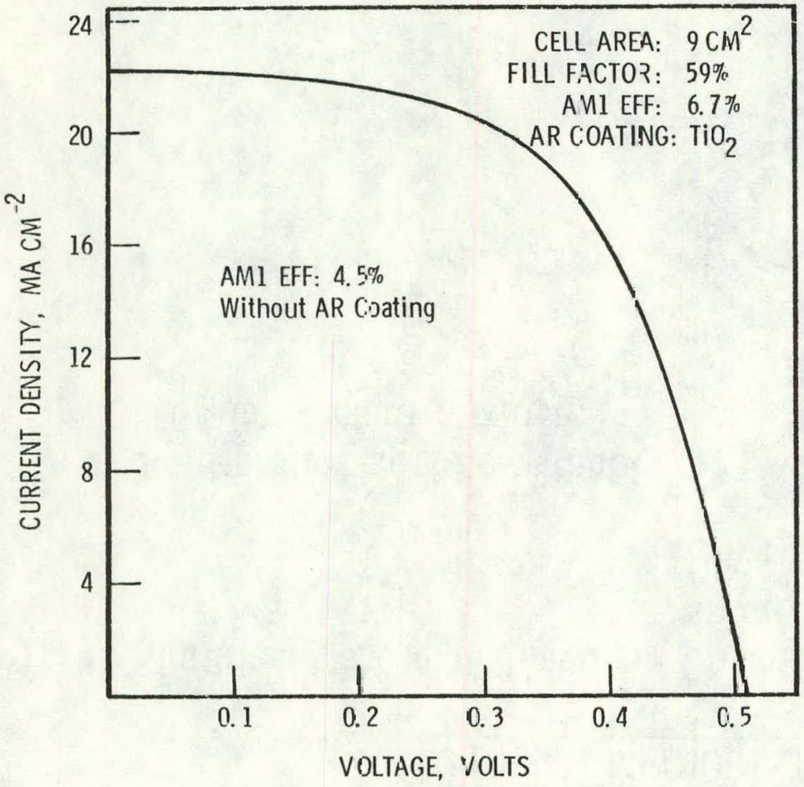


THIN FILM GALLIUM ARSENIDE SOLAR CELLS ON LOW COST SUBSTRATES

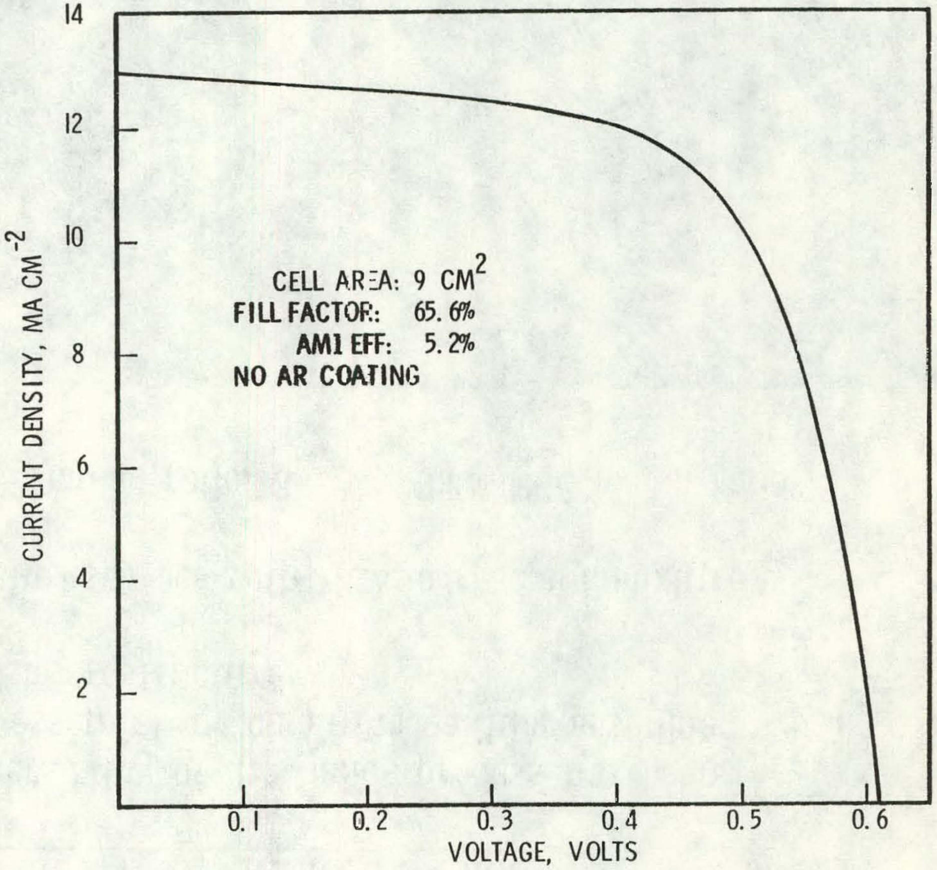
PREPARED UNDER SERI SUBCONTRACT XI-9-8007-I

SOUTHERN METHODIST UNIVERSITY - SHIRLEY S. CHU

- Significant Accomplishments: High conversion efficiency of large area (9 cm^2) solar cells has been demonstrated.
- Characteristics under illumination at 100 MW/CM^2 (Quartz-Halogen lamp)



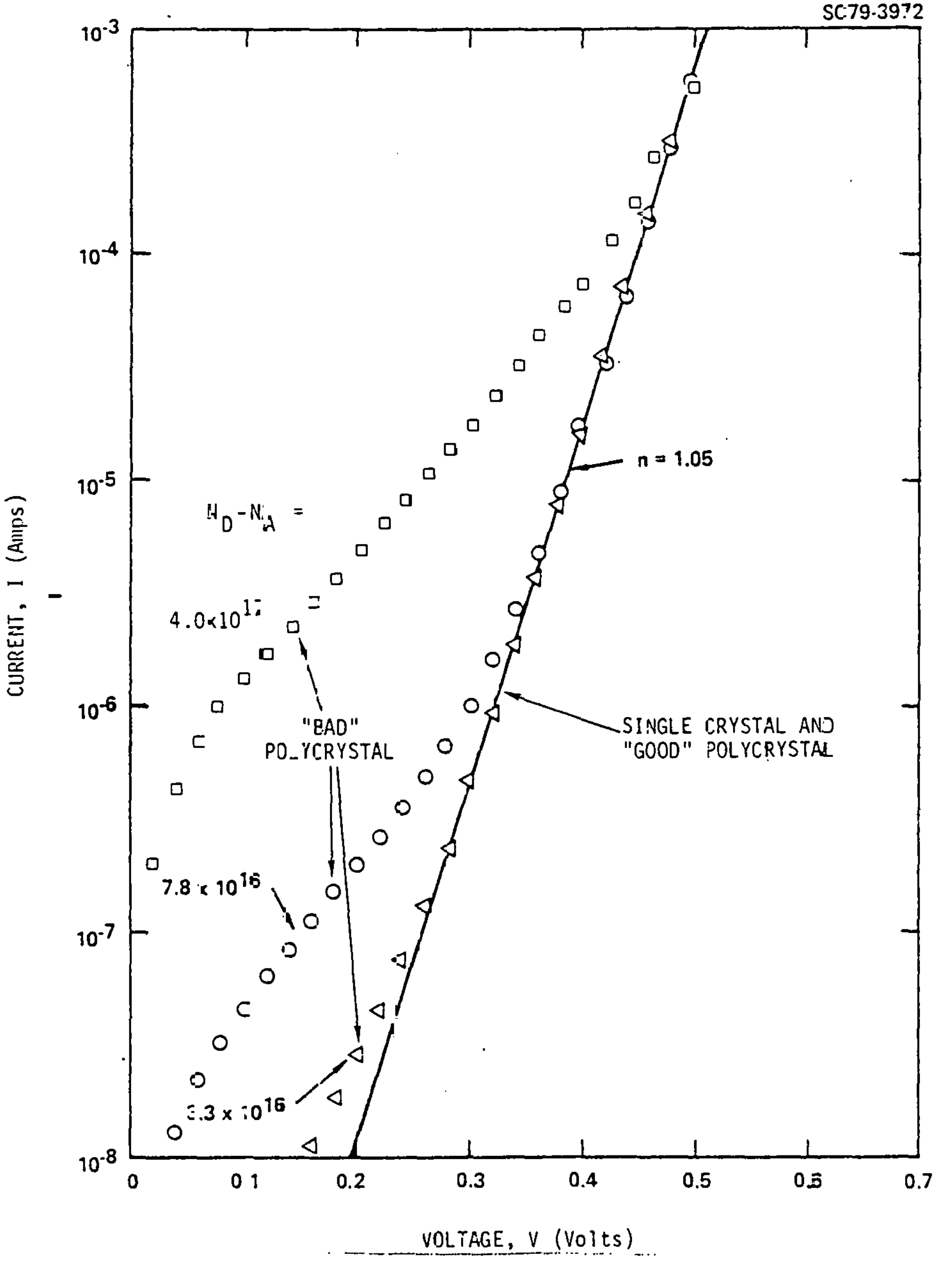
TiO_2/Au/oxide/n-GaAs/n^+-GaAs/W/graphite



Au/oxide/n-$GaAs_{1-x}P_x$/n-GaAs/n^+-GaAs/W/graphite

PROGRAM HIGHLIGHT

- CLEAR IDENTIFICATION AND CHARACTERIZATION OF GRAIN BOUNDARIES WHICH HAVE NO EFFECT ON THE BARRIER IN GaAs SOLAR CELLS



Rockwell International

MAJOR PROGRAM ACHIEVEMENTS

- IDENTIFICATION AND CHARACTERIZATION OF "GOOD" AND "BAD" GRAIN BOUNDARIES IN GaAs
- DEVELOPMENT OF AlGaAs/GaAs SCHOTTKY BARRIER CELL
- DEVELOPMENT OF A PHENOMENOLOGICAL MODEL FOR GRAIN BOUNDARIES IN GaAs
- GROWTH OF HIGHLY ORIENTED AND (111) TEXTURED GaAs LAYERS ON GRAPHITE BY MBE
- DEVELOPMENT OF SPIN-ON OXIDE TECHNIQUES FOR MOS SOLAR CELL FABRICATION
- DEVELOPMENT OF NEW ANALYTICAL TECHNIQUES (DLTS, PITS AND SCANNING AUGER PROFILE) FOR GRAIN BOUNDARY CHARACTERIZATION

Rockwell
International

Scope of the RFP

- Terrestrial Thin-Film GaAs Solar Cells
  - Fine grain films on low-cost substrates
  - High efficiency, large grain films on lattice-matched substrates
  - High efficiency, single-crystal separated films
- Satellite Power System Thin-Film GaAs Solar Cells

GaAs RFP Research Tasks

1. Development of the Materials Technology
    - Substrate selection
    - Optimization of electrical properties of the grains
    - Grain boundary passivation
    - Development of collecting barrier formation techniques
    - Development of handling techniques for separated thin films
2. Material Characterization
    - Structural
    - Electrical
    - Compositional
3. Solar Cell Fabrication and Evaluation
    - 1.0 cm^2 total area or greater
    - Dark and illuminated I-V
    - Temperature and wavelength dependence
4. Basic Studies (optional)
    - Measurement techniques
    - Grain boundary studies
    - Device modelling

NOTES

LOW-COST, HIGH-EFFICIENCY GaAs SOLAR CELLS

J. C. C. Fan
Lincoln Laboratory, Massachusetts Institute of Technology
Lexington, Massachusetts 02173

I. INTRODUCTION

The objectives of our GaAs R&D program are (a) to develop inexpensive thin GaAs cells with conversion efficiencies up to 20% at AM1 under one-sun illumination and (b) to develop GaAs/Ge monolithic tandem cells with conversion efficiencies up to 30% at AM1 under multiple-sun illumination.

If our efficiency goals can be achieved, GaAs solar cells could have a great advantage over lower efficiency cells of other materials with regard to total system costs. To achieve high-efficiency cells, we have concentrated for the last several years on developing efficient GaAs solar cells on single-crystal GaAs and Ge substrates. Over 20% efficient cells have been achieved on both types of substrates. In addition, fabrication techniques have been developed such that cells are made with no vacuum processing steps. We are currently developing techniques to utilize inexpensive substrates such as Si without significantly degrading cell efficiency.

II. TECHNOLOGY STATUS

A. Single-Crystal Shallow-Homojunction Cells

1. Chemical Vapor Deposition (CVD)

We have developed GaAs shallow-homojunction solar cells, with conversion efficiencies as high as 21% at AM1, that incorporate GaAs layers (total thickness about 4 μm) grown by CVD on single-crystal p^+ GaAs (1) or Ge (2) substrates (see Fig. 1). The CVD system employs the $AsCl_3$-Ga-H_2 method with a vertical fused-silica reactor. The cells employ an $n^+/p/p^+$ structure, without a GaAlAs window, in which surface recombination losses are reduced because the n^+ layer is so thin (< 1000 Å) that most of the photogenerated carriers are created in the p layer below the junction. These devices are fabricated without any vacuum processing steps, utilizing an antireflection coating prepared by anodic oxidation of the n^+ layer. The front and back contacts are electroplated Sn and Au, respectively. Typically, these all-CVD cells have open-circuit voltage V_{oc} about 1 V, short-circuit current density J_{sc} about 25 mA/cm^2, and fill factor ff over 0.80. The diode factor A is about 1.0 and the saturation current density J_o is about 1.4×10^{-17} A/cm^2. The cells fabricated are about 0.5 cm^2. It

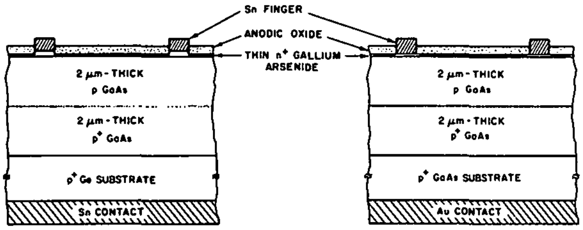


Figure 1. Schematic diagram of GaAs shallow-homojunction solar cells on GaAs or Ge substrates.

was found that Ge substrates play a passive role, permitting them to be substituted for GaAs substrates without any effect on cell efficiency. The cells grown on Ge substrates are the most efficient thin-film cells on foreign substrates so far reported.

2. Molecular Beam Epitaxy (MBE)

We have recently developed MBE GaAs solar cells (3) with conversion efficiencies up to 16% at AM1. These are the first efficient MBE solar cells of any type to be reported. The new cells use the same shallow-homojunction structure as the CVD cells, but the n^+, p, and p^+ GaAs layers are all grown by MBE on GaAs substrates. The fabrication techniques are similar to those used for CVD cells. Cells ranging in area from 0.45 to 9.5 mm^2 have been fabricated. For the most efficient cell, which also has the largest area, $V_{oc} = 0.92$ V, $J_{sc} = 23$ mA/cm^2 and ff = 0.76, giving a measured efficiency of 16% at AM1. The diode factor A is about 1.3 and J_o is 6×10^{-14} mA/cm^2. Since these devices are at an early stage of development, optimizing the MBE growth process should lead to a significant improvement in their performance. Because MBE growth permits the precise control of layer thickness and carrier concentration, it should be possible to develop MBE GaAs solar cells with conversion efficiencies approaching the theoretical limit.

3. Ion-Implanted, Laser-Annealed (IILA) Cells

Conversion efficiencies up to 12% at AM1 have been obtained for IILA GaAs cells (4) utilizing the $n^+/p/p^+$ structure. The n^+ layer was formed by Se^+-ion implantation into the p layer, which was grown epitaxially by CVD on a p^+ GaAs substrate. The implanted layer was annealed, without encapsulation, by scanning with a cw Nd:YAG laser. The front and back contacts are electroplated Sn-Ag and Au, respectively. The cell areas range from 0.28 to 4.7 mm^2. For the most efficient cell, which has the largest area, $V_{oc} = 0.79$ V, $J_{sc} = 20.4$ mA/cm^2 and ff = 0.73, giving a measured efficiency of about 12%. The diode factor A is about 1.8 and J_o is about 4.5×10^{-10} A/cm^2. Both of the latter values are higher than those for our all-CVD cells, resulting in the lower V_{oc} and ff of the IILA cells. Since the IILA devices, like the MBE cells, are at an early stage of development, optimizing the implantation and annealing parameters should lead to a significant improvement in their performance. The IILA cells have a distinct advantage over all-CVD cells, since the junction depth would not be very sensitive to surface morphology, as it is in all-CVD polycrystalline cells.

4. Theoretical Model

By using a simple analytical model for GaAs solar cells with the $n^+/p/p^+$ structure, we have obtained (5) good fits between computer calculations and experimental data for the external quantum efficiency QE_{ext} as a function of wavelength for thin-film GaAs cells with different values of n^+ layer thickness. By adjusting the values of several material parameters, good simultaneous fits are obtained to six sets of data for all-CVD cells with n^+ layer thicknesses of 300, 450, 750, 1000, 1300 and 1500 Å. The adjustable parameters that yield the best fit indicate that the minority-carrier hole diffusion length L_p in the n^+ layer is very small, about 0.05 μm. The minority-carrier electron diffusion length L_n in the p layer is much greater, about 20 μm, and the surface recombination velocity S_p in the anodized n^+ layer is about 2×10^7 cm/sec. By using these values of L_p, L_n and S_p, we have calculated the maximum conversion efficiency η_{max} at AM1 as a function of n^+ layer thickness for cells with the structures shown in Fig. 1. In Fig. 2 the measured values of η_{exp}

(represented by points) for four different cells on single-crystal Ge substrates are compared with the calculated values of η_{max} (represented by the solid line). With decreased n^+ thickness, η_{max} increases from 17% at 1600 Å to 24% at 300 Å. The η_{max} calculations take account of reflection losses for anodically oxidized cells but not of losses resulting from such effects as contact-finger shadowing and reduction in fill factor due to series resistance. Because of such losses, we expect the η_{exp} values for our cells to approximate 0.9 η_{max} (represented by the dashed line in Fig. 2). Within the limits of experimental error, this is generally the case. Preliminary calculations indicate that still higher conversion efficiencies would be obtained for n^+ layers with higher L_p and lower S_p. With an improved antireflection coating, conversion efficiencies up to 23-24% at AM1 should be possible with the $n^+/p/p^+$ shallow-homojunction structure.

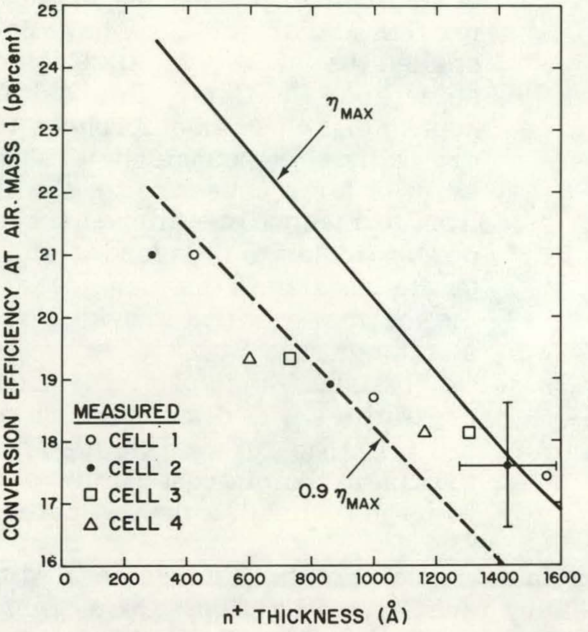


Figure 2. Photocurrent as a function of applied voltage for a GaAs shallow-homojunction solar cell on a single-crystal Ge substrate.

B. Polycrystalline Shallow-Homojunction Cells

As one step in the development of low-cost GaAs solar cells, we have been investigating the fabrication of cells incorporating $n^+/p/p^+$ shallow-homojunction structures prepared by CVD growth of polycrystalline GaAs layers on bulk-grown large-grained GaAs substrates. Conversion efficiencies as high as 13.2% at AM1 have been achieved. Epitaxial layers were deposited in the $AsCl_3$-Ga-H_2 system under growth conditions similar to those used in the preparation of single-crystal cells. Small (0.2 and 6 mm^2) cells were defined photolithographically, using electroplated Sn as a top contact and electroplated Au as a back contact. The photovoltaic response of some polycrystalline cells was found to improve with anodic thinning of the n^+ layer, as in the case of single-crystal GaAs shallow-homojunction cells. The antireflection coating was an anodic oxide grown in the presence of the Sn front contact. The characteristics at AM1 obtained for the best cell are $V_{oc} = 0.88$ V, $J_{sc} = 20$ mA/cm^2 and ff = 0.77, giving a measured efficiency of 13% (see Fig. 3). The area of this cell is 6 mm^2 and contains about half a dozen grains. The important feature of these small polycrystalline cells is that the values of V_{oc} are quite high, between 0.85 and 0.90 V. The major reason that their conversion efficiencies are lower than those of single-crystal cells is that the values of J_{sc} are reduced because of the variation in n^+ layer thickness from grain to grain.

C. Laser Crystallization to Form Large-Grained Semiconductor Sheets

In earlier investigations, we obtained large-grained films of Si and GaAs by scanning amorphous films of these materials with the slit image of a cw Nd:YAG laser to produce a solid-phase transformation to the crystalline form. With the objective of preparing large grained sheets of Ge for use as low-cost substrates for GaAs solar cells, we have now studied the laser crystallization of amorphous Ge films. The basic concept is that when an amorphous film is crystallized by scanning with a laser beam of large aspect ratio, the crystallites formed will be aligned not only perpendicular to the plane of the substrate but also in the plane because of the thermal gradient provided by the slit image (see Fig. 4). Not only have we obtained films containing oriented crystallites with dimensions up to 2-3 x 100 μm but we have also been able to explain the microstructure of these films in terms of a theoretical model.

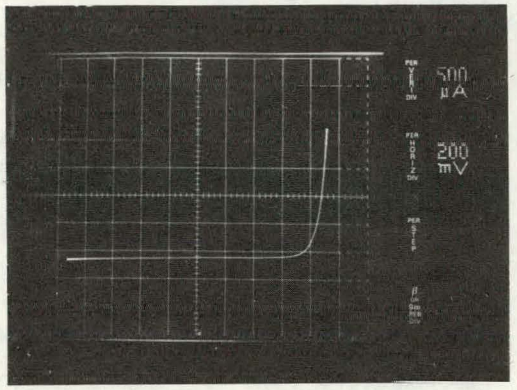


Figure 3. I-V characteristic of efficient GaAs polycrystalline solar cell.

In our initial experiments on Ge, before laser irradiation the film was heated to a temperature (T_b) close to the range yielding rapid crystallization. Once crystallization was initiated by momentary irradiation at a single point, the transformation was found to be self-sustaining, with the crystallization front rapidly propagating radially outward from the irradiated spot. At values of T_b below a certain minimum value (T_r), self-sustaining crystallization did not occur, but elongated crystallites were obtained. We then made a detailed study of the microstructure of crystallized Ge films as a function of T_b from room temperature to 500°C. When T_b was less than T_r, periodic features approximately parallel to the laser slit image were observed.

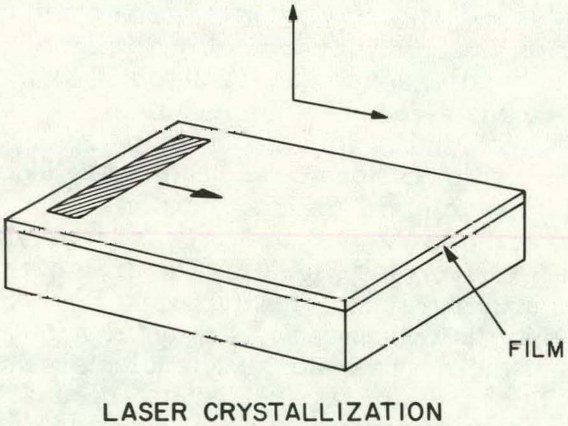


Figure 4. Schematic diagram of crystallization process utilizing a scanned laser image of large aspect ratio.

These experimental results can be explained by means of a theoretical model that we have used to calculate the motion of the crystallization front. The calculations are simplified by making the approximation that transformation occurs instantaneously when the film reaches a critical temperature (T_c). When an amorphous film heated to T_b is scanned with a laser beam, crystallization begins when the front edge of the film reaches T_c. The liberation of latent heat accompanying crystallization causes the heating of the film ahead of the laser, so that the T_c isotherm and therefore the crystallization front advance more rapidly than the laser, initially at a characteristic velocity v_{ac} that in our experiments is much higher than the laser velocity. If T_b is close enough to T_c, the continuing release of latent heat is sufficient to maintain this rapid motion indefinitely, causing self-sustaining crystallization. If T_b is less than T_r, however, the front eventually gets so far ahead of the laser beam that heat losses reduce its temperature below T_c, and its forward motion is halted. In this case, crystallization begins again when the laser beam gets close enough to heat the amorphous-crystalline boundary to T_c, and the process is repeated. Thus the motion of the crystallization front is periodic, resulting in the formation of the periodic features observed in the microstructure. Similar features have also been observed in Si and GaAs. With appropriate choice of experimental parameters, the laser crystallization can be expected to produce large-grained, or even single crystal semiconductor sheets for solar cell applications.

III. ONGOING R &D

A. 20% Efficient, Low-cost Thin GaAs Cells

The fabrication of GaAs solar cells with efficiencies over 20% at AM1 on single-crystal Ge substrates represents a major step in the development of low-cost, high-efficiency GaAs solar cells. To obtain efficient cells at lower cost, the Ge substrates must be replaced by inexpensive substrates without significantly degrading the conversion efficiencies. It may well be very difficult to obtain 20% efficient cells with substrates such as Mo or graphite sheets unless these sheets are covered with a thin layer of Ge or GaAs, composed of large lateral crystallites produced by laser crystallization. Laser-crystallized layers are generally well-textured, so that the variation in GaAs growth rates from grain to grain should be much reduced. Even if the growth rate variations present a problem, our developing technology in ion-implantation, followed by laser annealing may provide a solution.

As an alternative approach we are investigating whether inexpensive crystalline Si sheets can be used as substrates for GaAs solar cells. Unlike Ge, Si is poorly lattice matched to GaAs (about 4% mismatch). In addition, the thermal expansion coefficient of Si is about half that of GaAs. Therefore, CVD growth of GaAs directly on Si may be difficult unless special techniques can be developed to relieve the stress inherent in the mismatch. Another possibility would be to use a Ge-Si alloy layer between the GaAs layer and Si substrate (see Fig. 5). Since Ge and Si are totally miscible, forming alloys whose lattice constant and thermal expansion vary continuously with composition, an alloy layer with composition graded from Si at the substrate to Ge at the front surface should be effective in relieving the stress due to mismatch. The Si substrates would not have to be as pure as the material used for high-efficiency Si solar cells, nor would they have to be single-crystalline. The large-grained Si sheets being developed for low-cost Si solar cells should be of sufficient quality.

B. 30% Efficient GaAs-Ge Monolithic Tandem Cells

Our success in fabricating high-efficiency GaAs cells on Ge substrates suggests that even higher efficiencies may be obtained by mating GaAs solar cells and Ge cells. The bandgaps of GaAs (1.43 eV) and Ge (0.66 eV) are such that the photocurrents produced in GaAs and Ge will almost equal without the necessity of accurately controlling the thicknesses of GaAs and Ge. It is estimated that GaAs-Ge tandem cells could have conversion efficiencies between 25 to 28% at AM1 under one-sun illumination and efficiencies up to 30% at AM1 under multiple-sun illumination. Because of the relatively narrow bandgap of Ge, such tandem cells will be useful only if their temperature is kept near room temperature, since the photovoltage induced in the Ge cells will decrease rapidly with increasing temperature. Finally, the sheet resistance of the n^+ layer in the shallow-homojunction cells is about 150 ohm/square, a value close to values in GaAlAs/GaAs heteroface cells. Therefore, it is expected that shallow homojunction cells should perform quite similarly to GaAlAs/GaAs heteroface cells under concentration.

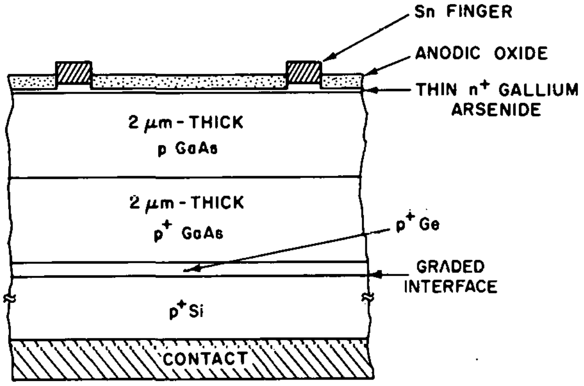


Figure 5. Schematic diagram of a GaAs shallow-homojunction solar cell on a Si substrate with a Ge/Si alloy graded interface.

ACKNOWLEDGEMENTS

Part of this work was performed in collaboration with C. O. Bozler, A. R. Calawa, R. L. Chapman, J. P. Donnelly, R. P. Gale, B. W. McClelland, and G. W. Turner.

This work was supported by the Department of the Air Force.

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2. C. O. Bozler, J. C. C. Fan, and R. W. McClelland, Proc. 7th Int. Symp. on GaAs and Related Compounds, St. Louis, 1978 (Institute of Physics, London, 1979), p. 40.

3. J. C. C. Fan, A. R. Calawa, R. L. Chapman, and G. W. Turner, Appl. Phys. Lett. (November 1979).

4. J. C. C. Fan, R. L. Chapman, J. P. Donnelly, G. W. Turner, and C. O. Bozler, Appl. Phys. Lett. 34, 780 (1979).

5. J. C. C. Fan, C. O. Bozler, and B. J. Palm, Appl. Phys. Lett. (November 1979).

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SESSION IV

STATUS OF PHOTOVOLTAIC CONCENTRATOR DEVELOPMENT*

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INTRODUCTION

Photovoltaic arrays which use optical concentrators as a means of achieving low cost are one of the baseline collector technologies being developed as part of the Department of Energy Photovoltaics Program. The major program milestones are as follows:

	$2.80/$W_p$	$0.70/$W_p$
Technology Feasibility	1978	1980
Technology Readiness	1980	1982
Commercial Readiness	1982	1986

The Concentrator Technology Development Project is structured into three major tasks which deal with concentrator cell development, solar concentrator development, and array subsystem development. A brief status report on each of these activities follows.

CONCENTRATOR CELLS

Solar cells with high conversion efficiency when operated in concentrated sunlight are essential to cost effective concentrator arrays. Currently, both single crystal silicon cells and advanced compound semiconductor cells such as GaAlAs cells are being developed for concentrator applications. Figure 1 illustrates the status of the various cell technologies being investigated. Silicon cells have demonstrated conversion efficiencies in the

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*This work was supported by the Distributed Solar Technology Division of the U. S. Department of Energy.

18-20% range (28°C junction temperature) at concentration ratios as high as 600X. Advanced compound semiconductor cells using either spectrum separation or multiple-junction configurations have the potential for conversion efficiencies in the 35-40% range. The development of these advanced cells is currently being emphasized in both the Sandia Technology Development effort and the SERI Advanced Research and Development effort.

SOLAR CONCENTRATORS

A number of concepts for low-cost solar concentrators suitable for operation with photovoltaic cells have been examined. Figure 2 lists both the primary and advanced approaches that have been chosen for continued engineering development. The primary approaches are point focus Fresnel lens and line focus parabolic troughs. A number of alternative designs, materials, and manufacturing processes for each approach are being studied, as indicated in Figure 2. A long-range goal is reliable concentrators having an installed cost in the \$200-300/m^2 range (1980\$).

ARRAY SUBSYSTEMS

Complete concentrator array subsystems including tracking structures and heat rejection systems are being built and tested as part of the concentrator development project. The objective of this activity is to evaluate the performance and reliability of concentrator arrays in real and accelerated environments and to provide hardware models for production process development and cost analysis. Currently, two 10 kW$_p$ concentrator arrays are operational in the Sandia test facility and a number of prototype modules in the 50-300 watt range are also being evaluated.

CELL TECHNOLOGY	CONCENTRATION RANGE	POTENTIAL EFFICIENCY	ACHIEVED EFFICIENCY
Silicon:			
Simple P^+-N	25-100	16-17%	16.4%
BSF P^+-N-N^+	50-200	20-21%	18.3%
HLE N^+-N-P	50-200	18-20%	19.2%
IBC	50-200	18-20%	17.0%
GVJ	100-1000	22-26%	20.4%
Single Junction GaAlAs	500-2000	24-26%	23%
Multiple Junction Stacks (GaAsSb/GaAlAsSb)	500-2000	30-40%	-
Multiple Cell-Spectral Separation (GaAlAs-Si)	500-2000	30-35%	31%
Thermophotovoltaic	5000-10000	30-40%	26%

Figure 1. Solar Cell Technologies For Concentrator Applications

PRIMARY APPROACHES: FRESNEL LENS CONCENTRATORS

- Flat Molded
- Curved Groove
- Curved Surface Linear
- Laminated
- Calendared Linear

REFLECTIVE TROUGH CONCENTRATORS

- Reflective Materials
  - Metallized Films
  - Polished Metals
  - Back-Surfaced Glass
- Trough Structures
  - Composites
  - Sheet Metal
  - Molded Epoxy

ADVANCED APPROACHES:

- Pressure Supported Dish
- Sealed Glass or Acrylic Dish
- Compound Parabolic Dish
- Luminescent
- Domed or Compound Fresnel

Figure 2. Solar Concentrator Technologies For Photovoltaics

NOTES

MULTIJUNCTION CONCENTRATORS

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Photovoltaics Program Office
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In concentrator photovoltaic systems, cell efficiency is a major parameter determining the ultimate bus bar cost of the electricity. Conventional planar junction solar cells are limited to theoretical efficiencies of about 25 - 27% at 1000 suns. GaAs concentrator cells have demonstrated efficiencies already close to 24%. One objective of the DOE concentrator cell program is to explore cell concepts which would achieve high efficiencies potentially above 30 percent. Three approaches are presently under study: (1) Beam Splitting Two-Junction Photovoltaic Converters; (2) Monolithic Cascade Two-Junction Photovoltaic Converters; and (3) Etched Multiple Vertical Junction Silicon Concentrator Cells.

Modelling of the two junction concentrator cell approaches indicate that efficiencies above 35% near ambient temperatures are achievable from series-connected cells, e.g., cascade converters, as well as cells operated separately at their maximum power points. In addition, photovoltaic conversion efficiencies of 25% or greater seems viable at temperatures of 180°C, compatible with hybrid photovoltaic/thermal system applications. Through previous Sandia-sponsored programs with Varian Associates and Research Triangle Institute, proof-of-concepts experiments were performed to verify the beam-split and monolithic cascade approaches. An efficiency of 28.5% was demonstrated by Varian with a Si/AlGaAs beam-split converter. In addition, RTI measured an open-circuit voltage of 2.3V on a GaAs/AlGaAs structure verifying cascade action. The present emphasis of the SERI/PVPO and other DOE programs is the improvement of the materials and device technologies to achieve the practical efficiency limits from these approaches. The materials/device fabrication requirements are particularly stringent in the monolithic cascade converter where two homojunctions are coupled electrically and optically through a low resistance interface. One approach to couple the two junctions is to fabricate a tunnel junction which is complicated by the need for high doping (high 10^{18} cm^{-3} or greater), narrow layer thicknesses (~ 10 Å), and low dopant diffusion coefficients to maintain the integrity of the junction during subsequent device processing. A second approach being pursued is to fabricate the top and bottom junctions separately and then bond them together to provide the necessary electrical, thermal, and optical interface. This approach would allow each junction to be fabricated under the best possible growth conditions. Possibly bonding schemes might involve thermal or laser fusion of the interface or bonding of co-incident electrical contact grids with a transparent thermal conductor coupling the active areas of the cells.

The etched multiple vertical junction Si concentrator cell investigated by Microwave Associates has recently demonstrated an efficiency above 20 percent in a Sandia-sponsored program. This cell concept relies on a vertical groove technology in single crystal silicon. A recently initiated contract with SERI/PVPO will investigate an alternate cell design in which the grooves will be alternately doped n and p eliminating the requirement of a top electrical grid. Experimental verification of theoretical efficiencies above 25% and demonstration of adequate electrical and thermal connections to the cell are emphasized.

In the talk each of the above approaches to high efficiency concentrator converters is reviewed. The existing high efficiency multijunction cell efforts are discussed. Finally, the key technology issues of this task are outlined.

High Efficiency Multijunction Concentrator Cell Development

K. Mitchell — Task Manager
J. Benner

Photovoltaics Advanced R&D Annual Review
Denver, CO
September 17-19, 1979

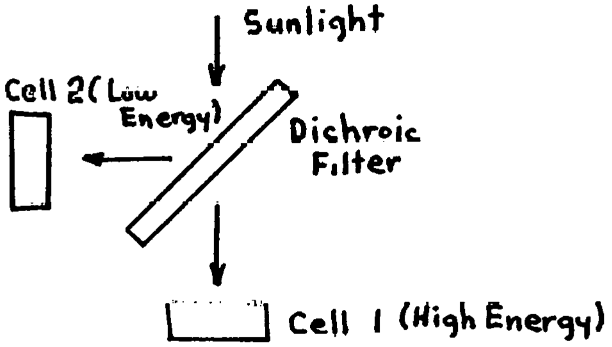
MULTIJUNCTION CELL CONCEPTS

1. IN A SINGLE JUNCTION SOLAR CELL, THE TRADE-OFF BETWEEN HIGH CELL OUTPUT VOLTAGE AND HIGH OUTPUT CURRENT LIMITS THE THEORETICAL EFFICIENCY TO ABOUT 25-27% AT 1000 SUNS.

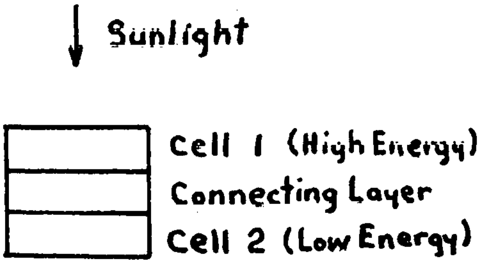
2. BY SPLITTING THE SOLAR SPECTRUM INTO HIGH AND LOW PHOTON ENERGY SPECTRA AND OPTIMIZING SEPARATE CELLS FOR EACH SPECTRA, CONVERSION EFFICIENCIES UP TO 39% AT 1000 SUNS FOR 2 CELLS IS EXPECTED.

3. TWO GENERAL APPROACHES:

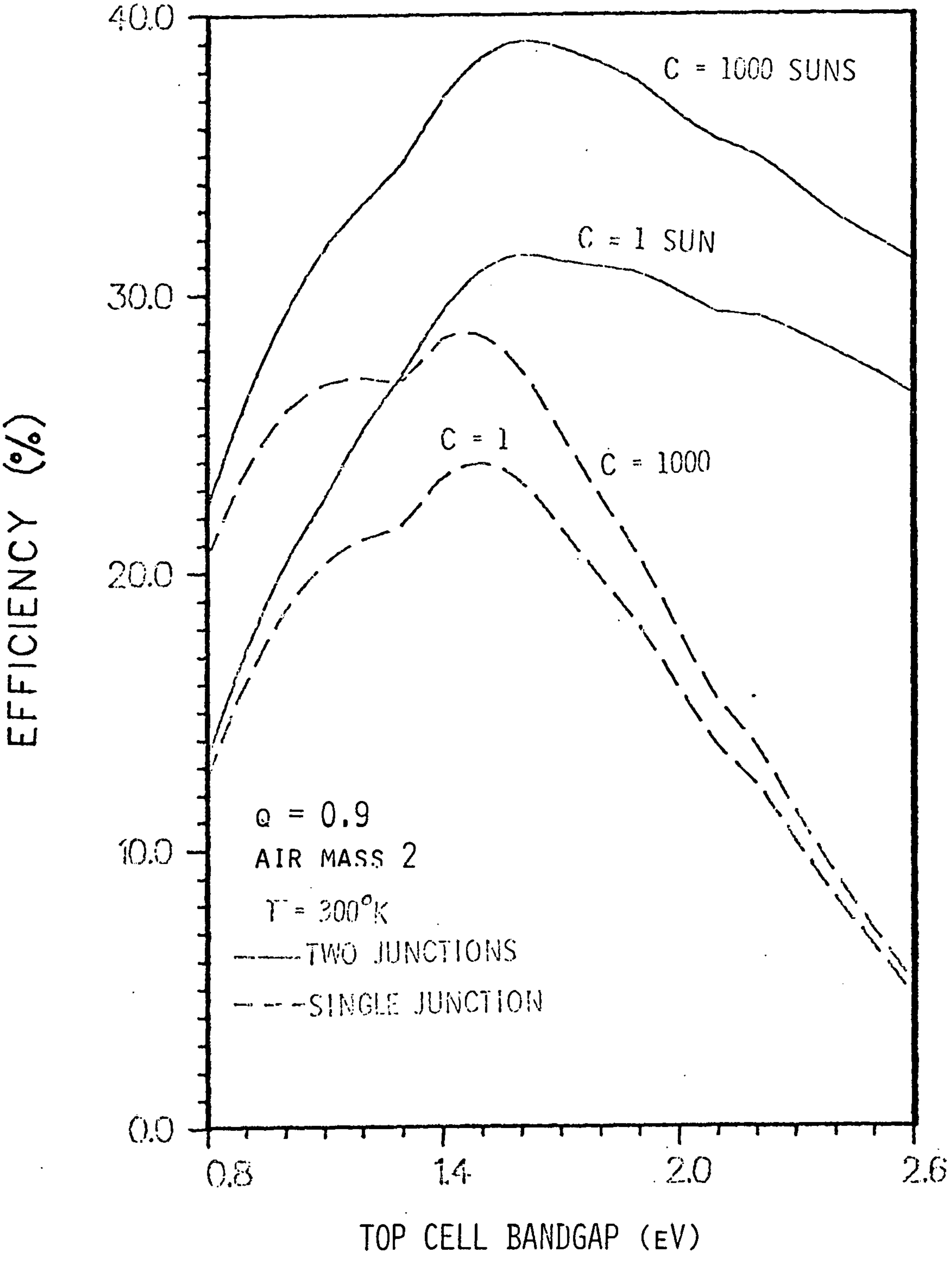
SPECTRAL SPLITTING



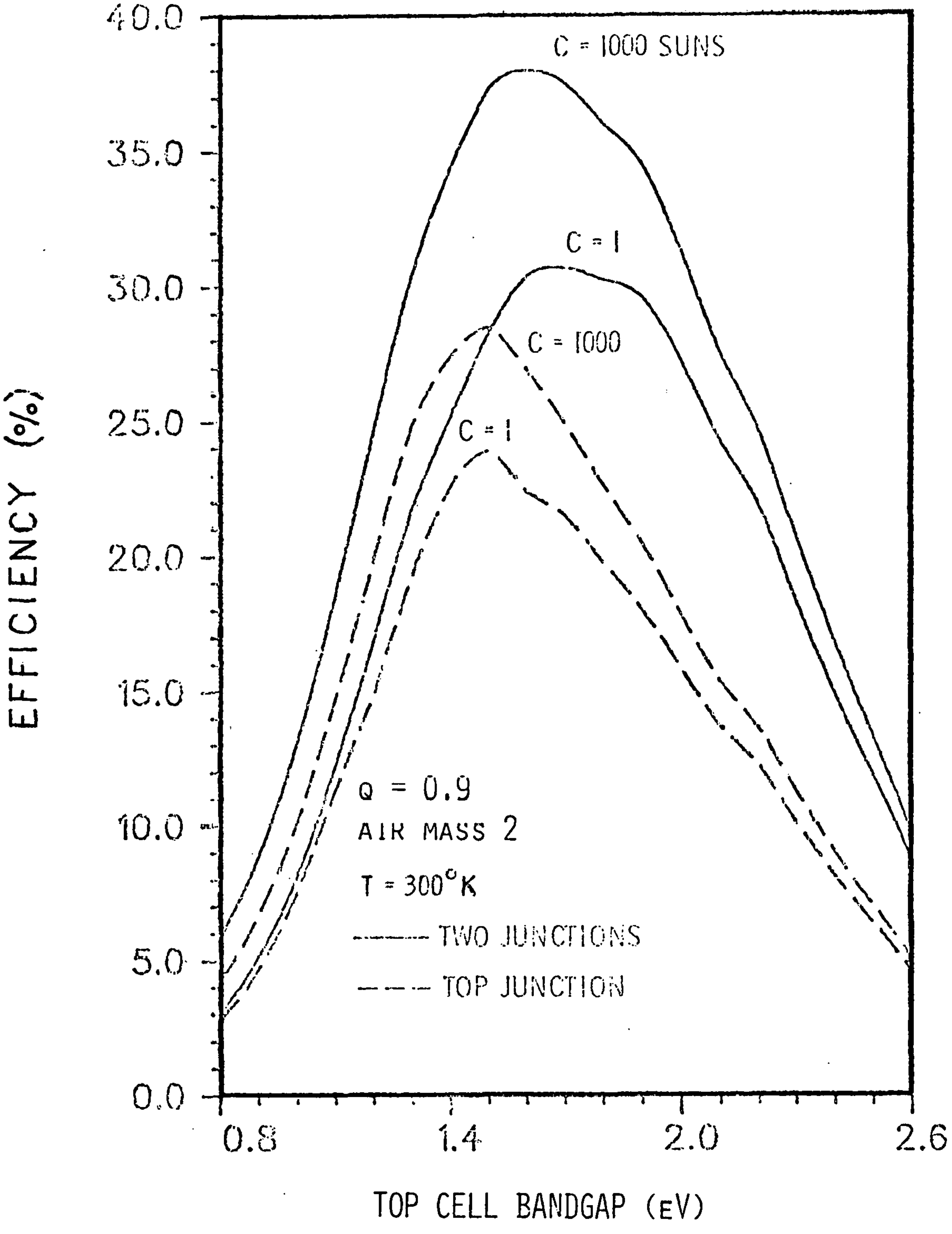
CASCADE



THEORETICAL EFFICIENCY VS BANDGAP FOR SINGLE JUNCTION AND TWO JUNCTIONS OPERATED INDEPENDENTLY



OPTIMUM THEORETICAL EFFICIENCY VS TOP CELL BANDGAP FOR TWO SERIES-CONNECTED CELLS



PERFORMANCE OF TWO-JUNCTION PHOTOVOLTAIC CONVERTERS

Temperature (°K)	300		450	
Cell Connection	Independent	Series	Independent	Series
Efficiency (%), 1000 AM2 Suns	39	38	29.2 (33.7)*	28.7
Optimum High Bandgap (eV)	1.6	1.6	1.6	1.7
Optimum Low Bandgap (eV)	0.95	0.9	0.95	1.0

* Low bandgap cell operated at 300°K

Beam-Splitting Two-Junction Photovoltaic Converters

Advantages

- Ease of fabricating individual cells
- Complex connecting junction not required
- Ability to operate cells independently at different temperatures

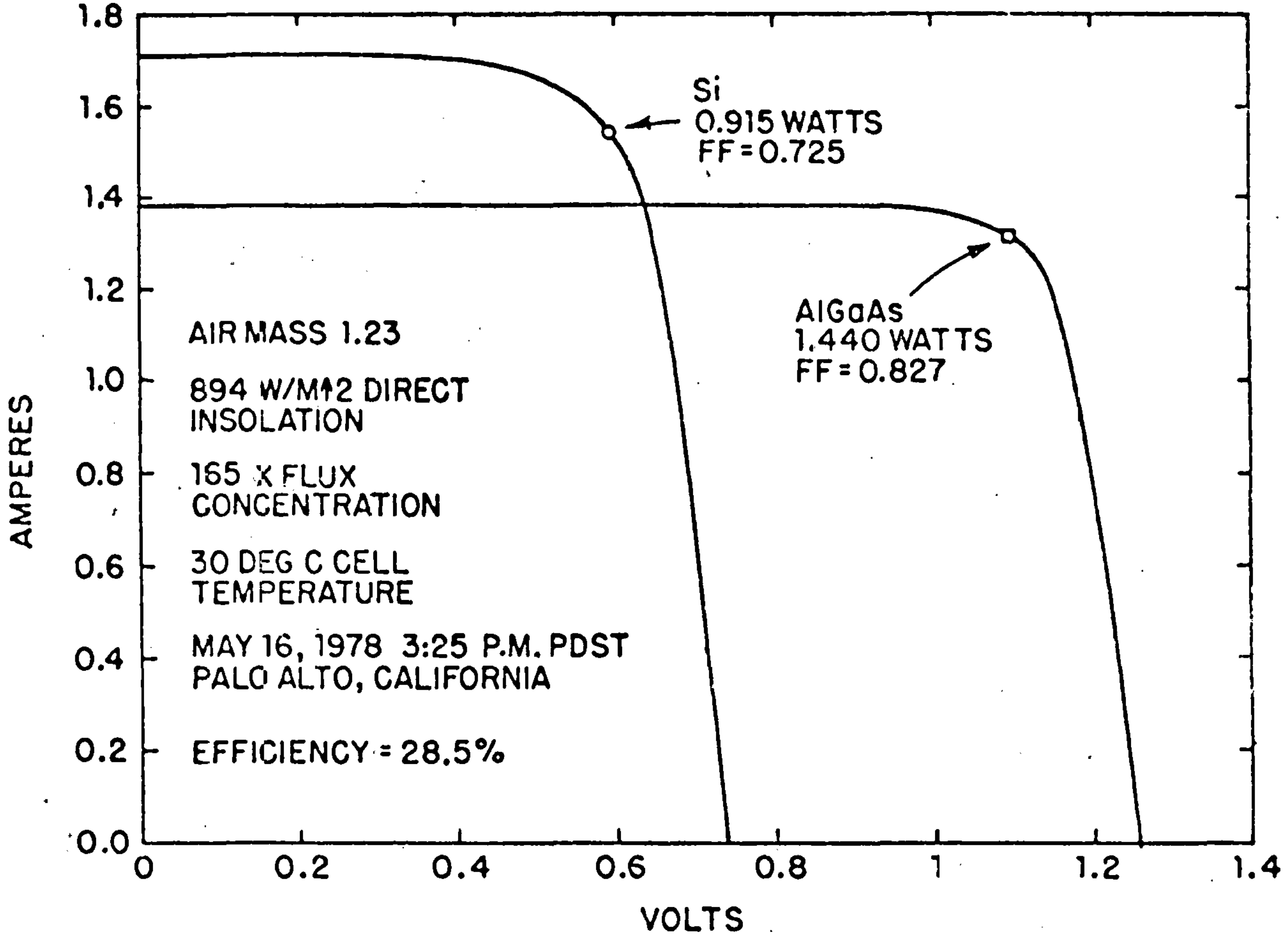
Disadvantages

- Increase component count (affects cost, system reliability)
- High cost of additional substrate
- Optical losses due to non-ideal dichroic filter

Status

- 28.5% photovoltaic converter efficiency demonstrated with AlGaAs/Si cells at 150 AM1.2 suns (Varian)
- Continued beam-split cell development sponsored by Sandia Labs (Varian)
- Si/AlGaAs beam-split array demonstration sponsored by Sandia Labs (Varian)

Si AND AlGaAs SOLAR CELLS OPERATED WITH A SPECTRAL SPLITTING FILTER



VARIAN

Monolithic Cascade Two-Junction Photovoltaic Converters

Advantages

- Two-terminal device structure
- Only one substrate required
- No losses due to dichroic filter

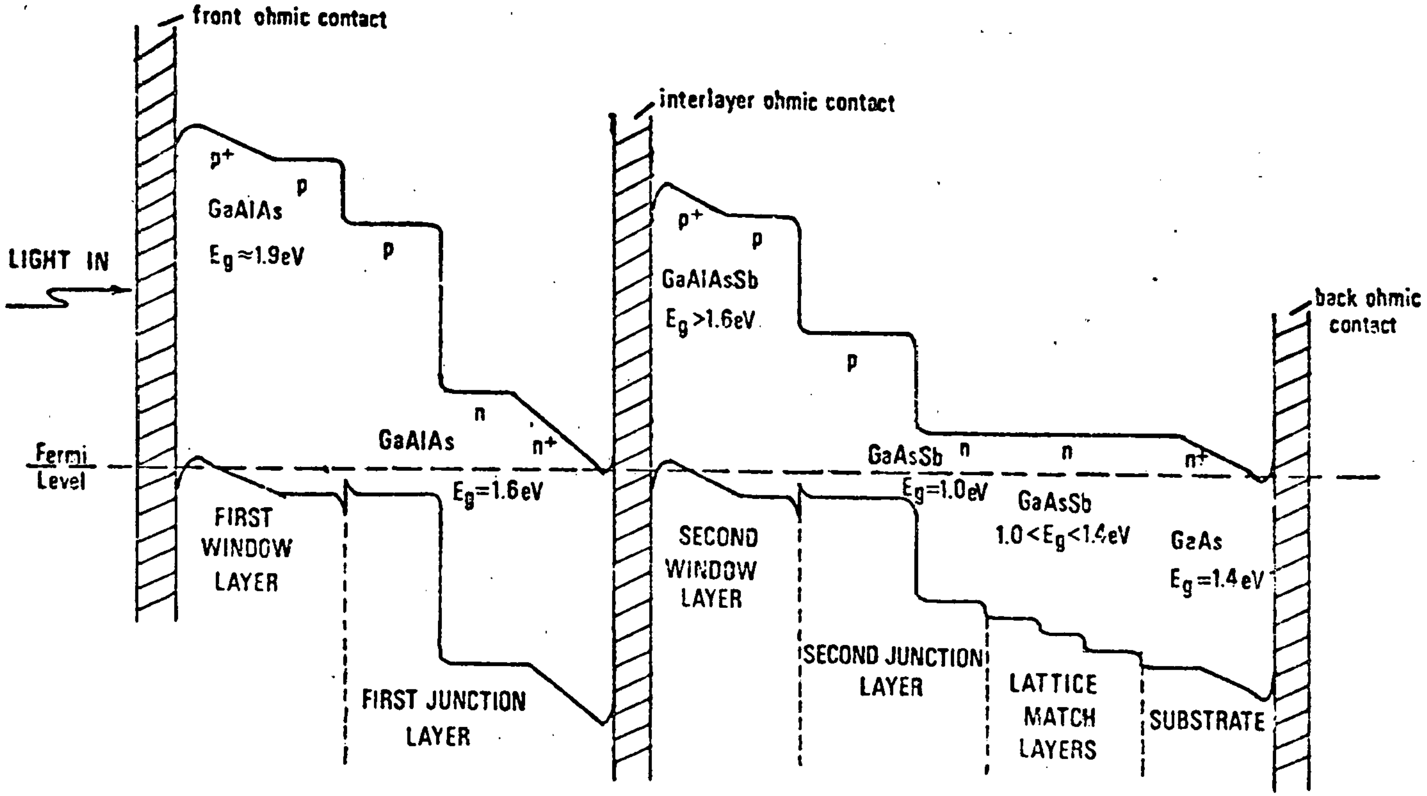
Disadvantages

- Complex connecting junction required
- Stringent material and growth parameters required to provide optimum solar cell performance
- Potentially lower production yield due to device complexity

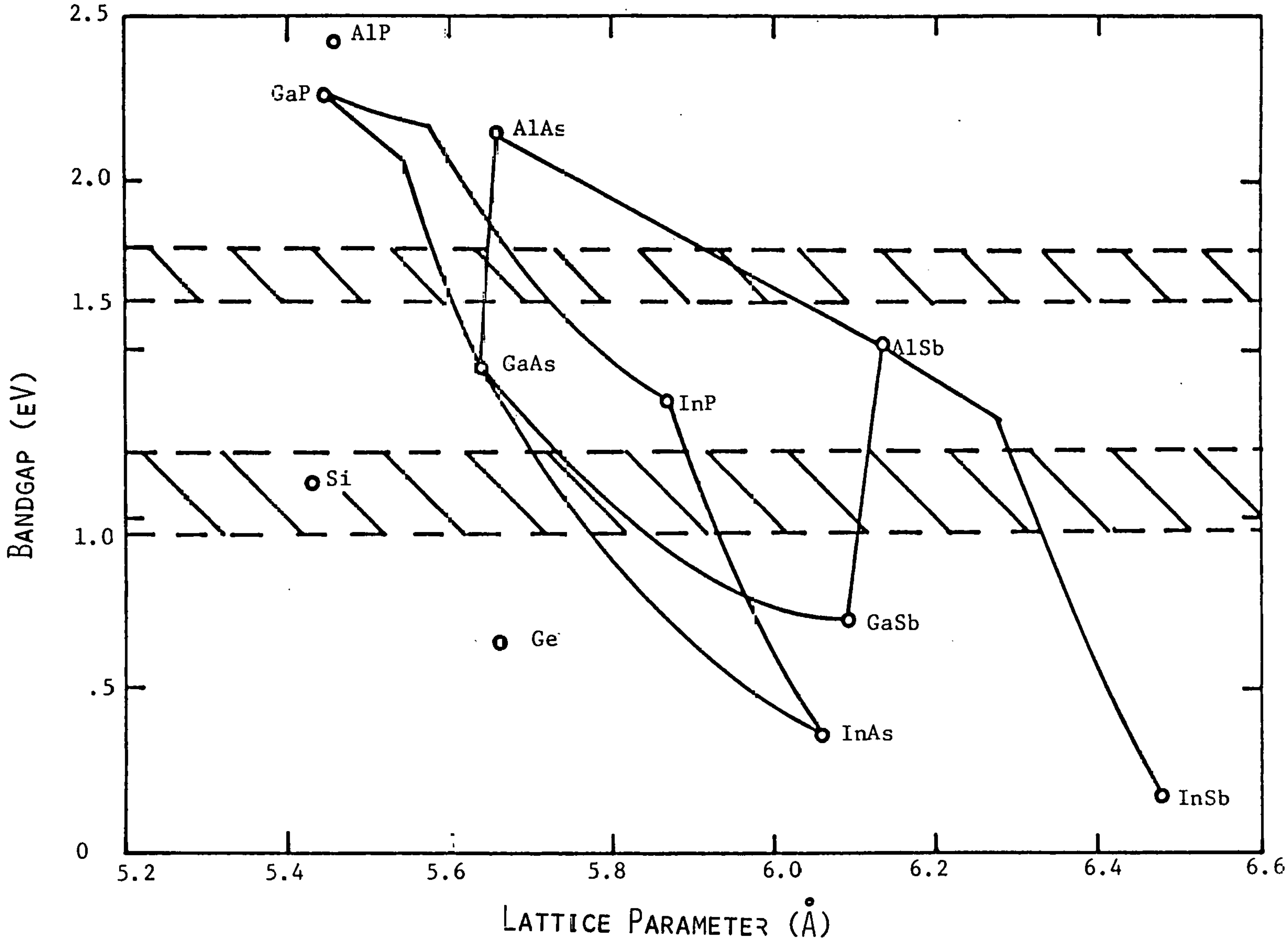
Status

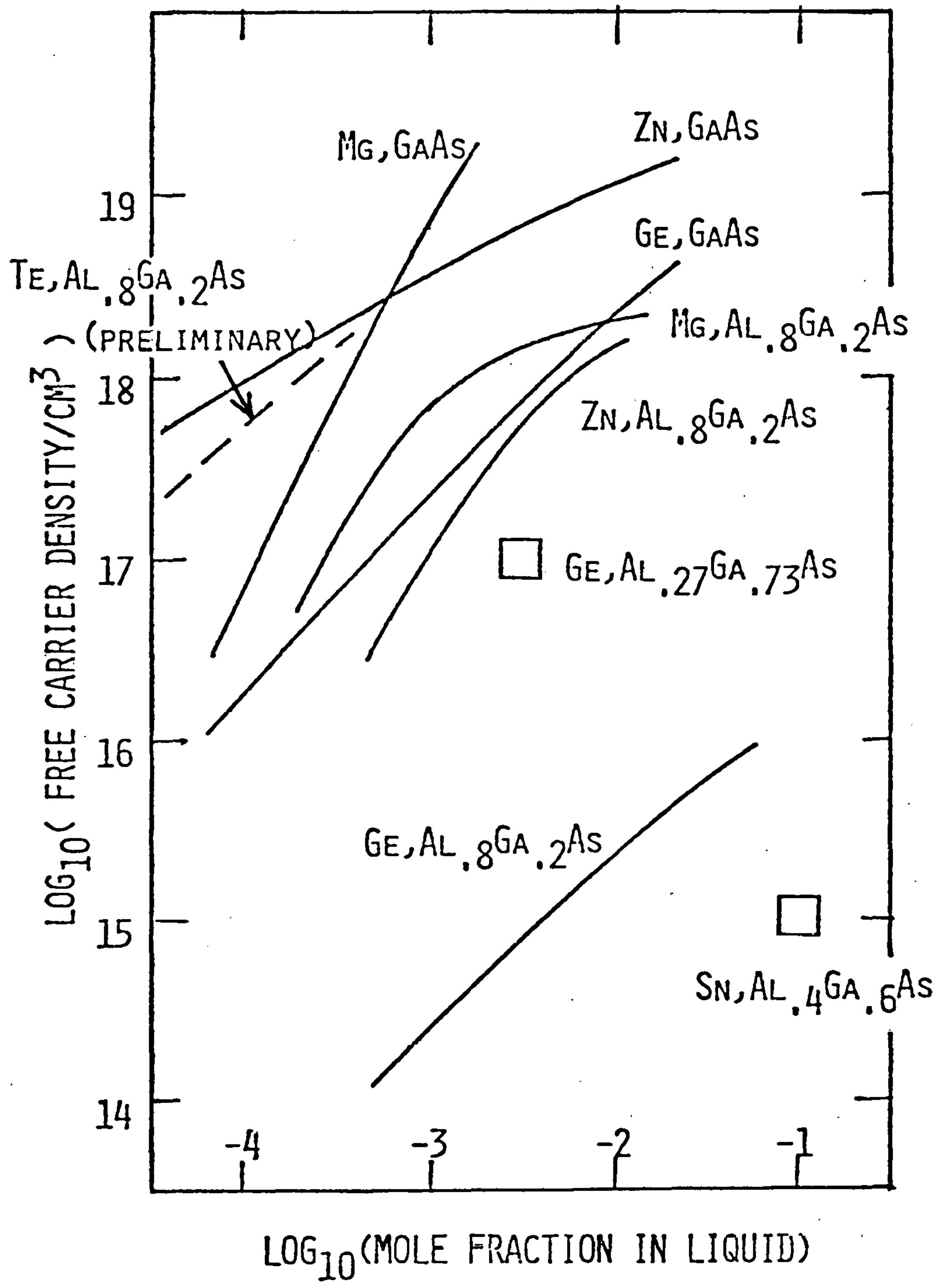
- > 2.3V open-circuit voltage measured demonstrating the cascade action of two-junctions connected by a tunnel junction
- Continued monolithic cascade cell development sponsored by SERI/PVPO (Research Triangle Institute, Varian)
- New methods to relax material and growth requirements sponsored by SERI/PVPO (N. Carolina State)
- Methods to bond two cells into stacked structure under consideration (Varian, Rockwell)

ENERGY BAND DIAGRAM FOR A TWO JUNCTION MONOLITHIC CASCADE CONCENTRATOR CELL (VARIAN)



BANDGAP AND LATTICE CONSTANT VALUES FOR THE III-IV SEMICONDUCTORS (RTI)





DISTRIBUTION BEHAVIOR OF ACCEPTORS AND DONORS IN THE AlGaAs SYSTEM (VARIAN)

PROGRAM GOALS

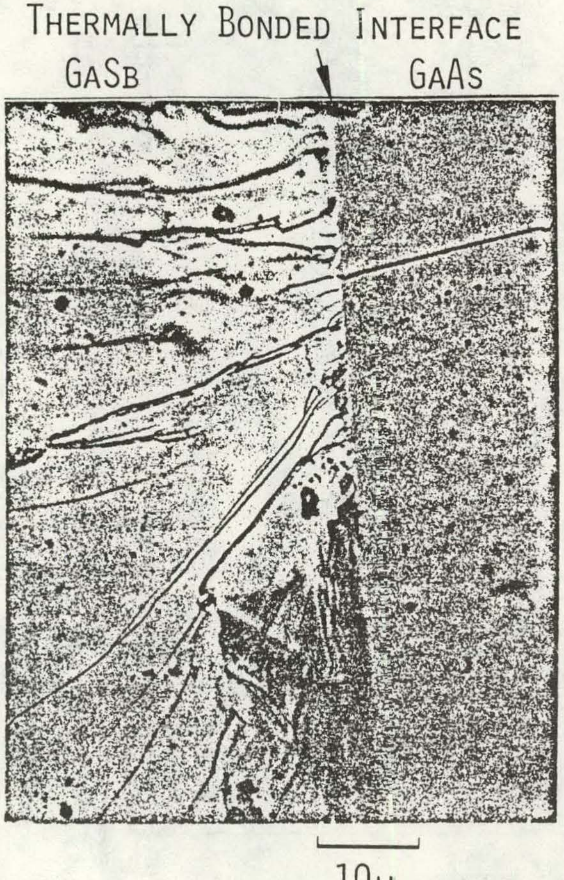
MAJOR GOAL

- DEMONSTRATE STACKED MULTIJUNCTION SOLAR CELLS WITH EFFICIENCIES >30% AT 25°C AND >25% AT 150°C UNDER 500-1000 SUN AM2 ILLUMINATION

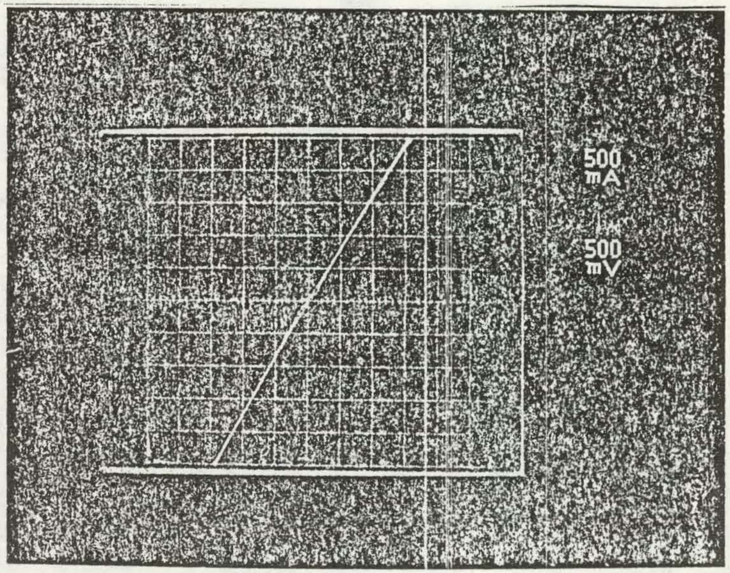
PROGRAM TASKS

- DEMONSTRATE OPTIMIZED SINGLE JUNCTION CELLS WHICH, IN COMBINATION CAN ACHIEVE THE OVERALL EFFICIENCY GOALS
- DEVELOP BONDING TECHNIQUES FOR STACKING SINGLE JUNCTION NON-LATTICE MATCHED CELLS TO GIVE THE REQUIRED LOW RESISTANCE, TRANSPARENT INTERCELL OHMIC CONTACTS
- EVALUATE INDIVIDUAL AND STACKED CELL PERFORMANCE AT TEMPERATURES OF 30-200°C UNDER 1-1000 SUN AM2 ILLUMINATION

OHMIC CONTACT BETWEEN·THERMALLY BONDED NON-LATTICE-MATCHED SEMICONDUCTORS



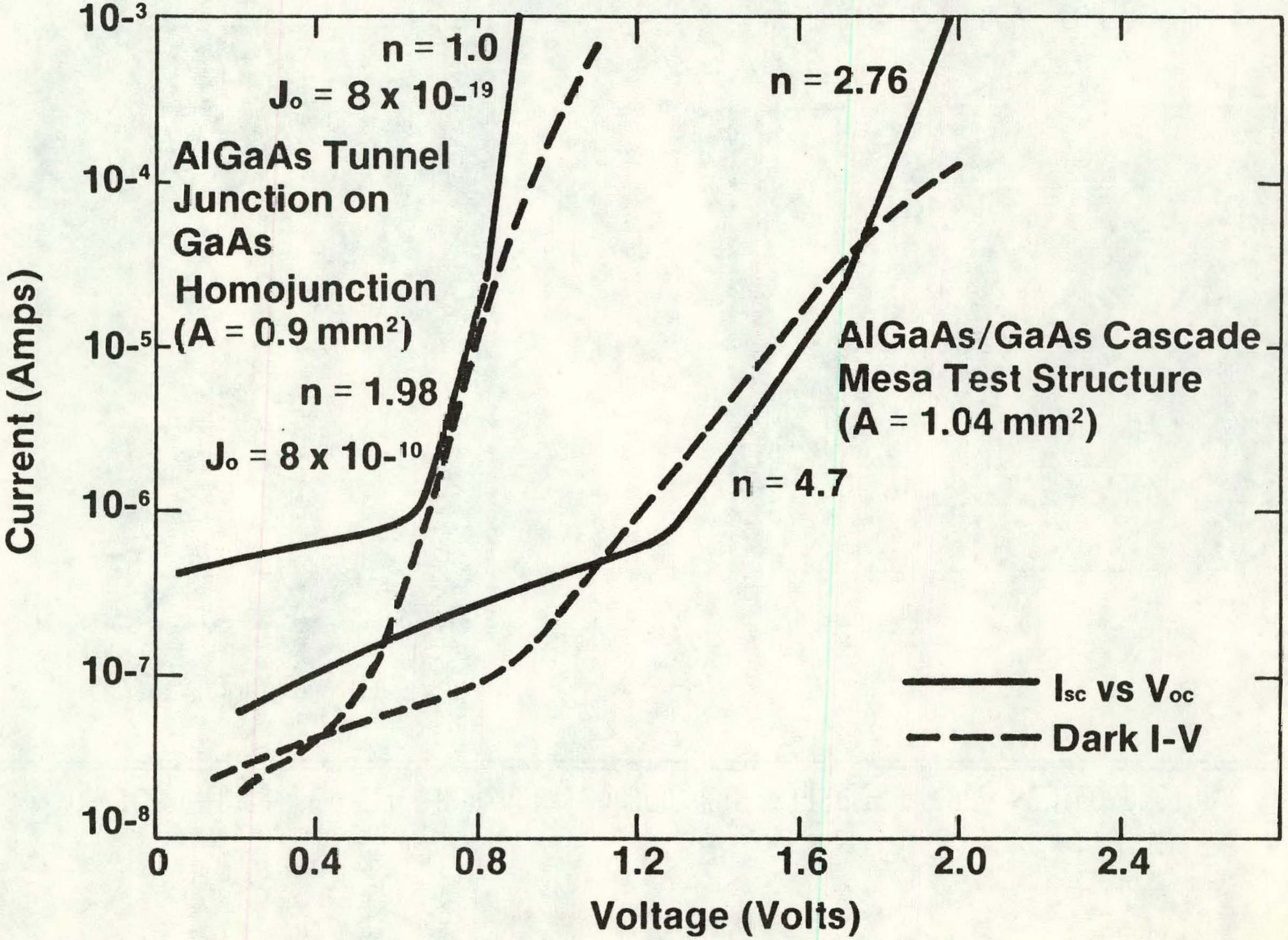
PHOTOMICROGRAPH OF BONDED INTERFACE



I-V CURVE FOR ABOVE CONTACT.
CONTACT AREA .15 cm^2
CONTACT RESISTANCE $<.09\,\Omega cm^2$

Rockwell International

Current-Voltage Characteristics of Prototype AlGaAs/GaAs Cascade Structure (RTI)



Etched Multiple Vertical Junction Silicon Concentrator Cells

Advantages

- Uses low cost silicon wafers
- Higher conversion efficiency than conventional silicon planar junction

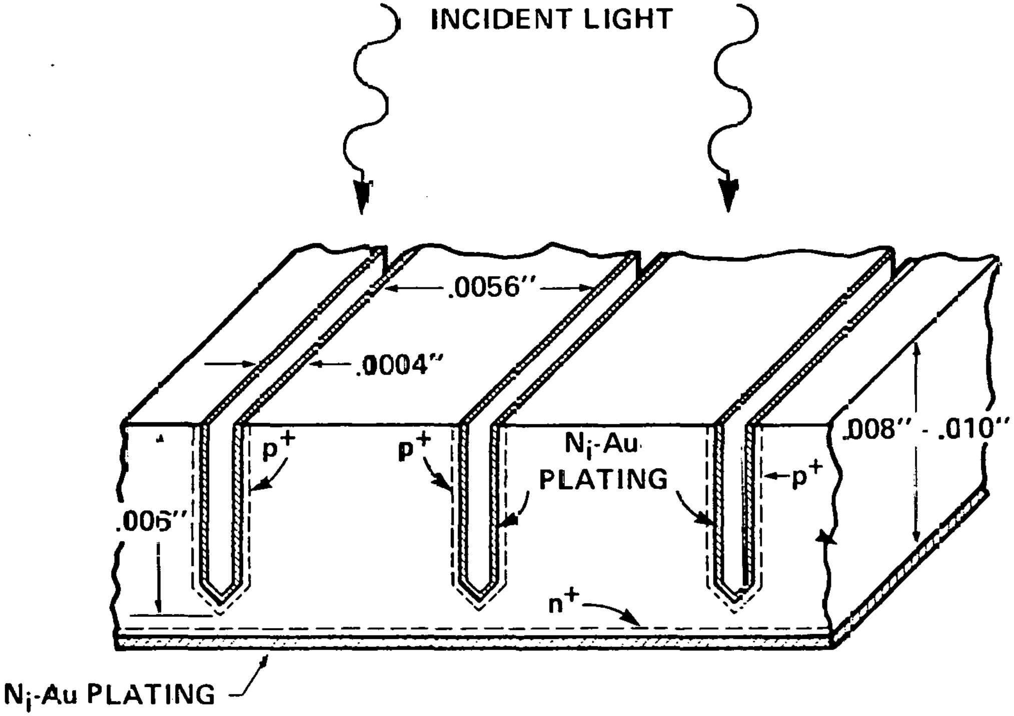
Disadvantages

- Projected theoretical efficiencies need experimental verification
- Adequate electrical and thermal connections to cells need to be demonstrated

Status

- 20% photovoltaic efficiency demonstrated in Sandia-sponsored program (Microwave Associates)
- SERI/PVPO sponsored program initiated to develop high efficiency EMJV Si concentrator cells (Microwave Associates)

SCHEMATIC OF EMVJ CELL STRUCTURE BEING FABRICATED FOR SANDIA (MICROWAVE ASSOCIATES)



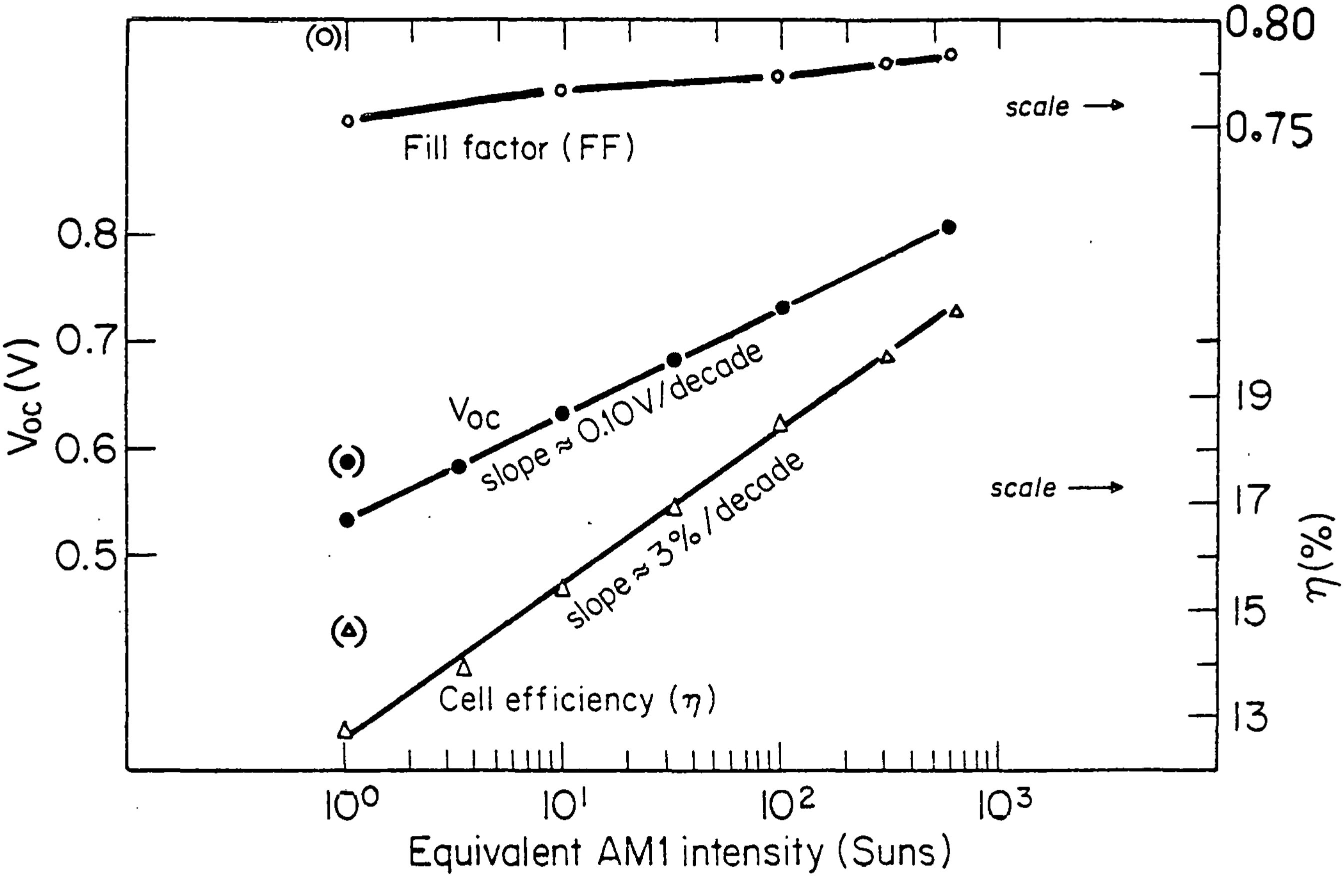
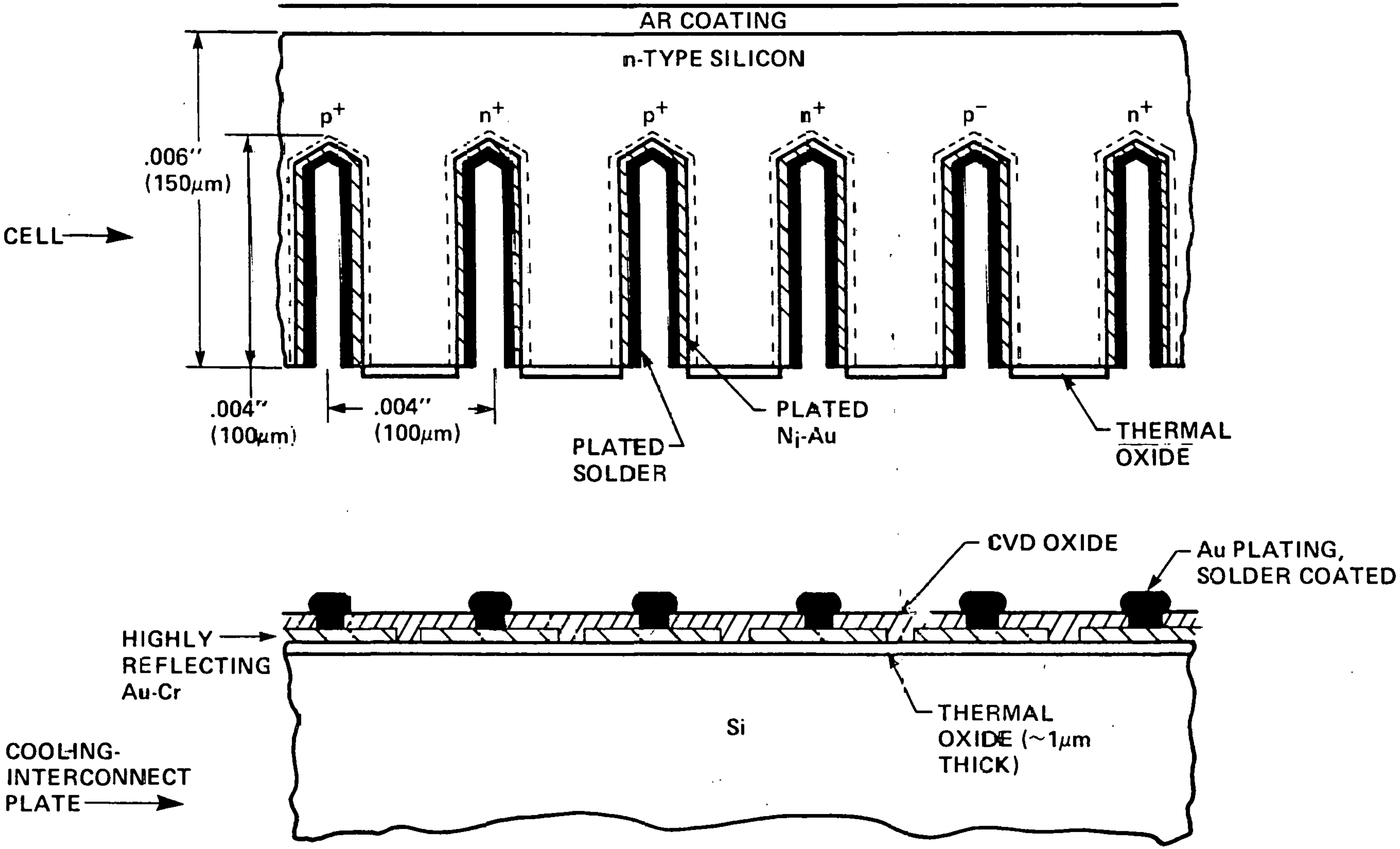


Figure 2. Experimental Results for V_{OC}, FF, and η As A Function Of Intensity. Values In Parentheses Are For Newer Cells Using Improved Processing.

CROSS-SECTIONAL VIEW OF PROPOSED BASELINE CELL AND COOLING - INTERCONNECT SUBSTRATE (MICROWAVE ASSOCIATES)



High Efficiency Multijunction Cell Efforts

Funding Organization	Title/Contractor
SERI/PVPO	Development of high efficiency cascade solar cells (RTI)
SERI/PVPO	Materials for high efficiency monolithic multigap concentrator cells (Varian)
SERI/PVPO	Development of high efficiency Etched Multiple Vertical Junction Si concentrator cell (Microwave Associates)
SERI/PVPO	Development of non-lattice matched cascade solar cells (Rockwell)
SERI/PVPO	Study of growth problems in lattice mismatched solar cells (N. Carolina State University)
Sandia	Development of Si EMJV concentrator cells (Microwave Associates)

Sandia	Further development of novel beam-splitting photovoltaic converter (Varian)
Sandia	Demonstration of beam-splitting photovoltaic array (Varian)
Wright-Patterson	Development of high efficiency stacked multigap solar cells for space applications (RTI, Rockwell)
NASA Lewis	Analysis of high efficiency photovoltaic converters for space application
EPRI	Thermophotovoltaic solar energy conversion (Stanford)

High Efficiency Concentrator Cell Technology Issues

- Assessment of various III-V material systems for efficient concentrator solar cells by LPE, OM-CVD, or vapor phase growth processes.
- Development of required cell interconnect technologies, especially tunnel junctions.
- Development of reliable, low resistance electrical contacts especially to high-bandgap materials.
- Development of required AR coatings and encapsulants (Note: Degradation of AlGaAs cells).
- Development of low-cost, high quality GaAs substrates or other appropriate substrates (e.g., Ge or GaInAs).
- Determination of cell degradation mechanisms under concentrator conditions.
- Development of III-V concentrator cell pilot production lines.
- Assessment of Si EMVJ concentrator cells.
- Assessment of thermophotovoltaic converters.
- Development of necessary concentrator optics, tracking, power conditioning and thermal cooling systems.

NOTES

LUMINESCENT SOLAR CONCENTRATORS

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The concept of solar concentration based on light pipe trapping of luminescence has received only two years of intensive research. The generic name for this device is the Luminescent Solar Concentrator (LSC). In the basic configuration, a transparent material is impregnated with luminescent species having strong absorption bands in the visible and ultraviolet regions of the solar spectrum and also having an efficient quantum yield of emission. Solar photons entering the upper face of the plate are absorbed and typically fluorescent photons are emitted. A large fraction of the fluorescent photons are trapped by total internal reflection. Successive reflections carry the fluorescent photons to the edge of the plate where they may enter an edge-mounted array of photovoltaic cells.

This paper describes the advantages and present limitations of luminescent solar concentrators, and reviews the past years research addressing those limitations. The last figure lists critical areas for research in the next year.

The author acknowledges the preparation and contribution of viewgraphs by the participants in this program.

Luminescent Solar Concentrator

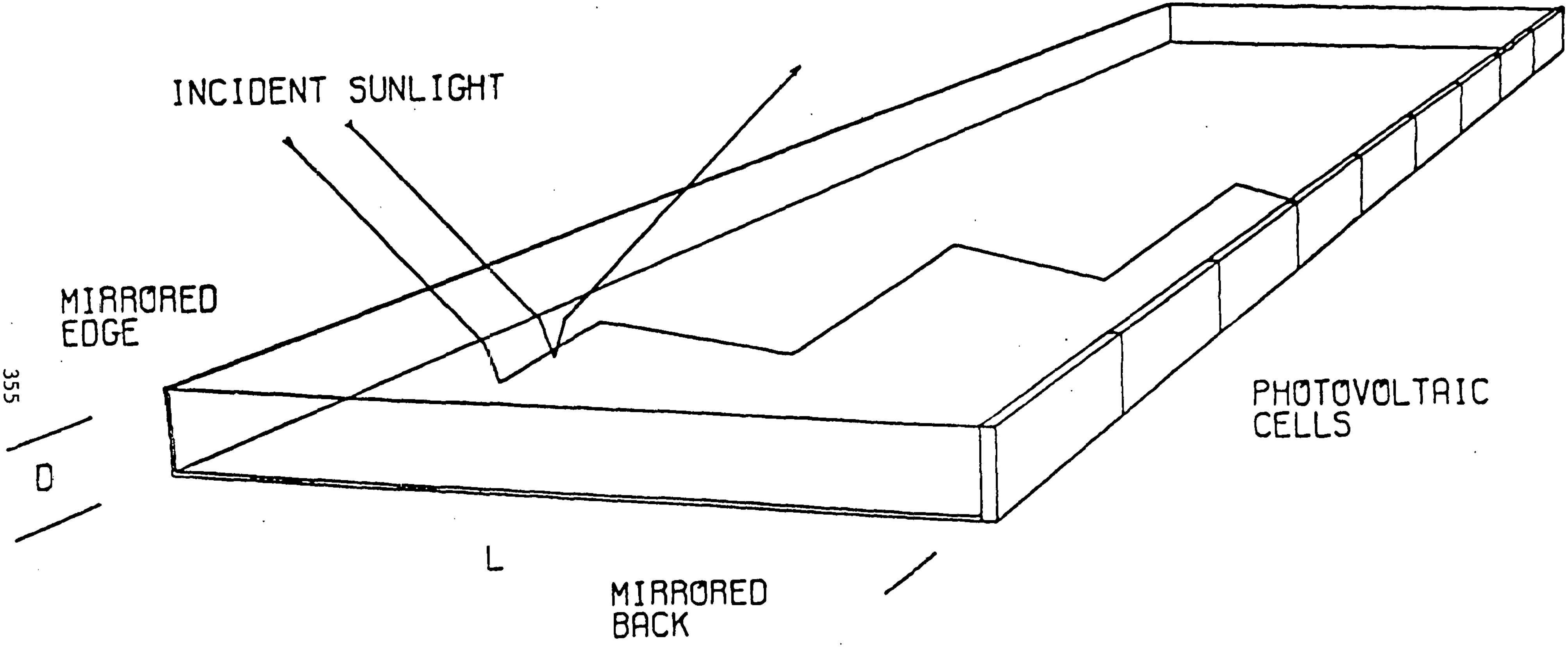
J. Benner
K. Mitchell

Photovoltaics Advanced R&D Annual Review
Denver, Colorado

September 17-19, 1979

Participant	Contract Amount	Duration
Owens-Illinois, Dr. P. Friedman	$173K	7 Months
California Institute of Technology, Dr. A. Zewail	$144K	12 Months

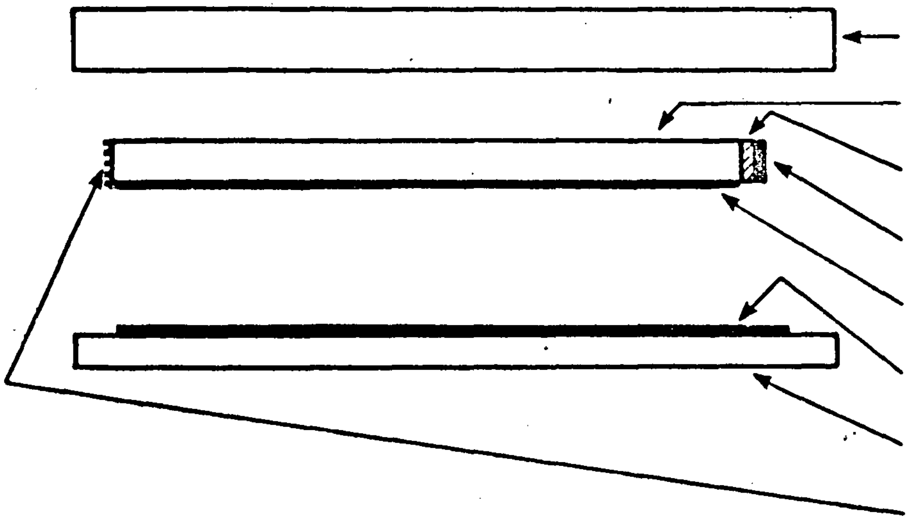
LUMINESCENT SOLAR CONCENTRATOR



Advantages of Luminescent Solar Concentrators

1. High Concentration Without Tracking
2. High Potential Efficiency in Diffuse Sunlight
3. Low Heat Dissipation in the Photovoltaic Cells
4. Narrow Band Output Yields High Cell Efficiency
5. Low System Cost
6. All Components of the Concentrating System are Currently Mass Produced

Cost Estimate of a 1 m², 10% Efficient Luminescent Collector



Tempered Glass Cover (1m²)	$4.30
Converter Sheet (1m x 1m x .5 cm)	8.60
Cell Bonding/Optical Couple	1.50
Solar Cell (50 cm² area)	5.00*
Dye-Plastic Film	.50
Back Mirror	.50
Back Cover Glass	2.70
Silvered Edges	1.00
Assembly and Packing	7.00
	$31.10/m² ($0.31/Wp)

*Assuming $1,000/m² Solar Cell Process Technology

Technical Barriers

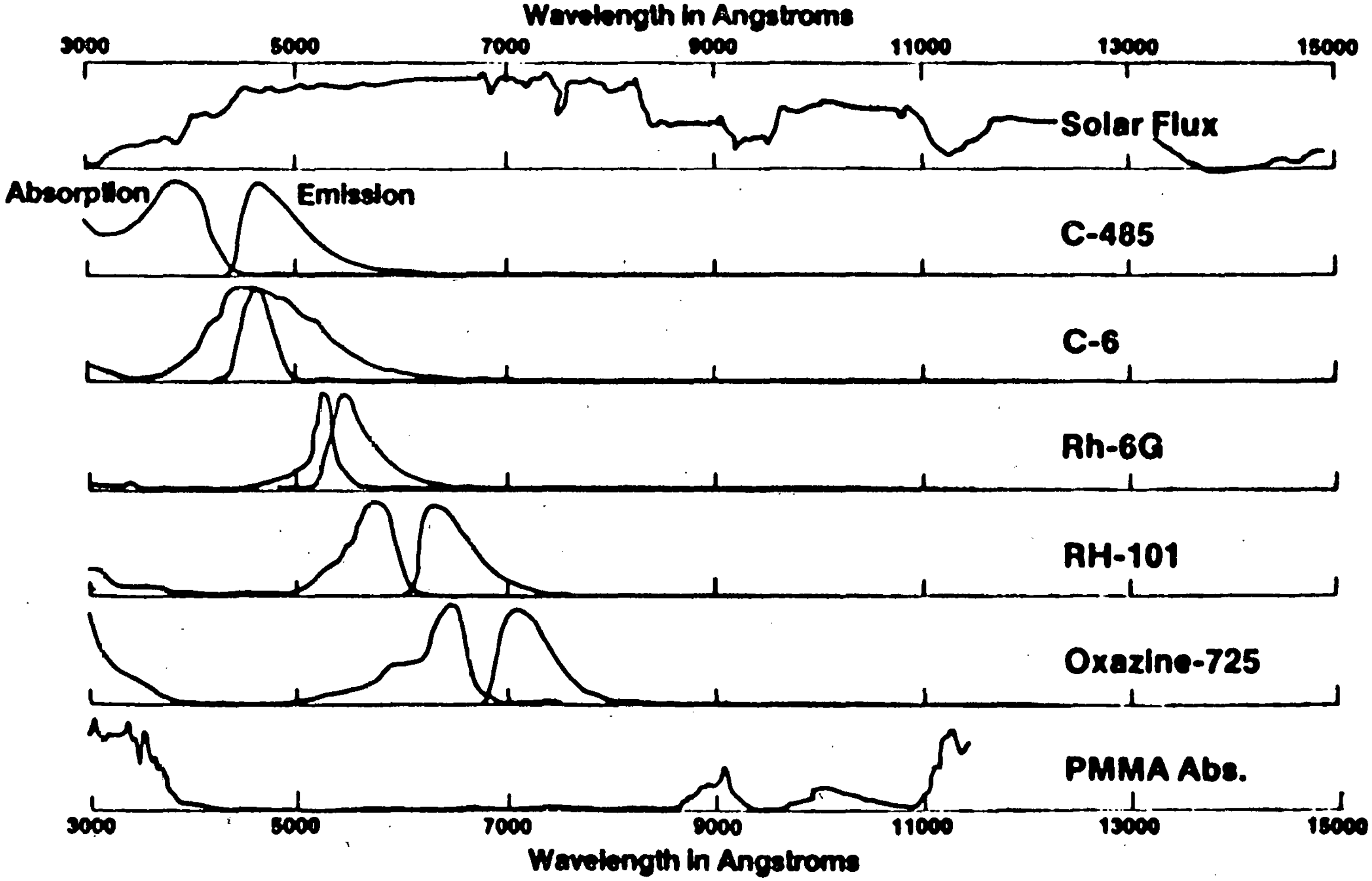
Efficiency

- Inadequate Absorption Bandwidth
- Self-Absorption
- Internal Reflectivity of Collecting Plates
- Critical Cone Losses

Stability

- Dye/Dye, Dye/Host, Dye/Impurity Reactions
- Host/Plate Degradation
- Photo-Dissociation of Dye Molecules

Absorption/Emission Spectra



LUMINESCENT GLASSES UNDER INVESTIGATION

DOPANTS:

Bi_2O_3, CeO_2, Cu_2O, Eu_2O_3, GeO, MnO,

Nd_2O_3, PbO, Sb_2O_3, SnO, TiO_2, Tl_2O_3,

U_3O_8 Yb_2O_3

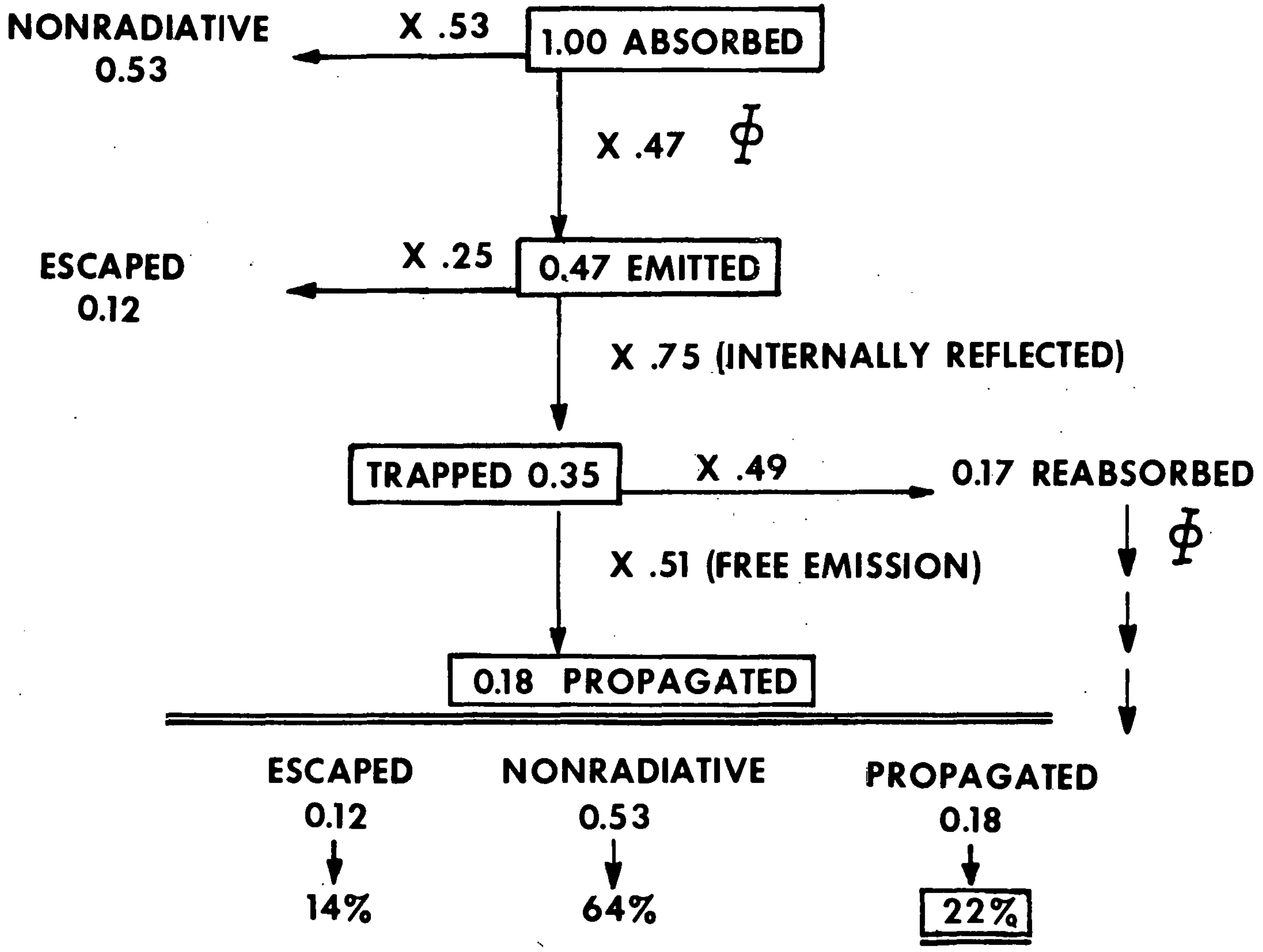
GLASS HOSTS:

BORATES, PHOSPHATES, SILICATES

OWENS-ILLINOIS

ENERGY PROPAGATION FOR U_3O_8 GLASS

Φ = 0.47 (MEASURED); 0.51 FREELY EMITTED



NONRADIATIVE 0.53

X .53

1.00 ABSORBED

X .47 Φ

ESCAPED 0.12

X .25

0.47 EMITTED

X .75 (INTERNALLY REFLECTED)

TRAPPED 0.35

X .49

0.17 REABSORBED

Φ

X .51 (FREE EMISSION)

0.18 PROPAGATED

ESCAPED	NONRADIATIVE	PROPAGATED
0.12	0.53	0.18
14%	64%	22%

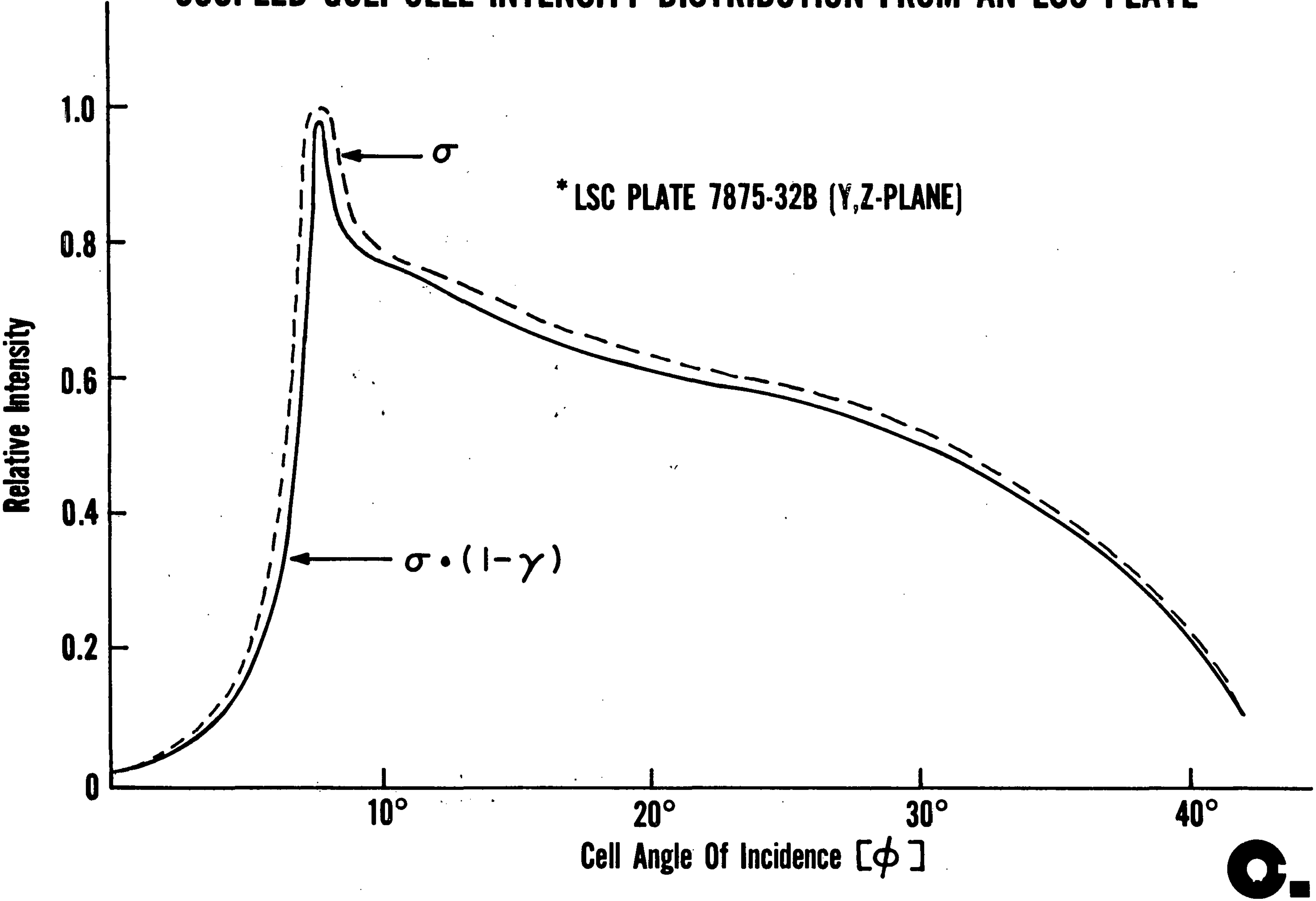
OWENS-ILLINOIS

COMPARISON OF ENERGY PROPAGATION CALCULATIONS

	FREE EMISSION	Φ	FRACTION ESCAPED	FRACTION NONRADIATIVE	FRACTION PROPAGATED
RHODAMINE 6G	0.22	1.00	0.61	0.00	0.39
U_3O_8 GLASS	0.51	0.47	0.14	0.64	0.22

OWENS-ILLINOIS

COUPLED OCLI CELL INTENSITY DISTRIBUTION FROM AN LSC PLATE*



*LSC PLATE 7875-32B (Y,Z-PLANE)

OWENS-ILLINOIS

RELATIVE COUPLING COEFFICIENT (K)

$$I_c = \frac{I_a}{K}, \text{ WHERE } K = \frac{1-r}{1-R}$$

$$1-r = \frac{\int \sigma (1-\gamma)\, d\phi}{\int \sigma \, d\phi}$$

I_c = POWER DENSITY INCIDENT UPON CELL FROM PLATE EDGE

I_a = POWER DENSITY AT NORMAL INCIDENCE UPON CELL IN AIR

r = CELL REFLECTANCE FROM GLUE INTERFACE FOR LIGHT EMITTED FROM PLATE EDGE

R = CELL REFLECTANCE FROM AIR INTERFACE FOR LIGHT NORMAL TO CELL AT EDGE EMISSION WAVELENGTH

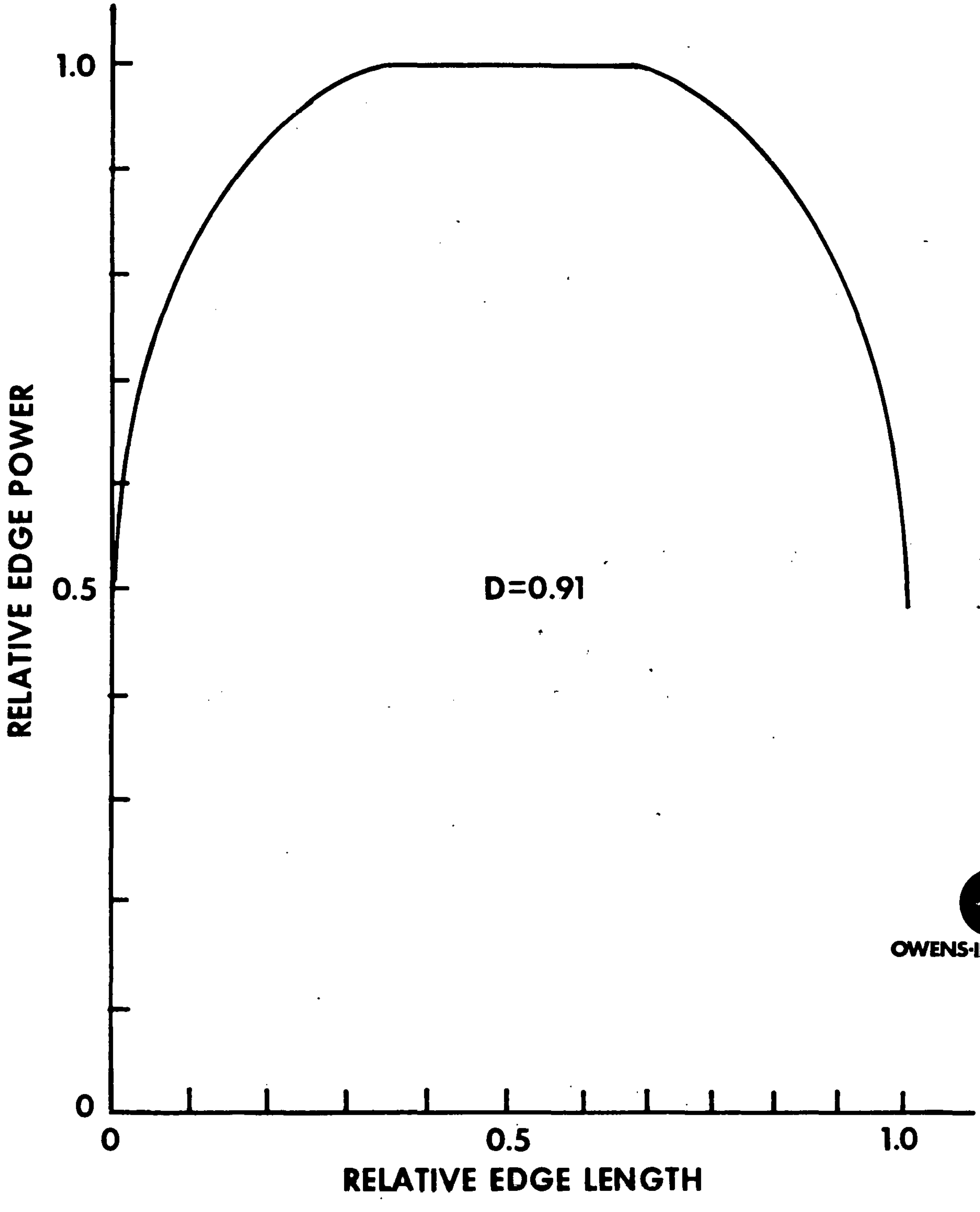
σ = EDGE RADIANT INTENSITY

γ = CELL REFLECTIVITY

ϕ = ANGLE OF INCIDENCE OF THE EMITTED RAY ON CELL FROM GLUE INTERFACE

OWENS-ILLINOIS

EDGE LUMINESCENCE DISTRIBUTION FACTOR



OWENS-ILLINOIS

LSC EFFICIENCY PARAMETERS

COLLECTOR EFFICIENCY

$$\eta = \frac{\text{COLLECTED EDGE POWER}}{\text{INCIDENT SURFACE POWER}} = \frac{J_m V_m a_e D}{I_i a_p a_c}$$

PLATE EFFICIENCY

$$\eta_p = \frac{\text{EMITTED EDGE POWER}}{\text{INCIDENT SURFACE POWER}} = \frac{I_c a_e D}{I_i a_p}$$

EDGE POWER DENSITY

$$I_e = \frac{100\, I_c D}{I_i}$$

CELL EFFICIENCY

$$\eta_{c\lambda i} = \frac{J_m V_m}{I_c a_c}$$

EFFECTIVE CONCENTRATION RATIO

$$X = \frac{\eta_{c\lambda} I_c D}{\eta_c I_i}$$

SOLAR ABSORPTION

$$A_s = 1 - \frac{\int I_s T_p \, d\lambda}{\int I_s \, d\lambda}$$

OWENS-ILLINOIS

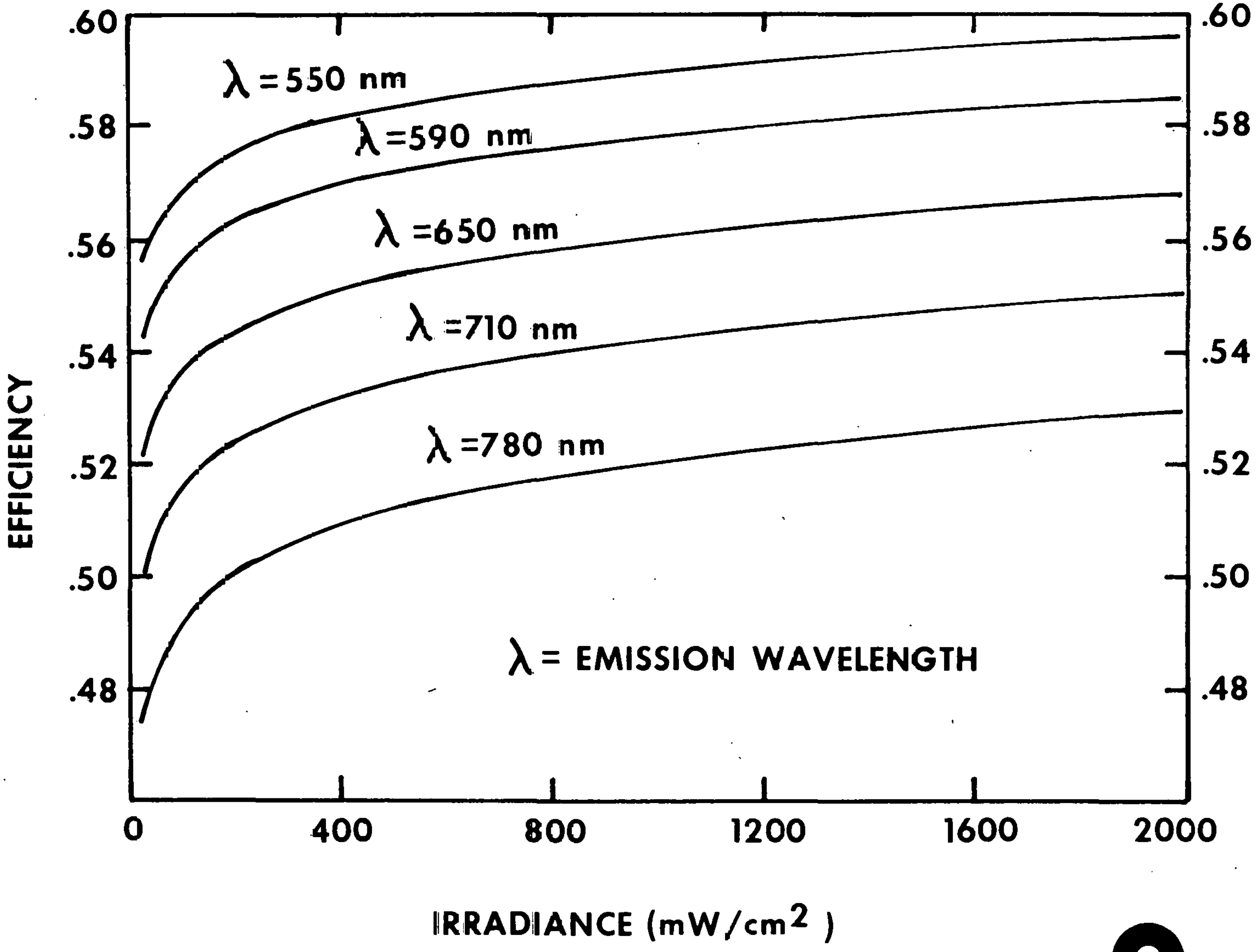
CALCULATED SILICON CELL MONOCHROMATIC EFFICIENCIES (SANDIA)*

TYPE	(nm)	n (%)
(n^+, p)	650	29
(n^+, p)	710	31
(p^+, n, n^+)	780	35
(p^+, n, n^+)	1000	43

*CELLS ARE OPTIMIZED AT 2000 mW/cm^2.

OWENS-ILLINOIS

CALCULATED ALGaAs CELL MONOCHROMATIC EFFICIENCIES (VARIAN)



OWENS-ILLINOIS

LSC DEVICE OPERATING TEMPERATURES *

AIR TEMPERATURE	22°C	
CLEAR ACRYLIC SUBSTRATE	46°C	(Δ T=24°)
LSC PLATE	61°C	(Δ T=39°)
CELL TEMPERATURE	52°C	(Δ T=30°)

*5.5 x 5.5 x 1/8" PLATE AT 106 mW/cm²

LUMINESCENCE EFFICIENCY

A.) 1.5×10^{-2} m COUMARIN -6 IN C.A.B. (45°A)

ABSORBANCE	RELATIVE EDGE LUMINESCENCE	FILM THICKNESS
2.5	97	.0007”
2.0	100	.0006
1.3	97	.0004
0.7	85	.0002

7.7×10^{-3} m COUMARIN -6 IN C.A.B. (57°A)

ABSORBANCE	RELATIVE EDGE LUMINESCENCE	THICKNESS
1.4	100	.0008”
1.0	89	.0006
0.6	71	.0003

B.) 1.4×10^{-2} m SULFORHODAMINE 101 IN C.A.B. (46°A)

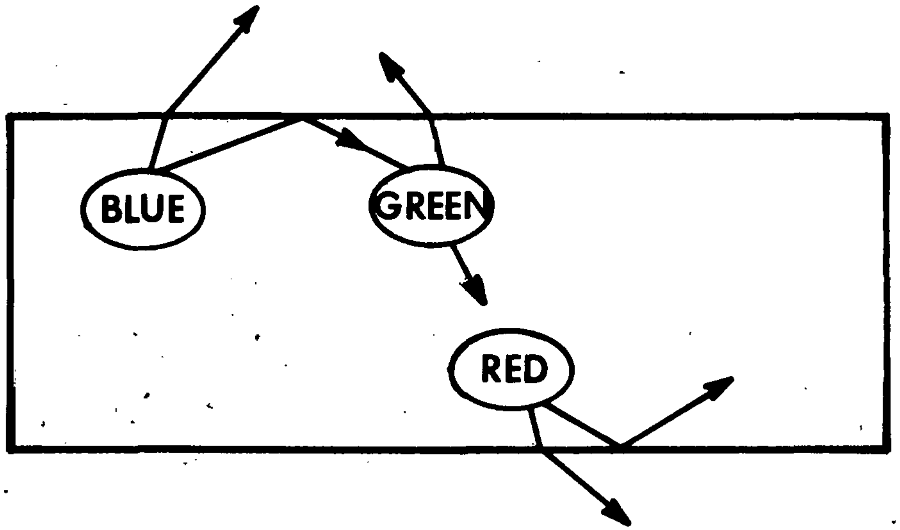
ABSORBANCE	RELATIVE EDGE LUMINESCENCE	THICKNESS
3.3	31	.0008”
2.2	33	.0005
1.6	44	.0003

6.9×10^{-3} m SULFORHODAMINE 101 IN C.A.B. (59 A)

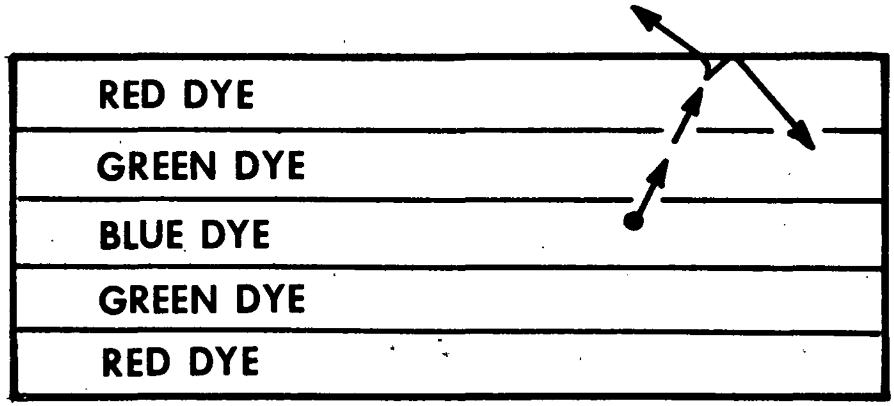
ABSORBANCE	RELATIVE EDGE LUMINESCENCE	THICKNESS
1.9	95	.0007”
1.5	100	.0005
1.1	95	.0004
0.8	89	.0003

MULTILAYER THIN FILM STRUCTURE

A. MIXED DYE FILM-THREE CRITICAL CONE LOSSES FOR BLUE DYE

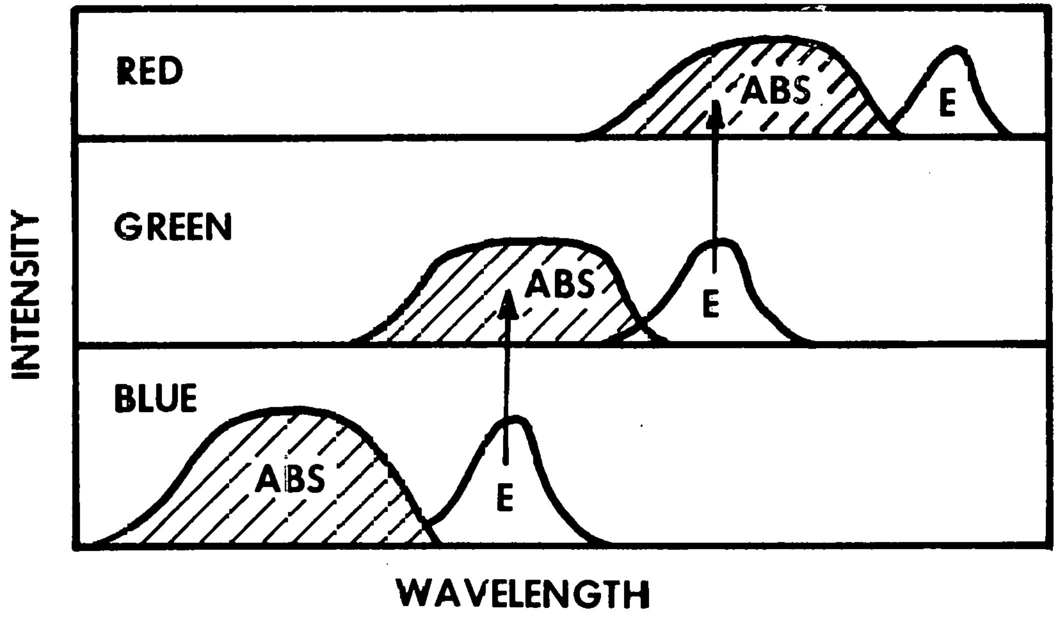


B. MULTILAYER DYE FILM-ONE CRITICAL CONE LOSS FOR BLUE DYE



OWENS-ILLINOIS

MULTILAYER THIN FILM STRUCTURE



ADVANTAGES:

1. REDUCTION OF CRITICAL CONE LOSSES BY MORE COMPLETE REABSORPTION
2. PHYSICAL SEPARATION OF CHEMICALLY ACTIVE DYES
3. BETTER CONTROL OF DYE CONCENTRATION AND OPTICAL DENSITY

OWENS-ILLINOIS

Critical Research Areas for Next Year

- Identification of dyes, chelates and/or ions for the near infrared
- Development of inorganic or hybrid collectors
    - Improved stability
    - UV protection
    - Improved trapping
- Non-radiative energy transfer to reduce loss

NOTES

MATERIALS FOR HIGH EFFICIENCY MONOLITHIC MULTIGAP CONCENTRATOR SOLAR CELLS

M. J. Ludowise, R. L. Bell, C. B. Cooper,
L. W. James, R. L. Moon and H. A. Vander Plas

Varian Associates
611 Hansen Way
Palo Alto, CA 94303

Program Objectives

This program addresses the materials problems associated with achieving a monolithic stacked two junction solar cell with AM2 conversion efficiency of 28% or higher at 500 to 1000 suns. The primary material system under investigation is AlGaInAs and the secondary system is AlInAsSb. The focus is on the growth technology of these systems by organometallic vapor phase epitaxy (OM-VPE), with additional explorations using chloride transport VPE and liquid phase epitaxy (LPE). Five major tasks have been defined: 1) develop and demonstrate the technology for a grading layer of $Ga_{1-x}In_xAs/GaAs$ and low (1.15 eV) bandgap cells, 2) demonstrate inter-cell tunnel junction contacts in the higher bandgap AlGaInAs, 3) demonstrate a higher bandgap concentrator cell in AlGaInAs alloys, 4) demonstrate a complete two-gap monolithic concentrator cell with AM2 efficiency of 28%, and 5) investigate the potential of AlInAsSb cells grown on InAs substrates.

Program Status

Work to date has concentrated on the construction of a computer controlled OM-VPE reactor for the growth of graded GaInAs layers and the growth of GaInAs by both chloride transport VPE and OM-VPE.

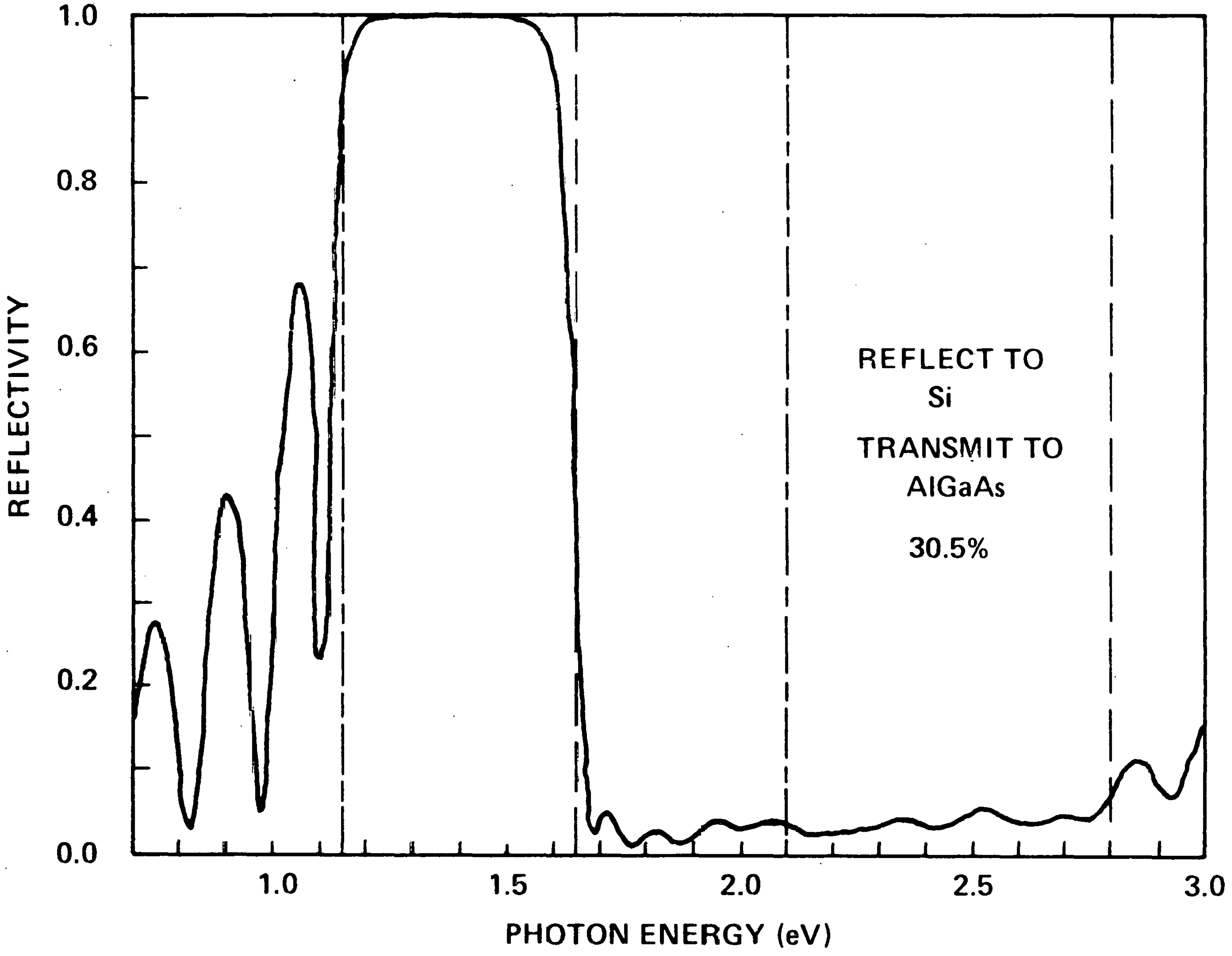
The chloride transport VPE GaInAs experiments are now complete. The results pertaining to the grading rate, layer thickness, and growth rates have yielded parameters that may be used for the OM-VPE. This is important since Al-bearing

AlGaInAs mixed crystal system must be grown by OM-VPE thus making it desirable to grow the graded GaInAs layer by OM-VPE as well. The major results of the chloride VPE experiments are: 1) growth temperatures between 710 and 750°C are optimum, 2) total column III flux must be kcpt constant during grading, 3) the best results are obtained for thicknesses of the grading layer of $> 3\mu m$, 4) step grading (~ 5%/μm, .25% steps) produces material with better electrical properties than continuous grading, and 5) growth rates $\leq .15\mu m/min.$ yield better material.

The growth of $Ga_{1-x}In_xAs$ by OM-VPE has also been established using a novel As transport agent, trimethylarsenic (TMAs) rather than arsene. A major difficulty in the growth of any InAs-bearing III-V alloy by OM-VPE has been the well-known room temperature gas phase reaction between triethylindeium (TEIn) and arsene. A dark brown powder forms upstream of the wafer/susceptor depleting the gas stream of TEIn and effectively inhibiting growth. This work has successfully used TMAs instead of arsene, thus avoiding any room temperature gas phase reaction with the TEIn. Epilayers of $Ga_{1-x}In_xAs$ with composition as high as $x = .24$ have been grown This represents a major step towards realization of practical (1 atmosphere) OM-VPE technology for InAs-bearing III-V alloys. Figure 1 shows a surface and cross section of a typical ungraded $Ga_{1-x}In_xAs$ ($x=.24$) epitaxial layer grown on GaAs oriented on (100) 2° towards (110). The cross-section (stained in 10:1:1 H_2O:HF:HNO_3) shows some dislocation etch pits in the epilayer due to lattice mismatch. The surface specularly reflective and shows the regular cross-hatch features typical of lattice mismatched III-V growths.

Directions

Continued work on this project will be directed at achieving the previously stated goals. Specifically, graded GaInAs will be grown by OM-VPE, p and n doping will be studied, and low gap cells will be fabricated in this material. Growths of 1.7 eV GaAlAs will be made using Zn and Se as p and n dopants, respectively, to determine the suitability for use in a tunnel junction structure. A study of the chemistry of alternate p-dopants with lower diffusion coefficients will also be made to determine the compatability with the OM-VPE process. Higher gap 1.7 eV AlGaInAs using TMAs will be grown on the graded GaInAs as it becomes available, and p and n-doping will be studied as well. High gap cells will be fabricated in this material. Finally, growth parameters for AlInAsSb on InAs substrates will be investigated.


REFLECTIVITY
1.0
0.8
0.6
0.4
0.2
0.0
1.0
1.5
2.0
2.5
3.0
PHOTON ENERGY (eV)
REFLECT TO
Si
TRANSMIT TO
AlGaAs
30.5%

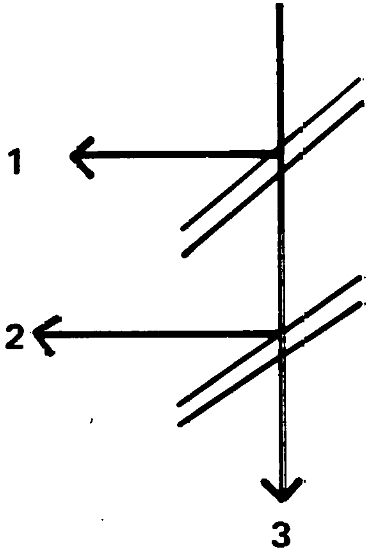
SPECTRUM SPLITTING EFFICIENCY CALCULATIONS
2 SOLAR CELLS
500 AM2 SUNS

REFLECTED		TRANSMITTED		TOTAL
MATERIAL	EFFICIENCY	MATERIAL	EFFICIENCY	EFFICIENCY
Si	11.6%	AlGaAs	18.9%	30.5%
AlGaAs	20.1%	Si	10.5%	30.6%

DEMONSTRATED: 489 AM 1.4 SUNS

REFLECTED		TRANSMITTED		TOTAL
MATERIAL	EFFICIENCY	MATERIAL	EFFICIENCY	EFFICIENCY
Si	8.4%	AlGaAs	17.6%	26.0%

SPECTRUM SPLITTING EFFICIENCY CALCULATIONS
3 SOLAR CELLS
500 AM2 SUNS

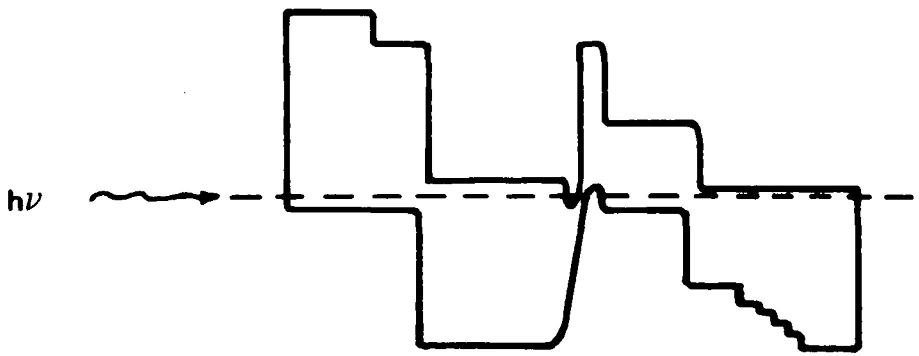


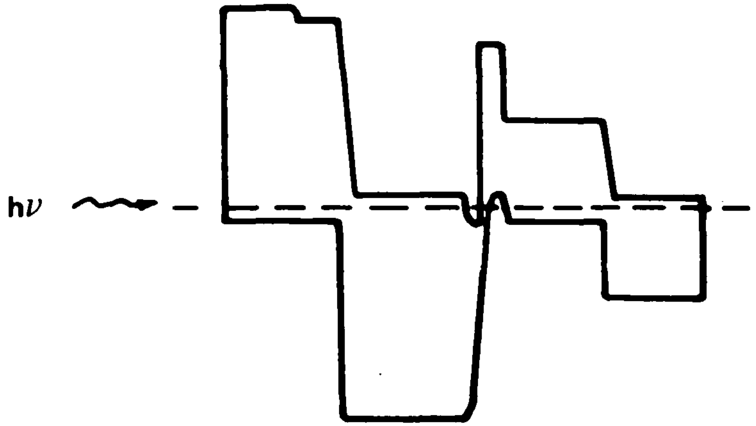
SOLAR CELL 1		SOLAR CELL 2		SOLAR CELL 3		TOTAL
MATERIAL	EFFICIENCY	MATERIAL	EFFICIENCY	MATERIAL	EFFICIENCY	EFFICIENCY
AlGaAs	20.2%	Si	10.0%	Ge	2.9%	33.1%
AlGaAs	20.2%	Ge	2.5%	Si	10.0%	32.7%
AlGaAs	20.2%	GaAs	5.6%	Si	5.8%	31.7%

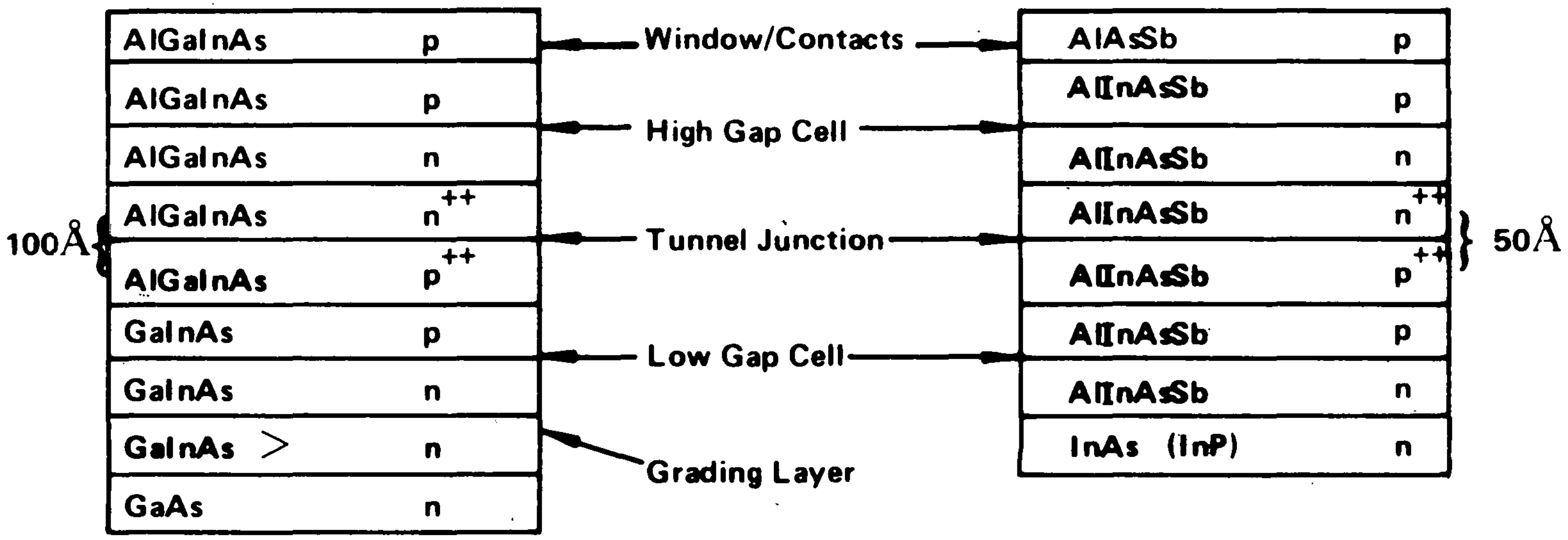
OVERALL OBJECTIVES

- 28% OR HIGHER AM2 EFFICIENT 2-GAP CELL AT 500-1000 SUNS
- DEVELOPMENT OF NECESSARY III-V MATERIALS TECHNOLOGY IN AlGaInAs, AlInAsSb

DEVICE STRUCTURES







	AlGaInAs	p	Window/Contacts	AlAsSb	p	
	AlGaInAs	p	High Gap Cell	AlInAsSb	p	
	AlGaInAs	n		AlInAsSb	n	
100Å	AlGaInAs	n^{++}	Tunnel Junction	AlInAsSb	n^{++}	50Å
	AlGaInAs	p^{++}		AlInAsSb	p^{++}	
	GaInAs	p	Low Gap Cell	AlInAsSb	p	
	GaInAs	n		AlInAsSb	n	
	GaInAs >	n	Grading Layer	InAs (InP)	n	
	GaAs	n				

SUBSTRATE

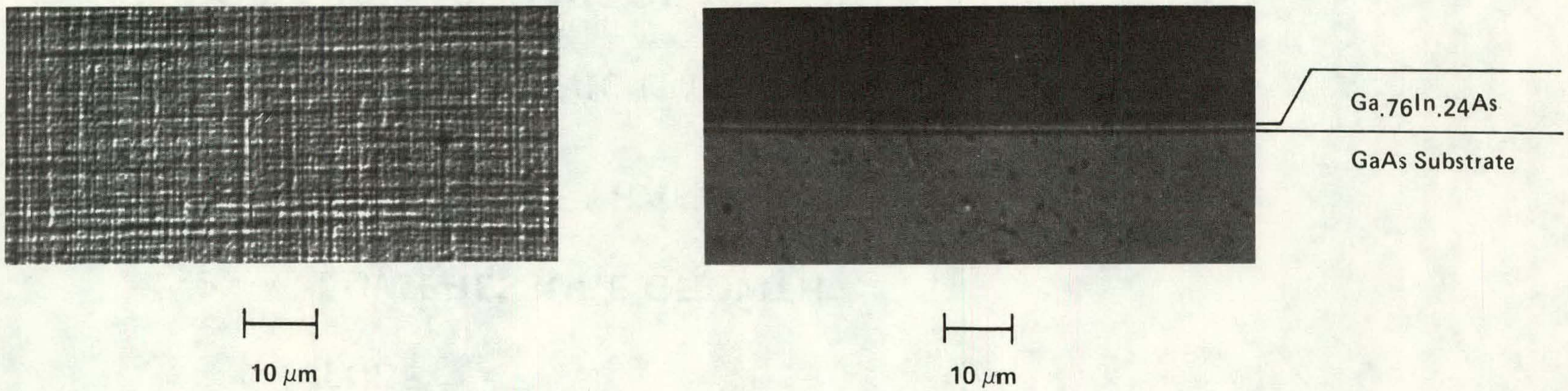
SUBSTRATE

GaInAs HCl TRANSPORT RESULTS

1. GROWTH TEMPERATURE BETWEEN 713 AND 725°C
2. TOTAL COLUMN III FLUX MUST BE KEPT CONSTANT DURING GRADING
3. BEST RESULTS $>$ 3 μM THICK GRADED REGION
4. STEP GRADING PRODUCES BETTER ELECTRICAL PROPERTIES THAN LINEAR GRADING (5%/μM, 0.25% STEPS TO 18%)
5. SLOWER GROWTH RATES ($\leqslant$ 0.15 μM/MIN) PRODUCE BETTER MATERIAL

InGaAs GROWTH BY OM-VPE

1. GaAs OM-VPE GROWTH UNDERSTOOD
2. InAs GROWTH USING TEIn AND AsH_3 PRODUCES GAS PHASE REACTION
   - A. PHYSICAL SEPARATION OF TEIn AND AsH_3–CONCENTRIC TUBE
   - B. LOW PRESSURE GROWTH
   - C. ALTERNATE TRANSPORT SPECIES
3. TRIMETHYLARSENIC (TMAs) AS As CARRIER
   - A. NO GAS PHASE REACTION
   - B. $Ga_{1-x}In_xAs$ $x = 0.24$ DEMONSTRATED



a)

b)

FIGURE 1

a) Surface of $Ga_{1-x}In_xAs$ (x = .24) OM-VPE layer and b) cross-section of same layer stained in 10:1:1 H_2O:HF:HNO_3.

SUMMARY

OBJECTIVES	ACCOMPLISHMENTS	PLANS
● GaInAs OM-VPE AND LOW GAP CELL	● HCl – VPE STUDIED OM-VPE ESTABLISHED	● BEGIN OM-VPE GRADING ON NEW SYSTEM BEGIN DOPING EXPERIMENTS BUILD P-N STRUCTURES
1.7 eV TUNNEL JUNCTIONS	● ZN-DOPED AlGaAs IN PROGRESS	● DEFINE ALTERNATE P-TYPE DOPANTS
● 1.7 eV CELL IN AlGaAs, AlInGaAs	● GROWTH OF 1.7 eV AlGaAs IN PROGRESS	● BEGIN AlInGaAs/GaAs GROWTH GROW ON GaInAs WHEN AVAILABLE
● EVALUATION OF AlInAsSB/InAs	● SUBSTRATES ON ORDER InAsSb PRELIMINARY GROWTH	● EVALUATE CHEMICAL COMPATABILITY OF TRANSPORT SPECIES.

NOTES

EMERGING MATERIALS SUMMARY

K. W. Mitchell
Photovoltaics Program Office
Solar Energy Research Institute
Golden, Colorado 80401

Emerging materials are defined to be those materials whose intrinsic properties indicate potential for low cost, greater than 10% efficiency cells in thin film form. Such materials may either be new, that is not previously investigated, or less developed, that is the photovoltaic properties in thin film solar cells have not been evaluated in sufficient detail. The present Emerging Materials Task consists of 20 contracts, with a total funding of $2.6M, 18 of which are devoted to materials studies and two of which emphasize assessment of the basic mechanisms of thin film solar cells. Most of the contracts are a result of the DOE PRDA ET-78-0-04-0039 solicitation and started recently. The materials being studied are: InP/CdS, CdTe, Cu_2O, Polyacetylene, Zn_3P_2, Cu_2Se/CdS, $ZnSiAs_2$, $CdSiAs_2$, and BAs. The major objectives of the Emerging Materials Task are to understand the mechanisms which limit the photovoltaic efficiency of these materials and devices in order to establish guidelines for directing further research; to establish realistic estimates for practical solar cells of these materials; and, finally, to improve the material and device quality to achieve the DOE goals of low cost and greater than 10% efficiency. The research tasks of the contracts emphasize thin film deposition by a variety of techniques such as vacuum evaporation, CVD, sputtering, MO-CVD, and electrodeposition; device fabrication of either homojunctions, heterojunctions, or Schottky barriers; and subsequent material and device analysis. The two Basic Mechanisms contracts are focussed on the theoretical calculation of important physical properties of these new materials, the theoretical analysis of grain boundary effects, and the evaluation of grain boundary passivation techniques.

The materials, such as InP and CdTe, have already demonstrated efficiencies of 15% and 12% respectively in single crystal form. The research efforts currently are directed towards evaluating the tradeoffs in producing thin film solar cells. The programs on copper oxide and polyacetylene, which have potential for extremely low cost, are emphasizing the verification of the potential of these materials for practical conversion efficiencies. The remaining materials programs are investigating the controllable deposition and doping of new materials to provide device quality layers, and the fabrication of devices to substantiate the photovoltaic potential of the materials.

Recent solicitations on the investigation of chemical spray and screen printing processes, for example, for CdTe, and Innovative Concepts studies of new materials,-such as $(SN)_x$, $ZnSnP_2$, and Zn_3P_2, are also discussed.

Emerging Materials Summary

K. Mitchell — Task Manager
R. Nottenburg
C. Herrington

Photovoltaics Advanced R&D Annual Review
Denver, CO
September 17-19, 1979

EMERGING MATERIALS OBJECTIVES

1. TO EVALUATE VARIOUS LESS-DEVELOPED MATERIAL SYSTEMS FOR ACHIEVING THE DOE GOALS FOR LOW COST (LESS THAN $0.50/WATT) AND EFFICIENT (GREATER THAN 10 PERCENT) SOLAR CELLS.
2. TO UNDERSTAND THE MECHANISMS WHICH LIMIT THE PHOTOVOLTAIC EFFICIENCY OF THE EXISTING MATERIALS AND DEVICES IN ORDER TO ESTABLISH GUIDELINES FOR DIRECTING FURTHER RESEARCH.
3. TO ESTABLISH REALISTIC ESTIMATES FOR PRACTICAL SOLAR CELLS OF THE VARIOUS MATERIALS.
4. TO IMPROVE THE MATERIAL AND DEVICE QUALITY IN ORDER TO ACHIEVE THE DOE GOALS.

Research Tasks

1. Theoretical modeling and calculations to evaluate
   - ideal conversion efficiency of the proposed material
   - mechanisms that limit the conversion efficiency of the material in thin film, polycrystalline form
   - practical conversion efficiency
   - compatibility of the materials with low cost substrates and available raw materials supplies
2. Growth and doping processes to prepare thin polycrystalline films with desirable P/V properties on low cost substrates
3. Measurements to provide definitive structural, compositional, electrical, and optical characterization
   - Parameters included in these measurements include
     carrier density and type
     carrier mobilities and lifetimes
     recombination mechanisms under solar illumination
   - Understand the correlation between the values of these parameters in thin polycrystalline film and single crystal material

Research Tasks (cont.)

4. Growth and doping processes to prepare thin polycrystalline film, low cost solar cell structures such as
   - p-n junction
   - Schottky barrier
   - heterojunction

   to achieve maximum cell efficiency
5. Theoretical and experimental evaluation of the efficiency parameters of the proposed solar cell structures such as
   - work functions
   - electron affinity
   - interface states
   - barrier height
   - collection efficiency
   - reflection losses
   - open circuit voltage
   - short circuit current
   - fill factor

   Investigate the stability of these parameters under typical operating and environmental conditions

PRESENT EMERGING MATERIALS CONTRACTS

● DEMONSTRATED η >10% IN SINGLE CRYSTAL		
- InP		
- HUGHES	KEN ZANIO	(5/24/79)
- ROCKWELL ERC	RALPH RUTH	(7/ 5/79)
- WESTINGHOUSE	JOHN SZEDON	(4/16/79)
- $CdTe$		
- MONOSOLAR	ROBERT ROD	(2/15/79)
- PENN STATE	K. VEDAM	(4/ 9/79)
- RADIATION MONITORING	GERALD ENTINE	(3/19/79)
- S.M.U.	TING CHU	(7/ 1/79)
● POTENTIAL FOR EXTREMELY LOW COST		
- Cu_2O		
- U. OF WASHINGTON	LARRY OLSEN	(5/ 1/79)
- WAYNE STATE	DAN TRIVICH	(4/ 9/79)
- POLYACETYLENE $(CH)_x$		
- U. OF PENNSYLVANIA	ALAN HEEGER	(3/19/79)
● POTENTIAL WITH RESPECT TO BASIC PHYSICS		
- Zn_3P_2		
- STANFORD	DICK BUBE	(2/26/79)
- U. OF DELAWARE IEC	TONY CATALANO	(9/ 1/78)
- Cu_2Se		
- BOEING	LEO BULDHAUPT	(5/ 1/79)
- $ZnSiAs_2$		
- R.T.I.	ED ANDREWS	(4/ 9/79)
- $CdSiAs_2$		
- V.P.I.	LARRY BURTON	(4/ 9/79)
- BAs		
- EAGLE PICHER	PAUL GRAYSON	(4/ 9/79)

TABLE 1: CdS/InP Solar Cells (AR Coated)

Single Crystal InP Cells

Ref.	T Substrate (°C)	Face of Sub.	p:InP (cm^{-3})	L:InP (μm)	ρ:CdS (Ω cm)	I_o (A/cm^2)	A	V_{oc} (V)	I_{sc} (mA/cm^2)	FF	η (%)	Solar Input (mW/cm^2)
(1)	620	(111)A	$2x10^{17}$	1.3	$\gtrsim 4.1x10^{-3}$	$2x10^{-8}$	2.31	0.79	18.7	0.75	15.0	74(AM2)
(2)	710	(110)	$9x10^{17}$		$1.5x10^{-3}$	$1.3x10^{-8}$	2.14	0.807	18.6	0.74	14.4	77(AM2)
					Thin Film InP Cells							
(1)		-	$3.3x10^{16}$	0.6		$1.0x10^{-6}$	1.85	0.46	13.5	0.68	5.7	74(AM2)
(1)		-				$3.8x10^{-6}$		0.40	15.4	0.62	5.2	74(AM2)

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(1) J. L. Shay, M. Bettini, S. Wagner, K. J. Bachmann, E. Buehler, IEEE Photovoltaic Specialist Conf., Baton Rouge, LA November 10-12, 1976.

(2) A. Yoshikawa, Y. Sakai, Solid-State Electronics 20, 133 (1977).

Organization: HUGHES RESEARCH LABS

Contract Title: InP/CdS SOLAR CELLS BY PLANAR REACTIVE DEPOSITION (PRD)

Principal Investigator: DR. KEN ZANIO

Funding: \$119,543 START DATE: 5/24/79

Key Technical Issues:

- GROWTH OF InP BY PRD AT LOW TEMPERATURES COMPATIBLE WITH CdS/InP CELL FABRICATION.
- ELECTRICAL AND OPTICAL CHARACTERIZATION ON InP FILM PROPERTIES FORMED BY PRD.
- EVALUATIONS OF MECHANISMS LIMITING EFFICIENCY OF ALL THIN FILM CELLS.
- DEVELOPMENT OF ADEQUATE DEVICE QUALITY TO ACHIEVE 10% EFFICIENCY.

Significant Accomplishments:

- GROWTH OF InP EPITAXIAL THIN FILMS ON InP SINGLE CRYSTALS AT 260°C, POTENTIALLY VIABLE FOR DEPOSITION ON CdS THIN FILMS.

Organization: WESTINGHOUSE ELECTRIC CORP., R & D CENTER
Contract Title: PLASMA INDUCED DEPOSITION ON InP
Principal Investigator: J. R. SZEDON
Funding: $129,798 START DATE: 4/16/79
Key Technical Issues:

- EVALUATION OF InP FILMS GROWN BY PID ON VARIOUS SUBSTRATES.
- EVALUATION OF CdS/InP, ITO/InP AND OTHER DEVICE STRUCTURES.
- DETERMINATION OF MECHANISMS WHICH LIMIT CELL EFFICIENCY.

Significant Accomplishments:

- SET-UP OF PLASMA DEPOSITION SYSTEM COMPLETE.
- INITIAL DEPOSITION USING TEIn INDICATE INCOMPLETE DISSOCIATION OF TEIn.

Organization: ROCKWELL INTERNATIONAL, ELECTRONIC RESEARCH CENTER
Contract Title: (MO-CVD) InP Thin Films for Photovoltaic Energy Conversion
Principal Investigator: Dr. Ralph Ruth
Funding: \$180,000 START DATE: 7/5/79
Key Technical Issues:

- Evaluation of InP films grown by MO-CVD.
- Deposition of device quality InP thin films on low cost substrates.
- Preparation and evaluation of CdS/InP and/or ITO/InP heterojunctions to determine mechanisms controlling efficiency.
- Development of adequate device quality to achieve >10% efficiency.

Significant Accomplishments:

- Modification of previous MO-CVD system to permit p-type doping capability using a premixed source tank of H_2 doped with dimethylzinc.

Table 2: CdS/CdTe Solar Cells

Single Crystal CdTe Cells

Ref.	ρ:CdTe (Ω cm)	ρ:CdS (Ω cm)	I_o (A/cm^2)	A	V_{oc} (V)	I_{sc}* (mA/cm^2)	FF	η (%)	Solar Input (mW/cm^2)
(3)	7	10^{-2}	3.7×10^{-9}	1.8	0.67	18.0(20.5)**	0.60	10.5(12.0)**	68
(4)	3	5.8***	1.7×10^{-8}	1.9	0.63	11.4(16.1)	0.66	5.6(7.9)	85
					Thin Film CdTe Cells				
(5)	0.1-1.0	0.2***			0.69	(31.4)	0.55	8.1	140 (AMO)

*Values in parentheses are for active area of device.

**I question these values because the light current measured is more than the photon flux available in the spectral bandpass of the cell at 68 mW/cm^2.

***These cells have an ITO electrode to the CdS layer.

(3) K. Yamaguchi, H. Matsumoto, N. Nakayama, S. Ikegami, Japan J. Appl. Phys. 15, 1575 (1976)

(4) K. Mitchell, PhD Thesis, Stanford U., Stanford, CA (1976).

(5) N. Nakayama, H. Matsumoto, K. Yamaguchi, S. Ikegami, Y. Hioki, Japan J. Appl. Phys. 15, 2281 (1976).

Organization: SOUTHERN METHODIST UNIVERSITY
Contract Title: CVD THIN FILM CDTE SOLAR CELLS
Principal Investigator: DR. TING CHU
Funding: $140,730 START DATE: JULY 1, 1979
Key Technical Issues:

- SELECTION OF OPTIMUM SUBSTRATE FOR CHEMICAL VAPOR DEPOSITION OF CDTE.
- CONTROLLABLE GROWTH OF N AND P-TYPE CDTE FILMS.
- FABRICATION OF THIN FILM CDTE HETEROJUNCTION, HOMOJUNCTION AND SCHOTTKY BARRIER SOLAR CELLS.
- IDENTIFY MECHANISMS CONTROLLING THE CONVERSION EFFICIENCY OF THE SOLAR CELLS.

Significant Accomplishments:

- SET-UP OF CDTE CVD SYSTEM COMPLETE.
- DEPOSITED CDTE ON A VARIETY OF GRAPHITE AND MULLITE SUBSTRATES WITH LARGE GRAIN SIZE.
- FABRICATED PRELIMINARY SCHOTTKY BARRIERS (ON HIGHER RESISTIVITY CDTE FILMS).

Organization: MONOSOLAR, INC.
Contract Title: ELECTRODEPOSITED CdTe FOR SOLAR CELL APPLICATION
Principal Investigator: DR. ROBERT ROD
Funding: $221,387 START DATE: 2/15/79

Key Technical Issues:

- ASSESSMENT OF ELECTRODEPOSITION FOR FABRICATING DEVICE QUALITY CdTe FILMS.
- REDUCTION OF SERIES AND SHUNT RESISTANCE IN CELLS DUE TO ELECTRICAL CONTACTS AND PINHOLES.
- EVALUATION OF MECHANISMS LIMITING EFFICIENCY OF ALL THIN-FILM CdTe CELLS.
- FABRICATION OF HETEROJUNCTION, HOMOJUNCTION, AND SCHOTTKY BARRIER CdTe SOLAR CELLS.

Significant Accomplishments:

- LOCATED SOURCES OF IMPURITIES AND IMPROVED PURITY OF CdTe ELECTRODEPOSITION SYSTEM.
- DEPOSITED MICRON THICKNESS CdTe FILMS.
- FABRICATED ITO/CdTe AND AulCdTe THIN FILM SCHOTTKY DIODES. OBSERVED Voc UP TO 0.5V.

Organization: RADIATION MONITORING DEVICES

Contract Title: HIGH EFFICIENCY THIN FILM CDTE SOLAR CELLS

Principal Investigator: DR. GERALD ENTINE

Funding: $225,407 START DATE: 3/19/79

Key Technical Issues:

- DEPOSIT CONTROLLABLE CDTE FILMS BY VAPOR DEPOSITION AND VAPOR REACTION PROCESSES.
- CHARACTERIZE PROPERTIES OF CDTE FILMS.
- FABRICATE LOW RESISTANCE OHMIC CONTACTS TO P-CDTE.
- FABRICATE CDTE HETEROJUNCTION AND HOMOJUNCTION CELL.
- EVALUATE MECHANISMS CONTROLLING THE CONVERSION EFFICIENCY.

Significant Accomplishments:

- SET-UP OF HIGH VACUUM DEPOSITION SYSTEM COMPLETE.
- SEVERAL FILM DEPOSITIONS MADE USING PHOSPHORUS (P-TYPE) AND HALOGENS (N-TYPE).
- IDENTIFIED OXIDE BARRIER BETWEEN CDTE AND COMMERCIALLY AVAILABLE ITO SUBSTRATES.

Organization: THE PENNSYLVANIA STATE UNIVERSITY

Contract Title: CONTROLLED CdTe THIN FILMS FOR SOLAR CELL APPLICATIONS

Principal Investigator: DR. K. VEDAM

Funding: \$73,706 START DATE: 4/9/79

Key Technical Issues:

- EVALUATE DEPOSITION PARAMETERS AND RESULTANT CdTe FILM PROPERTIES DEPOSITED BY SPUTTERING AND VACUUM EVAPORATION
- FABRICATION OF LOW RESISTANCE OHMIC CONTACTS TO P-CdTe.
- FABRICATION OF P-N CdTE DEVICES.
- EVALUATION OF THE MECHANISMS CONTROLLING CONVERSION EFFICIENCY.

Significant Accomplishments:

- INITIATED EVALUATION OF SPUTTER DEPOSITION PARAMETERS.
- DEPOSITED N-TYPE CdTe FILMS DOWN TO 10^{-2}ΩCM.

Organization: UNIVERSITY OF DELAWARE

Contract Title: Zn_3P_2 AS A NEW SOLAR CELL MATERIAL

Principal Investigator: DR. ANTHONY CATALANO

Funding: \$291,154 START DATE: 9/1/78

Key Technical Issues:

- GROWTH OF LOW RESISTIVITY Zn_3P_2.
- CONTROLLABLE DOPING OF THIN FILM Zn_3P_2.
- FABRICATION AND EVALUATION OF THIN FILM AND SINGLE CRYSTAL HETEROJUNCTIONS AND SCHOTTKY BARRIERS WITH Zn_3P_2.
- DETERMINATION OF MECHANISMS CONTROLLING CELL EFFICIENCY.

Significant Accomplishments:

- ROUTINE SYNTHESIS OF HIGH PURITY Zn_3P_2.
- TRANSPARENT METAL FILM DIODES HAVE BEEN FORMED BY THE JUNCTION OF MG, BE, AND AL TO Zn_3P_2.
- FABRICATION OF THIN FILM Zn_3P_2 SCHOTTKY BARRIER DEVICES.
- FABRICATION OF n-$(Zn_{1-x}Cd_x)_3P_2$/p-Zn_3P_2 PSEUDOHOMOJUNCTIONS.

Organization: STANFORD UNIVERSITY

Contract Title: PHOTOELECTRIC PROPERTIES OF ZN_3P_2 CRYSTALS, FILMS, AND HETEROJUNCTIONS

Principal Investigator: DR. RICHARD BUBE

Funding: $109,013 (24 MONTHS) START DATE: 2/26/79

Key Technical Issues:

- IDENTIFY DEFECT AND IMPURITY EFFECTS IN SINGLE CRYSTAL ZN_3P_2.
- PREPARE AND EVALUATE TRANSPORT PROPERTIES IN THIN FILM ZN_3P_2.
- FABRICATE AND EVALUATE HETEROJUNCTIONS FORMED WITH ZN_3P_2 USING CDS, ZNCDS, ZNO, ETC.

Significant Accomplishments:

- DEVELOPED CLOSED TUBE TECHNIQUE FOR GROWING SINGLE CRYSTAL ZN_3P_2 BY CONVERTING RED TO WHITE PHOSPHORUS FOR DIRECT SYNTHESIS WITH ZN.
- PRODUCED 10ΩCM AS-GROWN UNDOPED ZN_3P_2 SINGLE CRYSTAL.
- DEMONSTRATED CLOSE SPACE VAPOR TRANSPORT THIN FILM ZN_3P_2 DEPOSITION.

Organization: UNIVERSITY OF WASHINGTON (JCGS)

Contract Title: INVESTIGATION OF Cu_2O SOLAR CELLS

Principal Investigator: DR. LARRY OLSEN

Funding: $161,522 START DATE: 5/1/79

Key Technical Issues:

- CONTROLLABLY DOPE THE SOLAR CELL LAYERS, ESPECIALLY Cu_2O, ZNS, ZNSE, AND ZNO.
- BASED UPON THE UNDERSTANDING OF EXISTING Cu_2O SOLAR CELLS, DERIVE PRACTICAL LIMITS ON PHOTOVOLTAIC PARAMETERS.
- FABRICATE AND EVALUATE MIS AND HETEROJUNCTION Cu_2O SOLAR CELLS.
- DEVELOP ADEQUATE DEVICE QUALITY TO ACHIEVE IMPROVED CONVERSION EFFICIENCIES.

Significant Accomplishments:

- MBE SYSTEM ASSEMBLY IS COMPLETE.
- A PHOTOCURRENT OF 7.54 mA/cm^2 WAS ACHIEVED WITH A Cu/Cu_2O SCHOTTKY BARRIER, WITH A REASONABLE GOAL OF 10.4mA/cm^2 PREDICTED.
- V_{OC} OF 0.42 VOLTS WAS ACHIEVED WITH A $Cu/ZnO/Cu_2O$ CELL.

Organization: WAYNE STATE UNIVERSITY
Contract Title: CUPROUS OXIDE (Cu_2O) PHOTOVOLTAIC CELLS.
Principal Investigator: DR. DAN TRIVICH
Funding: $140,675 START DATE: APRIL 9, 1979
Key Technical Issues:

- IMPROVE QUALITY OF Cu_2O (RESISTIVITY, CARRIER LIFETIME).
- FEASIBILITY OF DOPING Cu_2O N-TYPE.
- CONTROLLABLY DOPE SOLAR CELL LAYERS, ESPECIALLY Cu_2O.
- FABRICATION AND EVALUATION OF MIS AND HETEROJUNCTION SOLAR CELLS.
- DEVICE DESIGN TO MINIMIZE THE CHEMICAL REACTION AT THE INTERFACE.

Significant Accomplishments:

- VOC DEPENDS PRIMARILY ON THE WORK FUNCTION OF THE METAL OF THE MIS STRUCTURE AND INTERFACE STATES ARE SECONDARY.
- $Al/SiO_2/Cu_2O$ SEEN AS BEST PERFORMING MIS STRUCTURE. ($J_{SC} = 1.4\ mA/cm^2$, $V_{OC} = 0.24V$)
- $ZnSe/Cu_2O$ HETEROJUNCTION INTERFACE APPEARS TO BE CHEMICALLY UNSTABLE.
- CONTINUED DEVELOPMENT OF CELL FABRICATION PROCESS WHICH YIELDED THE HIGHEST CELL EFFICIENCY ($\eta = 1.1\%$, $J_{SC} = 6.4\ mA/cm^2$, $V_{OC} = 0.37V$)

Organization: UNIVERSITY OF PENNSYLVANIA
Contract Title: DOPED POLYACETYLENE (CH)x FOR SOLAR CELL APPLICATION
Principal Investigator: DR. ALLAN HEEGER
Funding: \$185,870 START DATE: 3/19/79
Key Technical Issues:

- CONTROLLABLE GROWTH AND DOPING OF N AND P TYPE (CH)x FILMS.
- FABRICATION AND EVALUATION OF HOMOJUNCTION, HETEROJUNCTION, SCHOTTKY BARRIER AND MIS SOLAR CELLS.
- EVALUATION OF THE STABILITY OF (CH)x FILMS AND INTERFACES IN AIR.
- FEASIBILITY OF FORMING P-N JUNCTIONS BY MECHANICALLY PRESSING P AND N TYPE FILMS TOGETHER.

Significant Accomplishments:

- DEMONSTRATED A V_{OC} OF 0.8V WITH AN UPDOPED P-(CH)x / N-ZnS HETEROJUNCTION SOLAR CELL.
- I-V CURVES SUGGEST THAT SIGNIFICANT VARIATIONS IN BARRIER HEIGHT MAY BE ACHIEVED THROUGH THE USE OF DIFFERENT DOPANTS.
- A SCHOTTKY BARRIER CELL WITH METALLIC AsF_5 DOPED (CH)x ON N-Si SHOWED 10% DEGRADATION OF I_{SC} IN THREE DAYS IN AIR. NO CHANGE IN V_{OC}.

Organization: RESEARCH TRIANGLE INSTITUTE

Contract Title: Development of Low Cost $ZnSiAs_2$ Solar Cells.

Principal Investigator: Dr. J. Edward Andrews

Funding: \$128,737 START DATE: 4/9/79

Key Technical Issues:

- Demonstration of organometallic $ZnSiAs_2$ deposition system.
- Ability to controllably dope $ZnSiAs_2$ n and p type.
- Reduction of carrier concentration of $ZnSiAs_2$ below 10^{10} cm^{-3}.
- Demonstration of material concentration grading from Si to $ZnSiAs_2$ on Si substrates.
- Demonstration of $ZnSiAs_2$ homojunction.

Significant Accomplishments:

- New organometallic deposition system is operational and has demonstrated a greatly improved Si epi-layer over the previous system.
- Problems with growing stoichiometric $ZnSiAs_2$.
- $ZnSiAs_2$ films were Se ion-implanted in an attempt to dope them n-type. Films to be characterized.

Organization: VIRGINIA POLYTECHNIC INSTITUTE

Contract Title: CD SIAS2 THIN FILMS FOR SOLAR CELL APPLICATIONS

Principal Investigator: DR. LARRY BURTON

Funding: \$140,259 START DATE: 4/9/79

Key Technical Issues:

- DEVELOPMENT OF SPUTTERING AND VACUUM EVAPORATION DEPOSITION TECHNIQUES FOR CONTROLLABLY GROWING AND DOPING $CdSiAs_2$.
- ELECTRICAL AND OPTICAL CHARACTERIZATION OF $CdSiAs_2$ THIN FILM PROPERTIES.
- FABRICATION AND EVALUATION OF $CdS/CdSiAs_2$ HETEROJUNCTIONS USING SINGLE CRYSTAL AND THIN FILM CdS.

Significant Accomplishments:

- NEAR STOICHIOMETRIC $CdSiAs_2$ FILMS GROWN BY SPUTTERING.
- VERIFIED THAT VACUUM EVAPORATION OF THE TERNARY IS UNSUITABLE.

Organization: EAGLE PICHER

Contract Title: BORON ARSENIDE THIN FILMS FOR SOLAR CELL APPLICATION

Principal Investigator: PAUL E. GRAYSON

Funding: \$157,583 START DATE: 4/9/79

Key Technical Issues:

- DETERMINE THE BEST THIN FILM GROWTH TECHNIQUE FOR BAs.
- DETERMINE THE ELECTRICAL AND OPTICAL PROPERTIES OF BAs.
- FABRICATE SCHOTTKY BARRIERS AND OTHER STRUCTURES.
- EVALUATE THE CONTROLLING MECHANISMS GOVERNING EFFICIENCY.

Significant Accomplishments:

- DIBORANE (B_2H_6) AND ARSINE (AsH_3) DEPOSITION SYSTEM IS OPERATIONAL.
- BAs DEPOSITIONS HAVE BEEN MADE ON SILICON CARBIDE, SAPPHIRE AND QUARTZ.
- PRELIMINARY CHARACTERIZATION OF THE OPTICAL AND ELECTRICAL PROPERTIES OF BAs THIN FILMS.

Organization: BOEING AEROSPACE COMPANY

Contract Title: Copper Selenide-Based Thin Film Solar Cells.

Principal Investigator: Dr. Leo Buldhaupt

Funding: $77,869 START DATE: 5/1/79

Key Technical Issues:

- Assessment of $Cu_{2-x}Se$ thin film growth by vacuum evaporation.
- Evaluation of $CdS/Cu_{2-x}Se$ devices using single crystal and thin film CdS.
- Evaluation of the structure and stability of the $CdS/Cu_{2-x}Se$ interface.

Significant Accomplishments:

- Technique developed to overcome problem with producing $Cu_{2-x}Se$ films of uniform composition and electrical properties.
- Initial $Cu_{2-x}Se$ films possess 1μm grain size, hole mobilities from 6-9 cm^2/Vsec, and band gaps between 1.55 to 1.9 eV.

Organization: HUGHES RESEARCH LABS

Contract Title: GRAIN BOUNDARY STUDIES IN INP SOLAR CELLS

Principal Investigator: DR. KEN ZANIO

Funding: $119,497 START DATE: SEPTEMBER 27, 1978

Key Technical Issues:

- DEVELOP DETAILED BAND MODEL OF GRAIN BOUNDARY REGION OF POLYCRYSTALLINE THIN FILM SOLAR CELLS.
- EXPERIMENTALLY SUBSTANTIATE THE BAND MODEL DEVELOPED.
- PREPARE INP HOMOJUNCTIONS AND VERIFY EFFECT OF GRAIN BOUNDARIES ON CELL BEHAVIOR.
- EVALUATE TECHNIQUES FOR PASSIVATING GRAIN BOUNDARIES IN INP HOMOJUNCTIONS.

Significant Accomplishments:

- MODIFIED PLANAR REACTIVE DEPOSITION SYSTEM TO DEPOSIT INP FILMS AT TEMPERATURES DOWN TO 240°C.
- DEVELOPED BAND MODEL OF GRAIN BOUNDARY REGIONS IN POLYCRYSTALLINE SOLAR CELLS.
- DEVELOPED CHEMICAL ETCHES FOR PREFERENTIALLY ETCHING INP GRAIN BOUNDARIES.

Organization: LAWRENCE LIVERMORE LABORATORIES
Contract Title: THEORETICAL STUDY OF SOLAR CELL MATERIALS AND DEVICES
Principal Investigator: DR. JICK YEE
Funding: \$150,000 START DATE: OCTOBER 1, 1978
Key Technical Issues:

- THEORETICAL CALCULATION OF IMPORTANT PHYSICAL PROPERTIES OF NEW MATERIALS OF INTEREST FOR THE DOE PHOTOVOLTAIC R&D PROGRAM.
- THEORETICAL ANALYSIS OF GRAIN BOUNDARY EFFECTS ON HETEROJUNCTION SOLAR CELL PERFORMANCE.
- THEORETICAL STUDIES OF IMPURITY EFFECTS ON DIFFUSION LENGTH AND SOLAR CELL PERFORMANCE.

Significant Accomplishments:

- CALCULATED THEORETICAL OPTICAL ABSORPTION COEFFICIENTS VERSUS WAVELENGTH FOR $CdSiAs_2$, $CuInSe_2$, $ZnSiAs_2$, AND BAs. INDICATES BAs HAS DIRECT BANDGAP AT 4.0eV.
- EVALUATED THEORETICALLY THE BEHAVIOR OF THE SCHOTTKY BARRIER HEIGHT FOR Cu_2O.
- DERIVED EXPRESSION FOR MINORITY CARRIER DIFFUSION LENGTH IN $CuInSe_2$.

SPRAY/SCREEN PRINT SOLICITATION

TITLE	FUNDING LEVEL START DATE	INSTITUTION INVESTIGATOR
CHEMICAL SPRAY/ION EXCHANGE FORMATION OF CdS/Cu_2S SOLAR CELLS	\$191K (9/1/79)	EXXON H. P. MARUSKA
SCREEN PRINTED CDS BASED ON SOLAR CELLS	\$153K (9/15/79)	GLOBE-UNION G. GOODMAN
CHEMICAL SPRAY CDS/CDTE SOLAR CELLS	\$165K (8/15/79)	RAD. MONITORING G. ENTINE
CHEMICAL SPRAY COPPER TERNARY SOLAR CELLS AND SINTERED CDS/CDTESOLAR CELLS	\$173K (9/1/79)	SRI INTERNATIONAL J. MOONEY

INNOVATIVE CONCEPTS SOLICITATION

Title	Funding Level	Institution Investigator
Zinc Tin Phosphide Solar Cells	$ 84K	Exxon
Epitaxial Zn_3P_2 Film Growth by Activated Vacuum Evaporation of the Elements	$ 99K	Perkin Elmer D. Smith
Sulfur Nitride Polymer - Semiconductor Junctions for Solar Cell Applications	$ 99K	Rockwell M. Cohen

NOTES

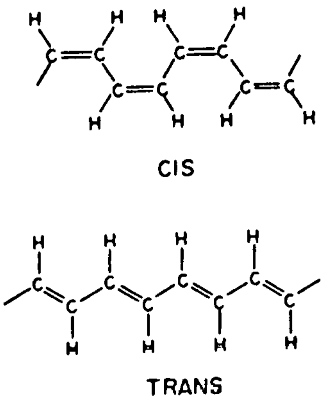
PHOTOVOLTAIC PHENOMENA IN POLYACETYLENE, $(CH)_x$

A. J. Heeger and A. G. MacDiarmid

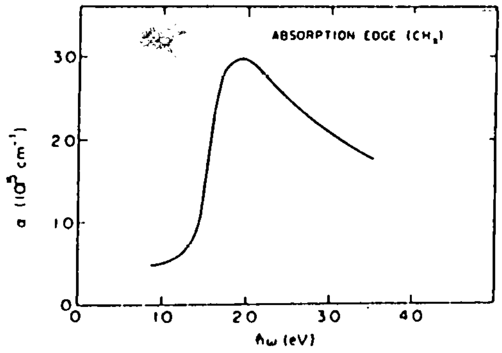
Laboratory for Research on the Structure of Matter
University of Pennsylvania
Philadelphia, PA 19104, U.S.A.

Abstract

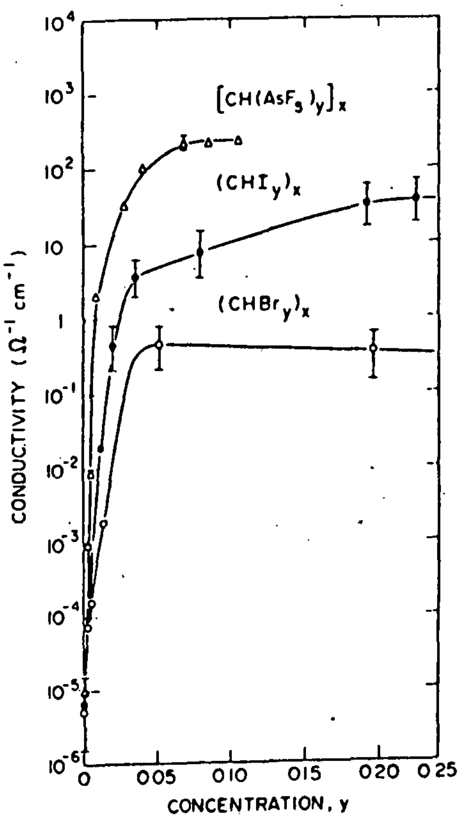
Polyacetylene, $(CH)_x$ is the simplest conjugated organic polymer. Through chemical doping, the electrical conductivity of films of $(CH)_x$ can be varied over twelve orders of magnitude with properties ranging from insulator ($\sigma < 10^{-10}$ ohm^{-1}cm^{-1}) to semiconductor to metal ($\sigma > 10^3$ ohm^{-1}cm^{-1}). A variety of rectifying junctions have been fabricated using doped and undoped $(CH)_x$. Schottky diodes formed between metallic AsF_5-doped $(CH)_x$ and n-type semiconductors indicate high $[CH(AsF_5)_y]_x$ electronegativity. The p-type character of undoped <u>trans</u>-$(CH)_x$ is confirmed by Schottky barrier formation with low work function metals. An undoped p-$(CH)_x$: n-ZnS heterojunction has been demonstrated with open circuit photovoltage of 0.8 V. Photoelectrochemical photovoltaic cells have also been fabricated using $(CH)_x$ as the active photoelectrode. These results point to the potential of $(CH)_x$ as a photosensitive material for use in solar cell applications.



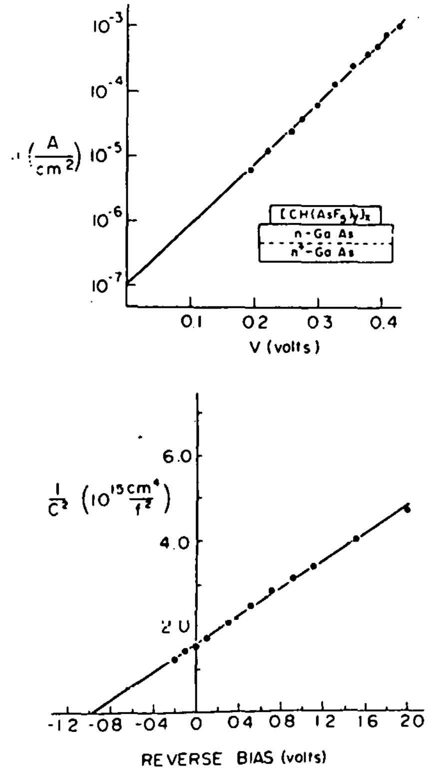
Molecular structure of cis and trans isomers of polyacetylene, $(CH)_x$.



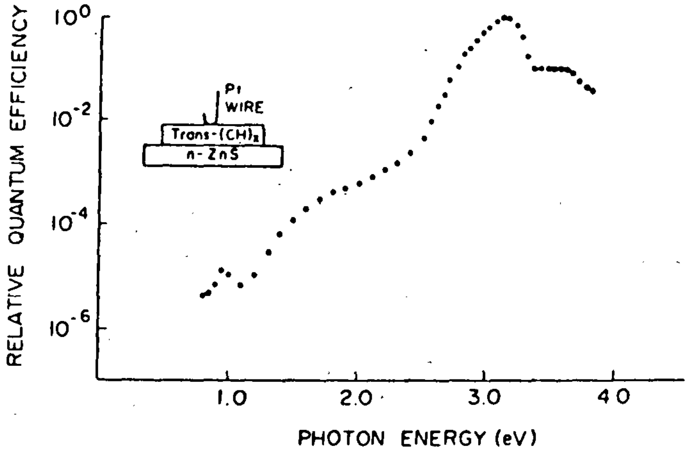
Absorption coefficient as a function of frequency; trans-$(CH)_x$



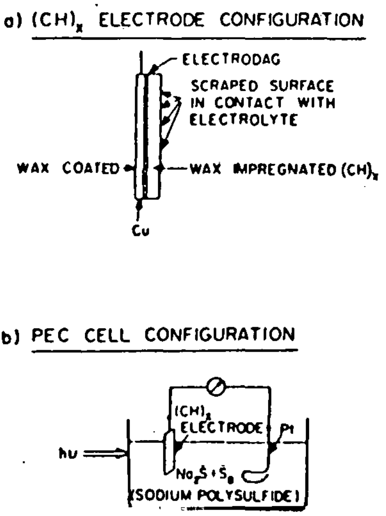
Electrical conductivity (room temperature) as a function of dopant concentration.



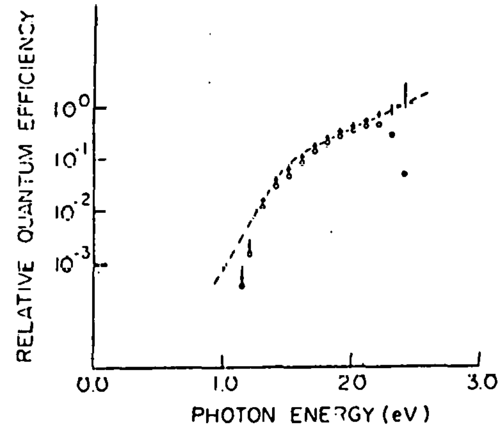
J-vs-V and C-vs-V characteristics of n-GaAs : metallic $[CH(AsF_5)_y]_x$ Schottky junction. Area $= 0.16$ cm^2; J-V corrected for $R_{series} = 500\ \Omega$. Least-squares fit: $n = 1.8$, $V_{bi} = 0.81$ V, assuming $A^* = 144$ A/cm^2 ^{0}K^2 (GaAs). C-V fit yields $V_{bi} = 0.95$ V, assuming $1/C^2 \propto (V_{bi} - V - kT/q$.



Photoresponse of n-ZnS:undoped trans-$(CH)_x$ n-p heterojunction. Quantum efficiency normalized to 3.1 eV peak where the absolute quantum efficiency is of order unity.



a. $(CH)_x$ electrode configuration
b. schematic diagram of PEC cell configuration



Relative quantum efficiency of the $(CH)_x$ PEC cell using an electrode configuration as in Figure 1a. The open circles represent data taken with light incident through the highly colored electrolyte. The crosses represent data corrected for light absorption by the electrolyte. The dashed curve represents photoconductivity response .

THIN FILM CADMIUM TELLURIDE SOLAR CELLS*

T. L. Chu, S. S. Chu, M. Y. Pauleau, and E. D. Stokes
Southern Methodist University, Dallas, Texas 75275

INTRODUCTION

Cadmium telluride is a direct gap semiconductor with a room temperature band gap energy of 1.5 eV. Solar cells made from cadmium telluride have higher theoretical conversion efficiency than those from silicon, gallium arsenide, and other semiconductors (1). Because of its sharp optical absorption edge and large absorption coefficient, solar radiation with energy in excess of the energy gap is essentially all absorbed within a few micrometers of the surface. Further, cadmium and tellurium are of considerably lower cost than the constituents of most other direct gap semiconductors. Thus, the use of thin film cadmium telluride solar cells appears to be a viable approach to meet the goals of the National Photovoltaic Program.

The deposition of cadmium telluride films and the fabrication of thin film solar cells have been under investigation for many years (2). The most commonly used method for the deposition of cadmium telluride films is the evaporation of the compound or the elements under a pressure of 10^{-4} to 10^{-9} Torr, and the effects of various process parameters, such as the surface structure and temperature of the substrate, the deposition rate, etc., have been extensively reviewed (3). Other techniques developed for the deposition of cadmium telluride films include chemical transport (4) and sublimation in an inert atmosphere(5). Cadmium telluride films are not suited for the fabrication of homojunction cells because of the large surface recombination loss associated with the high optical absorption coefficient. Also, the necessity of using a shallow junction could result in a high series resistance. Heterojunction solar cells have shown promising results. Solar cells prepared by the evaporation of n-type cadmium sulfide onto p-type cadmium telluride single crystals have conversion efficiences up to 8% (6). Thin film cells of the configurations p-$Cu_{2-x}Te$/n-CdTe/n-CdS/glass and n-CdS/p-CdTe/Mo have conversion efficiencies up to 6% (7,8).

The objective of this work is to investigate the chemical vapor deposition of cadmium telluride films on low cost substrates and the preparation of thin film cadmium telluride solar cells. The preliminary results are summarized below.

DEPOSITION AND STRUCTURAL PROPERTIES OF CADMIUM TELLURIDE FILMS

Cadmium telluride films have been deposited on graphite, coated graphite, and mullite substrates. Graphite is a relatively economic substrate for large area solar arrays and is compatible with cadmium telluride in properties. It is inert under the conditions used for the deposition of

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*Prepared for the Department of Energy under Contract No. DE-AC04-79ET 23009.

cadmium telluride. Also, graphite has high thermal and electrical conductivities and may be used as an ohmic contact to the solar cell. However, the surface of graphite is inhomogeneous due to its porosity, and graphite surface has been coated with carbon, silicon, tungsten, aluminum, and indium to overcome this problem (VU Graph 3).

The direct combination of cadmium and tellurium in a hydrogen atmosphere and the reaction between cadmium iodide and telluride in a hydrogen atmosphere have been used for the deposition of cadmium telluride films using the apparatus shown schematically in VU Graph 4. The reaction tube is of 55 mm ID and was held in a three-zone resistance heated furnace with each zone separately heated and controlled. The cadmium and telluride containers were placed in the appropriate temperature zones, and hydrogen was used to carry the elements to the substrate surface. Hydrogen iodide was used for the in-situ formation of cadmium iodide.

The important parameters in this deposition process are the substrate temperature and the composition and flow rate of the reactant mixture. The reactant composition is important in that cadmium and tellurium have limited solubilities in cadmium telluride and that cadmium telluride has finite vapor pressures at the deposition temperature 400°C - 780°C. No adherent and continuous films were obtained on silicon coated graphite substrates. The deposit on graphite, tungsten-coated graphite, and mullite substrates is adherent at a substrate temperature of 550°C and above. The reactant flow rate was adjusted to yield a deposition rate of about 1 µm/min. The average grain size in the deposit increases with increasing temperature (VU Graphs 6 & 7); crystallites with well developed faces, several tens of micrometers in size, are frequently present in films deposited at high temperatures. However, the rate of nucleation decreases with increasing temperature, and pin holes are often present in films deposited at high temperatures.

The crystallographic properties of cadmium telluride deposited on mullite, tungsten/graphite, and graphite substrates were examined by the X-ray diffraction technique. The films deposited in the temperature range 550° - 780°C are essentially all polycrystalline with only slight preferred orientations (VU Graph 8).

ELECTRICAL AND PHOTOVOLTAIC PROPERTIES OF CADMIUM TELLURIDE FILMS

Schottky barriers where prepared from cadmium telluride films to determine their electrical properties. The films deposited on mullite with no intentional doping are n-type with a room temperature electrical resistivity higher than 10^4 ohm-cm and electron mobility of 20 - 30 cm^2/V-Sec, as determined by Hall measurements. The current-voltage characteristics of Ag/n-CdTe/W/graphite and Ag/n-CdTe/Al/graphite structures indicate that the CdTe/substrate interface is rectifying in both cases (VU Graphs 9 and 10). The CdTe/substrate interface becomes ohmic when an indium interlayer is used (VU Graph 11); however a high series resistance is apparent.

The hole diffusion length in cadmium telluride films on In/W/graphite substrates has been measured on Au-CdTe Schottky barrier structures with a scanned electron beam for carrier injection. A single grain at the edge of the Schottky barrier structure was selected, and the beam position and the response of the Schottky barrier were measured simultaneously. The intragrain diffusion length, calculated from the plot of the logarithm of the relative current versus distance from the barrier, has been found to be in the range of 0.8 - 1.5 μm (VU Graph 12).

Preliminary work on the fabrication and characterization of Schottky barrier solar cells has been carried out. The conversion efficiency of these cells are relatively low at present (VU Graph 13). Current work is directed to the control of electrical resistivity of cadmium telluride, the reduction of CdTe/substrate interface resistance, and the investigation of n-CdS/p-CdTe heterojunctions.

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THIN FILMS CADMIUM TELLURIDE SOLAR CELLS

DOE CONTRACT DE-AC04-79ET23009

Work performed at Southern Methodist University

Period of Contract

July 1, 1979 - June 30, 1980

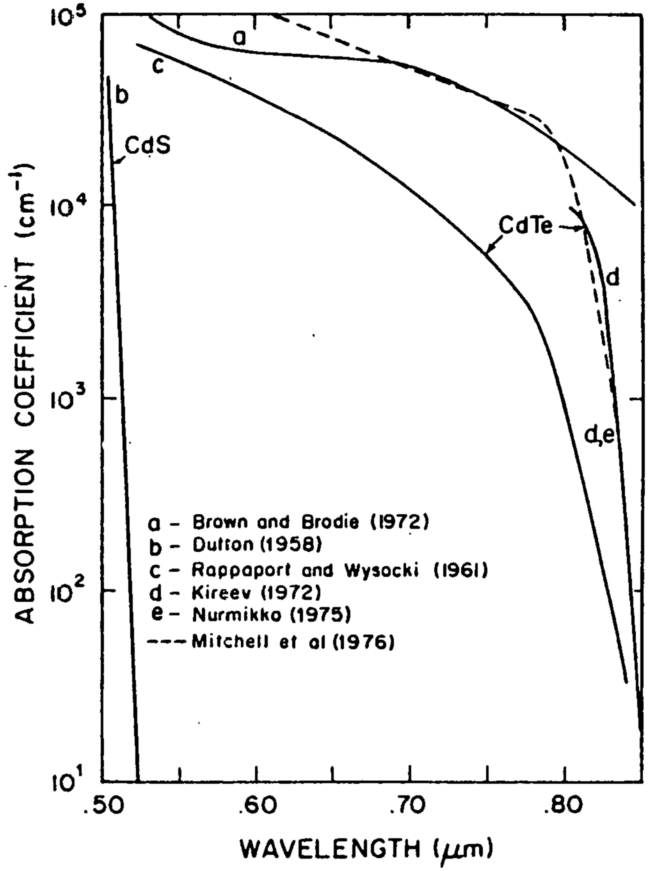
Funding Level: $140,730

Principal Investigator: Ting L. Chu

THIN FILM CADMIUM TELLURIDE SOLAR CELLS
PROPERTIES OF CADMIUM TELLURIDE

- Energy Gap (300^{0}K): 1.5 eV(D)
- Unit Cell Parameter: 6.481 Å
- Melting Point: 1098^{0}C
- Dissociation Press. at M.P.: 0.18 Atm
- Thermal Expansion Coeff.: 5.5×10^{-6} ^{0}C^{-1}
- μ_e (300^{0}K): 1050 cm^2/V-Sec
- μ_h (300^{0}K): 80 cm^2/V-Sec
- Strong Diffractions in Polycrystalline CdTe:
  (111) : (220) : (311) = 100 : 62 : 28

- Optical Absorption Coefficient



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THIN FILM CADMIUM TELLURIDE SOLAR CELLS
SELECTION OF SUBSTRATES

- REQUIREMENTS: Compatible with cadmium telluride in chemical, electrical, and mechanical properties.
- SUBSTRATES UNDER INVESTIGATION:
  - Graphite: POCO PLC graphite (TEC = 4.5 X 10^{-6} $^{o}C^{-1}$)
    surface inhomogeneous due to porosity
  - Coated Graphite:
    - Carbon coated graphite : by pyrolysis of propane
    - Silicon coated graphite : by thermal reduction of trichlorosilane
    - Tungsten coated graphite : by thermal reduction of tungsten hexafluoride
    - Aluminum and indium coated graphite and tungsten/graphite: by evaporation
  - Ceramic: Coors 183 J mullite (TEC = 4.3 X 10^{-6} $^{o}C^{-1}$)

TLC-3
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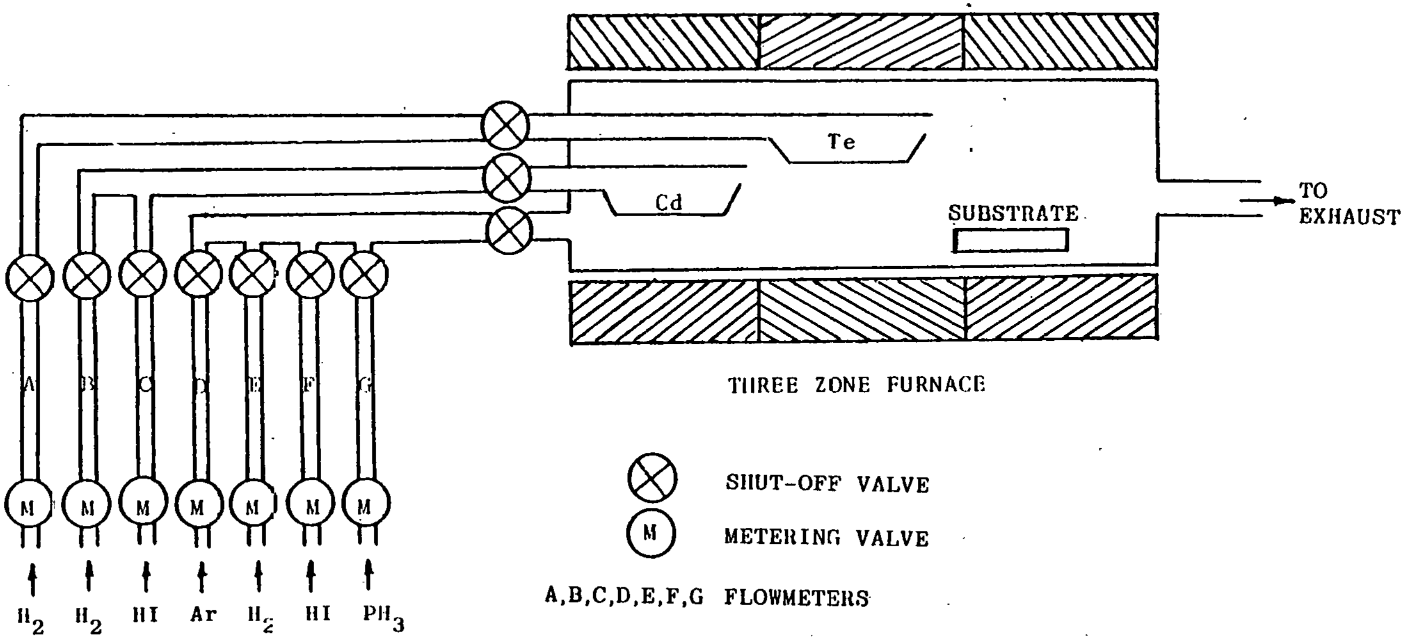
THIN FILM CADMIUM TELLURIUM SOLAR CELLS
DEPOSITION OF CADMIUM TELLURIDE FILMS

- SCHEMATIC DIAGRAM:



- REACTIONS:

$$2Cd(g) + Te_2(g) \longrightarrow 2CdTe(s)$$

$$2CdI_2(g) + Te_2(g) + 2H_2(g) \longrightarrow 2CdTe(s) + 4HI(g)$$

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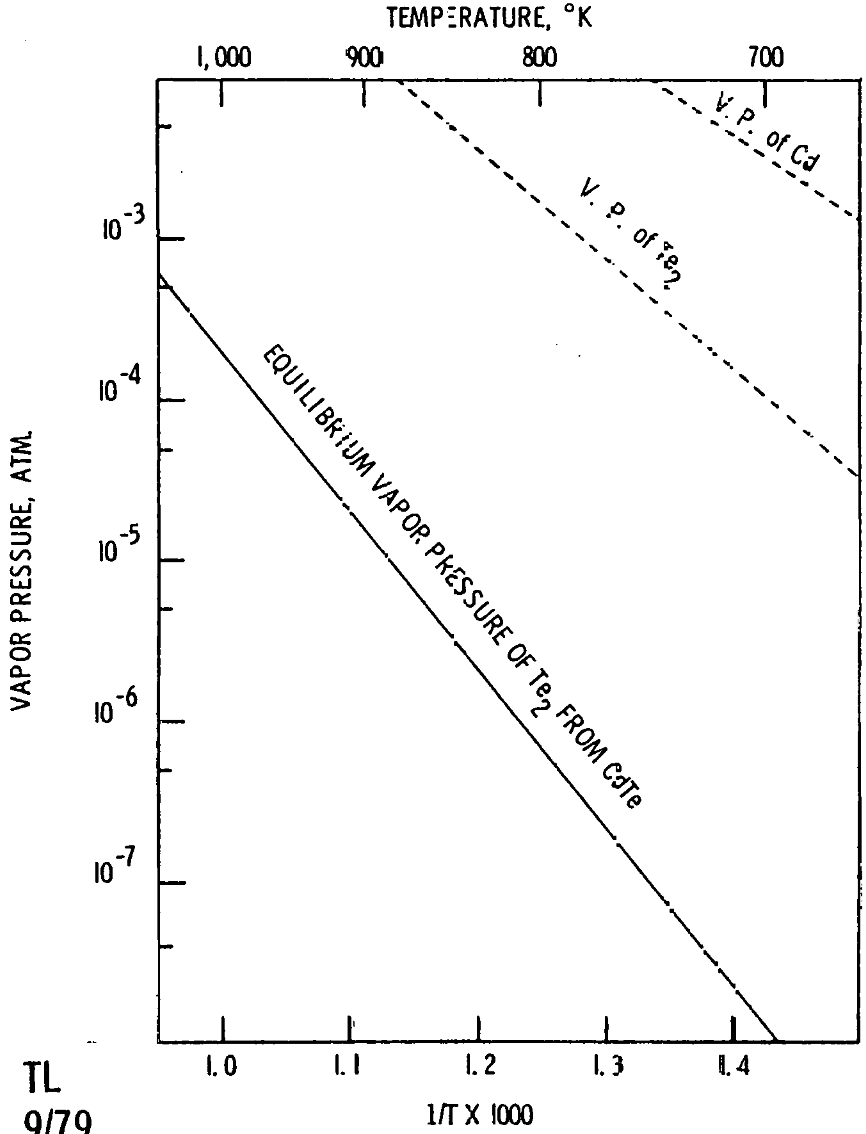
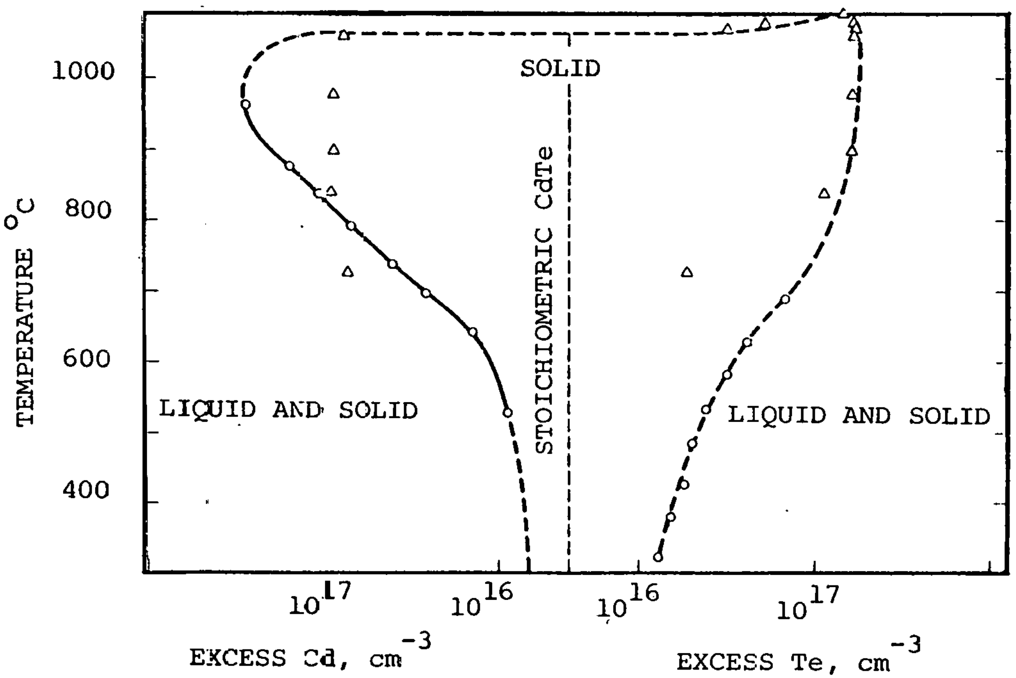
THIN FILM CADMIUM TELLURIDE SOLAR CELLS
DEPOSITION OF CADMIUM TELLURIDE FILMS

- DISSOCIATION PRESSURE

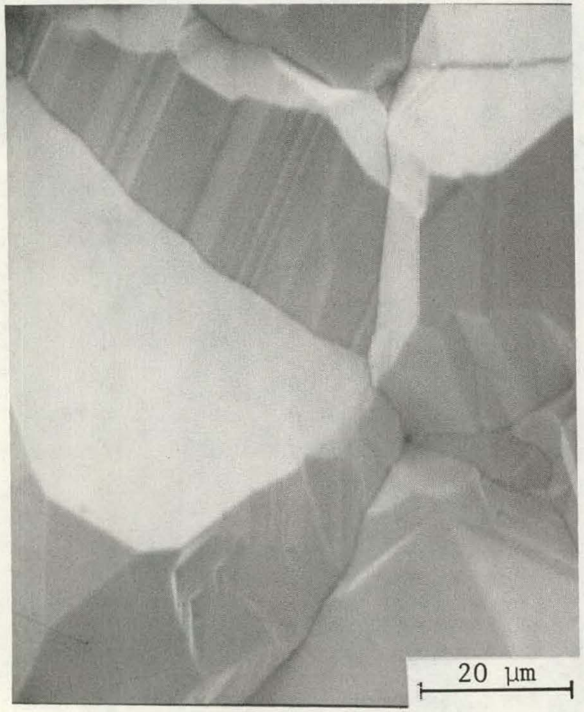


- ELECTRICALLY HOMOGENEOUS REGION

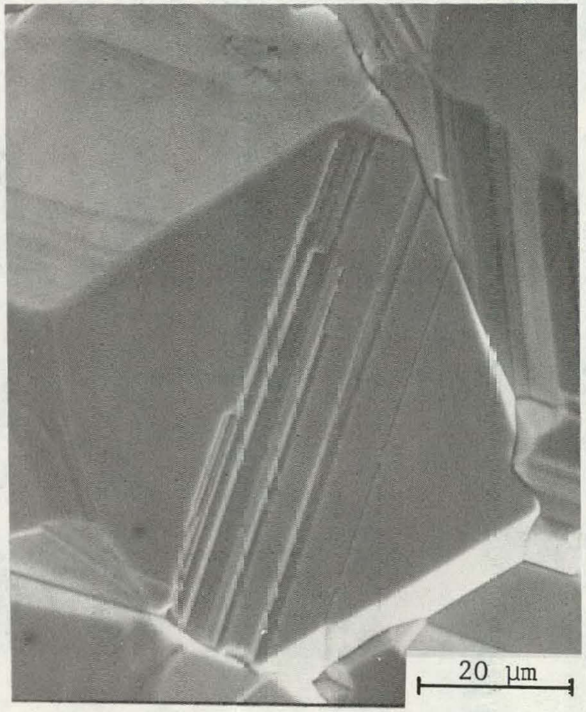


- IMPORTANT PROCESS PARAMETERS
  - Substrate temperature and surface condition
  - Composition and flow rate of reactant mixture

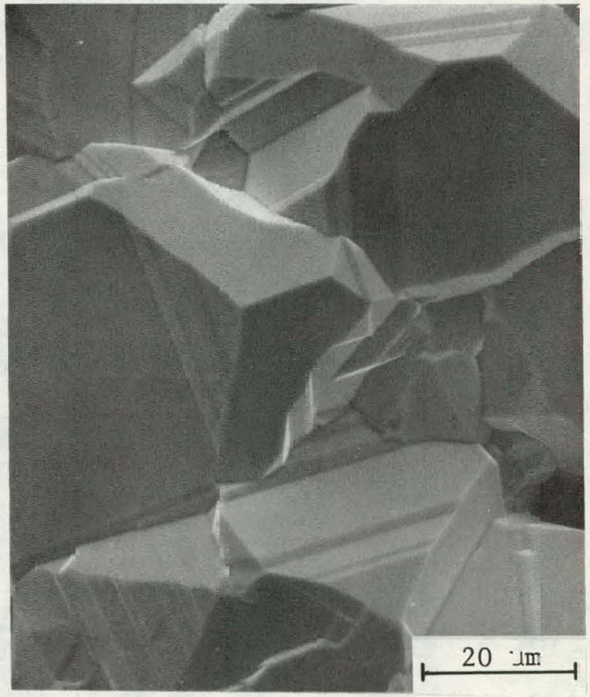
THIN FILM CADMIUM TELLURIDE SOLAR CELLS
MICROSTRUCTURE OF CdTe FILMS DEPOSITED AT 740°C



Mullite Substrate



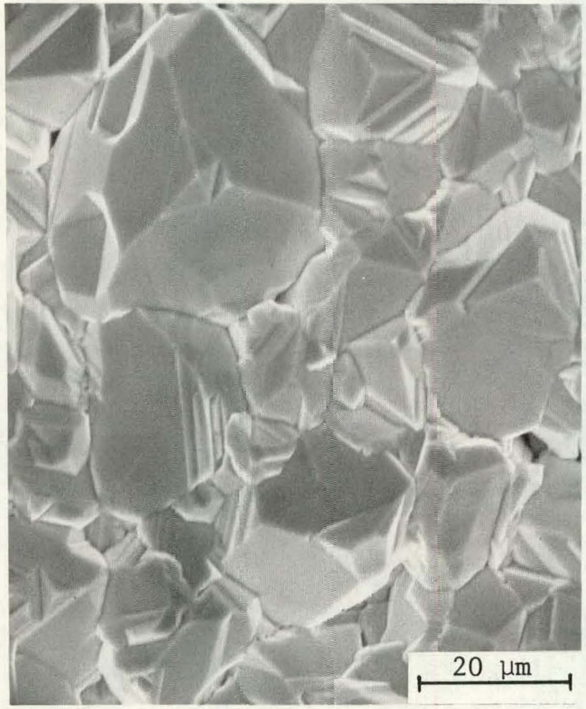
Tungsten/Graphite Substrate



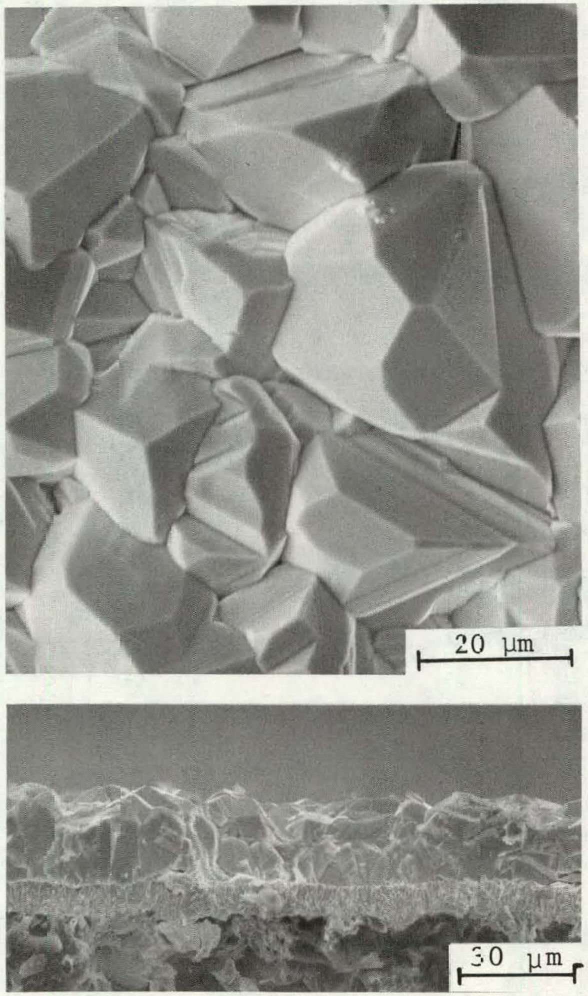
Graphite Substrate

TLC:6
9/79

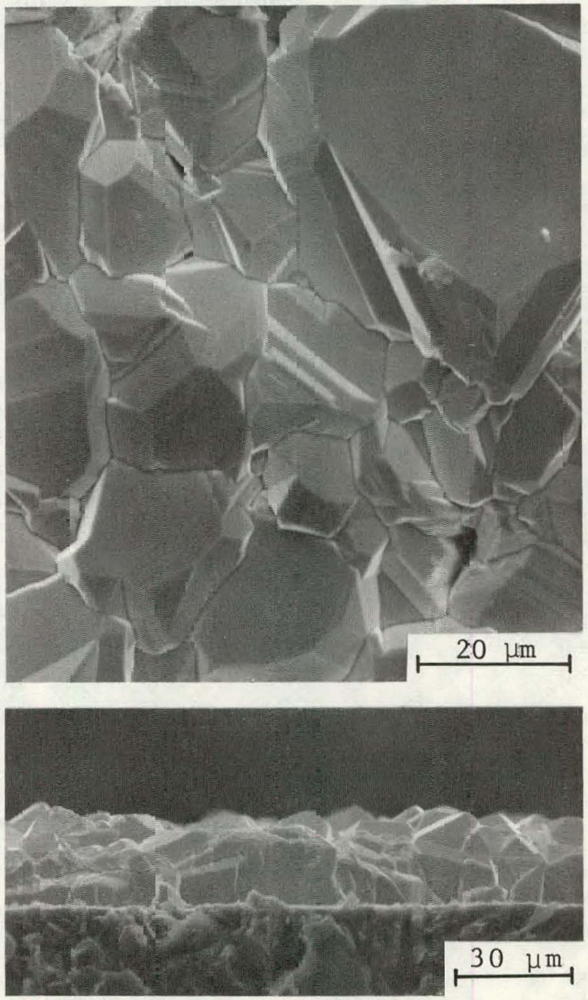
THIN FILM CADMIUM TELLURIDE SOLAR CELLS
MICROSTRUCTURE OF CdTe FILMS DEPOSITED AT 580°C



Mullite Substrate



Tungsten/Graphite Substrate

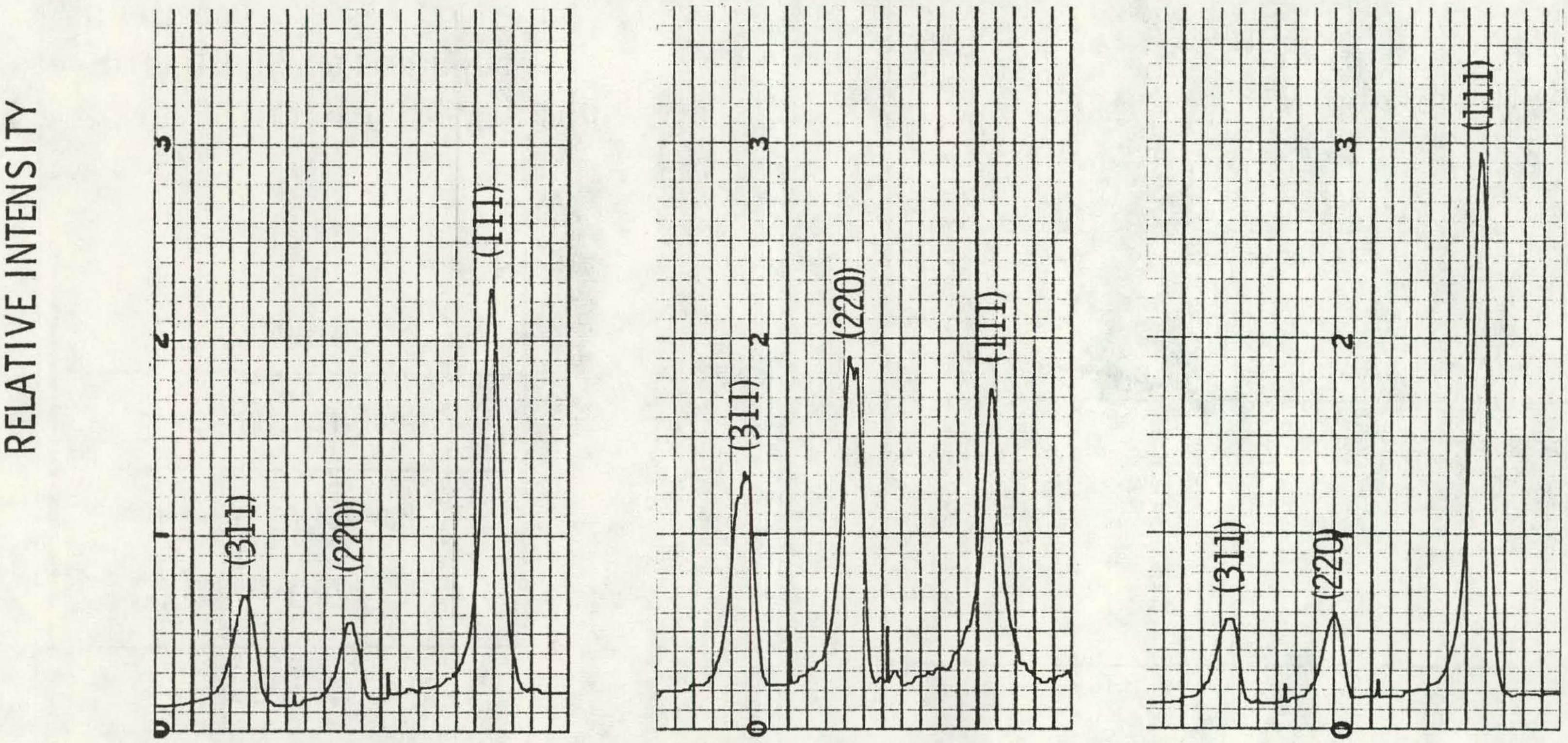


Graphite Substrate

THIN FILM CADMIUM TELLURIDE SOLAR CELLS

CRYSTALLOGRAPHIC PROPERTIES OF CdTe FILMS DEPOSITED AT 580°C

POLYCRYSTALLINE CADMIUM TELLURIDE (111) : (220) : (311) = 100 : 62 : 28



Mullite Substrate

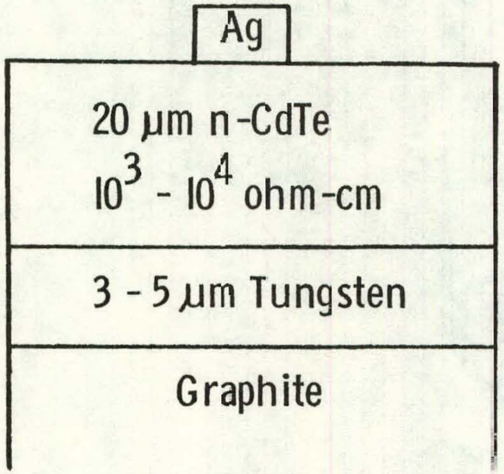
Tungsten/Graphite Substrate

Graphite Substrate

TLC:8
9/79

THIN FILM CADMIUM TELLURIDE SOLAR CELLS
PROPERTIES OF SCHOTTKY BARRIERS ON n-CdTe/W/Graphite

- CONFIGURATION



Ag

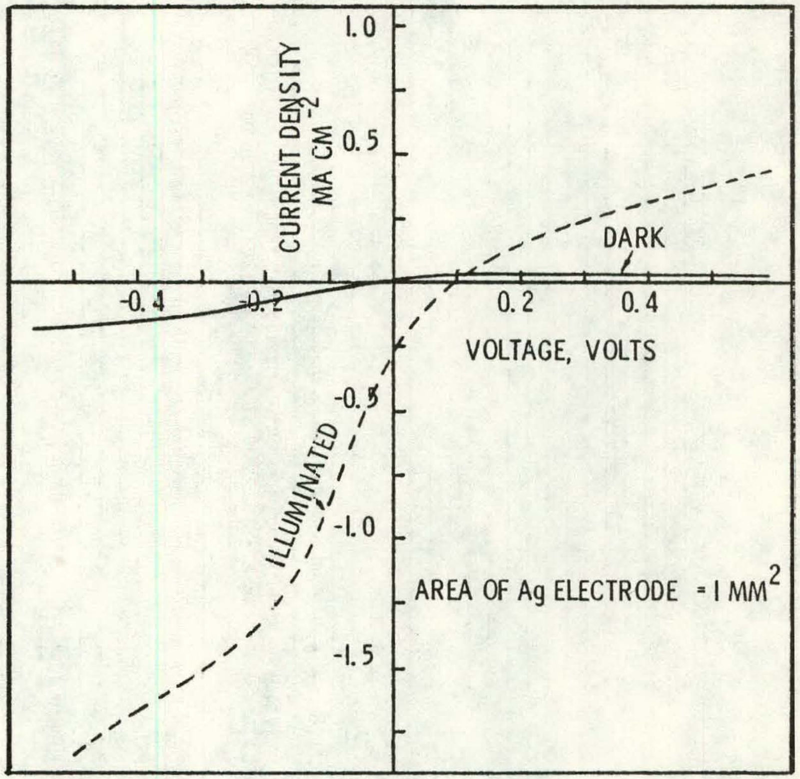
20 µm n-CdTe
$10^3 - 10^4$ ohm-cm

3 - 5 µm Tungsten

Graphite

- CONCLUSION: n-CdTe/W/graphite structure has a rectifying interface.

- CURRENT-VOLTAGE CHARACTERISTICS

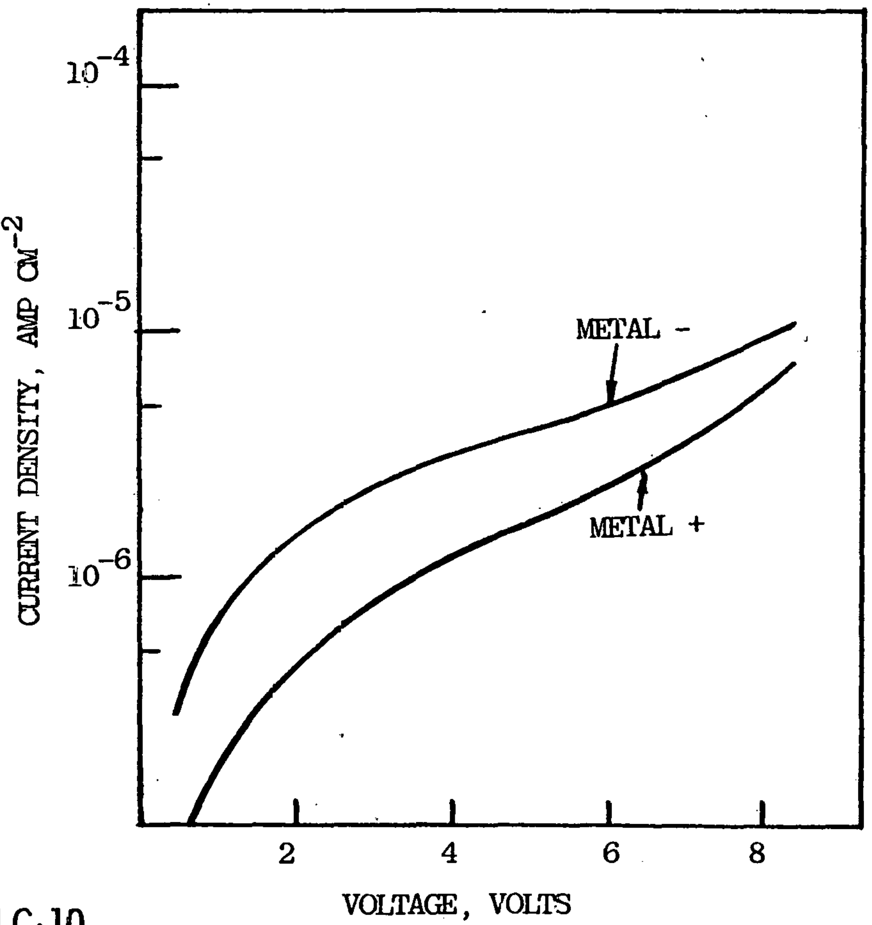


TLC:9
9

THIN FILM CADMIUM TELLURIDE SOLAR CELLS

CADMIUM TELLURIDE FILMS ON Al/GRAPHITE AND MULLITE SUBSTRATES

- CURRENT-VOLTAGE CHARACTERISTICS OF Ag/n-CdTe/Al/GRAPHITE

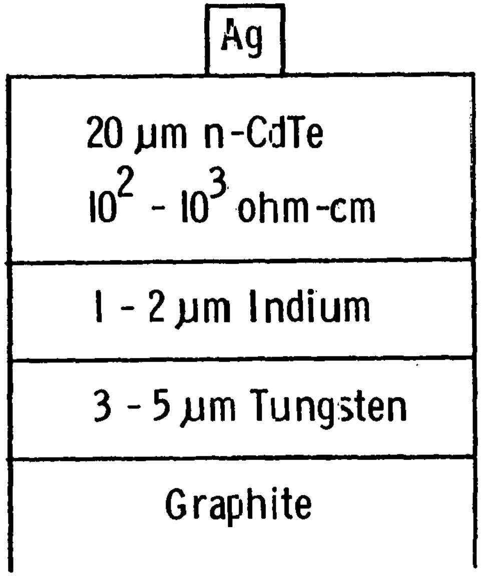


- Cadmium Telluride/Mullite
  - N-type
  - Carrier Concentration: $(6 - 9) \times 10^{12}$ CM^{-3}
  - Carrier Mobility: $(20\text{-}30)$ CM^2 /V-Sec
  - Resistivity: $(4 - 7) \times 10^4$ ohm-cm

TLC:10
9/79

THIN FILM CADMIUM TELLURIDE SOLAR CELLS
PROPERTIES OF SCHOTTKY BARRIERS ON n-CdTe/In/W/Graphite

- CONFIGURATION:



Ag

20 µm n-CdTe
$10^2 - 10^3$ ohm-cm

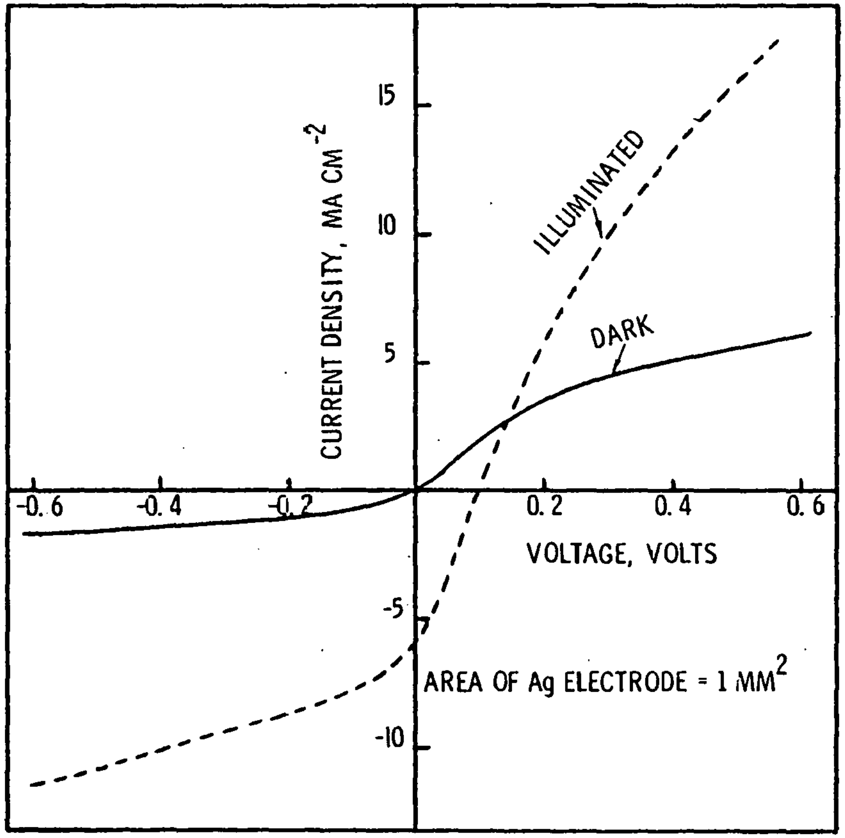
1 - 2 µm Indium

3 - 5 µm Tungsten

Graphite

- CONCLUSION: n-CdTe/In/W/graphite interface is ohmic.

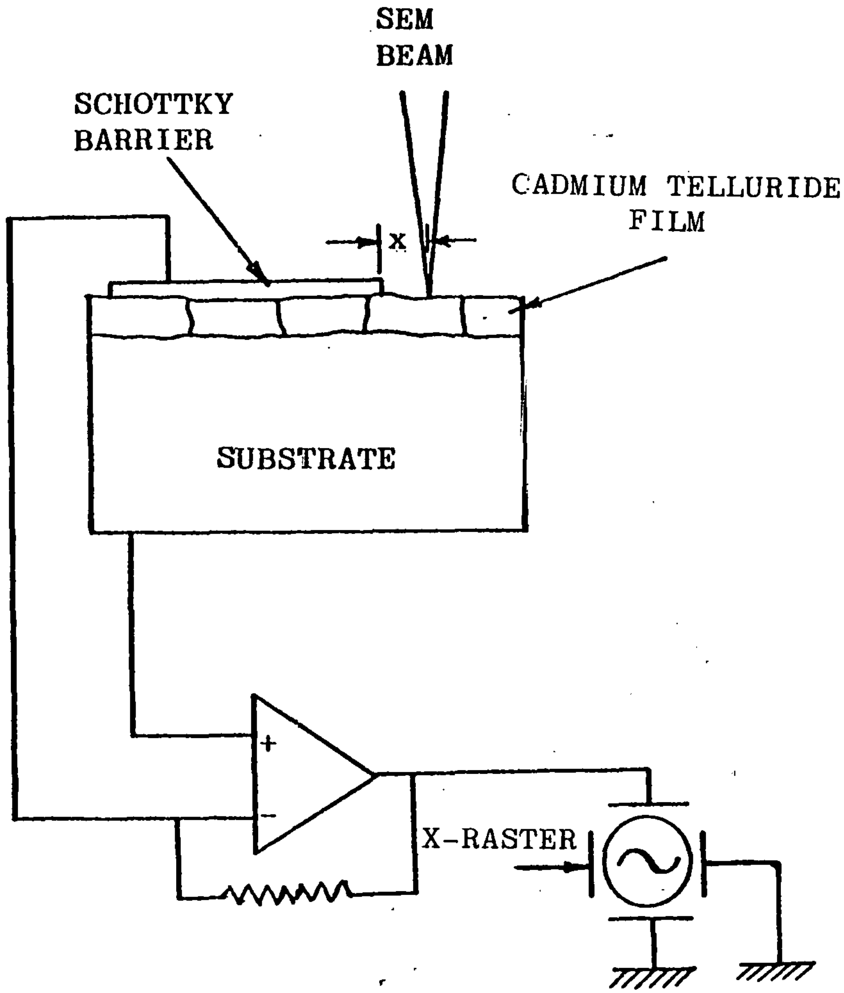
- CURRENT-VOLTAGE CHARACTERISTICS



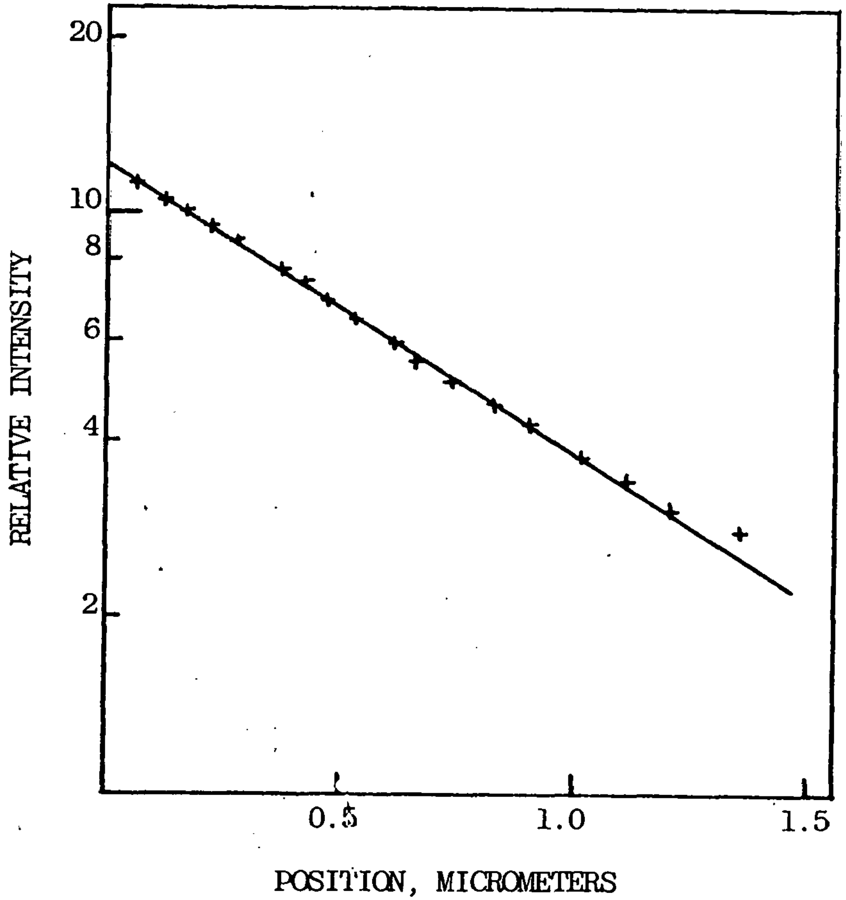
TLC:11
9

THIN FILM CADMIUM TELLURIDE SOLAR CELLS
INTRAGRAIN HOLE DIFFUSION LENGTH IN CdTe FILMS

- SCHEMATIC OF APPARATUS



- RESULTS



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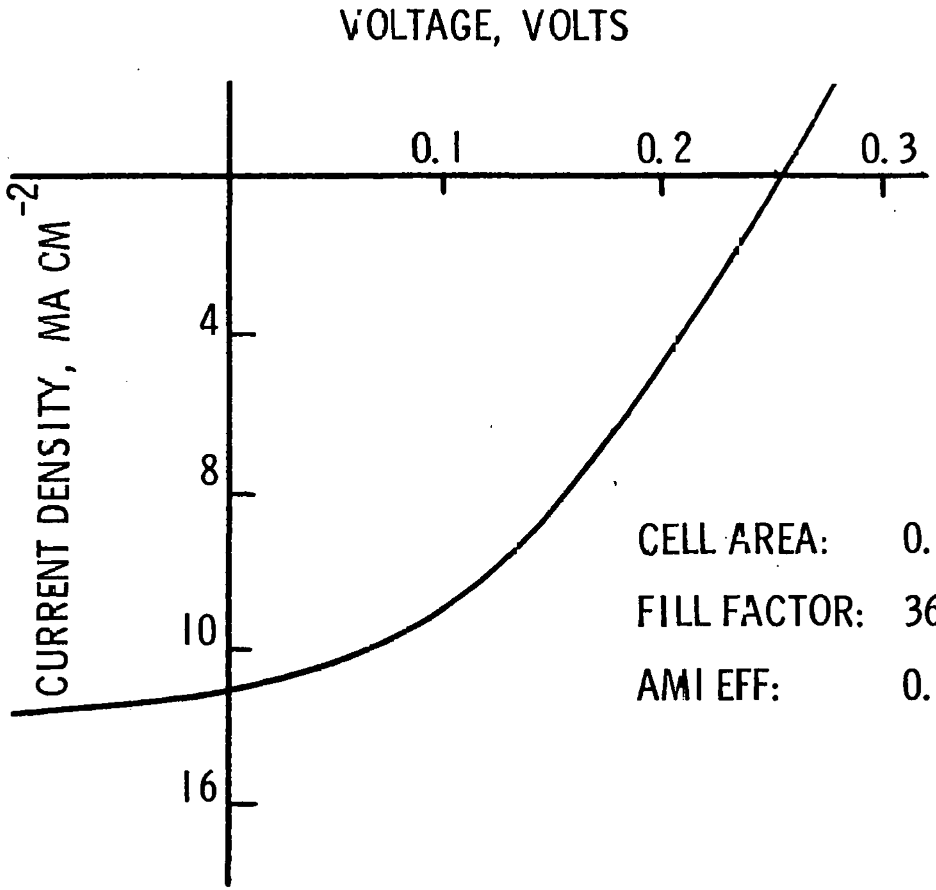
THIN FILM CADMIUM TELLURIDE SOLAR CELLS

CHARACTERISTICS OF Au/n-CdTe/In/W/GRAPHITE SOLAR CELL -- PRELIMINARY RESULT

- CURRENT-VOLTAGE CHARACTERISTICS UNDER AMI CONDITIONS



CELL AREA: 0.25 CM^2

FILL FACTOR: 36%

AMI EFF: 0.8%

TLC:13
( )

THIN FILM CADMIUM TELLURIDE SOLAR CELLS
PLANNED ACTIVITIES

- Reduction of electrical resistivity of n-type cadmium telluride films.
- Deposition of p-type cadmium telluride films and modification of substrate surface to minimize the interface resistance.
- Deposition and characterization of cadmium sulfide films.
- In-situ deposition and characterization of n-CdS/p-CdTe/substrate structures.

TLC:14
9/79

NOTES

SESSION VI

PHOTOVOLTAIC ARRAY COST - EFFICIENCY TRADEOFFS*

D. G. Schueler
Sandia Laboratory
Albuquerque, NM 87185

INTRODUCTION

The solar-to-electric conversion efficiency of a photovoltaic array is an extremely important characteristic influencing the cost of electrical energy from photovoltaic power systems. The array surface area required for a given array output power is inversely proportional to the array efficiency so that as array efficiency decreases, the area related costs comprise a larger fraction of the total installed array cost. This paper examines array cost-efficiency tradeoffs from the perspective of the long range system cost goals and array price goals of the Department of Energy (DOE) Photovoltaics Program. Residential, intermediate load center and central generating station applications are considered.

SYSTEM COST GOALS

To reach widespread commercial applications, photovoltaic system costs must be substantially reduced. The DOE Multi-Year Program Plan [1] has identified system cost goals for the major application sectors which if attained will make photovoltaic systems economically competitive in large potential markets. These program goals are shown in Figure 1 along with a breakdown of the system lifecycle cost (LCC) between the array subsystem and the balance of system. In this case, the balance of system cost is the lifecycle cost of the power conditioning and control hardware associated with interfacing the photovoltaic array to the load or a utility grid.

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*This work was supported by the Distributed Solar Technology Division of the U. S. Department of Energy.

ARRAY SUBSYSTEM COSTS

This section will establish the basic analytical relationships between array lifecycle cost and initial cost and between array efficiency and array module price. The relationship between the price of 1 kW_p of array modules, C_F, in $\$/kW_p$ and the area cost of the array modules, c_F, in $\$/m^2$ is given by

$$C_F = A c_F \qquad (\$/KW_P)$$

$$= \frac{c_F}{\eta}$$

WHERE: c_F = ARRAY PRICE IN $\$/M^2$

A = ARRAY SURFACE AREA FOR 1 KW_P

η = ARRAY CONVERSION EFFICIENCY

The relationship between the initial capital costs of an installed array, C_I, and the lifecycle costs of the array, LCC_A is

$$LCC_A = C_I + \frac{CRF}{FCR} PV\{C_R(T)\}$$

WHERE: C_I = INITIAL CAPITAL COST OF INSTALLED ARRAY

CRF = CAPITAL RECOVERY FACTOR

FCR = FIXED CHARGE RATE

$PV\{\ \}$ = PRESENT VALUE OPERATOR

$C_R(T)$ = RECURRING COSTS FOR OPERATION AND MAINTANANCE

FOR: $C_R(T) = C_O$ PER YEAR, $PV\{C_O\} = \frac{C_O}{CRF}$

$$LCC_A = C_I + \frac{C_O}{FCR} = C_I(1 + F)$$

WHERE: $F = C_O/(C_I \cdot FCR)$

The initial capital cost of an installed array subsystem is composed of: the array module factory cost; array marketing and distribution costs; area related costs for land, site preparation, foundations, array structures, installation, field wiring and lightning protection, and miscellaneous site costs; array perimeter related costs for fencing and safety zones; and finally indirect costs such as design and construction management, interest during construction, and spares. Analytically, the total initial cost, C_T, of an installed array of N kW_p is

$$C_T = (1+\beta)\left[N(1+\alpha)C_F + NAC_A + c_P(NA)^{1/2}\right]$$

$$= NC_I$$

WHERE: α = ARRAY MARKETING AND DISTRIBUTION MARKUP

β = SYSTEM INDIRECT COST FRACTION

c_A = AREA PROPORTIONAL COSTS ($\$/M^2$)

c_P = PERIMETER PROPORTIONAL COSTS ($/M)

C_I = INSTALLED CAPITAL COST OF 1 KW_P OF ARRAY

The capital cost of 1 kW_p of array is then

$$C_I = \frac{1+\beta}{\eta}\left[(1+\alpha)c_F + c_A + c_P\left(\frac{\eta}{N}\right)^{1/2}\right] \qquad (\$/KW_P)$$

and the associated array lifecycle cost is given by

$$LCC_A = \frac{1+\beta+F}{\eta}\left[(1+\alpha)\, c_F + c_A + c_P\left(\frac{\eta}{N}\right)^{1/2}\right]$$

The above expression allows examination of the tradeoff between array efficiency and array cost for a given array lifecycle cost and related installation costs.

Array Area Related Costs

The area related costs associated with deploying flat panel array modules into operational array fields have been studied in detail for variety of applications [2,3,4]. Figure 2 summarizes the projected area related costs for field deployed fixed tilted flat panel arrays. Such costs are in the \$35-60/m^2 range depending on site location and conditions. Costs in the \$30-60/m^2 range are typical of those projected for roof mounted arrays where savings in land cost and site preparation are possible but installation costs are typically higher than for field mounted arrays [4].

ARRAY COST-EFFICIENCY TRADEOFFS

Array lifecycle costs necessary to achieve the DOE system cost goals are shown in Figure 1 along with the associated price goals for array modules. Figures 3, 4, and 5 illustrate the tradeoff between array efficiency and allowable module factory cost for the required array lifecycle cost and a range of area related costs for residential, intermediate load center and central station applications respectively. For residential applications, arrays with efficiency less than about 8-10% begin to require more roof area than generally available on a residence without constraining the architecture. Figure 5 shows the cost-efficiency tradeoffs for central station applications on the basis of array module factory cost in \$/m^2. It is important to note that the slope of this efficiency-cost curve is independent of efficiency and area related cost. This means that for an array lifecycle cost of \$1.00/W_p, the allowable cost of an array module can increase only approximately \$7/m^2 for each percentage point increase in array efficiency.

For central station applications, an alternative approach to tilted array structures is horizontal deployment. This potentially reduces structure cost but simultaneously reduces the amount of solar energy falling on an array. In Figure 7, the allowable lifecycle cost of the array has been reduced to account for reduced annual energy production because of horizontal deployment and area related costs have been reduced to reflect lower structure costs.

SUMMARY

This paper has considered array cost-efficiency tradeoffs in the context of the DOE Photovoltaic Program system cost goals. These system cost goals have been established to ensure widespread commercial markets for photovoltaics in the 1986-1990 timeframe. However, many potential applications are projected to be cost effective at higher system costs. Figure 8 summarizes the minimum array efficiency consistent with the assumed required lifecycle cost of the array, for various module factory costs ranging from \$0.15-0.70/W_p.

REFERENCES

1. "National Photovoltaic Program: Multi-Year Program Plan", U. S. Department of Energy, DOE/ET-0105-D, June 6, 1979.
2. P. Masser, "Low-Cost Structures for Photovoltaic Arrays", SAND79-7006, Sandia Laboratories, June 1979.
3. H. A. Franklin, "Design of Low-Cost Structures for Photovoltaic Arrays", SAND79-7002, Sandia Laboratories, May 1979.
4. E. J. Buerger, et al, "Regional Conceptual Design and Analysis Studies for Residential Photovoltaic Systems", SAND78-7039, Sandia Laboratories, January 1979.

(1980\$)

	RESIDENTIAL	INTERMEDIATE	CENTRAL STATION
GOAL YEAR	1986	1986	1990
SYSTEM CAPITAL COST (\$/W_p)	1.60	1.60	1.10-1.30
ARRAY MODULE FACTORY PRICE GOAL (\$/W_p)	0.70	0.70	0.15-0.40
SYSTEM LCC	1.80	1.80	1.20-1.40
ARRAY SUBSYSTEM LCC	1.50	1.50	1.00-1.20
BALANCE OF SYSTEM LCC	0.30	0.30	0.20

Figure 1. DOE Photovoltaic Program System Cost and Array Price Goals and Associated Lifecycle Cost (LCC) Breakdown.

(1980 $)

-FIELD DEPLOYED FIXED TILTED ARRAYS-

	($/M^2)
ARRAY STRUCTURE & INSTALLATION	25-35
LAND PURCHASE	2-10
FIELD WIRING	4- 5
LIGHTNING PROTECTION	2- 6
MISC (DRAINAGE, ROADS)	2- 4
TOTAL:	35-60

Figure 2. Projected Array Area Related Costs For Field Mounted Fixed Tilted Flat Panel Modules (1980$).

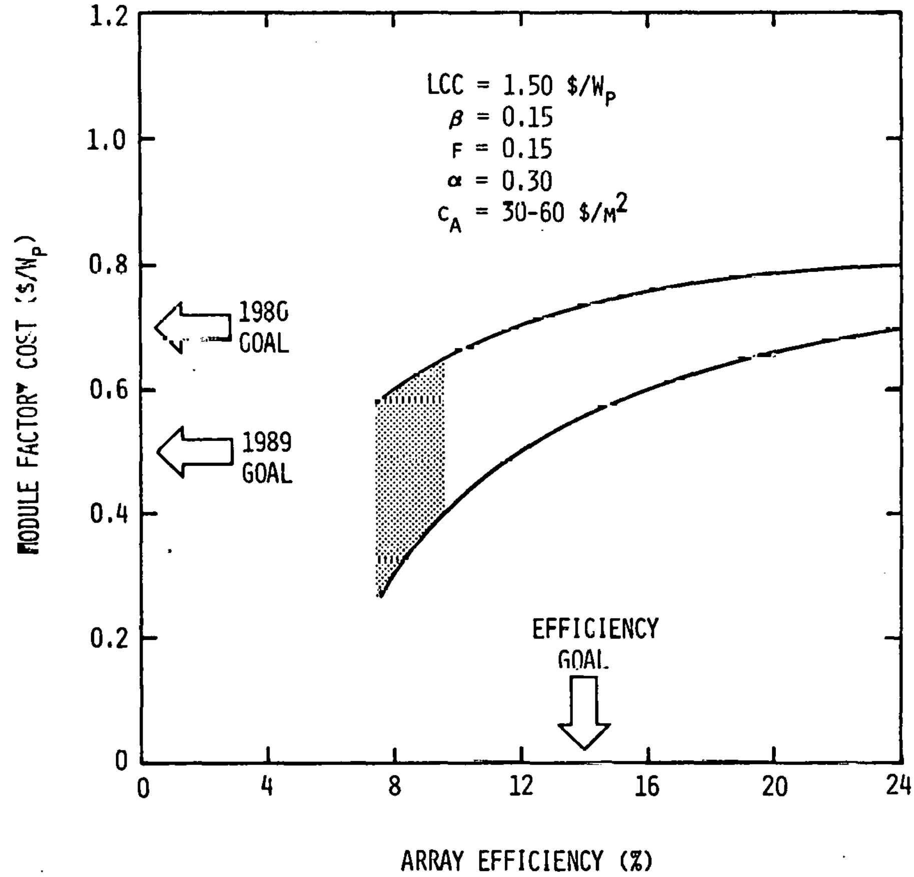

Figure 3. Array Cost-Efficiency Tradeoffs For Residential Rooftop Applications.

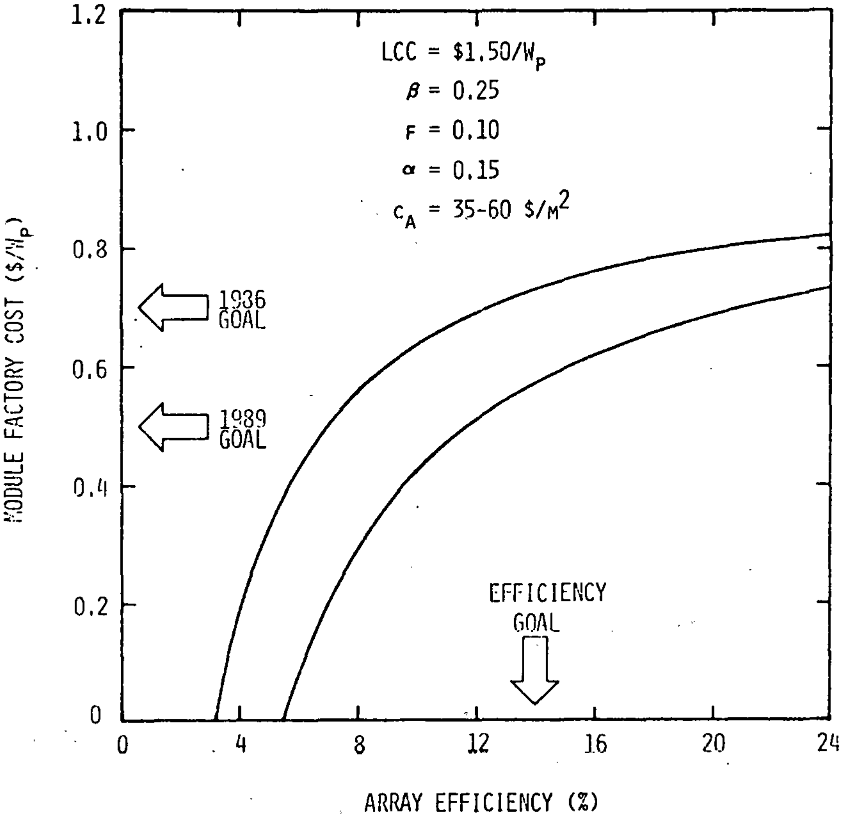

Figure 4. Array Cost-Efficiency Tradeoffs For Intermediate Load Center Applications.

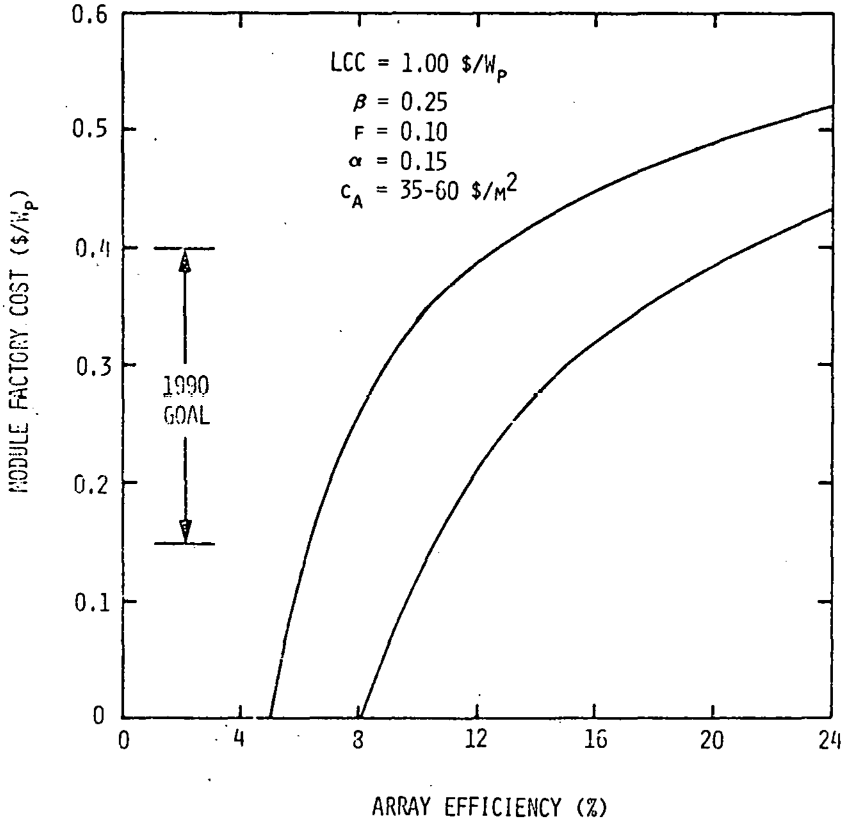

Figure 5. Array Cost-Efficiency Tradeoffs For Central Station Applications.

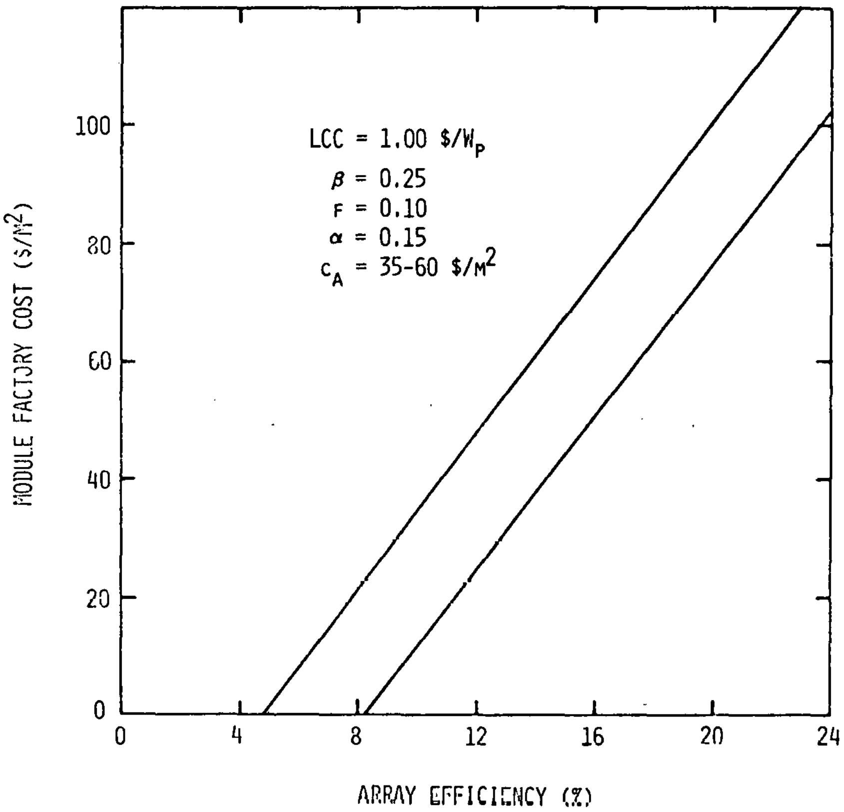

Figure 6. Array Cost-Efficiency Tradeoffs For Central Station Applications.

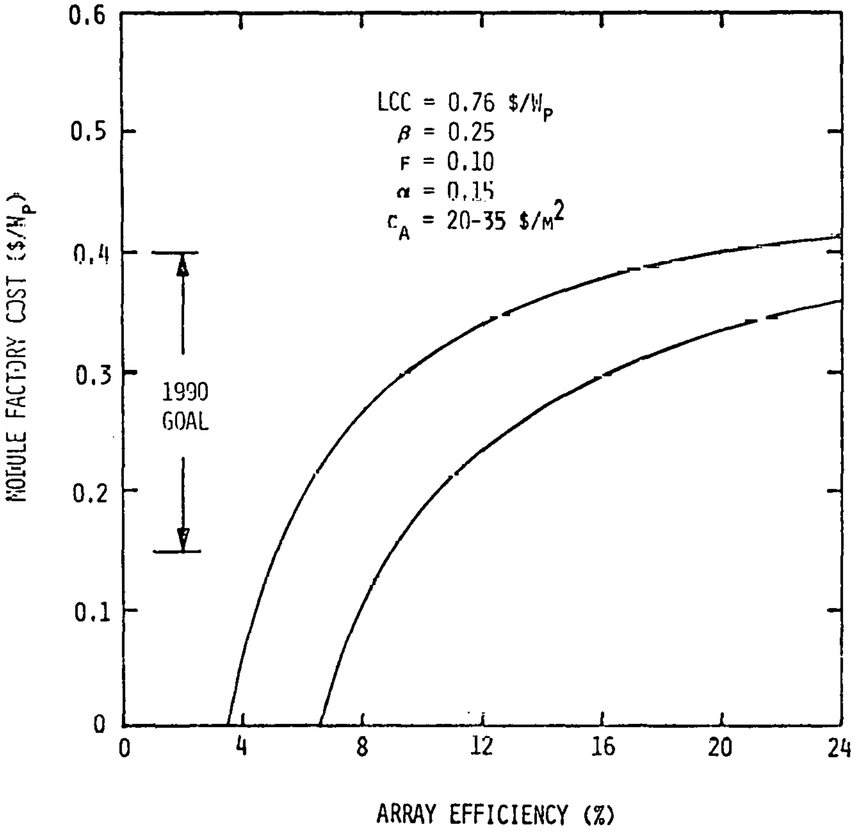

Figure 7. Array Cost-Efficiency Tradeoffs For Central Station Applications Employing Horizontal Deployment of Arrays.

MODULE FACTORY PRICE ($/W$_p$)	MINIMUM ARRAY EFFICIENCY (%)		
	RESIDENTIAL	INTERMEDIATE	CENTRAL STATION
0.70	14	14	--
0.50	10	10	20
0.40	8	8	14
0.25	8	6	10
0.15	8	5	8

Figure 8. Summary of Minimum Array Efficiencies Compatible With DOE SYSTEM Price Goals.

NOTES

AGENDA

Tentative Agenda

Photovoltaic Advanced R&D Annual Review Meeting

Stouffer's Denver Inn

Denver, Colorado

September 17 - 19, 1979

J. R. Burke - Chairman

Sunday, September 16, 1979

7:00 - 9:00 p.m.	Registration	Stouffer's Denver Inn Centennial Square Foye

Monday, September 17, 1979

	PLENARY SESSION - D. Feucht (Chairman)	
7:30 - 8:30 a.m.	Registration (coffee and rolls available)	Centennial Square Foye
8:30 - 9:10	The SERI Future	P. Rappaport/SERI
9:10 - 9:40	DOE/PV Overview	M. Prince/DOE
9:40 - 10:00	System Application Experiments	D. Schueler/Sandia
10:00 - 10:20	Residential Experiments	E. Kern/MIT Lincoln La
10:20 - 10:40	BREAK	
10:40 - 11:10	Storage For Photovoltaics	J. Appleby/EPRI
11:10 - 11:30	Overview of SERI R&D	S. Wagner/SERI
11:30 - 12:00	Potential Photovoltaic Materials	A. Zunger/SERI
12:00 - 12:20	Overview of Subcontract Activity	R. Burke/SERI
12:20 - 1:50	LUNCH	
	SESSION II - S. Wagner (Chairman)	
1:50 - 2:20	Amorphous Materials Research	J. Stone/SERI
2:20 - 2:45	Amorphous Silicon Cell Development	B. Williams/RCA
2:45 - 3:15	Photoelectrochemical (PEC) Cells	W. Wallace/SERI
3:15 - 3:45	State of the Art GaAs (PEC) Cells	B. Parkinson/Ames
3:45 - 4:05	BREAK	
4:05 - 4:25	Material Resources and Environmental Studies	S. Nagy/SERI

4:25 - 5:15	CdS Based Cells	Deb/SERI
5:15 - 5:45	Critical Properties of the Cu_2S/CdS Interface	W. Haines/SERI

Tuesday, September 18, 1979

SESSION III - T. Ciszek (Chairman)

8:30 - 9:15 a.m.	Low Cost Silicon Array Activities	L. Dumas/JPL
9:15 - 10:00	Polysilicon Research	T. Surek/SERI
10:00 - 10:25	Grain Boundary Characterization	L. Kazmerski/SERI
10:25 - 10:50	Grain Boundary Passivation	D. Ginley/Sandia
10:50 - 11:20	Poly GaAs Research	T. Surek/SERI
11:20 - 11:50	GaAs Talk Low Cost/High Efficiency GaAs Cells	J. Fan/MIT
11:50 - 1:20	LUNCH	

SESSION IV - L. Kazmerski (Chairman)

1:20 - 1:40 p.m.	Status of Concentrator Development	E. Boes/Sandia
1:40 - 2:15	Multijunction Concentrators	K. Mitchell/SERI
2:15 - 2:40	Luminescent Concentrators	J. Benner/SERI
2:40 - 3:00	High Efficiency Ternary/Quaternary Multijunction Cells	R. Moon/Varian
3:00 - 3:20	BREAK	
3:20 - 3:50	Emerging Materials Summary	K. Mitchell/SERI
3:50 - 4:15	Photovoltaic Effect in Polyacetylene	A. Heeger/Univ of P
4:15 - 4:40	CVD CdTe Cells	T. Chu/SMU

SESSION V - J. R. Burke (Chairman)

4:40 - 5:40	General Discussion	

Wednesday, September 19, 1979

SESSION VI - J. R. Burke (Chairman)

8:30 - 9:00 a.m.	Photovoltaic Array Cost/Efficiency Tradeoffs	D. Schuler/S[illegible]a

9:00 - 11:00 Panel Discussion - "Thin Film Cells Cost/Efficiency Tradeoffs"

11:00 Meeting Adjourned

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September 17-19, 1979

Denver, CO

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