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Proceedings of the ERDA Semiannual SOLAR PHOTOVOLTAIC PROGRAM Review Meeting

Orono, Maine

August 3-6, 1976

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Division of Solar Energy

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PROCEEDINGS OF THE ERDA SEMIANNUAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

University of Maine at Orono
Orono, Maine
August 3-6, 1976

Organized by the University of Maine at Orono
for the Energy Research and Development Administration
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College of Engineering and Science
University of Maine at Orono
Orono, Maine 04473

PREFACE

This report of the Proceeding of the Subject Meeting has been assembled to provide the participants and other interested parties with a compilation of abstracts of the talks given. Copies of visual aids used have been printed in the best available form.

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NATIONAL SOLAR PHOTOVOLTAIC

PROGRAM REVIEW MEETING

University of Maine at Orono
Aug 3-6, 1976

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LOW-COST SILICON SOLAR ARRAY PROJECT
NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW

ENCAPSULATION TASK

W. F. CARROLL
TASK MANAGER

AUGUST 1976

LOW-COST SILICON SOLAR ARRAY PROJECT
ENCAPSULATION TASK

- OBJECTIVE - 20-YEAR LIFETIME ENCAPSULATION SYSTEM
  - LOW COST
  - DEMONSTRATED LIFETIME
- SCOPE
  - COMPLETE PROTECTIVE SYSTEM
  - MULTIPLE DESIGN AND CONFIGURATION OPTIONS
  - MAY BE MULTI-FUNCTIONAL
    (E.G., STRUCTURAL, OPTICAL, ELECTRICAL)
- APPROACH
  - TWO-PHASE SUBCONTRACT INVESTIGATIONS
  - IN-HOUSE ANALYSIS AND TEST

LOW-COST SILICON SOLAR ARRAY PROJECT
PROGRESS

- ASSESSMENT OF EXPERIENCE WITH ENCAPSULATION COMPLETED
- PROPERTY DATA ON CANDIDATE ENCAPSULANT MATERIALS SUMMARIZED
- ENVIRONMENTAL ANALYSIS COMPLETED
  - METHODOLOGY DEVELOPED FOR SUITABLE CLIMATIC ANALYSIS
  - COMBINED ENVIRONMENTAL ANALYSIS FOR NINE SITES COMPLETED
  - APPROACH TO METHODOLOGY FOR ESTABLISHING TEST CONDITIONS AND SITE CORRELATIONS DEFINED
- ACCELERATED/ABBREVIATED (PREDICTIVE) STATISTICAL AND EXPERIMENTAL TECHNIQUES EVALUATED
  - BASIC APPROACH HAS BEEN DEFINED
  - USED TO EVALUATE RESULTS OF SEVERAL SYSTEMATIC STUDIES IN THE LITERATURE
  - NEED FOR IMPROVED DIAGNOSTICS DEMONSTRATED
- TWO EXPERIMENTAL PROGRAMS INITIATED

LOW-COST SILICON SOLAR ARRAY PROJECT

EXPERIENCE - TERRESTRIAL PHOTOVOLTAICS

- MORE THAN 60 EXAMPLES STUDIES
  - MAXIMUM 15 YEARS - MOST ARE MORE RECENT
- VARIETY OF TRANSPARENT COVER MATERIALS USED
  - GLASS
  - POLYCARBONATE
  - ACRYLIC
  - EPOXY
  - SILICONE
  - FLUOROCARBON
- RESULTS/CONCLUSIONS
  - SATISFACTORY PROTECTION AND STABILITY HAVE BEEN ACHIEVED
    - ASSOCIATED WITH HIGHER COST APPROACHES
  - SERIOUS PROBLEMS AND FAILURES HAVE OCCURRED
  - FOR LOW-COST/20 YEAR ENCAPSULATION MANY TESTS HAVE LIMITED UTILITY
    - STARTING MATERIAL/PROCESSING POORLY CHARACTERIZED
    - FAILURES, ANOMALIES, CHANGES INADEQUATELY CHARACTERIZED
    - ACTUAL ENVIRONMENTAL CONDITIONS NOT RECORDED

LOW-COST SILICON SOLAR ARRAY PROJECT

ENVIRONMENTAL ANALYSIS

PROBLEM

- COMBINATIONS OF ENVIRONMENTAL CONDITIONS SIGNIFICANTLY AFFECT DEGRADATION RATE (E.G. TEMPERATURE, ULTRAVIOLET, HUMIDITY)
- PREVIOUSLY AVAILABLE INDIVIDUAL AND COMBINATION STATISTICS WERE INADEQUATE

APPROACH - DEFINE SIMULTANEOUS OCCURRANCE OF ENVIRONMENTAL FACTORS

- NINE SELECTED SITES - "REPRESENTATIVE EXTREMES" (EXCLUDE EXTREME MARINE, DESERT, MOUNTAIN)
- MERGED DATA TAPES - CLIMATIC, INSOLATION, OTHER
- ACTUAL STATISTICS OF SIMULTANEOUS OCCURRANCE FOR 10 YEARS

RESULTS

- STATISTICS ON INDIVIDUAL CONDITIONS WAS BY-PRODUCT
- 20 YEAR PREDICTION OF COMBINATIONS
- SPECIAL HAZARDS (TORNADOES, HAIL, ETC.) AS GENERAL OR REGION STATISTICS

LOW-COST SILICON SOLAR ARRAY PROJECT
ENVIRONMENTAL ANALYSIS

CONCLUSIONS

- COMBINATIONS OF EXTREMES DO NOT GENERALLY OCCUR
- "ABUSIVE" COMBINATIONS OCCUR WITH LIMITED FREQUENCY
- SYSTEMATIC CORRELATION BETWEEN SITES IS POSSIBLE
- "NESTED TEST SETS" APPEAR FEASIBLE
- METHODOLOGY USED IS APPLICABLE TO MANY SOLAR ENERGY PROBLEMS
- MAJOR DEFICIENCIES EXIST IN AVAILABLE ULTRAVIOLET DATA

LOW-COST SILICON SOLAR ARRAY PROJECT
TEST APPROACHES

- REAL TIME OUTDOOR WEATHERING
  - 20 YEAR EXPOSURE IMPOSSIBLE AND IMPRACTICAL
  - AT LEAST ONE FULL ANNUAL CYCLE REQUIRED FOR ANY EXTRAPOLATION
- PREDICTIVE TESTING - GENERAL CATEGORIES
  - ACCELERATED - ONE OR MORE ENVIRONMENTAL STRESSES (TEMP., HUMIDITY, U.V.) INCREASED ABOVE NORMAL
  - ABBREVIATED - SHORTER THAN EXPECTED LIFE WITH MECHANISMS AND RATES DETERMINED WITH SUFFICIENT ACCURACY TO PERMIT EXTRAPOLATION
  - TIME COMPRESSED - SHORTEN OR ELIMINATE PERIODS DURING WHICH DEGRADATION DOES NOT OCCUR OR OCCURS AT VERY LOW RATES
  - EVENT COMPRESSED - TESTS CONDUCTED AT SELECTED (E. G. MOST ABUSIVE) REAL CONDITIONS
- THESE ARE NOT NECESSARILY MUTUALLY EXCLUSIVE, MANY TESTS INCORPORATE ELEMENTS OF TWO OR MORE
- THERE ARE MAJOR POTENTIAL PROBLEMS/ERRORS ASSOCIATED WITH EACH

LOW-COST SILICON SOLAR ARRAY PROJECT

PREDICTIVE TESTING

- AVAILABLE DATA HAS BEEN ANALYZED
  - DATA IS VALUABLE - BUT IS INSUFFICIENT TO VALIDATE APPROACH FOR THIS PROJECT
  - EACH MAJOR INVESTIGATION INCLUDES ONE OR MORE INADEQUACIES
    - STATISTICS AFTER-THE-FACT
    - REPLICATE SAMPLES
    - DATA FREQUENCY OR INTERVALS
    - ACTUAL ENVIRONMENT MEASUREMENT/RECORD
    - BATCH AND LOT VARIATION IN MATERIALS

- PRELIMINARY TEST DESIGN HAS:
  - CONFIRMED THE IMPORTANCE OF STATISTICS IN TEST DESIGN
  - PROVIDED INITIAL DEFINITION OF MEASUREMENT FREQUENCY AND ACCURACY
  - CONFIRMED THE REQUIREMENT FOR IMPROVED DIAGNOSTICS

LOW-COST SILICON SOLAR ARRAY PROJECT

PREDICTIVE TESTING

ILLUSTRATION OF MEASUREMENT ACCURACY/TIME REQUIRED

ASSUMED FRACTIONAL DEGRADATION AT END OF 20 YEARS, PER CENT	FRACTIONAL DEGRADATION EXPECTED TO OCCUR AT END OF TIME SHOWN, PER CENT					
	1 DAY	30 DAYS	90 DAYS	180 DAYS	270 DAYS	360 DAYS
20	0.000	0.001	0.003	0.006	0.008	0.011
40	0.001	0.002	0.006	0.013	0.019	0.025
60	0.001	0.004	0.011	0.022	0.033	0.044
80	0.002	0.007	0.020	0.039	0.058	0.076

LOW-COST SILICON SOLAR ARRAY PROJECT

PREDICTIVE TESTING
EXPERIMENTAL EVALUATION

COMBINATION TESTING

- STATISTICAL TEST DESIGN
- OUTDOOR
  - FLORIDA - 45^0 SOUTH
  - ARIZONA - 45^0 SOUTH
    - ACCELERATED
    - ACCEL. WITH WATER SPRAY
- SELECTED MATERIALS
  - DEGRADABLE - UNSTABILIZED LEXAN
  - "STABLE" - TEDLAR
- "IDENTICAL" SPECIMENS
  - ENCAPSULANT
  - FREE FILM

LABORATORY PARAMETERS - FULL FACTORIAL

- TEMPERATURES 5^oC, 50^oC
- HUMIDITY 0%, 50%, 100%
- SIMULATED SUNLIGHT 0, 0.5, 1.0 AM-I - 0/1 ALTERNATING

LOW-COST SILICON SOLAR ARRAY PROJECT

MATERIALS TESTING

- AVAILABLE CANDIDATE TRANSPARENT COVERS
- OBJECTIVES
  - INTERIM RECOMMENDATIONS
  - EARLY PREDICTION DATA
  - LONG-RANGE DATA
- CONDITIONS
  - HEAT-AGING 55°C, 100°C
  - HEAT-AGING 55°C, 100°C PLUS ULTRAVIOLET
    55°C AT 95% RH PLUS ULTRAVIOLET
  - WEATHEROMETER

LOW-COST SILICON SOLAR ARRAY PROJECT

PROBLEMS WITH PREDICTIVE TESTING

- MECHANISMS AND RATES CAN CHANGE DRASTICALLY WITH "STRESS" LEVEL
- VARIATIONS IN STARTING MATERIALS
  (CONTENT OF "IMPURITIES" CRITICAL TO WEATHERING, CAN VARY 10^3)
- DEPENDENT ON PROCESS AND USE CONDITIONS
  - MECHANICAL STRESS
  - ANISOTROPY AND NONHOMOGENEITY
  - IMPURITES
- CHANGING MATERIAL - MATL DEGRADING IN 10TH YEAR NOT THE SAME MATERIAL AS FIRST YEAR
  (MECHANISM AND RATE DEPEND ON CONDITION AND COMPOSITION)

LOW-COST SILICON SOLAR ARRAY PROJECT

AVAILABLE ENCAPSULATION MATERIALS GLASS-BASED SYSTEMS - AT LEAST AS AN INTERIM

- ADVANTAGES
  - DEMONSTRATED SYSTEMS CAN BE ON-STREAM SOONER
    - INHERENTLY MORE WEATHER RESISTANT
    - AVAILABLE STABILITY DATA
  - HERMETICITY - BETTER PROTECTION OF CONTACTS AND INTERCONNECTS FROM H_2O, SO_x, ETC.
  - DOUBLE AS MODULE STRUCTURE (REDUNDANT STRUCTURE WILL NOT BE PERMISSIBLE AT LOW-COST)
  - PRODUCTION AND TECHNOLOGY AVAILABLE (500 mw/yr - 5×10^6 m^2/yr $\approx$ 2% OF U. S. ANNUAL FLAT GLASS PROD.)
  - ENERGY CONSUMPTION/PAYBACK COMPETITIVE
- DISADVANTAGES
  - IMPACT SENSITIVITY
  - MECHANICAL PROCESSING INTO MODULES DIFFICULT
  - TOTAL COST - MATERIALS AND PROCESSES - HIGHER THAN COMPETITION POSSIBLE RAW MATERIALS AVAILABILITY (FOR BOROSILICATE ONLY)

LOW-COST SILICON SOLAR ARRAY PROJECT
AVAIABLE MATERIALS
QUESTIONS

- MATERIAL COSTS
  - WHAT COSTS ARE NOW HIGH BECAUSE OF LIMITED MARKET?
  - WHAT COSTS ARE NOW LOW-MATERIAL IS BASED ON BY-PRODUCT?
  - WHAT IS EFFECT OF LOWER ACCEPTABLE "OPTICAL QUALITY" ON GLASS COSTS?
- TECHNICAL/MARKET
  - WHAT PRODUCTS ARE DEVELOPED OR BEING DEVELOPED THAT COULD BE AVAILABLE FOR PHOTOVOLTAIC?
  - WHAT CURRENT PRODUCTS WILL NOT BE AVAILABLE IN THEIR PRESENT FORM, QUALITY, ETC.?

LOW-COST SILICON SOLAR ARRAY PROJECT
NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW

SOLAR ARRAY AUTOMATED ASSEMBLY TASK

WALTER A. HASBACH
TASK MANAGER

AUGUST 1976

ABSTRACT

TASK 4. SOLAR ARRAY AUTOMATED ASSEMBLY

Using the results and experience gained from various studies, the objective is to fabricate solar arrays of 10% or better conversion efficiency at a price of $0.50/watt or less at a rate of 500 megawatts per year with a 20 year operating life. Phase I (technology assessment) of this task has these specific objectives:

- To identify the requirements for economical manufacturing processes and facilities.
- To assess the current technology used in the manufacture and assembly processes that could be applied to solar arrays.
- To determine the level of technology readiness to achieve the high-volume, low-cost production.
- To propose processes for development.

TECHNICAL BACKGROUND

The manufacture of solar cells and arrays is presently performed under the direct judgment and control of individual operators. Because of the limited quantities of solar cells and arrays produced, costs are high. Automation accomplishes more than the obvious reduction of labor. In addition, automation causes a uniformity of processing which results in a more uniform product with a corresponding reduction of waste due to rejected product.

ORGANIZATION OF THE TASK 4 EFFORT

Task 4 is divided into five phases, occurring over a 10 year period of time, the phases are:

I. Technology Assessment
II. Process Development
III. Facility and Equipment Design
IV. Pilot Plant Construction
V. Conversion to Mass Production Plant (by 1986).

Phase I contracts have been awarded to three contractors (Motorola, RCA, and Texas Instruments) to perform parallel efforts. The three-contractor paralle effort philosophy was selected to obtain the broadest possible view of recommendations and conclusions upon which to base the contractual efforts of Phase II.

Phase I contractors will address the areas of defining the requirements for automation as applicable to solar cell manufacturing by evaluation of processes which are now used by the semiconductor industry and how these processes could be modified for high-volume, low-cost production of solar cell modules. Cost analyses will be performed to provide economic guidelines to maintain an overall view of LSSA Project objectives.

Two support efforts have been contracted which contribute to the development of Task 4 objectives. A contract is underway with Simulation Physics for exploring the feasibility of a unique process for forming a solar cell P/N junction at room temperature. Another contract is just getting started with Texas Instruments for the optimization of current proven semiconductor techniques to produce silicon wafers in the most cost effective manner.

MOTOROLA

Motorola's program plan starts out with work on designs of solar cells and with process adaptation. This is followed by process sequencing and encapsulation design. Costing, cell fabrication and encapsulation experiments will be carried out to be followed by a selection of a recommended sequence and concepts of scaling up to the required production volume.

A list of 45 individual processes was assembled for study. The processes have been categorized into four groups in relation to their applicability to solar cells; (1) judged unlikely; (2) potentially promising; (3) present solar cell use and (4) semiconductor processes not usually applied to solar cells. Eight of these processes are being studied by laboratory experimentation. Higher efficiency cells require less encapsulation and structure. When the cost of slight increases in efficiency is weighed against the cost of slight reductions in the need for encapsulation and structure, it indicates that medium to high efficiencies are most cost effective.

RCA LABORATORIES

The RCA program plan begins with the development of a cost analysis procedure. This procedure has been applied to existing process technologies to obtain very detailed costs. The development of cost effective approaches and the identification of cost/manufacturing obstacles also began at the onset. The work on the solutions to the obstacles, with experimental demonstrations has begun. The final step will be to define the most cost effective approach for manufacturing the solar cell modules.

RCA is using an analytical system which relies on three organizational diagrams. These are: (1) A silicon quality materials matrix; (2) A processing matrix; and (3) An array module cost analysis interaction diagram. The silicon quality matrix is a five row by seven column pattern of possible silicon purity levels and physical forms. The processing matrix catalogues 28 separate processes which contain the many options for fabricating solar cells from the different grades of silicon quality as determined in the silicon quality matrix. Every reasonable alternative in these matrices is being evaluated and the detailed costs defined. In general, each step is integrated into some entire manufacturing sequence of processes and then the costs compared. A performance index is determined for each process as it relates to the way it affects cell parameters. A manufacturing sequence has an overall figure of merit which is the product of the individual process performance indices. In this way evaluations are accomplished which relate to solar cell costs in terms of dollars per watt.

TEXAS INSTRUMENTS

A design-to-cost analysis has been used to set allowable cost goals for each process element of the solar cell module fabrication process. A baseline process, using current technology, was costed which showed that current technology is about an order of magnitude too expensive at each process element when compared to the design-to-cost goals. The cell metallization step has been shown to be the least cost effective step in the baseline cell process. Several alternate cell metallization processes are being studied.

The allowable cost goals for each process element derived from the TI design-to-cost analysis have been further broken down to give models of labor, overhead, material and depreciation cost goals. These cost goals are related to a set of factory throughput values.

The TI baseline design focuses on hexagonal cells close packed on an encapsulated ten watt module. This geometry has a more efficient cell packing density than circular solar cells. It is pointed out that both packing density and cell efficiency must be improved to meet the project goals. Their analyses using the design-to-cost concept show that low efficiency solar cells are not justified with expected costs per unit area for module fabrication and encapsulation.

PROCESSING TECHNOLOGY FOR HIGH RATE LOW ENERGY EXPENDITURE FABRICATION OF SILICON SOLAR CELLS - SIMULATION PHYSICS

The goal of this program is to demonstrate the feasibility of an unique process for solar cell manufacture. The technique incorporates an ion implanter and an electron beam processor to manufacture solar cells in a vacuum environment at room temperature. The program is scheduled for 12 months duration. After

1. Feasibility Demonstrated. 9.5% AMO efficient solar cells have been produced at room temperature in vacuum.
   a. An ion implant of phosphorus is made on the front surface of cells, boron or an aluminum eutectic is implanted on its rear surface.
   b. An electron beam is used for the implant anneal process and also to sinter the aluminum contacts and AR coating.
2. Cell Manufacturing Simplified. There is no present need for wafer cleaning, acid etching or sandblasting processes. No special forming gas atmosphere is required. There is no acid waste or other waste disposal problem. No materials are used that do not form part of the cell.
3. Controlled Reproducible Processes. Ion species of a given quantity delivered at given energies can be precisely implanted at given depths and annealed. This technique offers a much wider selection for cell development and for cell production processes than does the conventional diffusion furnace process.
4. Net Process Time Small. Net wafer-to-cell process time on this program has now been reduced to 36 seconds per cm^2 of wafer area. The program goal is under 30 seconds per cm^2 for 2 x 2 cm cell. Less than 5 seconds per cm^2 is a possibility. Times are a summation of the various steps for cell processing. Equipment doesn't yet exist for a continuous process line.
5. Low Cost. This technique promotes low cost solar cell processing. Inherent manufacturing simplicity permits high volume processing at high speed with good process control requiring little labor surveillance. The method also promises high yield with little material waste and with efficient energy utilization. Equipment costs are moderate.
6. Electron Beam Problem. The electron beam in use is somewhat dirty because it attracts and deposits at the cell junction unwanted contaminating ions. Present lack of electron beam flux uniformity may contribute to crystal lattice damage. The consequence is a slight reduction in cell Voc, about 30 mV typically for a 2 x 2 cm cell. However, the typical cell output current and its I-V curve fill factor are very good.

LARGE AREA CZOCHRALSKI SILICON - TEXAS INSTRUMENTS

Goal: The contract is to optimize current proven semiconductor techniques to produce silicon wafers in the most cost effective manner.

Objectives:

a. Using melt replenishment techniques, 30 kilograms of silicon in the form of 3 crystals 12 cm in diameter will be grown during one continuous heat cycle.

b. Multiblade sawing techniques will be optimized to produce .025 cm (.010") thick wafers from 12 cm diameter crystals.

c. Laser shaping techniques will be developed to produce hexagons from the 12 cm diameter wafers at an edge rate of 10 cm per second.

d. T.I. will develop and continually update an economic model of the crystal growth, wafering and shaping techniques described above.

Status:

The initial two months of the contract have resulted in the following:
The preliminary economic model of the Czochralski crystal growing and wafering processes shows that processing techniques optimization will result in sheet costs of less than $30 per square meter with polysilicon starting material input costs of 10 per kilogram.
Theoretical yields for the melt replenishment technique being developed show 80% yields should be obtainable (in the specified resistivity range) rather than the 60% originally anticipated. Additionally, thermal modeling has shown that 15 cm per hour growth rates should be obtainable and that the 12 cm per hour specified in the Contract is reasonable. Furnace modifications are underway to prove their theoretical models are accurate.
Sawing experiments using 400 grit SiC abrasive and both .02 cm (.008") and .01 cm (.004") thick blades have shown very reasonable yields (98%). The results also indicate that several crystals could be sliced simultaneously at the same rate as a single crystal provided the blade load is kept constant. Slice plus kerf thickness will be reduced to the Contract goals of .05 cm (.020").

LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK

GOAL

- FABRICATE SOLAR ARRAY MODULES > 10% EFFICIENT
- PRICE < $0.50 PER PEAK WATT
- PRODUCTION CAPABILITY > 500 MEGAWATT PER YEAR
- OPERATING LIFE > 20 YEARS

LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK

ORGANIZATION OF TASK

I	TECHNOLOGY ASSESSMENT	(1 YEAR)
II	PROCESS DEVELOPMENT	(2 YEARS)
III	FACILITY & EQUIPMENT DESIGN	(2 YEARS)
IV	PILOT PLANT DEVELOPMENT AND OPERATION	(3 YEARS)
V	PILOT PLANT TO MASS PRODUCTION CONVERSION	(2 YEARS)

LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY

<u>OBJECTIVES - PHASE I</u>

RELATIVE TO LOW-COST, HIGH VOLUME PRODUCTION OF SOLAR CELLS/ MODULES

1 - IDENTIFY REQUIREMENTS FOR ECONOMICAL MANUFACTURING PROCESSES AND FACILITIES

2 - ASSESS THE CURRENT TECHNOLOGY USED IN THE MANUFACTURING AND ASSEMBLY PROCESSES

3 - DETERMINE THE PRESENT LEVEL OF TECHNOLOGY READINESS

4 - PROPOSE PROCESSES FOR DEVELOPMENT

LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY PHASE I TECHNOLOGY ASSESSMENT

CONTRACTS

PARALLEL EFFORT CONTRACTS HAVE BEEN AWARDED TO MOTOROLA, RCA AND TEXAS INSTRUMENT TO:

- ANALYZE EXISTING TECHNOLOGIES
- IDENTIFY COSTS OF PROCESSING AND TESTING STEPS
- DEVELOP COST EFFECTIVE APPROACHES AND IDENTIFY OPTIONS AVAILABLE
- IDENTIFY COST/MANUFACTURING OBSTACLES
- CONCEPTUAL SOLUTIONS TO THESE OBSTACLES
- DEMONSTRATE COST EFFECTIVE SOLUTIONS
- DEFINE THE CONCEPTUAL APPROACH THAT APPEARS MOST COST EFFECTIVE TO ACHIEVE THE PROJECT GOALS

LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK
PHASE I - SUPPORT CONTRACTS

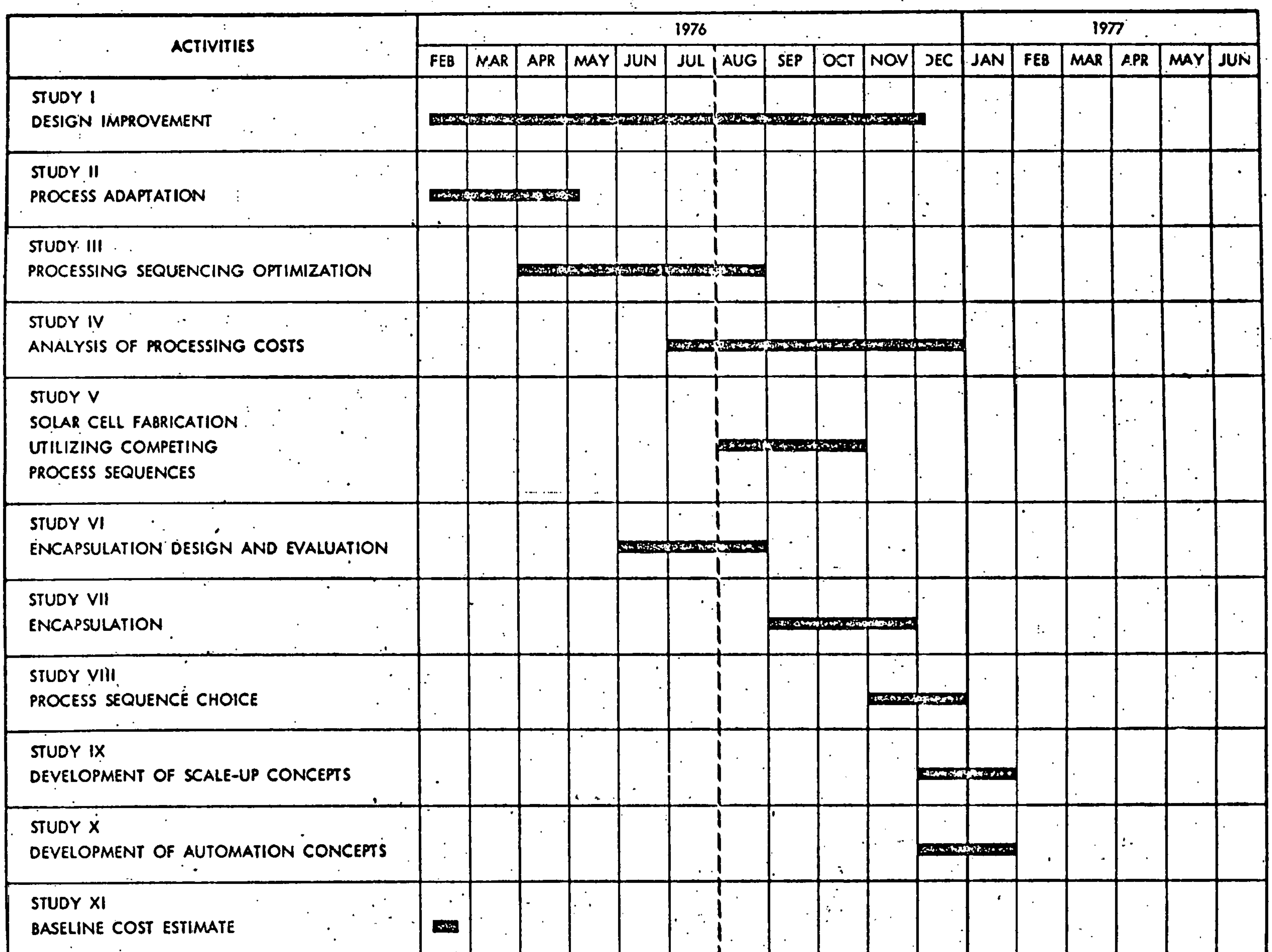
CONTRACTS

- SIMULATION PHYSICS - EXPLORING THE FEASIBILITY OF A UNIQUE PROCESS FOR FORMING A SOLAR CELL P/N JUNCTION AT ROOM TEMPERATURE

- TEXAS INSTRUMENT - OPTIMIZATION OF CURRENT PROVEN SEMI-CONDUCTOR TECHNIQUES TO PRODUCE SILICON WAFERS IN THE MOST COST EFFECTIVE MANNER

LOW-COST SILICON SOLAR ARRAY PROJECT

MOTOROLA INC.



LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK

MOTOROLA

STATUS

- 45 INDIVIDUAL PROCESSES HAVE BEEN CATEGORIZED INTO 4 GROUPS IN RELATION TO THEIR APPLICABILITY TO SOLAR CELL PROCESSING

  1 - JUDGED LIKELY

  2 - POTENTIALLY PROMISING

  3 - PRESENT SOLAR CELL USE

  4 - SEMICONDUCTOR PROCESSES NOT USUALLY APPLIED TO SOLAR CELLS

- 8 OF THE 45 PROCESSES ARE BEING STUDIED BY LABORATORY EXPERIMENTATION

LOW-COST SILICON SOLAR ARRAY PROJECT

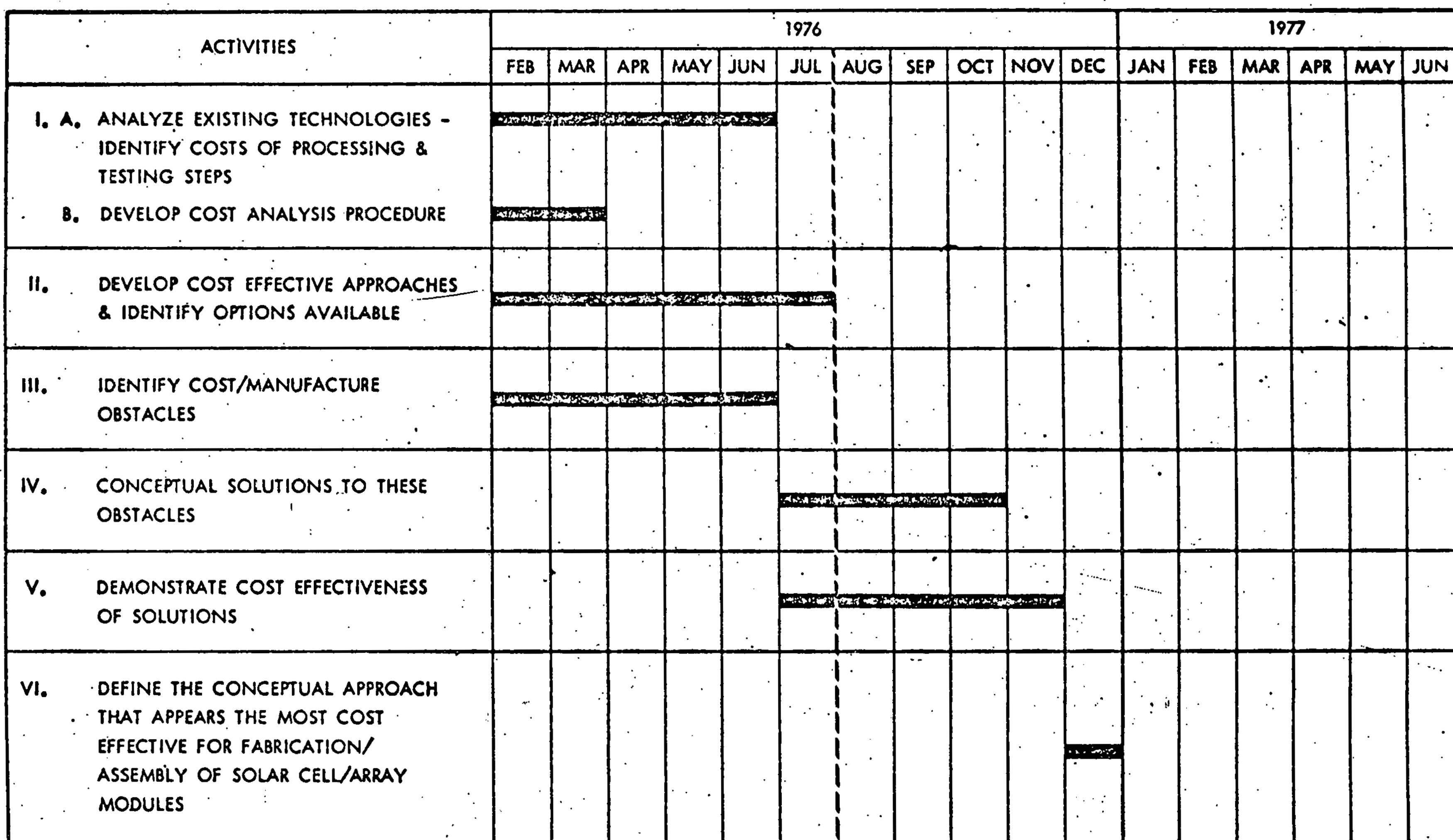
SOLAR ARRAY AUTOMATED ASSEMBLY TASK

MOTOROLA (CONTD)

- COST TO PRODUCE HIGHER EFFICIENCY CELLS WEIGHED AGAINST COST OF ADDED ENCAPSULATION, STRUCTURE AND VOLUME PRODUCTION, INDICATED HIGHER EFFICIENCY CELLS TO BE MORE COST EFFECTIVE
- TEXTURE ETCH FRONT SURFACE CELLS RESULT IN HIGHER EFFICIENCY, LOWER CONTACT RESISTANCE OF METALLIZED AREAS AND DAMAGE FREE ETCHED SURFACE
- MOTOROLA IS INVESTIGATING THE BENEFITS OF MAKING THE BACK OF CELLS REFLECTING TO IMPROVE EFFICIENCY
- VARIOUS METALLIZATION PROCESSES ARE BEING EVALUATED
- VARIOUS METALS AND MATERIALS ARE BEING TESTED TO EVALUATE THEIR ABILITY TO WITHSTAND THE OUTDOOR ENVIRONMENT AND SEAL OUT MOISTURE

LOW-COST SILICON SOLAR ARRAY PROJECT

RCA LABORATORIES



LOW-COST SILICON SOLAR ARRAY PROJECT
SOLAR ARRAY AUTOMATION ASSEMBLY TASK
RCA LABORATORIES

STATUS

- A DETAILED COST ANALYSIS PROCEDURE HAS BEEN APPLIED TO EXISTING PROCESS TECHNOLOGIES TO OBTAIN DETAILED COSTS
- COST EFFECTIVE APPROACHES AND THE IDENTIFICATION OF COST/ MANUFACTURING OBSTACLES IS COMPLETE
- WORK ON THE SOLUTIONS TO THESE OBSTACLES, WITH EXPERIMENTAL DEMONSTRATIONS HAS BEGUN.

LOW-COST SILICON SOLAR ARRAY PROJECT
SOLAR ARRAY AUTOMATION ASSEMBLY TASK
RCA LABORATORIES (CONTD)

STATUS (CONTD)

- THE ANALYTICAL SYSTEM RELIES ON THREE ORGANIZATIONAL DIAGRAMS

1 - SILICON MATERIALS MATRIX

a - FIVE ROWS BY SEVEN COLUMN PATTERN OF POSSIBLE SILICON PURITY AND PHYSICAL FORMS

2 - PROCESSING MATRIX

a - CATALOGUES 28 SEPARATE PROCESSES WHICH CONTAIN THE MANY OPTIONS FOR FABRICATING SOLAR CELLS FROM DIFFERENT GRADES OF SILICON QUALITY

3 - AN ARRAY MODULE COST ANALYSIS INTERACTION DIAGRAM

a - EVERY REASONABLE ALTERNATIVE IN THESE MATRICES IS BEING EVALUATED AND THE DETAILED COSTS DEFINED

b - COSTING PROCEDURE USES 8 BASIC ELEMENTS

i - INCOMING UNIT COSTS
ii - SUPPLIES, MATERIAL, GASES, ELECTRICITY, ETC.
iii - DIRECT LABOR
iv - INDIRECT LABOR
v - LABOR OVERHEAD
vi - INTEREST
vii - DEPRECIATION
viii - FACTORY OVERHEAD
ix - INVESTMENT

LOW-COST SILICON SOLAR ARRAY PROJECT
SOLAR ARRAY AUTOMATION ASSEMBLY TASK
RCA LABORATORIES (CONTD)

STATUS (CONTD)

4 - RCA RECOGNIZES THAT THIS COST ACCOUNTING APPROACH TO PROCESS EVALUATION HAS WEAKNESSES -

a - MAY NOT PERMIT DIRECT COMPARISONS DUE TO DIFFERENCES IN THE QUALITY OF THE OUTPUT OF TWO ALTERNATIVE PROCESSES

5 - METHOD OF USE -

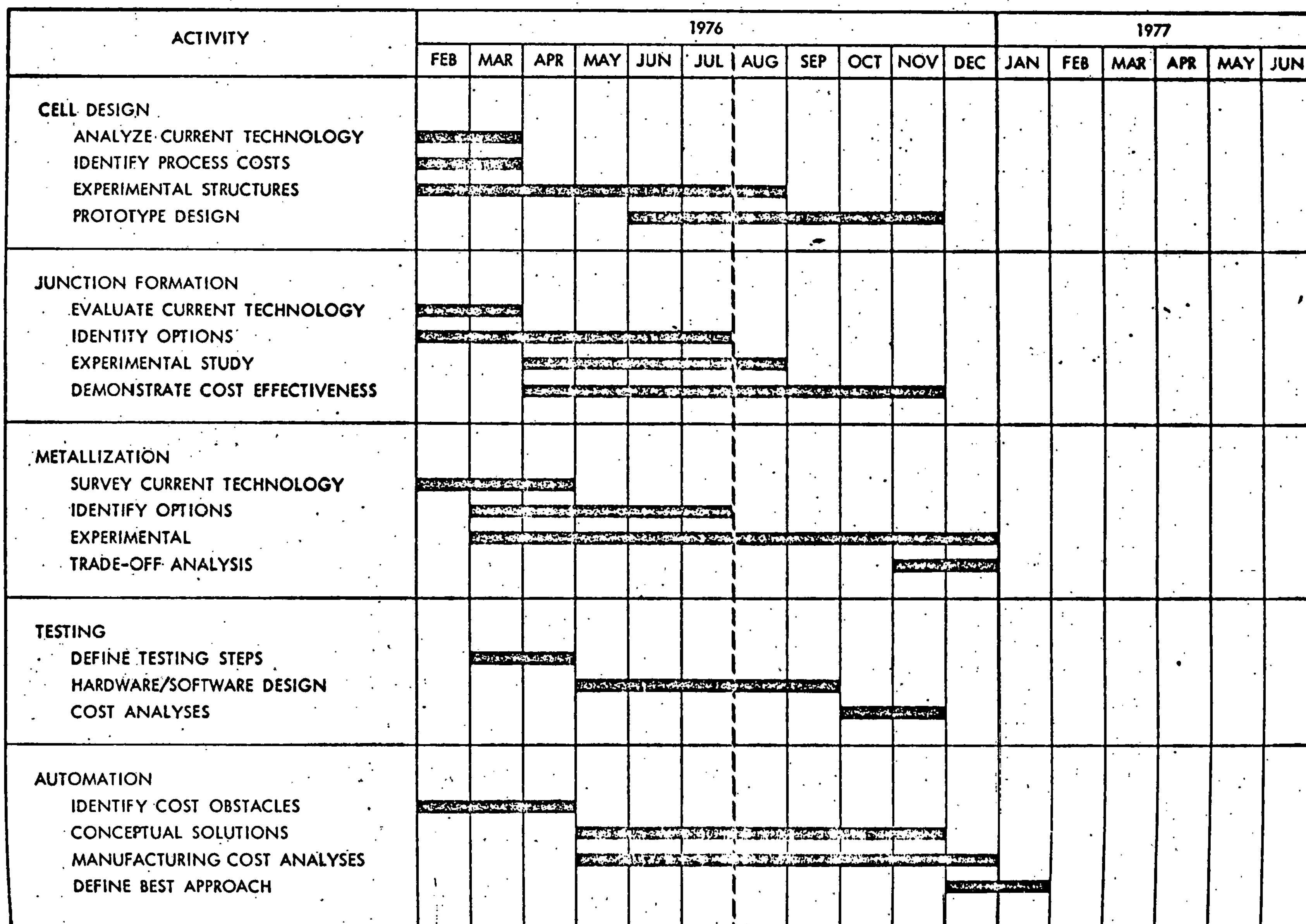
a - EACH STEP IS INTEGRATED INTO SOME ENTIRE MANUFACTURING SEQUENCE OF PROCESSES AND THEN THE COSTS ARE COMPARED

b - A PERFORMANCE INDEX IS DETERMINED FOR EACH PROCESS AS IT RELATES TO THE WAY IT AFFECTS CELL PARAMETERS

c - A MANUFACTURING SEQUENCE HAS AN OVERALL FIGURE OF MERIT WHICH IS THE PRODUCT OF THE INDIVIDUAL PROCESS PERFORMANCE INDICES

EVALUATIONS ARE ACCOMPLISHED WHICH RELATE TO SOLAR CELL COSTS IN TERMS OF DOLLARS PER WATT.

LOW-COST SILICON SOLAR ARRAY PROJECT
TEXAS INSTRUMENTS INC.



LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK

TEXAS INSTRUMENTS

STATUS

- TECHNOLOGY ANALYSIS WAS STARTED RIGHT OFF WITH THE CELL DESIGN, JUNCTION FORMATION, AND METALLIZATION
- COST STUDIES WERE IMMEDIATELY BEGUN FOR CELL DESIGN AND AUTOMATION
- WITHIN TWO MONTHS, EXPERIMENTAL STUDIES WERE UNDERWAY ON CELL DESIGN, JUNCTION FORMATION, AND METALLIZATION.

LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK

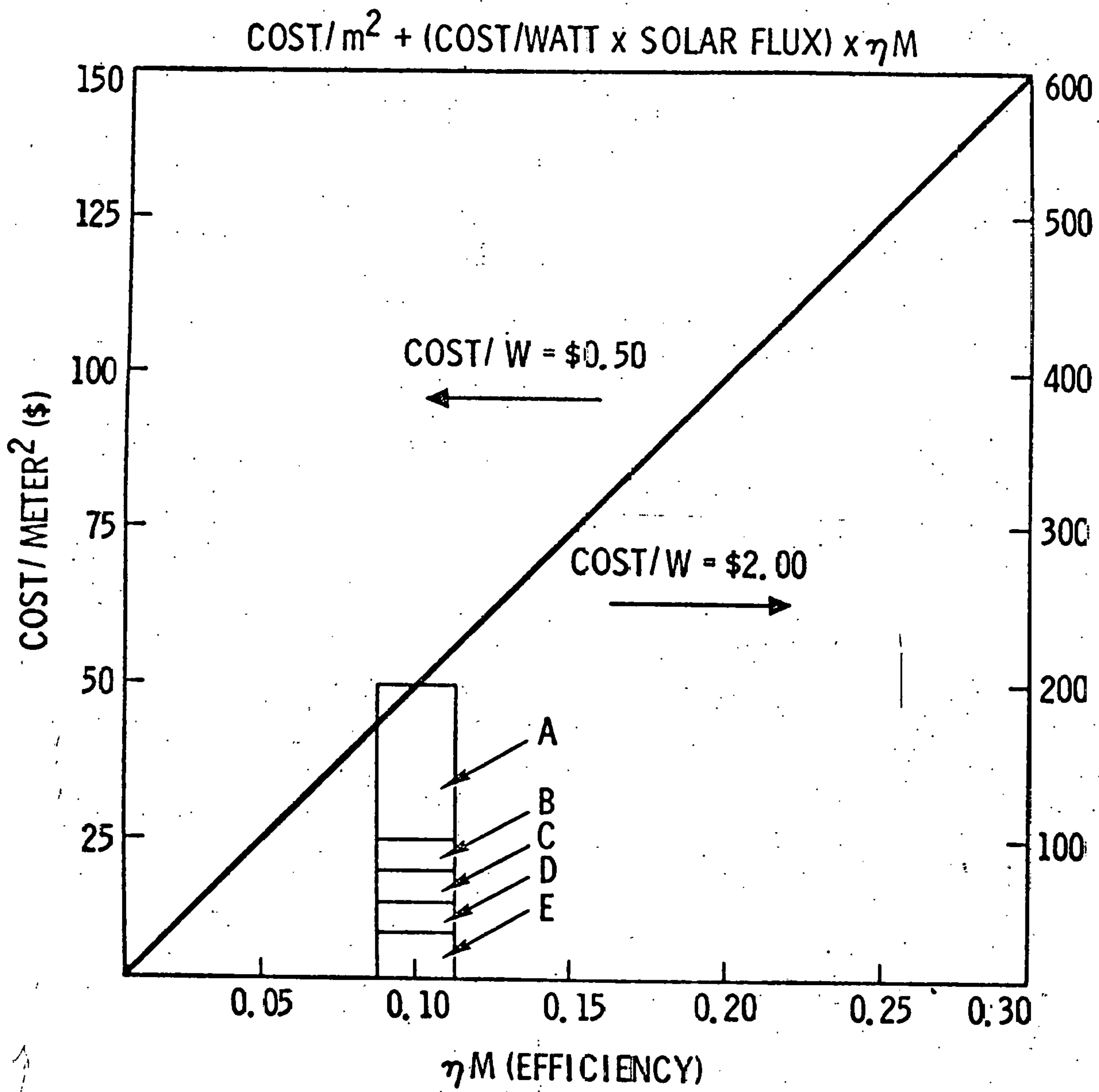
TEXAS INSTRUMENTS

STATUS

- A DESIGN-TO-COST ANALYSIS HAS BEEN USED TO SET ALLOWABLE COST GOALS FOR EACH PROCESS ELEMENT
- A BASELINE PROCESS, USING CURRENT TECHNOLOGY, WAS COSTED WHICH SHOWED THAT CURRENT TECHNOLOGY IS ABOUT AN ORDER OF MAGNITUDE TOO EXPENSIVE AT EACH PROCESS ELEMENT WHEN COMPARED TO THE DESIGN-TO-COST GOALS
- CELL METALLIZATION HAS BEEN SHOWN TO BE THE LEAST COST EFFECTIVE STEP IN THE BASELINE CELL PROCESS
- SEVERAL ALTERNATE CELL METALLIZATION PROCESSES ARE BEING STUDIED AND A TEST PATTERN HAS BEEN DEVELOPED AND USED TO EVALUATE SPECIFIC CONTACT RESISTANCE
- EXPERIMENTS AND DEVELOPMENT WORK ON SILK SCREENED THICK FILM METALLIZATION SYSTEMS ARE BEING CONDUCTED
- THE ALLOWABLE COST GOALS FOR EACH PROCESS ELEMENT DERIVED FROM THE DESIGN-TO-COST ANALYSIS HAVE BEEN FURTHER BROKEN DOWN TO GIVE MODELS OF LABOR, OVERHEAD, MATERIAL, AND DEPRECIATION COST GOALS. THESE COST GOALS ARE RELATED TO A SET OF FACTORY THROUGHPUT VALUES.

LOW-COST SILICON SOLAR ARRAY PROJECT

COST/UNIT AREA vs MODULE EFFICIENCY



DESIGN TO COST ALLOCATIONS COST/METER^2 (MODULE)

CODE:

A	SILICON SHEET	$25.
B	FUNCTION FORMATION	$ 5.
C	METALLIZATION	$ 5.
D	AR COATING	$ 5.
E	MODULE ASSEMBLY AND ENCAPSULATION	$10.
	TOTAL	$50.

LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK

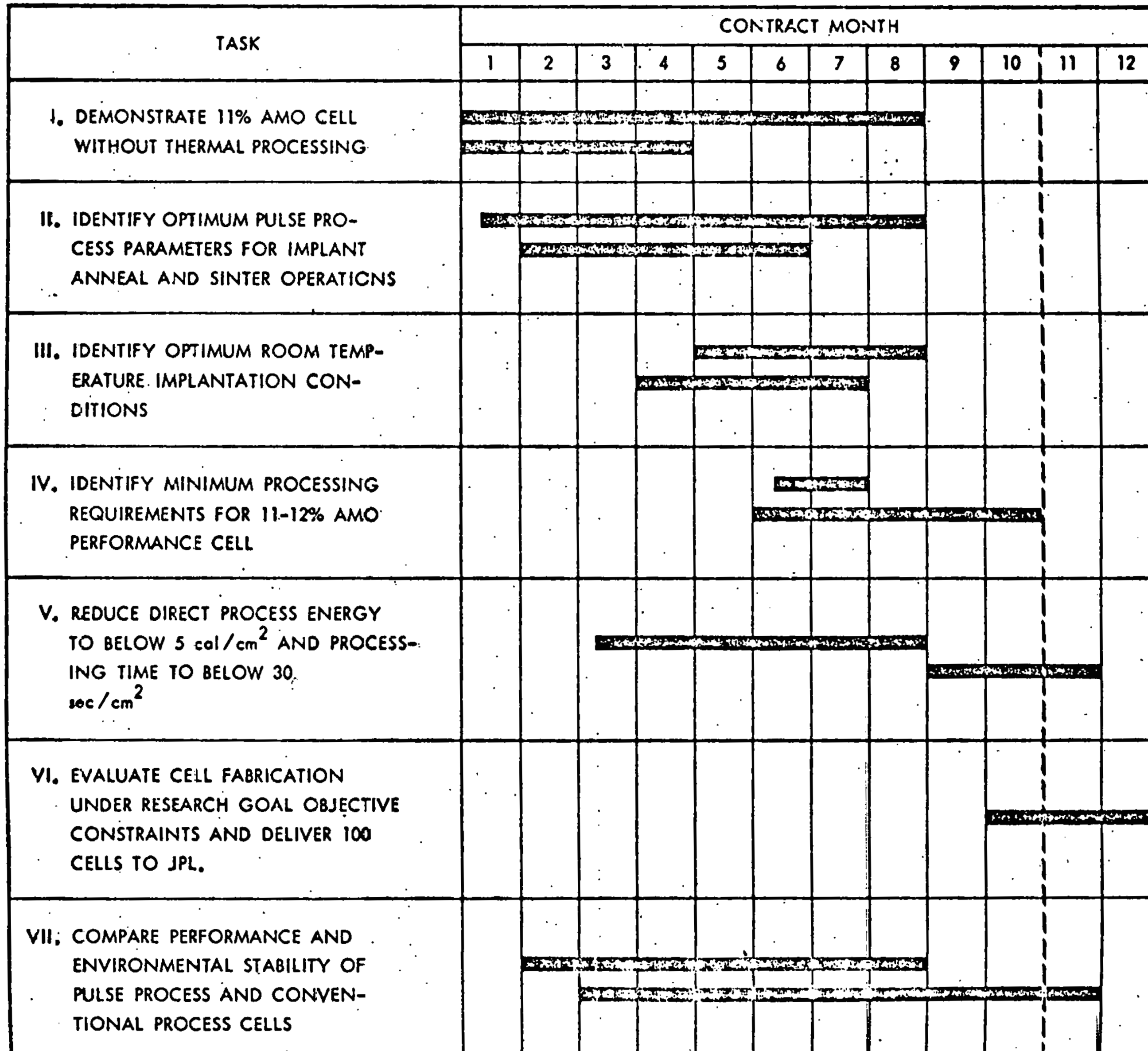
SIMULATION PHYSICS

GOAL -

DEMONSTRATE THE FEASIBILITY OF AN UNIQUE PROCESS FOR SOLAR CELL MANUFACTURE. THE TECHNIQUE INCORPORATES AN ION-IMPLANTER AND AN ELECTRON BEAM PROCESSOR TO MANUFACTURE SOLAR CELLS IN A VACUUM ENVIRONMENT AT ROOM TEMPERATURE.

LOW-COST SILICON SOLAR ARRAY PROJECT

SIMULATION PHYSICS (CONTD)



LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK
SIMULATION PHYSICS

STATUS

- FEASIBILITY DEMONSTRATED - 9.5% AMO (CONTRACT GOAL 11% AMO) SOLAR CELLS HAVE BEEN PRODUCED

  a - AN ION-IMPLANT OF PHOSPHOROUS IS MADE ON THE FRONT SURFACE OF THE CELL, BORON OR AN ALUMINUM EUTECTIC IS IMPLANTED ON ITS REAR SURFACE

  b - AN ELECTRON BEAM IS USED FOR THE IMPLANT ANNEAL PROCESS AND ALSO TO SINTER THE ALUMINUM CONTACTS AND AR COATING

- CELL MANUFACTURING SIMPLIFIED

  a - NO SPECIAL FORMING GAS ATMOSPHERE

  b - NO ACID WASTE OR OTHER WASTE DISPOSAL PROBLEMS

  c - NO MATERIALS ARE USED THAT DO NOT FORM PART OF THE CELL

- LOW ENERGY TO MANUFACTURE

  a - MEASURED IN MICROSECONDS OR FRACTIONS THEREOF, PULSES USED IN THE PROCESSES HAVE LITTLE POWER CONTENT

- NET PROCESS TIME SMALL

  a - WAFER-TO-CELL PROCESS TIME HAS BEEN REDUCED TO 36 SECONDS PER CM^2 (CONTRACT GOAL 30 SECONDS), LESS THAN 5 SECONDS PER CM^2 APPEARS FEASIBLE.

LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK

SIMULATION PHYSICS

DEVELOPMENT REQUIRED

- THE ELECTRON BEAM IN USE ATTRACTS AND DEPOSITS AT THE CELL JUNCTION UNWANTED CONTAMINATING IONS
- PRESENT LACK OF ELECTRON BEAM FLUX UNIFORMITY MAY BE CONTRIBUTING TO CRYSTAL LATTICE DAMAGE
- THE CONSEQUENCE IS A REDUCTION IN CELL V_{OC} OF ABOUT 30 mV TYPICALLY

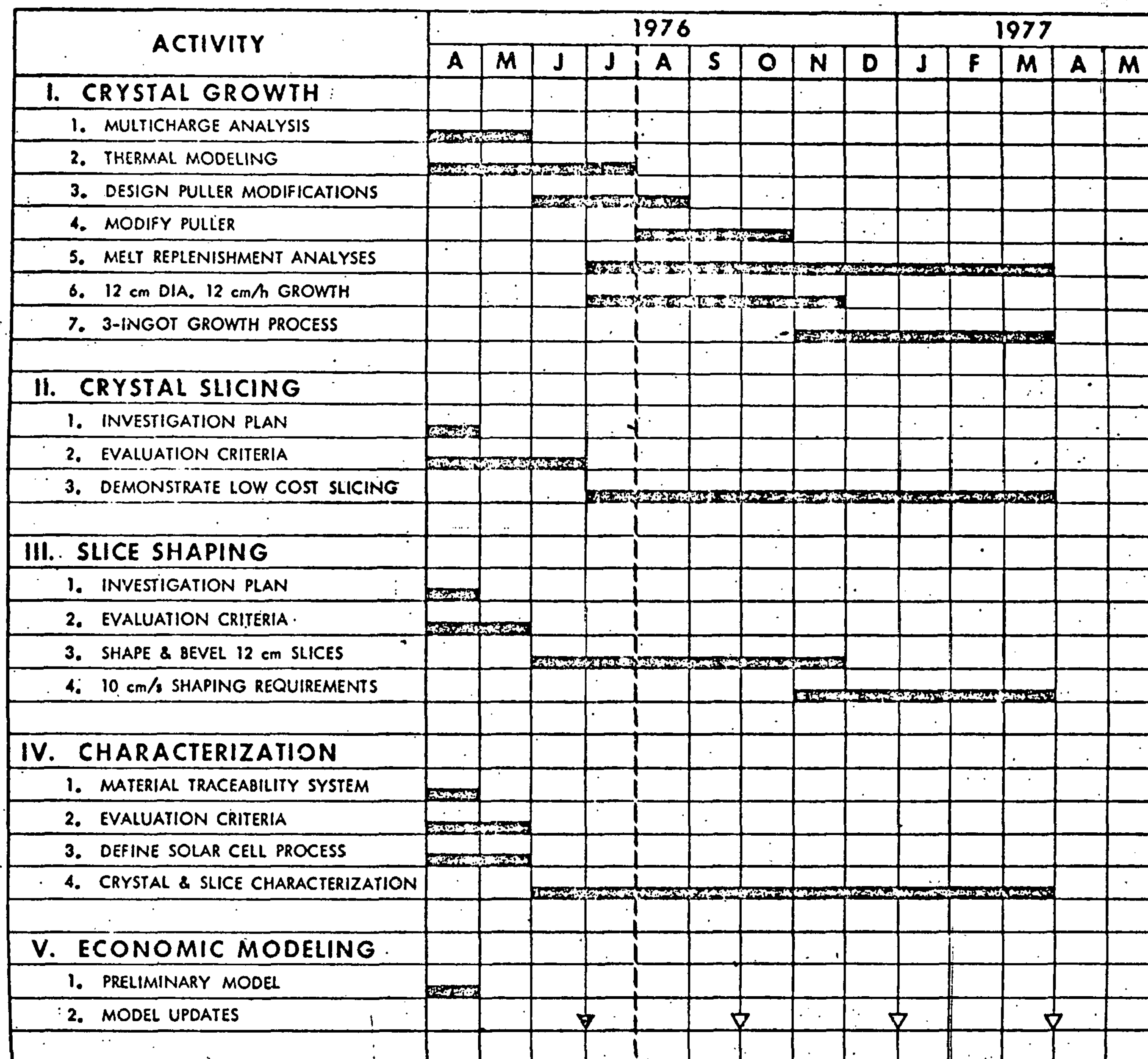
LOW-COST SILICON SOLAR ARRAY PROJECT
SOLAR ARRAY AUTOMATED ASSEMBLY TASK
TEXAS INSTRUMENT

GOAL

OPTIMIZE CURRENT PROVEN SEMICONDUCTOR TECHNIQUES TO PRODUCE SILICON WAFERS MOST COST EFFECTIVELY

LOW-COST SILICON SOLAR ARRAY PROJECT

TEXAS INSTRUMENTS INC.



LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK

TEXAS INSTRUMENTS

STATUS

- A PRELIMINARY ECONOMIC MODEL OF THE CZOCHRALSKI CRYSTAL GROWING AND WAFERING PROCESSES HAS BEEN COMPLETED

- THE ANALYSIS SHOWS THAT PROCESSING OPTIMIZATION CAN RESULT IN SHEET COSTS OF LESS THAN $30 PER SQUARE METER WITH POLYSILICON STARTING MATERIAL INPUT COSTS OF $10 PER KILOGRAM

- THEORETICAL YIELDS FOR MELT REPLENISHMENT SHOW THAT 80% YIELDS SHOULD BE OBTAINABLE IN THE SPECIFIED RESISTIVITY RANGE

LOW-COST SILICON SOLAR ARRAY PROJECT

SOLAR ARRAY AUTOMATED ASSEMBLY TASK

TEXAS INSTRUMENTS (CONTD)

STATUS

- FEASIBILITY DEMONSTRATED - 9.5% AMO (CONTRACT GOAL 11% AMO) SOLAR CELLS HAVE BEEN PRODUCED
  - a - AN ION-IMPLANT OF PHOSPHOROUS IS MADE ON THE FRONT SURFACE OF THE CELL, BORON OR AN ALUMINUM EUTECTIC IS IMPLANTED ON ITS REAR SURFACE
  - b - AN ELECTRON BEAM IS USED FOR THE IMPLANT ANNEAL PROCESS AND ALSO TO SINTER THE ALUMINUM CONTACTS AND AR COATING
- CELL MANUFACTURING SIMPLIFIED
  - a - NO SPECIAL FORMING GAS ATMOSPHERE
  - b - NO ACID WASTE OR OTHER WASTE DISPOSAL PROBLEMS
  - c - NO MATERIALS ARE USED THAT DO NOT FORM PART OF THE CELL
- LOW ENERGY TO MANUFACTURE
  - a - MEASURED IN MICROSECONDS OR FRACTIONS THEREOF, PULSES USED IN THE PROCESSES HAVE LITTLE POWER CONTENT
- NET PROCESS TIME SMALL
  - a - WAFER-TO-CELL PROCESS TIME HAS BEEN REDUCED TO 36 SECONDS PER CM^2 (CONTRACT GOAL 30 SECONDS), LESS THAN 5 SECONDS PER CM^2 APPEARS FEASIBLE.

LOW-COST SILICON SOLAR ARRAY PROJECT
SOLAR ARRAY AUTOMATED ASSEMBLY TASK
TEXAS INSTRUMENTS (CONTD)

STATUS (CONTD)

- THERMAL MODELING HAS SHOWN THAT 15 CM PER HOUR GROWTH RATES SHOULD BE OBTAINABLE AND THAT THE 12 CM PER HOUR SPECIFIED IN THE CONTRACT IS REASONABLE

- FURNACE MODIFICATIONS ARE UNDERWAY TO PROVE THE VALIDITY OF THE THEORETICAL MODELS

- SAWING EXPERIMENTS USING 400 GRIT SiC ABRASIVE AND BOTH .02 CM (.008") AND .01 CM (.004") THICK BLADES HAVE SHOWN YIELDS OF 98%. ALSO THE SLICE PLUS KERF THICKNESS WILL BE REDUCED TO THE CONTRACT GOALS OF .05 CM (.020").

LOW-COST SILICON SOLAR ARRAY PROJECT

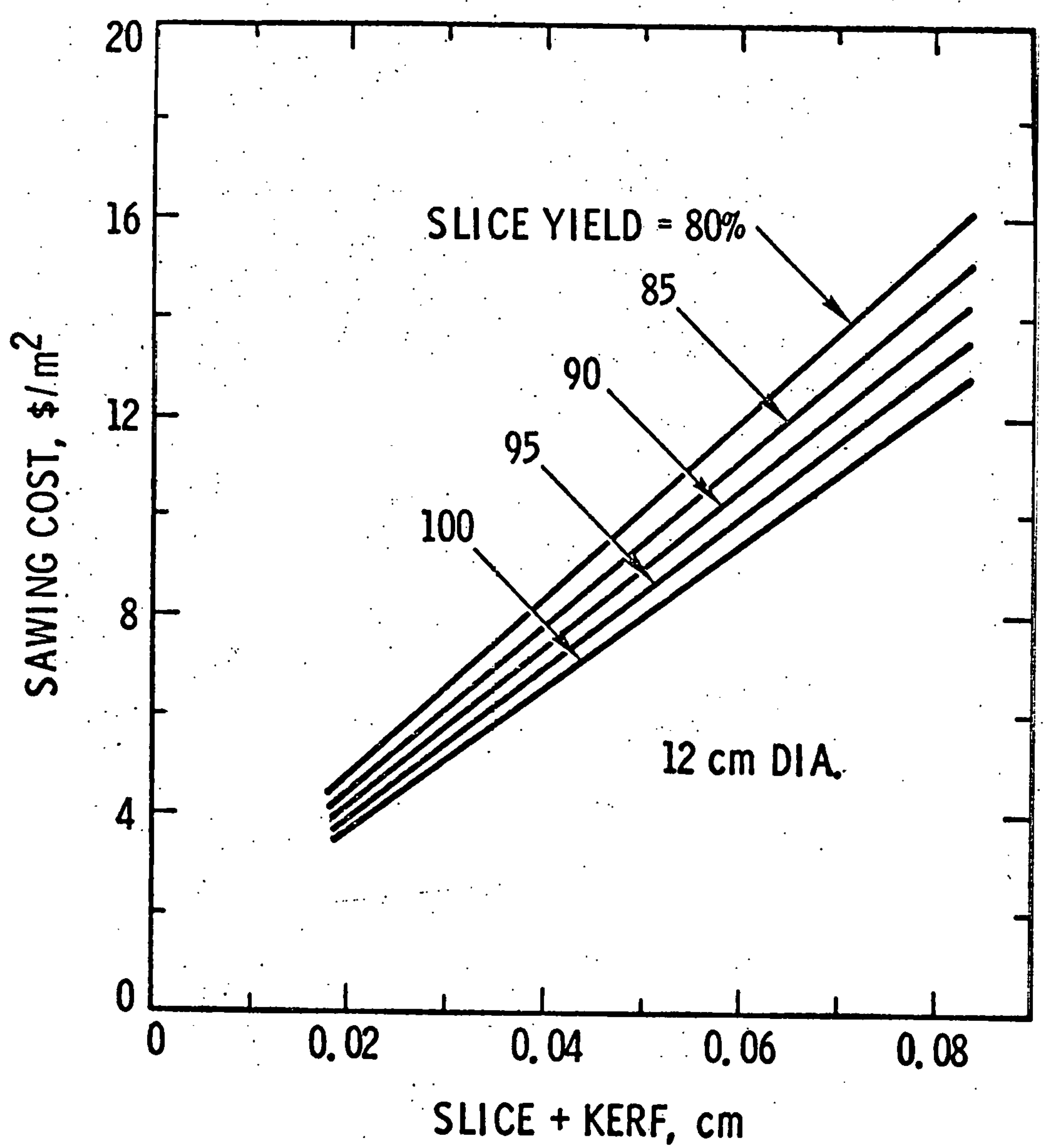
SOLAR ARRAY AUTOMATED ASSEMBLY TASK
TEXAS INSTRUMENTS (CONTD)

OBJECTIVES

- USING MELT REPLENISHMENT TECHNIQUES; GROW 30 KILOGRAMS OF SILICON IN THE FORM OF 3 CRYSTALS, 12 CM IN DIAMETER DURING ONE CONTINUOUS HEAT CYCLE
- MULTIBLADE SAWING TECHNIQUES WILL BE OPTIMIZED TO PRODUCE .025 CM (.010") THICK WAFERS FROM 12 CM DIAMETER CRYSTALS
- LASER SHAPING TECHNIQUES WILL BE DEVELOPED TO PRODUCE HEXAGONS FROM 12 CM DIAMETER WAFERS AT AN EDGE RATE OF 10 CM PER SECOND
- DEVELOP AND CONTINUALLY UPDATE AN ECONOMIC MODEL OF THE CRYSTAL GROWTH, WAFERING, AND SHAPING TECHNIQUES DESCRIBED ABOVE.

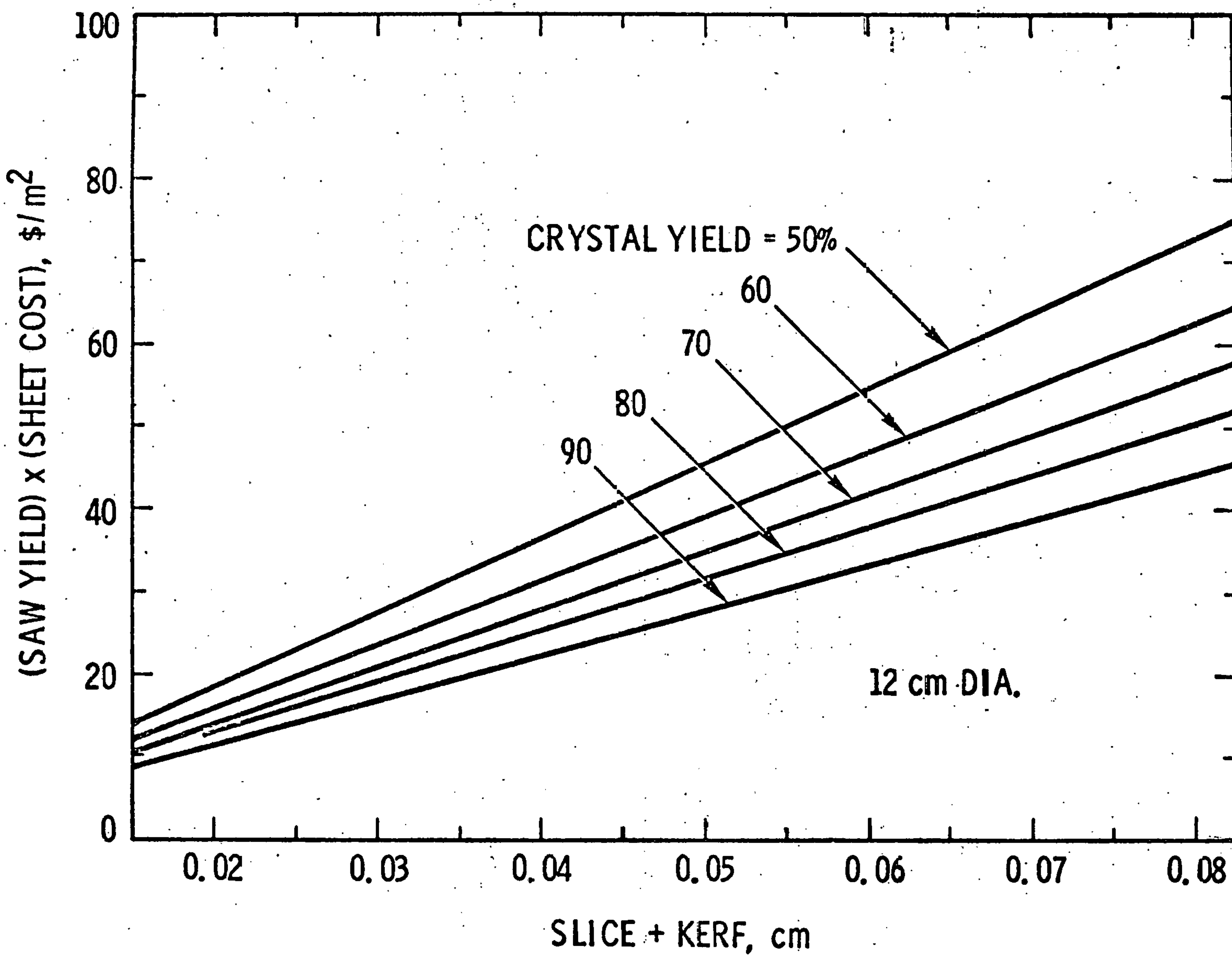
LOW-COST SILICON SOLAR ARRAY PROJECT

MULTIBLADE SLURRY SAWING COSTS



LOW-COST SILICON SOLAR ARRAY PROJECT

CZOCHRALSKI SILICON SHEET COST



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LOW-COST SILICON SOLAR ARRAY PROJECT

CONCLUSIONS

- COST TO PRODUCE HIGHER EFFICIENCY CELLS WEIGHED AGAINST COST OF ADDED ENCAPSULATION, STRUCTURE AND VOLUME PRODUCTION, INDICATE HIGHER EFFICIENCY CELLS TO BE MORE COST EFFECTIVE

- COST ANALYSES OF CURRENT TECHNOLOGY SHOWED THAT CURRENT TECHNOLOGY IS ABOUT AN ORDER OF MAGNITUDE TOO EXPENSIVE AT EACH PROCESS ELEMENT WHEN COMPARED TO DESIGN-TO-COST GOALS

- ANALYSIS SHOW THAT CZOCHRALSKI INGOT GROWTH AND MULTI-BLADE SAWING CAN RESULT IN SHEET COSTS OF LESS THAN $30 PER SQUARE METER WITH POLYSILICON STARTING MATERIAL INPUT COSTS OF $10 PER KILOGRAM

LOW-COST SILICON SOLAR ARRAY PROJECT

NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW

LARGE SCALE PRODUCTION TASK

E. SEQUEIRA

TASK MANAGER

AUGUST 1976

ABSTRACT

LARGE-SCALE PRODUCTION

TASK 5

The overall objectives of Task 5 are to provide ERDA (LeRC) with 11.11 megawatts of solar cell modules over the next ten-year period and to advance the state-of-the-art technology to effect a price reduction in the cost of solar cell modules. In addition, the experience acquired in these activities will be utilized to assist in the technology development of other LSSA tasks. The 1976 objective is to provide ERDA (LeRC) with approximately 170KW of solar cell modules.

The approach used to accomplish the objectives was to initiate a series of procurements with each consecutive procurement reflecting increased module quantities. The first procurement was for a total of 46KW and is approximately 65% completed. Module deliveries are contracted with the following companies:

Solar Power Corporation	15KW
Solarex Corporation	10KW
M7 International	3KW
Spectrolab, Inc.	10KW
Sensor Technology, Inc.	8KW

A similar multiple-contracts approach was used to procure a second block of modules totaling 130KW with the exception that a two-month period will be devoted to design and development.

The Task 5 status shows that qualification modules have been received from all contractors, environmental tests have been conducted at contractors' facilities and at JPL, and 28KW of solar cell modules have been delivered to LeRC for the ERDA Demonstration Program.

Negotiations for the procurements of 130KW with the selected contractors is complete. Beginning of the design effort has started by some of the contractors and it is anticipated that all contracts will be underway by the first week of August 1976.

LOW-COST SILICON SOLAR ARRAY PROJECT

LARGE SCALE PRODUCTION TASK

AGENDA

- OBJECTIVES
- APPROACH
- CURRENT STATUS
- SCHEDULES
- PROBLEMS ENCOUNTERED
- SUMMARY

LOW-COST SILICON SOLAR ARRAY PROJECT
LARGE SCALE PRODUCTION TASK

OBJECTIVES

OVERALL OBJECTIVES:

- PROVIDE 11.11 MEGAWATTS OF SOLAR CELL MODULES TO ERDA FOR THE TEST AND DEMONSTRATION PROGRAM OVER THE NEXT 10 YEARS

- ADVANCE STATE-OF-THE-ART TECHNOLOGY AND EFFECT A PRICE REDUCTION IN THE PROCUREMENT OF SOLAR CELL MODULES

- UTILIZE THE EXPERIENCE ACQUIRED TO ASSIST IN THE TECHNOLOGY DEVELOPMENT OF OTHER LSSA TASKS

1976 OBJECTIVE

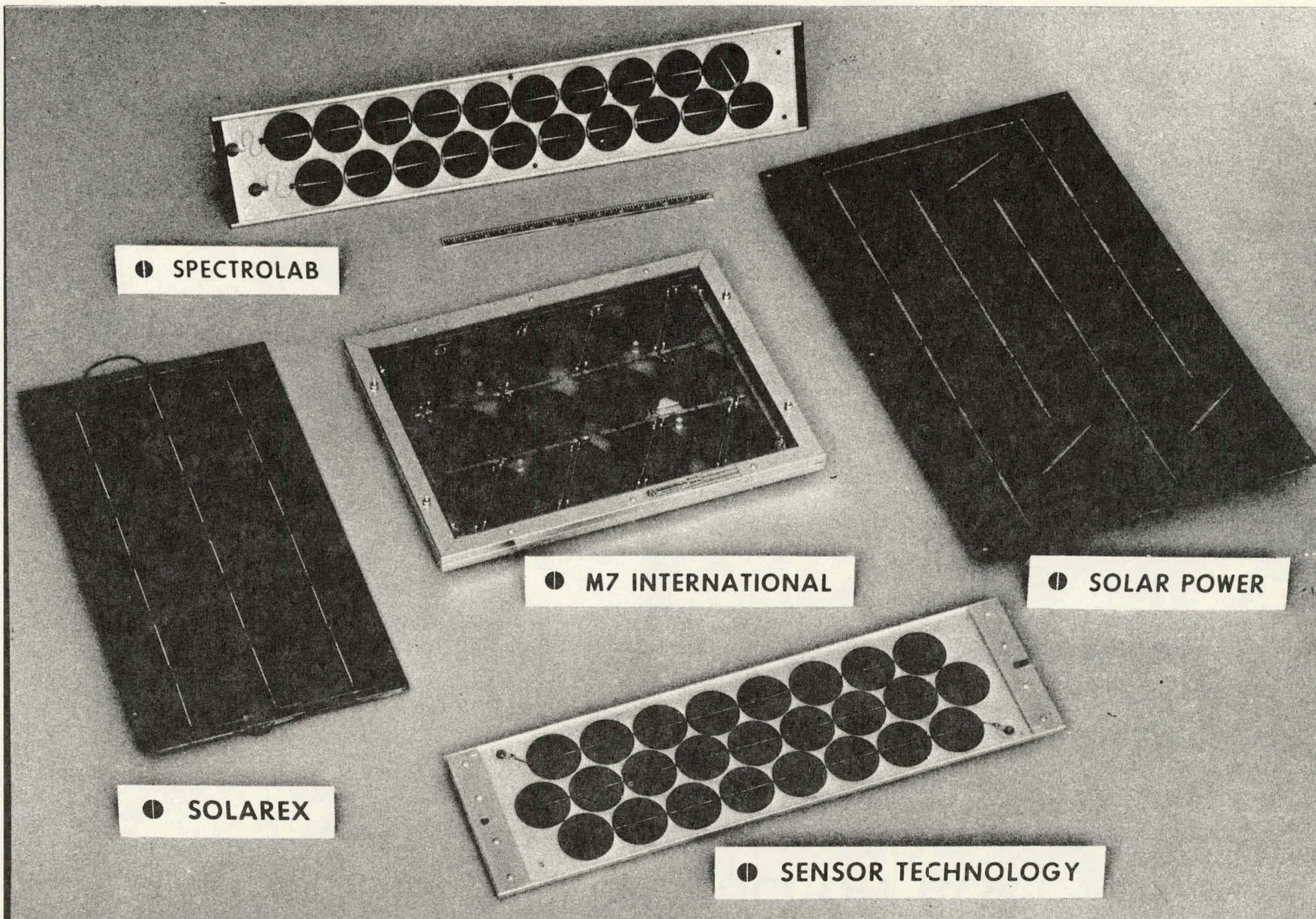
- PROVIDE ERDA WITH 170 KW OF SOLAR CELL MODULES

LOW-COST SILICON SOLAR ARRAY PROJECT
CURRENT STATUS

46 KW PROCUREMENT

CONTRACTORS	KW
SOLAR POWER CORP.	15
M7 INTERNATIONAL	3
SENSOR TECHNOLOGY	8
SPECTROLAB	10
SOLAREX	10

- THE CONTRACTORS DELIVERED A TOTAL OF 29 KW OF SOLAR CELL MODULES
- OF THE 29 KW TOTAL, 1.2 KW WERE DELIVERED TO JPL FOR ENVIRONMENTAL TESTING
- JPL AND CONTRACTORS COMPLETED ENVIRONMENTAL TESTS
    - ELECTRICAL PERFORMANCE; 100 MW/cm^2, 28°C
    - 100 THERMAL CYCLES; -40 TO +90°C, 4 HRS/CYCLE
    - 168 HOURS HUMIDITY; 95% RH AT 70°C
- ADDITIONAL ENVIRONMENTAL & SPECIAL TESTS PERFORMED
    - STRUCTURAL LOADING
    - THERMAL CHARACTERISTICS
    - MATERIALS TESTING - ENCAPSULANTS
    - INITIATED FIELD TESTS



46 KW MODULES

LOW-COST SILICON SOLAR ARRAY PROJECT
LARGE SCALE PRODUCTION TASK

PROBLEMS ENCOUNTERED

- MATERIAL SHORTAGE - SYLGARD 184
- MODULE DESIGN MODIFICATION - MOUNTING HOLES
- MODULE DESIGN MODIFICATION RESULTING FROM EXPOSURE TO ENVIRONMENTAL TESTING

LOW-COST SILICON SOLAR ARRAY PROJECT

LARGE SCALE PRODUCTION TASK

PROGRESS

130 KW PROCUREMENT

CONTRACTORS

SPECTRO LAB
SENSOR TECH
SOLAR POWER
SOLAREX
M7

- CONTRACT NEGOTIATIONS COMPLETE
- FOUR CONTRACTORS UNDER CONTRACT
- ONE CONTRACT IN REVIEW/SIGNATURE CYCLE

LOW-COST SILICON SOLAR ARRAY PROJECT
46KW AND 130KW KEY PROCUREMENT SPECIFICATIONS

SPECIFICATION	46 KW	130 KW
ELECTRICAL PERFORMANCE	100 MW/cm^2, 28°C	100 MW/cm^2, 60°C
TEMPERATURE CYCLING	100 CYCLES, -40 TO + 90°C	50 CYCLES, -40 TO +90°C
HUMIDITY	168 HOURS, 95% RH, 70°C	5 CYCLES, 95% RH, 23 TO 41°C
WIND LOADING	N/R	100 CYCLES, ± 50 lb/ft^2
INSULATION RESISTANCE	N/R	> 100 MΩ, 1000 VDC
HIGH VOLTAGE BREAKDOWN	N/R	1500 VDC, 1 MINUTE
PACKAGING ENVELOPE	N/R	ENVELOPE OF 4' x 4' FRAME
REDUNDANCY	N/R	TERMINAL AND IN SOME CASES CELL TO CELL REDUNDANCY

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LOW-COST SILICON SOLAR ARRAY PROJECT

LARGE SCALE PRODUCTION TASK

SUMMARY & CONCLUSIONS

- 29 KW OF MODULES DELIVERED FOR ERDA TEST & DEMONSTRATION PROGRAM
- EXTENSIVE ENVIRONMENTAL TESTING PERFORMED WHICH RESULTED IN UPGRADING THE STATE-OF-THE-ART MODULE DESIGNS
- FUTURE PROCUREMENTS WILL FOCUS ON STANDARDIZATION OF:
    - CONFIGURATION OF MODULES AT THE INTERFACE LEVEL
    - ELECTRICAL PERFORMANCE MEASUREMENT METHODS AND STANDARDS
    - INSPECTION AND ACCEPTANCE CRITERIA
- FUTURE PROCUREMENTS SHOULD REFLECT LONGER PERIODS FOR DESIGN DEVELOPMENT PHASE AND PRODUCTION PHASE

LOW-COST SILICON SOLAR ARRAY PROJECT

LARGE-SCALE PROCUREMENT DESIGN REQUIREMENTS

R. G. ROSS

LSSA ENGINEERING MANAGER

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LOW-COST SILICON SOLAR ARRAY PROJECT

DESIGN REQUIREMENT OBJECTIVES

- PROVIDE SOLAR CELL MODULES CONSISTENT WITH DEMO SYSTEM REQUIREMENTS
- STIMULATE THE INFUSION OF NEW DESIGNS AND TECHNOLOGY WHICH RESULT IN IMPROVED PERFORMANCE (COMMERCIAL VIABILITY)
  - PRICE
  - LIFE/RELIABILITY
  - ELECTRICAL/MECHANICAL PERFORMANCE
  - INTERCHANGEABILITY
  - SAFETY
  - ADAPTABILITY/CONVENIENCE
- MINIMIZE RISK OF DEMO FAILURES
- PROVIDE SMOOTH CONTINUITY FROM CURRENT DESIGNS TO FUTURE NEEDS

LOW-COST SILICON SOLAR ARRAY PROJECT

APPROACH TO REQUIREMENT DEFINITION

- UNDERSTAND USER/SYSTEM NEEDS
  - SYSTEM ANALYSIS & TESTING
  - USER SURVEYS
  - EXPERIENCE IN RELATED FIELDS
- UNDERSTAND MODULE/ARRAY DESIGN FACTORS AND SENSITIVITIES
  - ARRAY ANALYSIS AND TESTING
  - MODULE ANALYSIS AND TESTING
  - MANUFACTURERS EXPERIENCE
- UNDERSTAND MANUFACTURING FACTORS AND LIMITATIONS
  - MANUFACTURERS EXPERIENCE
  - MANUFACTURING STUDIES
- UNDERSTAND MARKETING FACTORS
  - MARKET STUDIES
  - MANUFACTURER, SYSTEM MANUFACTURER, AND USER EXPERIENCE

LOW-COST SILICON SOLAR ARRAY PROJECT
46 kW MODULE TESTS

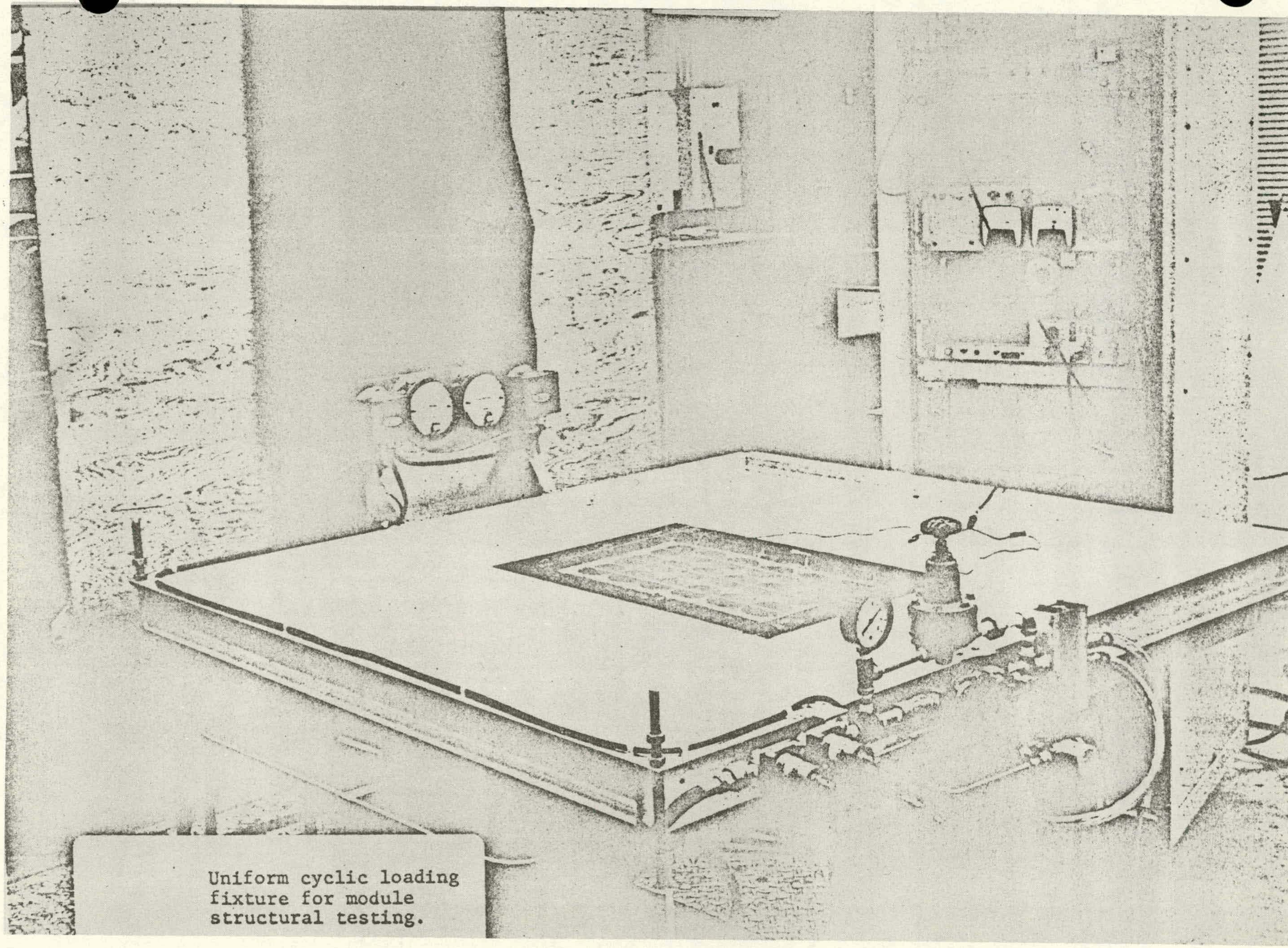
- ● QUALIFICATION TESTS
  - ● ELECTRICAL OUTPUT (100 mW/cm^2, 28^{0}C, AM1)
  - ● THERMAL CYCLING (-40 TO 90^{0}C, 100 CYCLES)
  - ● HUMIDITY (70^{0}C, 95% RH, 168 HRS)
- ● CHARACTERIZATION TESTS
  - ◉ STRUCTURAL LOADING ($\pm$50 PSF, 100 CYCLES)
  - ◉ INSULATION RESISTANCE (MΩ AT 100 VDC)
  - ◉ THERMAL EQUILIBRIUM (FIELD EXPOSURE)
  - ○ SALT FOG
  - ○ HEAT AND RAIN
  - ○ HUMIDITY FREEZING
  - ○ FUNGUS
  - ○ HIGH VOLTAGE

○ PLANNED TESTS

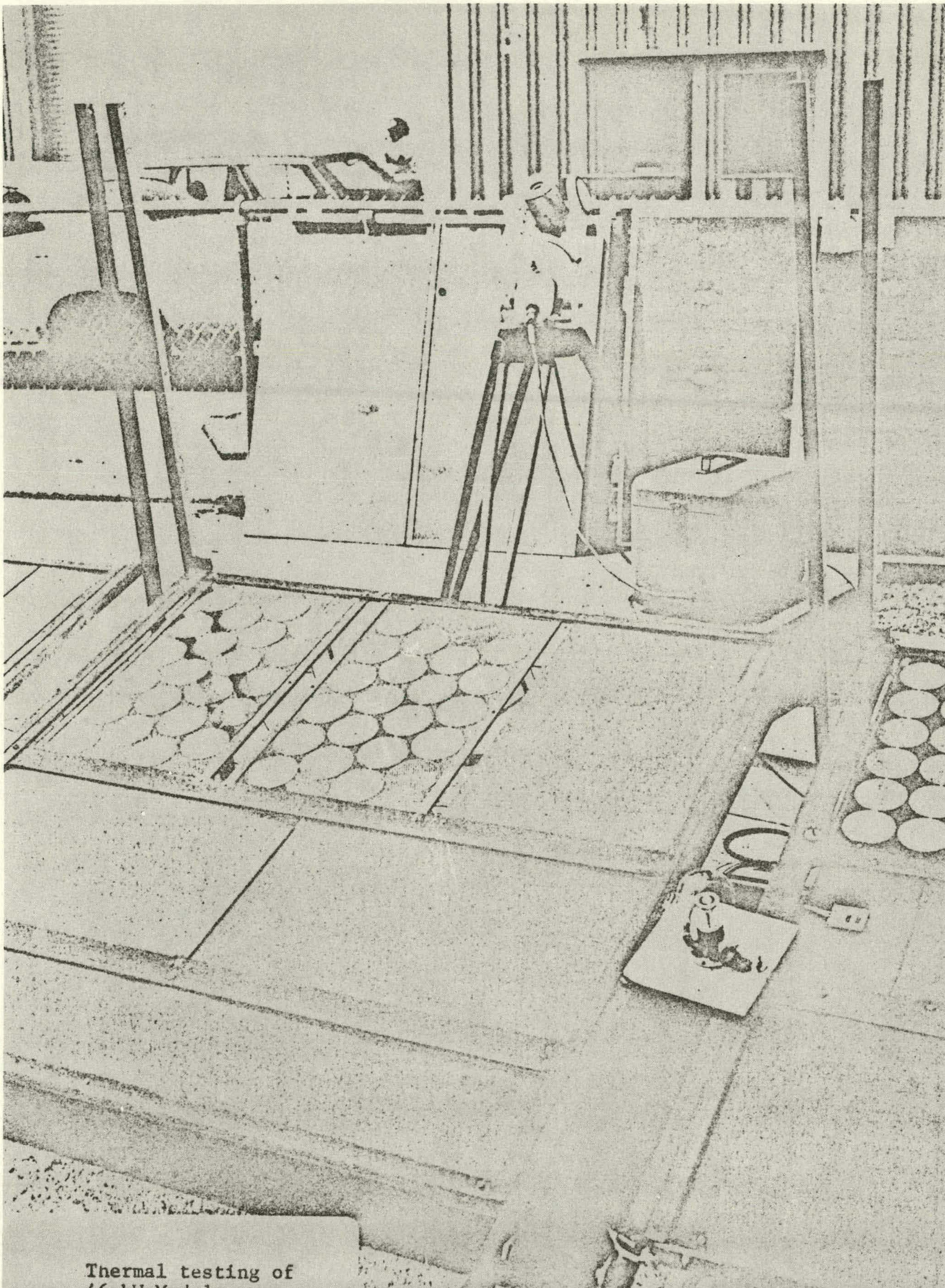
LOW-COST SILICON SOLAR ARRAY PROJECT

TEST RESULT SUMMARY

TEST	DEGRADATION	CORRECTION	RELATIVE OCCURANCE
THERMAL CYCLE	ENCAP. DELAMINATION AND CRACKING	IMPROVED CLEANING PRIMERS IMPROVED QC	● ● ● ●
	CELL CRACKING	INCREASED BOND THICKNESS UNDER CELL	●
	INTERCONNECT STRUCTURAL FATIGUE	STRESS RELIEF LOOPS LESS SOLDER	● ● ● ●
	ELECTRICAL TERMINAL CRACKING & DELAMINATION	REWORK	● ●
HUMIDITY	CELL CONTACT DEGRAD. (30% POWER LOSS)	PALADIUM IN CONTACT IMPROVED SEALING	● ● ●
	STRUCTURAL BOND DELAMINATION	NEW ADHESIVES	●
STRUCTURAL CYCLING	INTERCONNECT STRUCTURAL FATIGUE	STRESS RELIEF LOOPS	●



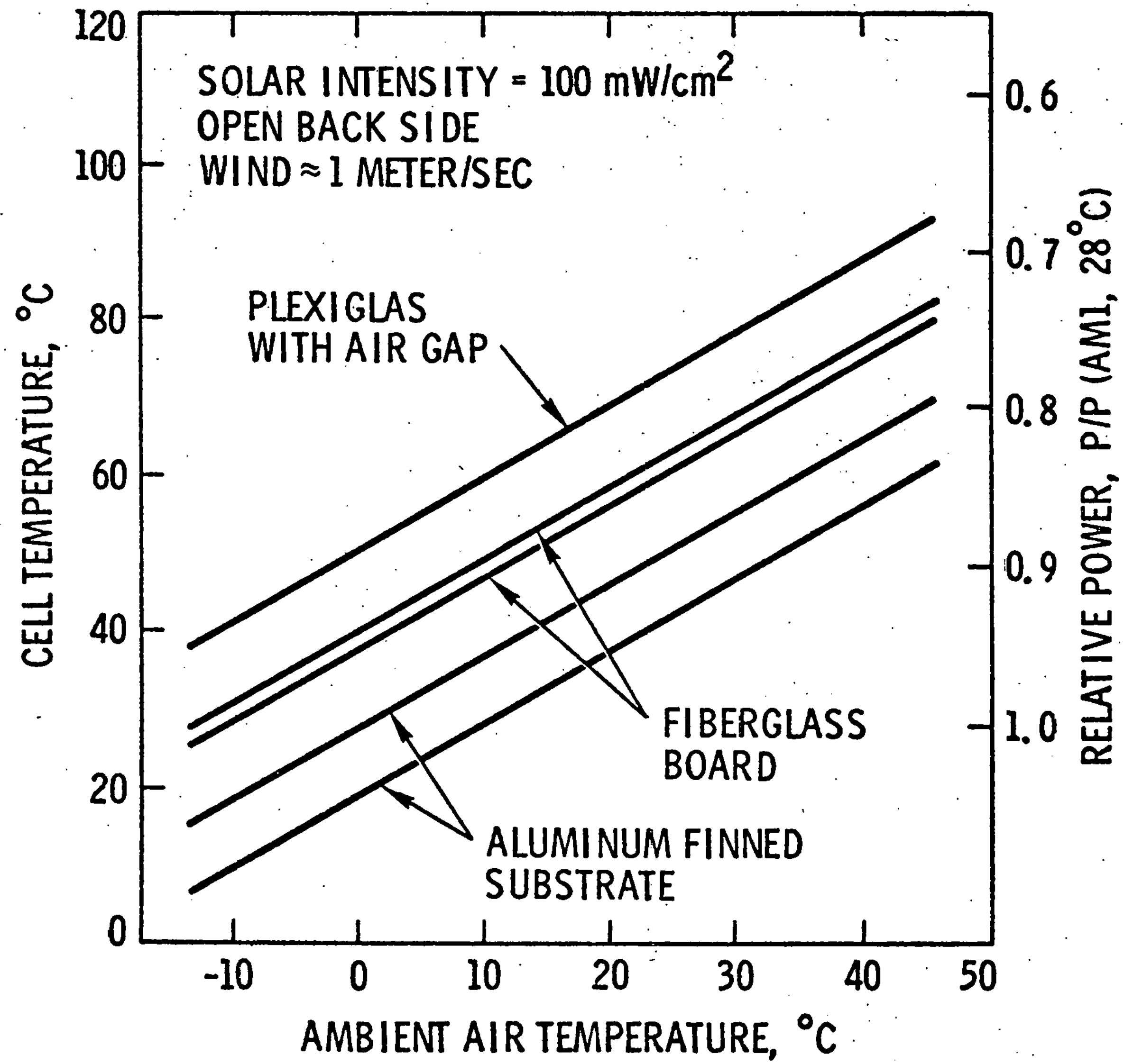
Uniform cyclic loading fixture for module structural testing.



Thermal testing of
46 kW Modules.

LOW-COST SILICON SOLAR ARRAY PROJECT

TYPICAL OPERATING TEMPERATURES OF 46 kW MODULES



LOW-COST SILICON SOLAR ARRAY PROJECT

CONCLUSIONS

- FUTURE DESIGNS SHOULD LOOK CAREFULLY AT
  - ENCAPSULANT INTEGRITY
  - CELL CONTACT SENSITIVITY TO TEMPERATURE/HUMIDITY
  - CELL INTERCONNECT MECHANICAL FATIGUE
  - ELECTRICAL INSULATION INTEGRITY AT HIGH VOLTAGES
  - MECHANICAL DIMENSION TOLERANCES VS. INTERCHANGE-ABILITY
  - USE OF STANDARDIZED ELECTRICAL TERMINATIONS (CONNECTORS)
- FUTURE DESIGN AND TEST REQUIREMENTS SHOULD CONSIDER VARIATION IN OPERATING TEMPERATURE BETWEEN MODULE TYPES

PROGRESS AND PLANS FOR THE ERDA TESTS AND APPLICATIONS PROJECT

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CLEVELAND, OHIO

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NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

AUGUST 3-6, 1976

UNIVERSITY OF MAINE AT ORONO

ORONO, MAINE 04473

Abstract

The Tests and Applications Project is one of several interrelated projects making up the ERDA National Photovoltaic Conversion Program. Objectives of the Tests and Applications Project are to conduct tests, demonstrations, and evaluations of photovoltaic systems and subsystems in applications having national significance. Experience and information gained through this project will be used to evaluate emerging systems technology, provide systems-related guidance to the other projects of the national program, and develop information for future photovoltaic program planning.

During the past six months, project efforts have emphasized a number of implementation activities in addition to participation in ERDA program planning. Systems have been designed and fabricated to utilize solar cell modules from the JPL 46 kW procurement. About 25 kW of these modules have been delivered since April 1976. Over 5½ kW have now completed processing and are installed in various field tests. The remaining modules are in various processing stages, such as: characterization sampling, panel assembly, array calibration, shipping, etc. Identification and implementation of S/GA systems for field testing has also been a major effort. Other work has been concerned with improvements to LeRC solar cell measurement facilities and methods as well as the initiation of endurance testing of solar cell modules materials. Project-to-project interfacing has occurred extensively with JPL, Sandia, and DoD on a variety of topics related to modules, application planning, and system design and support.

Specific activities in each of the major subprojects follow.

"Applications" Subproject

Construction of phase IA of the Photovoltaic System Test Facility at LeRC has proceeded on schedule. The control center is now operational. Array field preparations are nearly complete for providing 10 kW of capacity. All wiring between the field and control center is in place. Lead-acid batteries for storage and two types of inverters for power condition have been installed as well. About 1.5 kW of solar-cell modules have been installed in the field and initial system exploratory tests involving the utility feed-back mode of system operation have been initiated. An additional 8.5 kW of modules from the JPL 46 kW buy will be installed as they are available for testing of system configurations up to 10 kW. Plans and preparations for expansion of the facility capacity beyond 10 kW's is also underway.

Residential tasks activities have involved completing the two 6-month system experiment definition contracts with GE and Martin-Marietta. These contracts were to study and recommend photovoltaic residential systems, siting, and test requirements for up to eight regionally sited experiments. These studies, based on the consideration of use of current technology components, have been completed and final reports are being prepared. Design and preparation of construction drawings for one residential test unit, planned for siting at LeRC, are also nearly complete. Other residential activity has involved the development of photovoltaic residential test implementation strategies and plans.

Special and Governmental Application (S/GA) development has focused on three activities. First, the design, assembly, and deployment of small "mini-applications"

Two photovoltaically powered small refrigerators have been assembled and deployed to Isle Royale National Park, Michigan and the Papago Indian Reservation, Arizona, respectively. Public information news releases thus far have generated many inquiries both nationally and foreign (Australia, Japan, South Africa, etc.). Other mini-applications, such as water pumping, are being developed for deployment in the next 2-4 months.

A second S/GA activity has involved implementation of cost-shared tests of photovoltaic applications relevant to near-term needs of user-agencies of government. Agreements have been reached with the National Weather Service (NWS) for tests of photovoltaic systems to power six remote automated meteorological observation stations (RAMOS) which NWS is developing. NWS expects to deploy several hundred such systems throughout the U.S. (many in remote areas) over the next several years. Solar cells appear to be attractive for powering many of these stations. Two systems are also being fabricated for use by the U. S. Forest Service on fire lookout towers in California.

The third S/GA activity has involved the identification of new applications in government through mailings of a descriptive brochure. The purpose of the mailing has been to solicit others for needs in order to identify a wide range of potential applications for development of photovoltaic systems that can be cost-effective in the near term (by 1986). Two mailings (800 each) have elicited a very encouraging interest and response. These responses are now in the process of followup and evaluation.

Approximately 25 kW of the initial JPL 46 kW procurement of solar cell modules has been allocated for DoD applications. Arrays of these modules have been designed and are now being fabricated, assembled, and shipped to MERADCOM at Ft. Belvoir, Virginia, the designated DoD coordinating organization.

"Device and Performance and Diagnostics"

A second workshop on terrestrial photovoltaic measurements will be held in Baton Rouge, Louisiana, November 10-12, 1976. The time and place are adjacent to the IEEE Photovoltaic Specialists Conference. Three main topics will be covered: (1) terrestrial sunlight and its effect on solar cell performance; (2) solar simulation; and (3) techniques for cell and array measurement and standard cell calibration.

In an effort to determine the sensitivity of solar cell performance to a range of atmospheric conditions and insolation components, an insolation measurement facility has been set up. The approach is to measure the insolation using a solar cell and a black body detector in each of several different orientations. Detectors are in place in several orientations (horizontal; horizontal-shadow banded; inclined, 37^o above horizontal, etc.). The data acquisition system is nearing completion and will be operational in late summer.

The cell measurement facility has been automated with a HP 9830 calculator-interface bus system. I-V curves, spectral response curves, cell dark forward I-V characteristics and cell V_{OC}-I_{SC} characteristics can be readily obtained. The data is acquired, calculations made and results presented or plotted using the 9830. During the last six months, over 1500 measurements were made for about 40 different organizations.

In parallel with performing measurements for investigations, an on-going calculation and experimental activity has been addressing reference conditions and methodology. These include the variation of standard cell calibration coefficients with atmospheric conditions and the error in cell measurements introduced by spectral mismatch between sunlight, simulator, test cells, and standard cells.

To date, 54 interim reference cells have been calibrated and distributed to 17 organizations. Both silicon cell and cadmium sulfide cell standards have been delivered. The calibration coefficients are affected by atmospheric water vapor content (up to about 5%) and to a lesser extent by turbidity. An updated standard cell holder has been designed and procurement of materials for it is in progress. The main improvement is the field of view which allows the cell to be used in any orientation.

During the last six months, over 2600 modules from the 46 kW ERDA/JPL buy have been delivered to Lewis. This represents nearly half of the modules and well over half of the power of the 46 kW order. Measurements have been made (I-V) on about 13% of the modules. A pulsed solar simulator has been installed and is operational with a target area 32" in diameter. A larger area (5' x 9') will soon be available. Module and array measurements can also be made outdoors using the HP calculator system. Temperature and irradiance are measured and corrections made.

A prototype insolation measurement instrument has been designed and fabricated. The instrument is self-contained and uses a silicon solar cell as a sensor. Field instruments are being made for distribution to a variety of test sites. These include all application sites for the 46 kW buy and all endurance testing sites.

"Endurance Testing"

Endurance testing is now in progress at commercial testing sites in Florida, Arizona and Puerto Rico. Both real time and accelerated tests are in progress, with the accelerated tests only at the Arizona site. Presently, solar cells and modules are being tested and plans for testing various module components are being developed.

"Summary"

During the past six months, project efforts have emphasized implementation of plans previously developed. In the next six months, completion of tasks started, such as deployment to field tests of the balance of the modules from the 46 kW JPL procurement, will be carried out. In this same period an expanding effort will be applied to identification and implementation of S/GA opportunities resulting from brochure leads and other thrusts now being developed. These efforts, plus the refinement of existing plans and the development of new project plans, directions, and intermediate goals, will be addressed to insure maximum benefit of the project to the national program.

ERDA PHOTOVOLTAIC TESTS AND APPLICATIONS PROJECT

NASA-LEWIS RESEARCH CENTER

CLEVELAND, OHIO

PRESENTED AT THE

NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

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PROJECT OBJECTIVES

APPLICATIONS

- STIMULATE EARLY MARKETS FOR SOLAR CELLS BY OPERATING SYSTEMS IN SPECIAL NEAR-TERM APPLICATIONS
- DEMONSTRATE TECHNICAL FEASIBILITY OF P/V SYSTEMS FOR APPLICATIONS WITH SIGNIFICANT NATIONAL ENERGY DEMAND

DEVICE PERFORMANCE AND DIAGNOSTICS

- ESTABLISH AND MAINTAIN METHODS FOR MEASUREMENT OF SOLAR CELL PERFORMANCE
- PROVIDE DIAGNOSIS OF SPECIAL SOLAR CELL AND ARRAY PROBLEMS

ENDURANCE TESTING

- PERFORM REAL TIME AND ACCELERATED ENVIRONMENTAL TESTS OF SOLAR CELL ARRAYS AND MATERIALS

PROJECT EFFORTS SINCE JANUARY HAVE EMPHASIZED:

- DESIGN AND FABRICATION OF SYSTEMS TO UTILIZE MODULES FROM JPL 46 KW PROCUREMENT
- RECEIPT, PROCESSING, ASSEMBLY AND SHIPMENT OF 46 KW ARRAYS FOR SYSTEM TESTING
- IDENTIFICATION AND IMPLEMENTATION OF S/GA SYSTEMS FOR FIELD TESTING
- IMPROVEMENTS TO MEASUREMENT FACILITIES AND METHODS
- INITIATION OF ENDURANCE TESTING
- PLANNING AND IMPLEMENTATION ACTIVITIES RELATED TO JPL 130 KW BUY
- PARTICIPATION IN ERDA PROGRAM PLANNING ACTIVITIES

TASKS

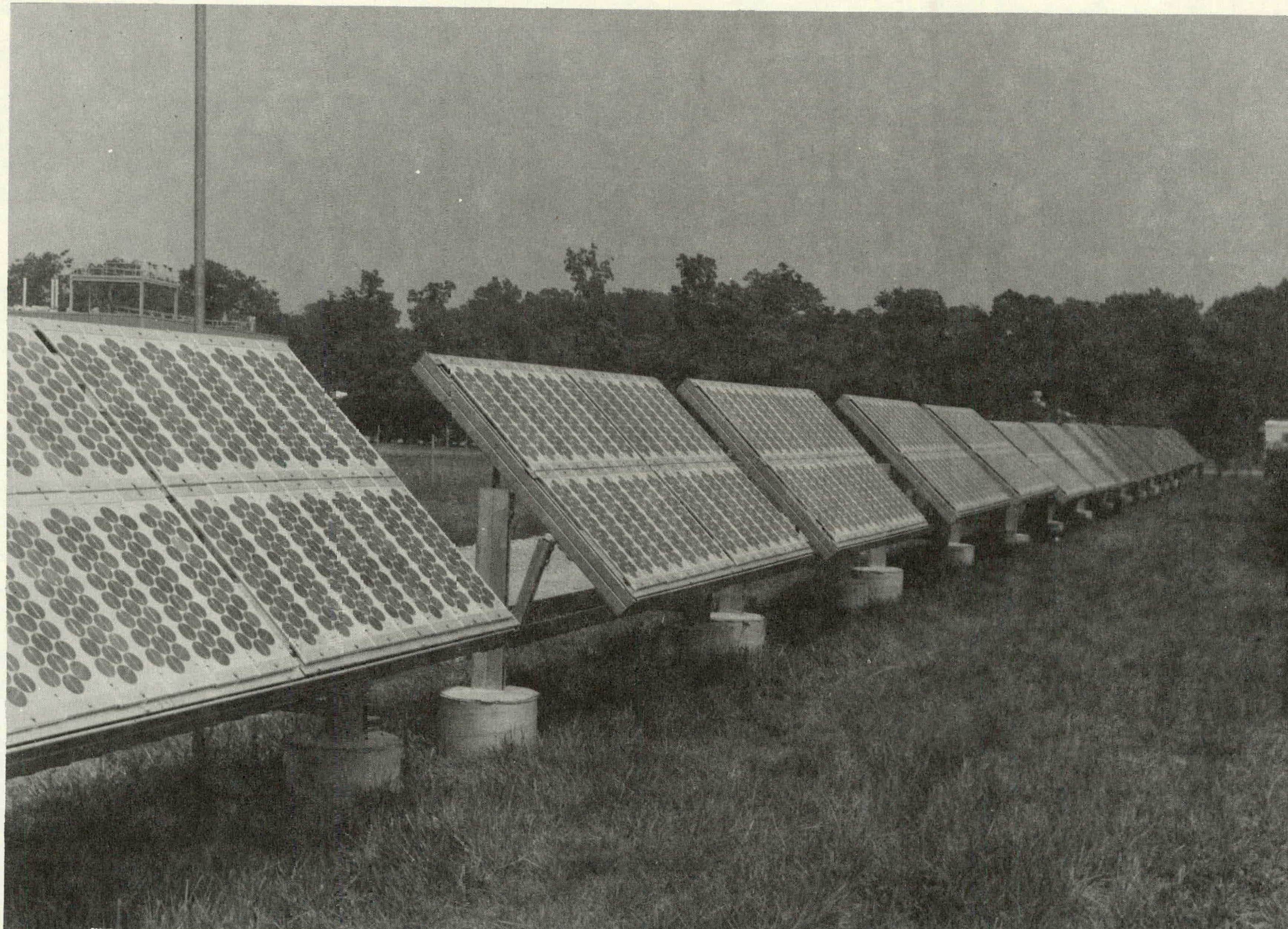
APPLICATIONS	SPEAKER
1. SYSTEM TEST FACILITY	DEYO
2. RESIDENTIAL SYSTEMS TESTS	"
3. SPECIAL & GOVERNMENTAL APPLICATIONS (S/GA)	RATAJCZAK
4. DOD SUPPORT	"
DEVICE PERFORMANCE AND DIAGNOSTICS	
1. WORKSHOP AND MANUAL	BRANDHORST
2. SOLAR CELL MEASUREMENTS	"
3. REFERENCE CELLS	"
4. MODULE AND ARRAY MEASUREMENTS	"
5. SOLAR CELL INSOLATION MEASUREMENT INSTRUMENT	"
ENDURANCE TESTING	
1. REAL TIME	BRANDHORST
2. ACCELERATED	"

APPLICATIONS

SYSTEM TEST FACILITY

PROGRESS: (PHASE IA - 10 KW)

1. ARRAY FIELD PREPARATIONS NEAR COMPLETION
2. 1.5 KW OF MODULES INSTALLED. 8.5 KW ADDITIONAL TO BE INSTALLED (BASED ON 46 KW ALLOCATION, DELIVERY AND TEST REQUIREMENTS)
3. CONTROL CENTER OPERATIONAL
4. STORAGE AND POWER CONDITIONING EQUIPMENT IN PLACE
5. SYSTEM TESTING INITIATED ON UTILITY FEED-BACK MODE
6. PLANS AND PREPARATIONS FOR FACILITY EXPANSION BEYOND 10 KW UNDERWAY



INITIAL SOLAR CELL ARRAY INSTALLATION FOR
PHOTOVOLTAIC SYSTEM TEST FACILITY AT LeRC

APPLICATIONS

RESIDENTIAL SYSTEMS

PROGRESS:

1. FINAL REPORTS IN PREPARATION FOR SYSTEM AND EXPERIMENT DEFINITION STUDIES* BY GE AND MARTIN-MARIETTA

* CONSIDERED PRESENT TECHNOLOGY ONLY

2. CONSTRUCTION DRAWINGS NEAR COMPLETION FOR LeRC RESIDENTIAL TEST UNIT

3. LONG RANGE RESIDENTIAL PLAN LEADING TO "DEMONSTRATIONS" IN PREPARATION

S/GA AND DOD APPLICATIONS ACTIVITIES

- SPECIAL AND GOVERNMENTAL APPLICATIONS

  MINI-APPLICATIONS

  COST-SHARED APPLICATIONS

- APPLICATIONS IDENTIFICATION

  SELECTION OF FUTURE

  APPLICATIONS PROJECTS

- DOD APPLICATIONS SUPPORT

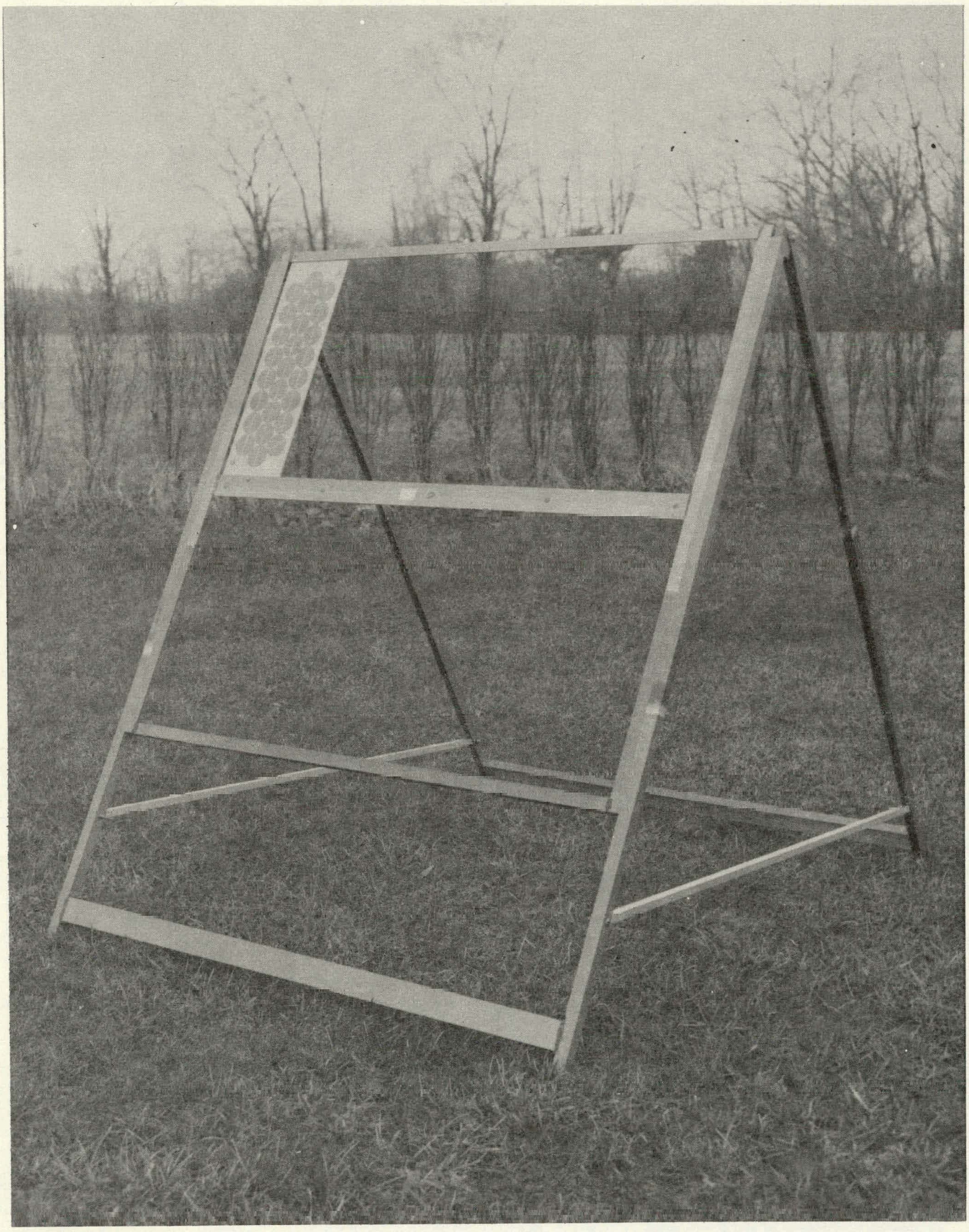
  DESIGN AND FABRICATE P/V ARRAYS FOR 6 DOD

  APPLICATIONS

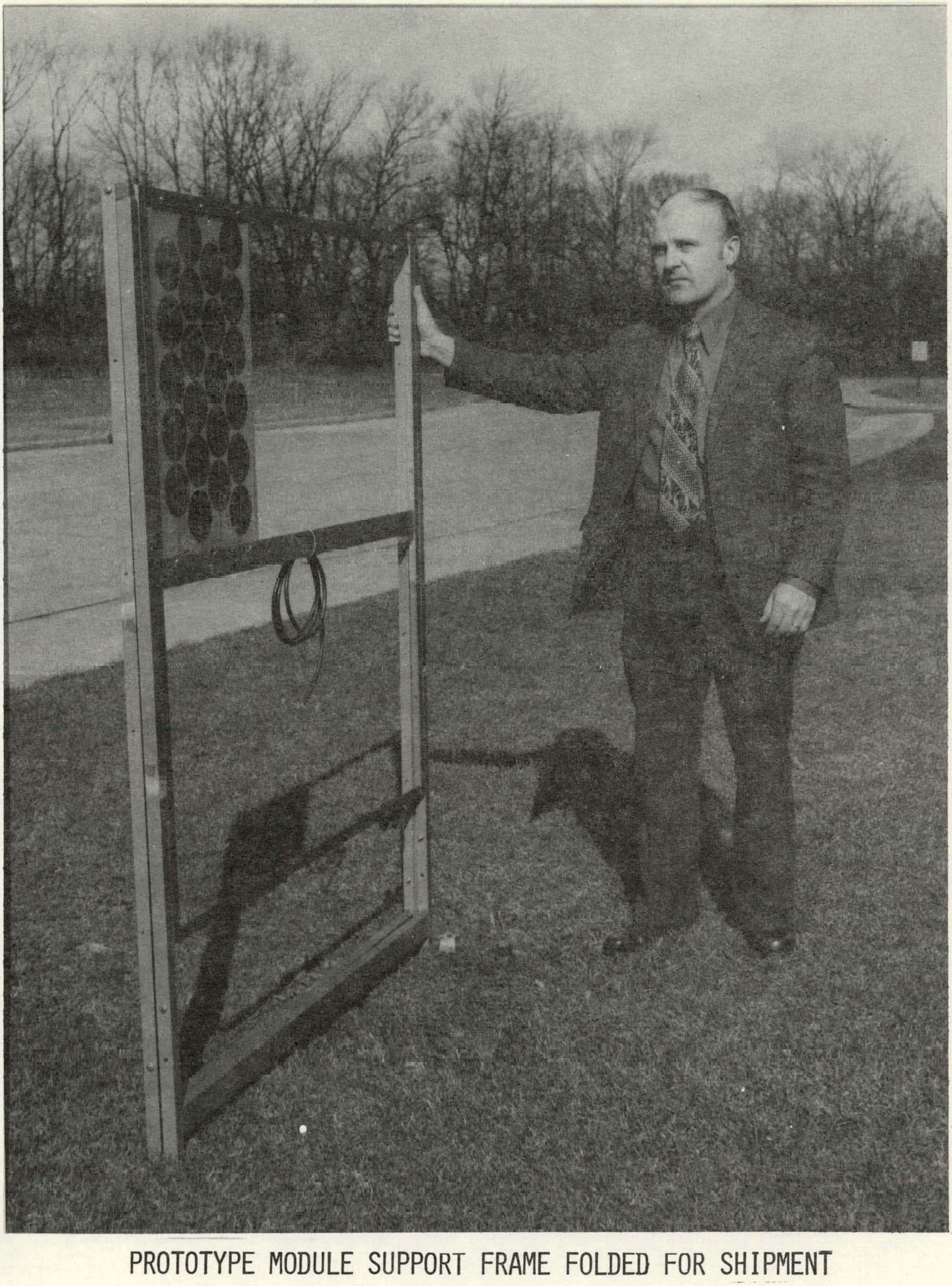
APPLICATIONS PERSPECTIVE FOR "46 KW" BUY

- DOD APPLICATIONS: 25-27 KW
- SYSTEM TEST FACILITY: ~10 KW
- S&GA: 7-9 KW

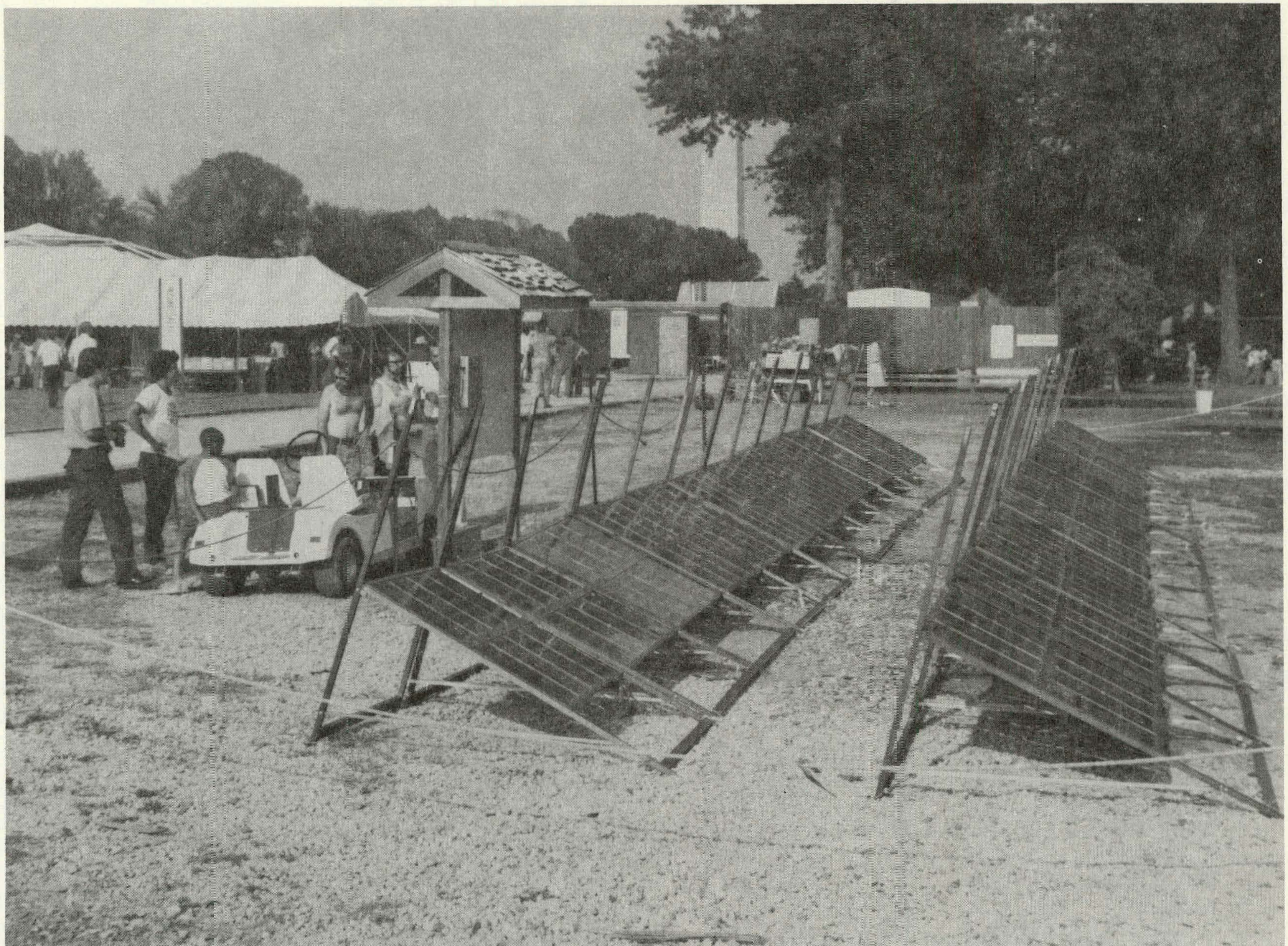
ALLOCATIONS INCLUDE ~10% SPARES



PROTOTYPE SELF-STANDING MODULE SUPPORT FRAME SHOWING
ONLY ONE MODULE INSTALLED



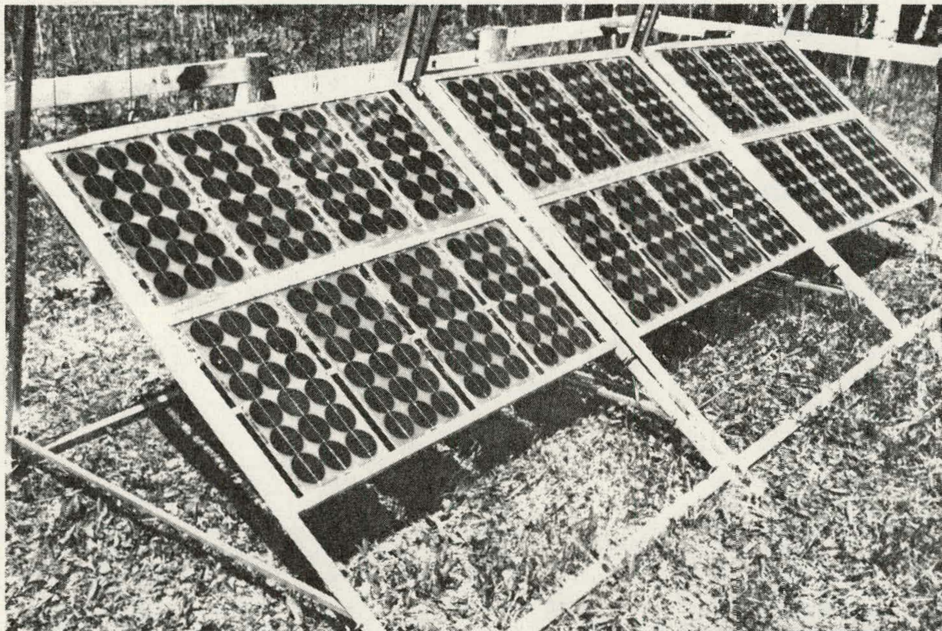
PROTOTYPE MODULE SUPPORT FRAME FOLDED FOR SHIPMENT

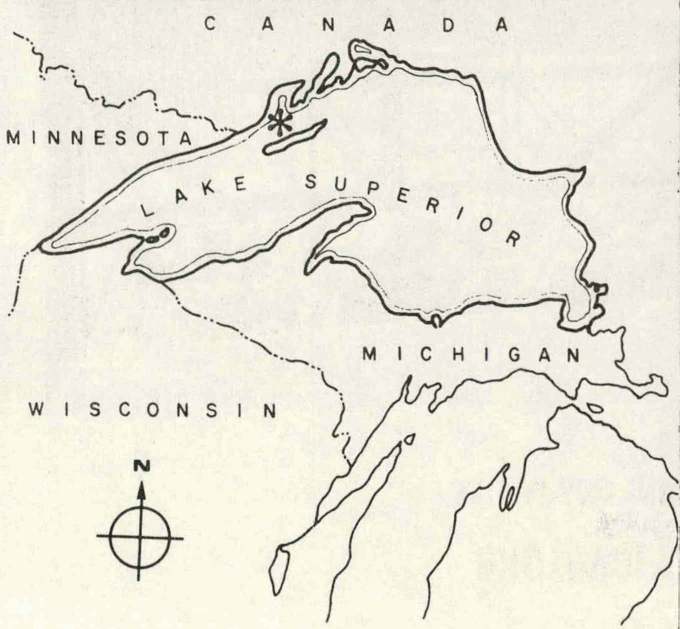


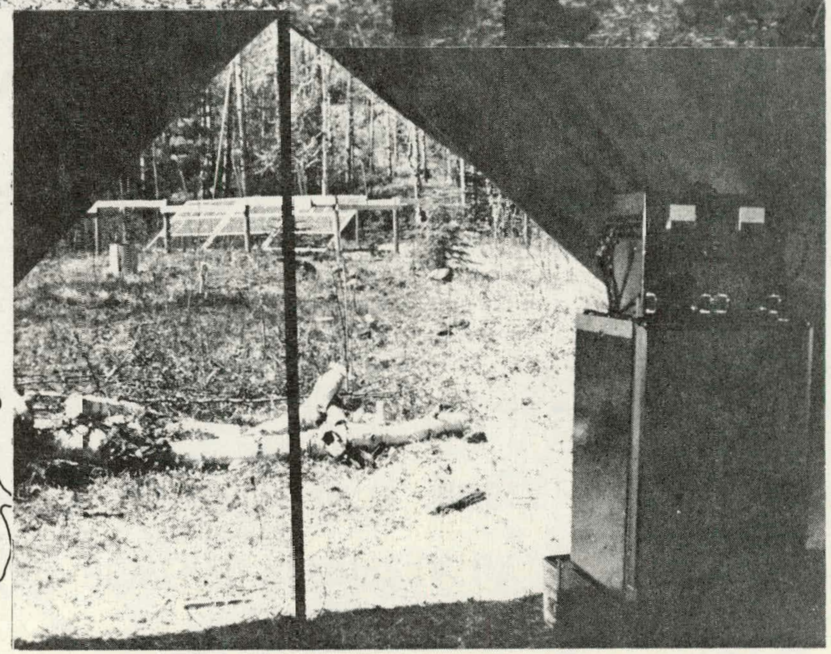
ELECTRIC VEHICLE PHOTOVOLTAIC BATTERY CHARGING SYSTEM
IN OPERATION AT THE FESTIVAL OF AMERICAN FOLKLIFE - WASHINGTON, D. C.

PHOTOVOLTAIC POWERED REFRIGERATOR

AT WILDERNESS TRAIL CONSTRUCTION CAMP - ISLE ROYALE NATIONAL PARK - MICHIGAN

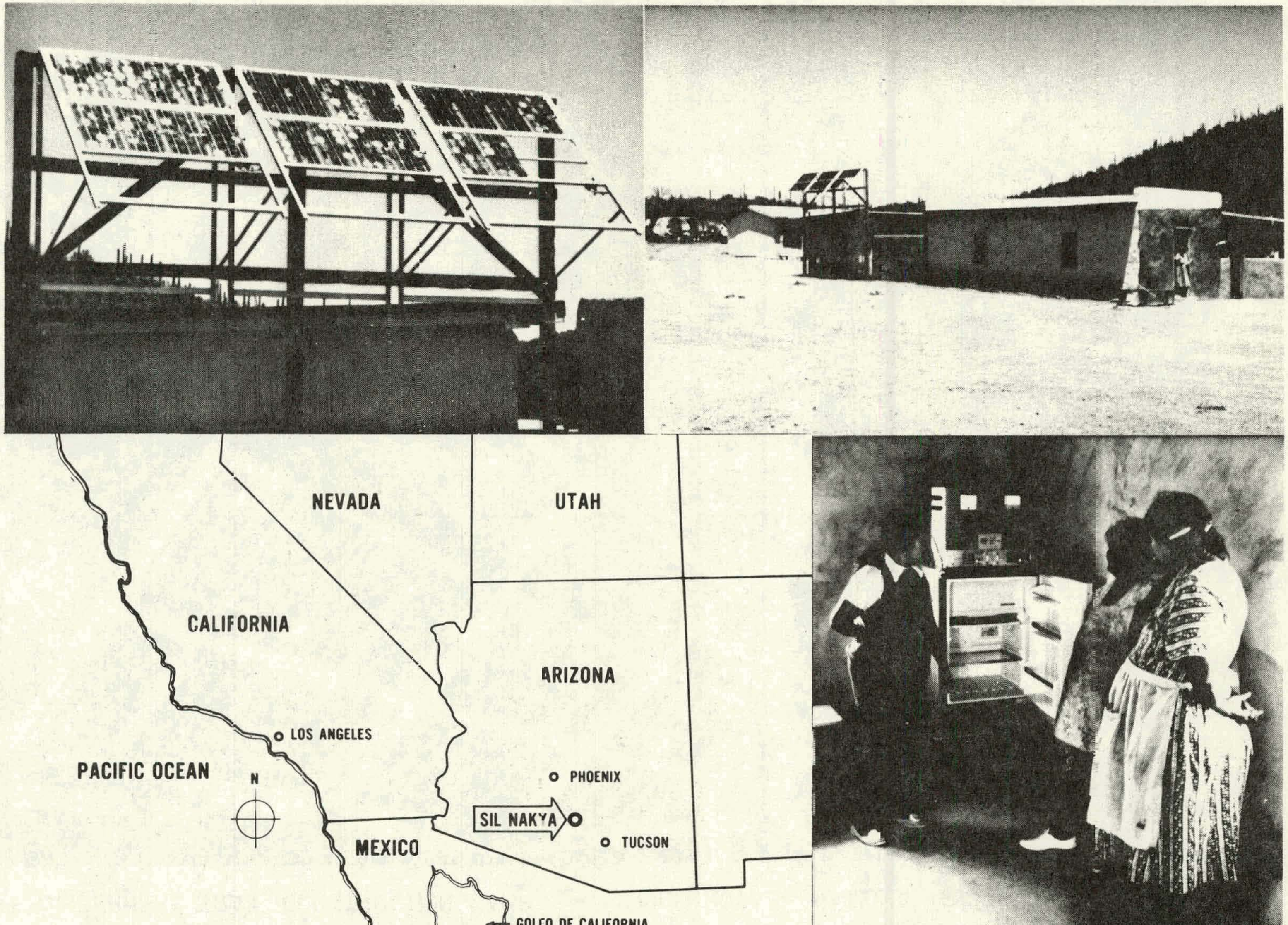






PHOTOVOLTAIC POWERED REFRIGERATOR

AT PAPAGO INDIAN VILLAGE OF SIL NAKYA, ARIZONA



P/V POWERED REFRIGERATOR

NEWS RELEASE

INQUIRIES

AUSTRALIA

ENGLAND

JAPAN

GHANA

SOUTH AFRICA

UNITED STATES

S/GA IDENTIFICATION PURPOSE

IDENTIFY A WIDE RANGE OF USES FOR P/V POWER SYSTEMS FROM WHICH TO SELECT OPTIMUM APPLICATIONS FOR DEVELOPMENT.

S/GA IDENTIFICATION TECHNIQUE

TWO DIRECT MAILINGS OF 800 BROCHURES, COVER LETTERS AND RESPONSE CARDS TO KEY OFFICIALS IN:

DOI	HUD	NSF
DOT	HEW	USDC
USDA	EPA	STATE DEPT.
	ERDA	

S/GA IDENTIFICATION RESULTS

- 100 (12.5%) REPLIES TO DATE (1ST MAILING)
- SUGGESTED USES:
  - VISITOR CENTERS
  - COMFORT STATIONS
  - RADIO AND RADAR
  - SECURITY
  - ENVIRONMENTAL MONITORS
  - LIGHTING
  - CATHODIC PROTECTION
  - WATER PUMPING
  - NAVIGATIONAL AIDS
  - ADMINISTRATIVE COMPLEX
  - MINING APPLICATIONS
  - AIR MONITORS
  - COMMUNICATIONS

ADDITIONAL "46 KW" BUY APPLICATIONS

- NWS - RAMOS TYPE WEATHER STATIONS
- USFS - FOREST LOOKOUTS
- WATER PUMPING

SECOND WORKSHOP ON CELL AND ARRAY MEASUREMENTS FOR TERRESTRIAL APPLICATIONS

- DATE: NOVEMBER 10-12, 1976
- LOCATION: BATON ROUGE, LA; HILTON AT CORPORATE SQUARE
- PROPOSED AGENDA:

  NOV. 10 - TERRESTRIAL SUNLIGHT AND ITS EFFECT ON SOLAR CELL PERFORMANCE

  NOV. 11 - SOLAR SIMULATION

  NOV. 12 - TECHNIQUES FOR CELL AND ARRAY MEASUREMENT AND STANDARD CELL CALIBRATION

INSOLATION MEASUREMENTS AT LeRC

- PURPOSE:
  - DETERMINE SENSITIVITY OF SOLAR CELL PERFORMANCE TO A RANGE OF ATMOSPHERIC CONDITIONS
  - COMPARE PERFORMANCE OF SOLAR CELLS AS SENSORS WITH PYRANOMETER AND PYRHELIOMETERS
  - DETERMINE SENSITIVITY OF SOLAR CELL TO EACH INSOLATION COMPONENT
  - VERIFY CONCLUSIONS OBTAINED FROM ATMOSPHERIC MODELLING

- APPROACH:
  - HOURLY INTEGRATION OF INSOLATION RECEIVED BY SOLAR CELLS AND BLACK BODY DETECTORS IN IDENTICAL ORIENTATIONS IS BEING OBTAINED.
  - SENSOR ORIENTATIONS:
    - HORIZONTAL
    - HORIZONTAL, SHADOW BAND
    - COLLIMATED, SUN TRACKING
    - INCLINED, 37 ABOVE NORIZONTAL
    - INCLINED, 60 ABOVE HORIZONTAL
  - INFLUENCE OF WATER VAPOR, TURBIDITY, CLOUD COVER, SUNLIGHT COMPONENT AND ORIENTATION WILL BE DETERMINED.

DEVICE PERFORMANCE AND DIAGNOSTICS

- OVER 1500 INDIVIDUAL MEASUREMENTS MADE IN LAST 6 MONTHS.
- MEASUREMENTS REQUESTED BY ABOUT 40 ORGANIZATIONS INCLUDING:

JPL	U. OF DELAWARE
SOLAREX	SMU
SPECTROLAB	MIT
SOLAR POWER CORP.	TI
SENSOR TECHNOLOGY	MOBIL-TYCO
M-7	RCA
OCLI	OWENS-ILLINOIS

SOLAR CELL MEASUREMENT FACILITY

- ALL DATA ACQUISITION AND REDUCTION IS CALCULATOR CONTROLLED
- MEASUREMENTS AVAILABLE:
  - NATURAL SUNLIGHT
    - CELL CALIBRATION (COLLIMATED: WITH N/P
    - CELL I-V, TEMPERATURE CONTROLLED
    - CELL I-V, T AND INTENSITY CORRECTED
  - LABORATORY
    - Xe-ARC SOURCE, CELL I-V, 1 $Ft.^2$ AREA
    - TUNGSTEN LAMP (ELH), CELL I-V, 4'' X 4'' AREA
    - CELL DARK FORWARD I-V CHARACTERISTIC
    - CELL V_{oc}-I_{sc} CHARACTERISTIC
    - 9-POINT, FULLY AUTOMATIC SPECTRAL RESPONSE/ QUANTUM YIELD MEASUREMENT
    - 18-POINT, SEMIAUTOMATIC, SPECTRAL RESPONSE/ QUANTUM YIELD SYSTEM, WITH WHITE LIGHT BIAS

AVERAGE ERROR IN SHORT-CIRCUIT CURRENT FOR DIFFERENT SIMULATORS (12 SOLAR CELLS - Z-01 STANDARD @ AM1)

SIMULATOR	AVE. ERROR (%)	RANGE (%)
XENON	0.9%	-3.4 --- +0.5
QUARTZ-HALOGEN	7.2%	-21.5 --- +9.8
ELH	2.3%	-5.4 --- +2.9

REFERENCE CELLS

- 54 INTERIM REFERENCE CELLS CALIBRATED AND DISTRIBUTED TO 17 ORGANIZATIONS INCLUDING:

JPL	MERADCOM	SENSOR TECHNOLOGY
SOLAREX	U. OF DELAWARE	SPECTROLAB
M-7	MITRE	SOLAR POWER CORP.
SANDIA	OCLI	

- CALIBRATION COEFFICIENTS AFFECTED BY:
  - ATMOSPHERIC WATER VAPOR - STRONG
  - TURBIDITY - MODERATE
  - COLLIMATION RATIO - WEAK
- UPDATED REFERENCE
  - NO WALL SHADOWING (< 0.1%)
  - PLANAR WINDOW
  - WITHSTANDS TEMPERATURE CYCLING +40 - -25%
  - INEXPENSIVE

MODULE AND ARRAY MEASUREMENT FACILITIES AVAILABLE AT LEWIS

LABORATORY - PULSED SOLAR SIMULATOR
32'' DIA. BEAM (5' X 9' IN AUGUST)
MAX. V_{OC} - 100 VOLTS
ROOM TEMP. - 100 mW/cm^2

OUTDOORS - TERRESTRIAL SUNLIGHT
TEMP. AND IRRADIANCE MEASURED,
I-V CURVE CORRECTED TO STANDARD CONDITIONS
(100 mW/CM^2, 28^o C)
MAX. VOL. ≈ 90 VOLTS (600 V IN SEPTEMBER)
DATA ACQUISITION, CALCULATIONS AND OUTPUT
AUTOMATIC - (HP 9830)

IN BOTH CASES IRRADIANCE MEASURED WITH IDENTICAL STANDARD SOLAR CELLS

MODULE STATUS FOR 46 KW BUY

MANUFACTURER	NUMBER RECEIVED	NUMBER MEASURED	AVERAGE POWER (W)
M-7	30	19	5.06
SENSOR TECHNOLOGY	791	96	5.73
SOLAREX	897	136	9.24
SOLAR POWER	737	80	13.81
SPECTROLAB	189	25	5.06
	2644	356 (13.5%)	

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INSOLATION MEASUREMENT INSTRUMENT

PURPOSE: TO OBTAIN INSOLATION DATA AT TEST SITES, TO PROVIDE DIRECT INPUT TO ARRAY SIZING CALCULATIONS AND TO PROVIDE A DATA BASE NOT DIRECTLY AVAILABLE IN THE CLIMATIC ATLAS.

TEST LOCATIONS:

- ALL APPLICATION SITES FOR 46 KW PRODUCTION
- ALL ENDURANCE TESTING SITES
- NEW LOCATIONS AS DEVELOPED

INSOLATION MEASUREMENT INSTRUMENT PACKAGE

- SENSOR -- SILICON SOLAR CELL, INCLINATION VARIABLE
- READOUT SENSITIVITY -- 0.1 $\frac{W\text{-}Hr}{M^2}$ IMTERNAL SENSITIVITY $\frac{10^{-5} W\text{-}Hr}{M^2}$
- READOUT -- 6 PLACE DIGITAL METER;
0-3 V TO 0-5 V ANALOG
- ACCURACY -- < 1%
- ABSOLUTE ACCURACY -- ± 5% (SENSOR LIMITED, BLACK BODY REFERENCE)
- OPERATING TEMPERATURE RANGE -- +30 TO -20° C
- POWER SUPPLY -- ANY 12-20 VOLT DC SOURCE
- CURRENT DRAIN -- 10 mA

ERDA/NASA-LEWIS
EXPOSURE TESTING OF SOLAR MODULES, ARRAYS AND MATERIALS

SITE	TEST TYPE	SAMPLE SIZE	START TIME
MIAMI, FL	REAL TIME	ANY	IN PROGRESS
MIAMI, FL	REAL TIME, SALT ENVIRONMENT	ANY	IN PROGRESS
POMPANO BEACH, FL	REAL TIME	ANY	IN PROGRESS
PUERTO RICO	REAL TIME	ANY	IN PROGRESS
PHOENIX, AZ	REAL TIME	ANY	IN PROGRESS
PHOENIX, AZ	ACCELERATED	5" X UP TO 55"	IN PROGRESS
PHOENIX, AZ	ACCELERATED	UP TO 15" X 96"	EARLY '77
CLEVELAND, OH AIR POLLUTION CONTROL CTR.	REAL TIME	4' X 8' TEST BEDS	OCT. '76
CLEVELAND, OH NASA-LeRC	REAL TIME	4' X 8' TEST BEDS	OCT. '76
CLEVELAND, OH NASA-LeRC	ACCELERATED	LESS THAN 2.5" X 11"	SEPT. '76

PROJECT PLANS (NEXT 6 MONTHS)

- EXPAND S/GA IDENTIFICATION AND IMPLEMENTATION ACTIVITIES
- COMPLETE DEPLOYMENT TO FIELD TESTING OF ALL 46 KW MODULES
- BEGIN IMPLEMENTATION OF SYSTEMS PLANNED FOR 130 KW MODULES
- IMPLEMENT MEASUREMENT REVISIONS DEVELOPING FROM NOVEMBER '76 WORKSHOP AND LeRC INVESTIGATIONS
- EXPAND ENDURANCE TESTING
- DEVELOP PLANS, DIRECTIONS, AND INTERMEDIATE GOALS RECOMMENDING FUTURE EFFORT RELATED TO THE PROJECT AND THE NATIONAL PROGRAM

SOLAR PHOTOVOLTAIC FIELD TESTS AND APPLICATIONS PROGRAM

MARVIN D. POPE
M.I.T. LINCOLN LABORATORY
LEXINGTON, MASSACHUSETTS

PRESENTED TO
ERDA SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING
UNIVERSITY OF MAINE AT ORONO

4 AUGUST 1976

ERDA PHOTOVOLTAIC CONVERSION PROGRAM

General Objective:

Promote widespread use of solar photovoltaic systems in residential, commercial, and military applications.

Specific Objectives:

Within 10 years--- Total plant capacity = 500 Peak MW/year prod rate
Array price less than 500 $/Peak kW

Within 25 years--- Total plant capacity = 50,000 Peak MW/yr prod rate
Array price less than 100-300 $/Peak kW

Program Elements:

R and D Program--- Explore all technologies for PV devices that show large (100X) potential cost reduction

Systems and Applications studies----- Determine suitable missions and applications for PV systems; establish appropriate system designs

Field Tests --------- Install and operate various types of PV systems which promise to be cost-effective

Demonstrations-----Demonstrate both technical and economic feasibility of various types of PV Conversion Systems

SOLAR PHOTOVOLTAIC FIELD TESTS AND APPLICATIONS

Overall Objectives:

Provide useful and meaningful markets for solar cell arrays so that sustained production at increased rate is possible

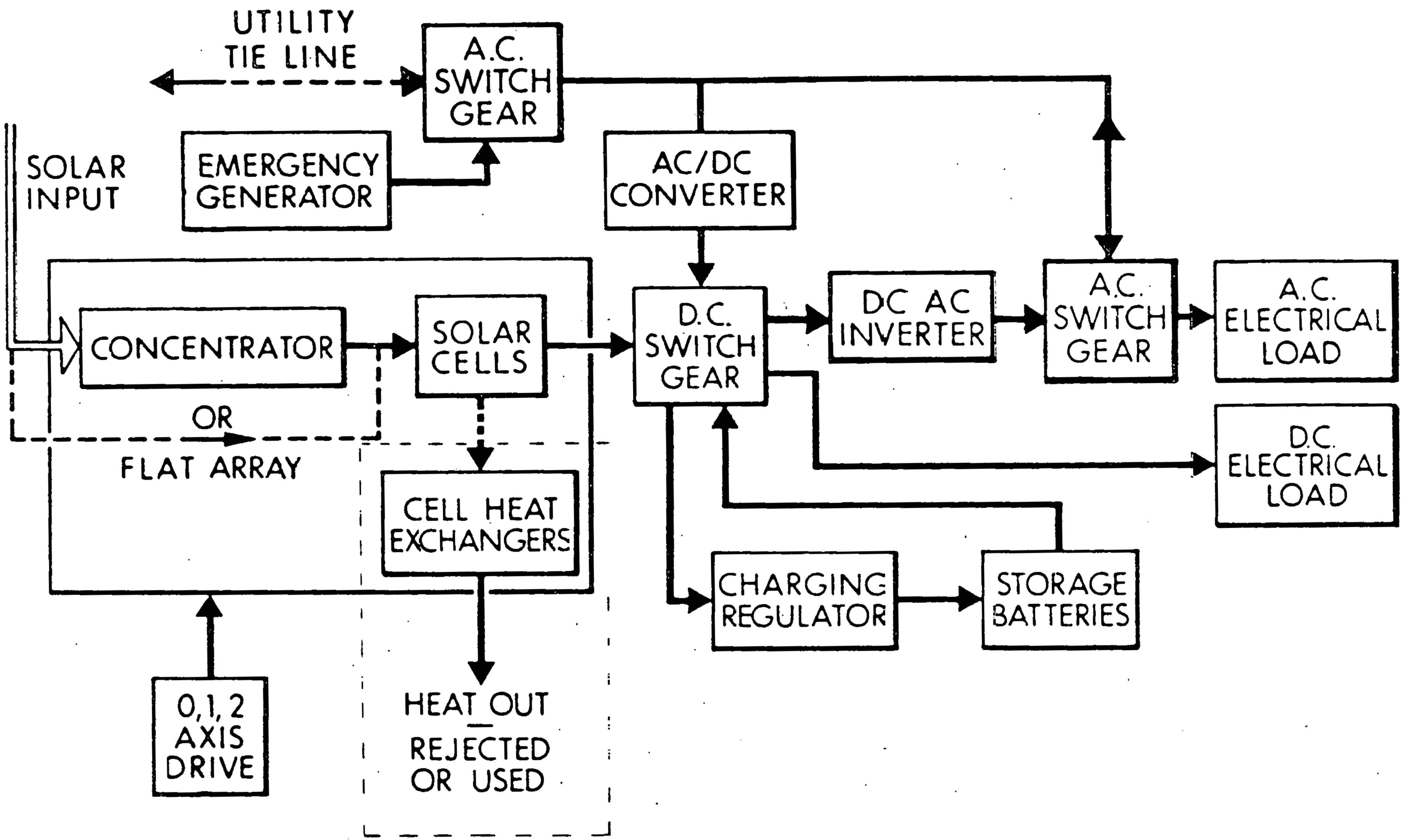
Stimulate growth of commercial/industrial expertise re: design, mfg, testing, installation, servicing of PV systems

Specific Objectives:

Do detailed design, integration, testing and evaluation of PV systems for selected applications

Act as integrator for the engineering-manufacturer-user-utility complex

Interface with other ERDA Prime Contractors involved in the unified National Program in Photovoltaics



SOLAR PHOTOVOLTAIC POWER PLANT SCHEMATIC

APPLICATIONS AND USERS

Some Issues -------

Ownership

Cost Sharing

Legal Liability

Governmental Jurisdiction

Responsibility for O and M

Interfaces
- Physical
- Institutional

Recording of systems perf. data

APPLICATIONS AND USERS

Some Considerations------

Is Application already being exploited?

Potential Capacity

- Near term (1986)
- Long term (2000)

Is there credible market capture potential?

- with 1986 cost goals
- with 2000 cost goals

Is there sufficient visibility?

- By being widespread
- By being of large unit size
- Because of great appeal (publicity)

Is it technically feasible?

How much will it cost?

Political Acceptability

- Environ. improvement
- Improved use of agricultural lands
- Improved habitability of land
- Displacement of PNG fuels

Usefulness

- Immediately
- Near term (1986)
- Long term (2000)

Will we learn from it?

- Technical/professional communities
- The Public at large

Will prospective User Cost-Share?

- Provide equipment
- Perform site mods
- Maintain equipment
- Collect/Evaluate System perf data

SELECTION OF APPLICATIONS AND USERS

FAIR AND UNBIASED

PREPARED AND KNOW IN ADVANCE OF SOLICITATIONS

CONSIDER VARIOUS EVALUATION SCHEMES

- UNIFORMLY WEIGHTED SUMS
- SEQUENTIAL YES - NO DECISIONS
- LINEAR FUNCTIONS WITH WEIGHTING COEFFICIENTS
- MAXIMUM LIKELIHOOD ESTIMATION ON MULTIVARIATE DISTRIBUTION

POSSIBLE SOLAR PHOTOVOLTAIC SYSTEM APPLICATIONS

SPECIAL / REMOTE POWER SYSTEMS (1W - 1kW PEAK)

- RADIO BEACON SYSTEM FOR LIFE RAFTS
- SOLAR-POWERED STREET LIGHT
- HIGHWAY TELEPHONE CALL BOX
- BEACON / COMMUNICATIONS WITH LOST HIKERS, HUNTERS, ETC.
- REMOTE HIGHWAY SIGN LIGHTING SYSTEM
- ARRAYS TO CHARGE RADIOS FOR EMERGENCY USE - CAMPING, HIKING, ETC.
- C.B. DISASTER RADIO NETWORK FOR SEARCH / RESCUE TEAMS
- SMALL COMMUNICATIONS TERMINALS FOR GLOBAL POSITIONING SYSTEM
- OPERATION OF MOTORS AND SMALL MACHINES IN DEVELOPING COUNTRIES
- HIGHWAY BARRIER FLASHER

LOW POWER SYSTEMS (1 to 10kW PEAK)

- ON-BOARD POWER GENERATION FOR TETHERED, FREE, AND SELF-POWERED BALLOONS
- PROVIDE LIGHTING FOR TRAIL HUTS
- RESORT OR VACATION HOME POWER
- INTERMITTENT PUMPING FOR LOW-YIELD OIL WELLS
- TOTAL ENERGY SYSTEM FOR INDIAN SCHOOL
- REFRIGERATION SYSTEM FOR REEFER TRUCKS AND FOOD-STORAGE COMPANIES

POSSIBLE SOLAR PHOTOVOLTAIC SYSTEM APPLICATIONS (CONT'D)

INTERMEDIATE POWER SYSTEMS (10 - 500 kW PEAK)

- POWER FOR SMALL, REMOTE MINING OPERATIONS
- AIRPORT RUNWAY LIGHTING SYSTEMS
- ELECTRICAL ENERGY TRANSPORTATION SYSTEMS
  - CENTRAL POWER / STORAGE STATION CHARGING FLEET OF ELECTRIC CARS - SMITHSONIAN, CAPITAL-TO-LINCOLN MEMORIAL, POSTAL DELIVERY, ETC.
- SOLAR-POWERED LIGHTING SYSTEM FOR WHITE HOUSE, WASHINGTON MONUMENT, LINCOLN MEMORIAL, ETC.

PRESENT PLAN FOR FIELD TEST SYSTEMS

CATEGORY	POWER RANGE	FY '77	FY '78-'80
Special/Remote Systems	1W-1kW Peak	6	10 per year
Low Power Systems	1 - 10 kW Peak	1	5 per year
Intermediate Power Systems	10 - 500 kW Peak	1 (design)	2 per yr after '79 1 during '79
High Power Systems	Greater than 500 kW	-	TBD

MILITARY APPLICATIONS OF PHOTOVOLTAIC SYSTEMS

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

INTERAGENCY AGREEMENT NO. E(49-26)-1031

Period of Agreement: 1 November 1976 - 30 September 1976

Value: $596,000

DONALD D. FAEHN

Program Manager

US Army Mobility Equipment Research & Development Command

DRXFB-E

Fort Belvoir, Virginia 22060

Presented at the National Solar Photovoltaic Program Review Meeting

August 3 - 6, 1976

University of Maine at Orono

Orono, Maine 04473

MILITARY APPLICATIONS OF PHOTOVOLTAIC SYSTEMS (MAPS)

I. OBJECTIVES

The principal objective of the MAPS program is to investigate the applicability of solar photovoltaic energy conversion systems to a wide variety of military power consuming equipment. This is to be accomplished by a comprehensive demonstration program, involving six DOD systems with a total array peak power rating of approximately 90 KW. Five of these projects will be operational in 1976. Initially, the smaller demonstration projects will be operated at a centralized location (Fort Belvoir, Virginia), after which they will be evaluated under more realistic military environments.

The outcome of this demonstration program is expected to facilitate the early introduction of solar cell power systems to the anticipated substantial market within DOD. Wide exposure of the attributes and military potential of photovoltaic energy systems and early identification and solution of technology problem areas will minimize the time period required for research, development, and acquisition of these systems.

Development of the early market within DOD will accordingly expedite attainment of the National goals.

II. PREVIOUS ACTIVITIES

A previously funded study effort by MERADCOM was completed in August 1975. Numerous DOD systems were identified as candidate p/v demonstration projects. These were analyzed and evaluated and the most promising candidates were submitted for joint ERDA/DOD selection. Five projects (requiring approximately 30 KW) were ultimately recommended for the first phase of the demonstration program and a sixth project (60 KW) was recommended for implementation in FY 77.

The MAPS program began 1 November 1975. The five demonstration projects, listed in the accompanying Table, range in array peak power rating from 80 watts to 12 kilowatts and similarly span a wide spectrum of nominal voltage and duty requirements. Each project was selected to uniquely address one or more p/v system/application characteristics. For example, all systems will employ secondary battery energy storage but only minimal battery storage is needed for the water purification plant; rather, energy is stored in the form of purified water in the reservoir.

III. CURRENT EFFORTS

Engineering work on the five FY 76 demonstration projects has been completed and development of these systems is nearing completion. The Small Battery Charger, Radio Relay System, and Telephone Communications Station are operational and are undergoing check-out testing prior to initiation of the centralized demonstration phase, scheduled for 1 September 1976.

The Water Purification System will become operational in October, when the complete 10.8 KW array allocated to this project becomes available.

Siting plans are complete for the Remote Radar, which will be located at the Naval Weapons Center throughout its demonstration period, which will begin 1 December 1976. Electrical switchgear and dc/ac converter for this system are 50 percent complete.

The Remote Island demonstration is scheduled for implementation in FY 77. Recommendations for siting this 60 KW photovoltaic system (which will be augmented by wind powered generators) have been made to the Military Applications Coordinating Committee.

IV. FUTURE PLANS

The centralized demonstration activities will be initiated at Fort Belvoir 1 September 1976.

MILITARY APPLICATIONS OF PHOTOVOLTAIC SYSTEMS

INTERAGENCY AGREEMENT E(49-26) -1031

US ARMY MOBILITY EQUIPMENT RESEARCH AND DEVELOPMENT COMMAND

1 NOVEMBER 1975 - 30 SEPTEMBER 1976

$596K

DONALD D. FAEHN
PROGRAM MANAGER

PLANNED ACTIVITY – LAST SIX MONTHS

- DESIGN AND FABRICATE POWER SUPPLY SYSTEMS, AND MODIFY MILITARY EQUIPMENT FOR FIVE DEMONSTRATION PROJECTS
- PLAN SIXTH DEMONSTRATION PROJECT (REMOTE ISLAND)
- PREPARE PLANS TO EXPEDITE EARLY DEPLOYMENT OF PHOTOVOLTAIC SYSTEMS WITHIN DOD

PROGRESS

- SMALL BATTERY CHARGER DESIGNED AND FABRICATED
- MILITARY EQUIPMENT OBTAINED FOR DEMONSTRATION PROJECTS
    - SENSORS
    - TRANSMITTERS/RECEIVERS
    - RELAYS
    - CONSOLES
    - TELEPHONE OFFICE
    - TRUCKS
    - FIELD TELEPHONES
    - WATER PURIFICATION PLANT
    - RADAR SET
- MODIFICATIONS 90% COMPLETE
- PLANNING COMPLETED FOR CENTRALIZED DEMONSTRATIONS (FT BELVOIR)
- SITE RECOMMENDED FOR REMOTE ISLAND PROJECT
- PLAN PREPARED FOR EXPEDITING EARLY DEPLOYMENT OF SOLAR CELL POWER AT MILITARY TEST SITES

PLANNED ACTIVITY – NEXT SIX MONTHS

- INITIATE CENTRALIZED DEMONSTRATION ACTIVITIES – SEPTEMBER 1976
  - SMALL BATTERY CHARGER
  - RADIO RELAY SYSTEM
  - TELEPHONE COMMUNICATIONS STATION
  - WATER PURIFICATION (OCTOBER 76)
- INITIATE REMOTE RADAR DEMONSTRATION AT NAVAL WEAPONS CENTER (NOVEMBER 76)
- DESIGN REMOTE ISLAND PROJECT
- PLAN FIELD DEMONSTRATIONS AT OTHER MILITARY INSTALLATIONS
  - SMALL BATTERY CHARGER
  - RADIO RELAY SYSTEM
  - TELEPHONE COMMUNICATIONS STATION
- INVESTIGATE MILITARY TEST SITE APPLICATIONS

RELATED PROGRAM
MILITARY MARKET INVENTORY ANALYSIS

(SPONSORED BY THE FEDERAL ENERGY ADMINISTRATION)

- TO PROVIDE AN ESTIMATE OF MARKET VOLUME VS PRICE
- EMPHASIS ON NEAR TERM MARKET
- IMPACT OF COMBINED PHOTOVOLTAIC/THERMAL SYSTEMS
- TECHNOLOGY TRANSFER TO OTHER GOVERNMENT AND PRIVATE SECTORS

ERDA

PHOTOVOLTAIC SYSTEMS DEFINITION PROJECT

CONCENTRATOR DEVELOPMENT TASK

D. G. SCHUELER, PROJECT MANAGER
SANDIA LABORATORY
ALBUQUERQUE, NM 87115

PRESENTED AT THE
NATIONAL SOLAR PHOTOVOLTAIC PROGRAM
REVIEW MEETING

AUGUST 3-6, 1976
UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE 04473

CONCENTRATOR DEVELOPMENT TASK OF THE ERDA PHOTOVOLTAIC SYSTEMS DEFINITION PROJECT*

Donald G. Schueler
Sandia Laboratory
Albuquerque, New Mexico 87115

One of the tasks of the ERDA Photovoltaic Systems Definition Project, managed by Sandia Laboratories, is to investigate the use of solar collectors which concentrate sunlight onto solar cells as a means of improving the overall cost effectiveness of terrestrial photovoltaic power systems. Concentration provides a possible means of reducing near-term array costs to the $2000 - $5000 per peak kW range. Such near-term cost reduction of photovoltaic arrays may open significant new and early markets for photovoltaic power systems and stimulate the growth of the commercial photovoltaic industry. In the long-term (1986 and beyond), concentration may continue to prove cost-effective even with solar cell costs in the $\$50/m^2$ range. For example, non-tracking, low concentration ratio hollow trough compound parabolic collectors integrated into low-profile silicon sheet arrays may provide significant cost advantages by reducing the required amount of cell area, improving the array packing factor, and improving the solar cell conversion efficiency over one-sun operation.

The present approach to photovoltaic-concentrator development is to investigate both basic performance of system components as well as system-level considerations. Solar cells which have high power conversion efficiencies at high sunlight intensity and elevated temperature are being studied. Both single crystal silicon and single crystal gallium arsenide solar cell technologies are being

* This work sponsored by the Energy Research and Development Administration

developed and evaluated. The cost and performance of a variety of concentrator technologies is being studied, as well as solar cell cooling methods and the potential of combined electrical and thermal conversion total energy systems. Several prototype concentrator arrays having peak output in the 100 We to 1 kWe range are currently being constructed for performance evaluation.

The technical work of this project is being performed primarily by contract to industry, universities, and other government laboratories, with some complementary and supporting work performed at Sandia Laboratories. The attached visual aid material provides an overview of the project objectives and milestones and a status report of the current technical work.

PHOTOVOLTAIC-CONCENTRATOR DEVELOPMENT

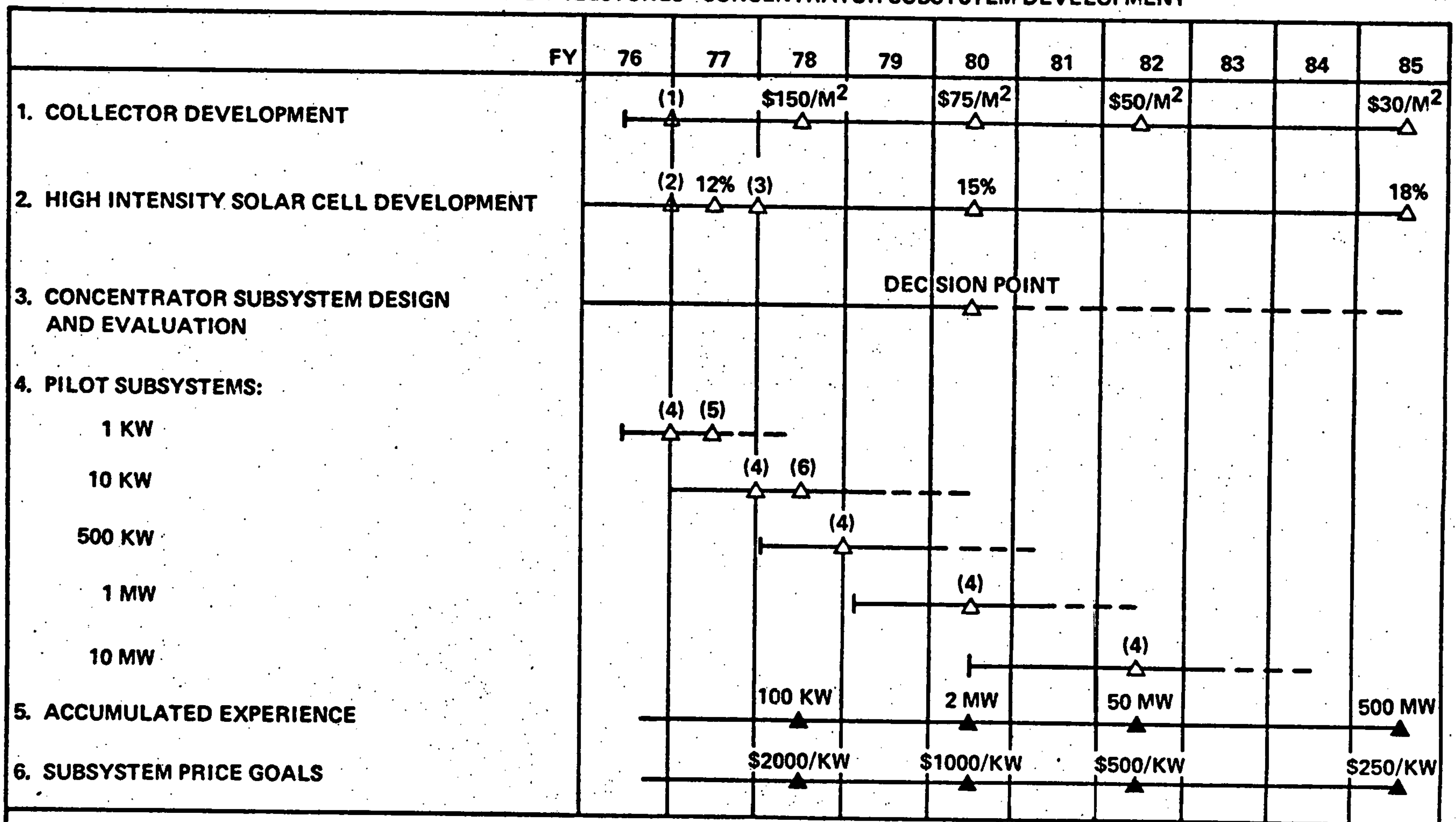
OBJECTIVE -

- IMPLEMENT COST REDUCTION BY REPLACING SOLAR CELL AREA WITH LOWER COST REFLECTIVE OR REFRACTIVE MATERIALS

APPROACH -

- SOLAR ENERGY AVAILABLE TO CONCENTRATING COLLECTORS
- PERFORMANCE OF SOLAR CELLS AT HIGH ILLUMINATION INTENSITY
- COST AND PERFORMANCE OF SOLAR CONCENTRATORS
- SYSTEM CONSIDERATIONS AND DESIGN TRADEOFFS
- PROTOTYPE CONCENTRATOR ARRAY EXPERIMENTS

PLANNING SCHEDULE AND MILESTONES - CONCENTRATOR SUBSYSTEM DEVELOPMENT



NOTES:
(1) PROTOTYPE CONCENTRATORS AVAILABLE
(2) MODIFIED SI CELLS AVAILABLE
(3) GALLIUM ARSENIDE CELLS AVAILABLE
(4) INITIAL OPERATION
(5) EVALUATION COMPLETE
(6) ADDITIONAL PRODUCTION

PHOTOVOLTAIC-CONCENTRATOR DEVELOPMENT

PRESENT ACTIVITIES

CONTRACTS -

- CONCENTRATOR SUBSYSTEM ANALYSIS AND ECONOMICS
- HIGH INTENSITY SILICON SOLAR CELLS
- HIGH INTENSITY GALLIUM ARSENIDE SOLAR CELLS
- PROTOTYPE CONCENTRATOR ARRAYS

SANDIA IN-HOUSE -

- COMPLEMENTARY SYSTEM ANALYSIS
- HIGH INTENSITY SILICON SOLAR CELLS
- 1 KW CONCENTRATOR ARRAY

CONCENTRATOR SYSTEM ANALYSIS AND DESIGN TRADEOFFS

SANDIA LABORATORY - E. C. BOES, M. W. EDENBURN

OBJECTIVE -

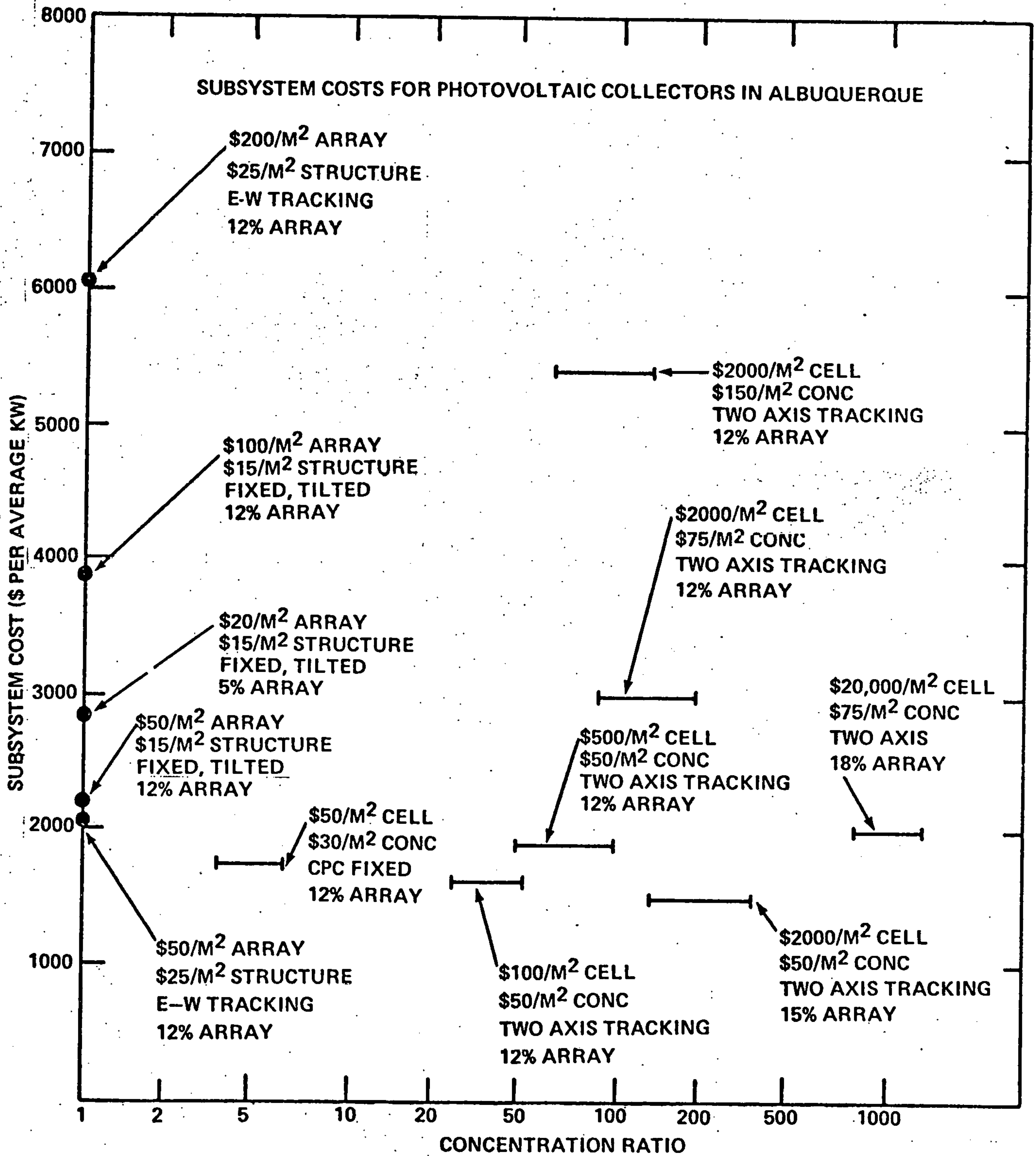
- DEFINE FUNDAMENTAL SYSTEMS CONSIDERATIONS AND ECONOMICS OF PHOTOVOLTAIC CONCENTRATOR ARRAYS

APPROACH -

- SOLAR ENERGY AVAILABLE TO VARIOUS COLLECTORS AND GEOGRAPHIC INFLUENCE
- TRACKING ARRAY STRUCTURE DESIGNS AND COSTS
- PARAMETRIC MAPPING OF SUBSYSTEM COST-PERFORMANCE CHARACTERISTICS

AVERAGE ENERGY COLLECTED BY VARIOUS ARRAY TYPES
(KWH/m^2 DAY)

COLLECTOR TYPE	ALBUQUERQUE	BLUE HILL	OMAHA
I. NONTRACKING			
FLAT-PLATE, TILTED AT LATITUDE	5.9	4.0	4.6
CPC, E-W AXIS, CR=7	4.0	2.4	2.5
II. ONE AXIS TRACKING			
FLAT-PLATE, TILTED AT LATITUDE	7.4	5.0	5.5
PARABOLIC CYLINDER, E-W AXIS	4.6	2.8	2.9
PARABOLIC CYLINDER, N-S AXIS, TILTED	5.7	3.4	3.6
FIXED SEGMENTED REFLECTOR, E-W AXIS	3.7	2.2	2.3
III. TWO AXIS TRACKING			
FLAT-PLATE	7.7	5.2	5.6
PARABOLOID	5.9	3.6	3.7
FRESNEL LENS	6.3	3.8	3.9



SUBSYSTEM COSTS FOR PHOTOVOLTAIC COLLECTORS IN ALBUQUERQUE
SUBSYSTEM COST ($ PER AVERAGE KW)
8000
7000
6000
5000
4000
3000
2000
1000
1
2
5
10
20
50
100
200
500
1000
CONCENTRATION RATIO
$200/M2 ARRAY
$25/M2 STRUCTURE
E-W TRACKING
12% ARRAY
$100/M2 ARRAY
$15/M2 STRUCTURE
FIXED, TILTED
12% ARRAY
$20/M2 ARRAY
$15/M2 STRUCTURE
FIXED, TILTED
5% ARRAY
$50/M2 ARRAY
$15/M2 STRUCTURE
FIXED, TILTED
12% ARRAY
$50/M2 ARRAY
$25/M2 STRUCTURE
E–W TRACKING
12% ARRAY
$50/M2 CELL
$30/M2 CONC
CPC FIXED
12% ARRAY
$100/M2 CELL
$50/M2 CONC
TWO AXIS TRACKING
12% ARRAY
$500/M2 CELL
$50/M2 CONC
TWO AXIS TRACKING
12% ARRAY
$2000/M2 CELL
$150/M2 CONC
TWO AXIS TRACKING
12% ARRAY
$2000/M2 CELL
$75/M2 CONC
TWO AXIS TRACKING
12% ARRAY
$20,000/M2 CELL
$75/M2 CONC
TWO AXIS
18% ARRAY
$2000/M2 CELL
$50/M2 CONC
TWO AXIS TRACKING
15% ARRAY

SILICON SOLAR CELLS FOR MULTIPLE-SUN, HIGH TEMPERATURE APPLICATIONS

SANDIA LABORATORY - J. G. FOSSUM

OBJECTIVE -

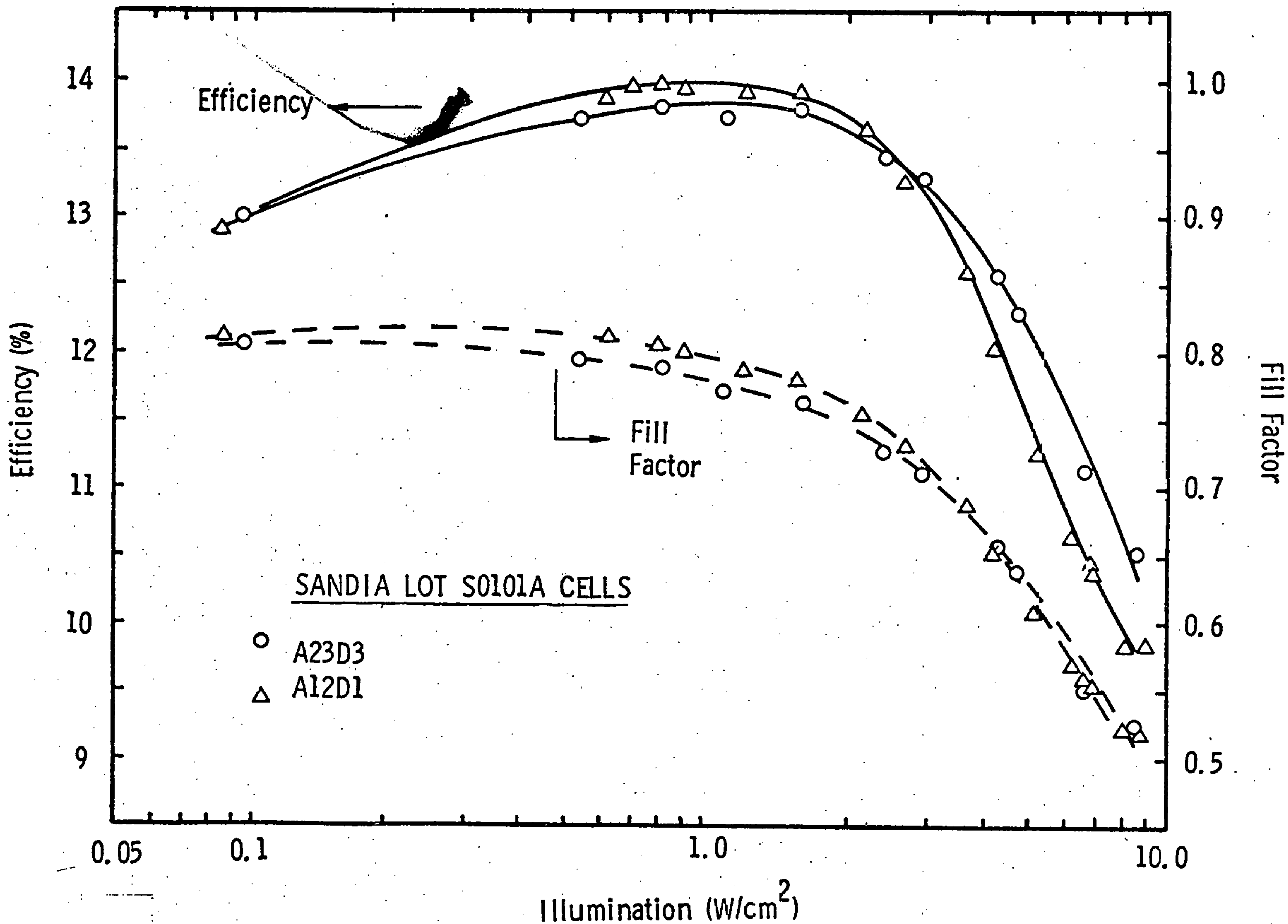
OPTIMIZE PERFORMANCE AND DEVELOP FABRICATION PROCESSING FOR SILICON SOLAR CELLS OPERATING IN 40 - 100 SUN INTENSITIES AND AT ELEVATED TEMPERATURES (100°C)

STATUS -

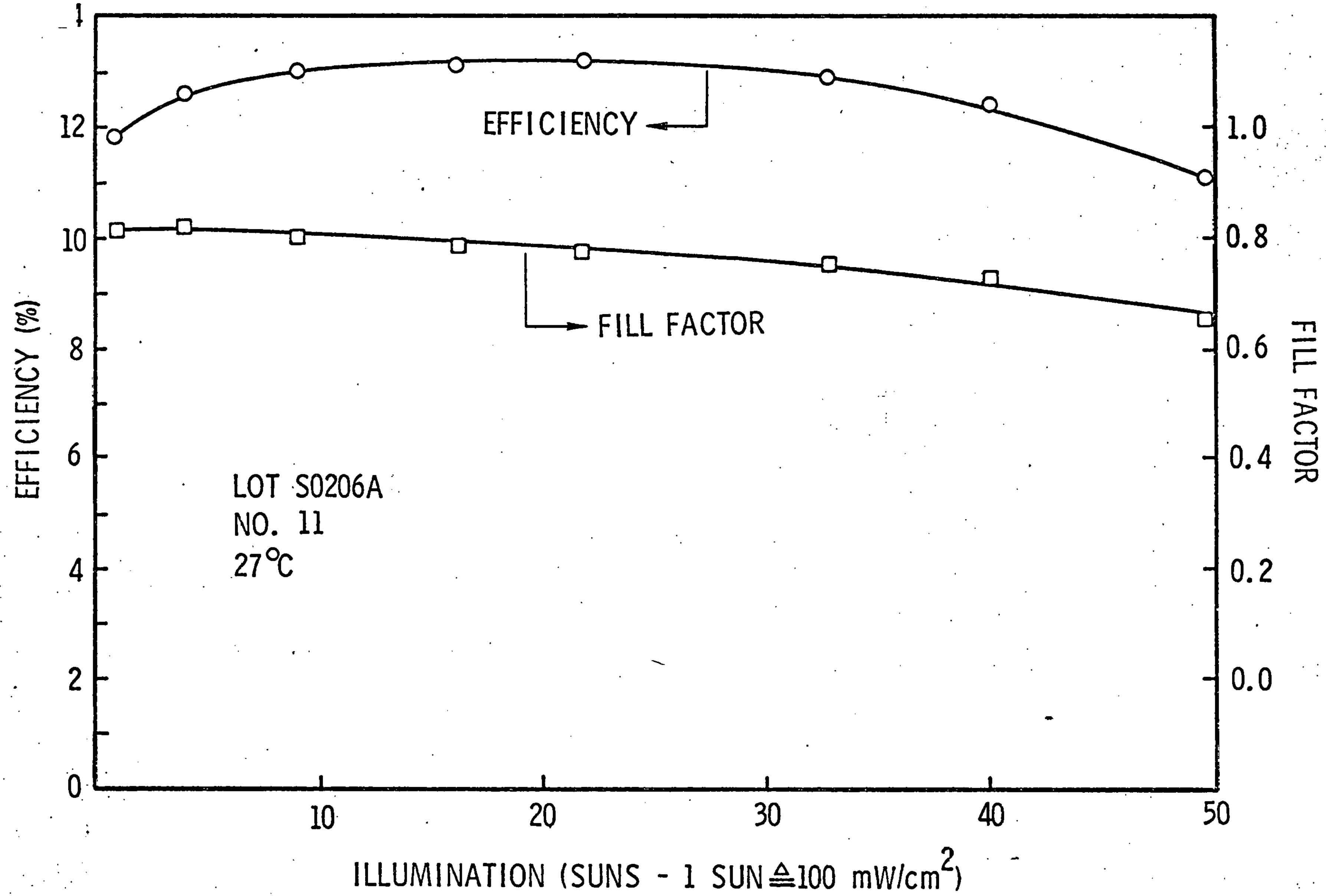
CONVERSION EFFICIENCY GREATER THAN 10% AT 40 SUNS AND 100°C ACHIEVED, TWO INCH WAFER DESIGN DEVELOPED

SILICON SOLAR CELLS FOR MULTIPLE-SUN, HIGH TEMPERATURE APPLICATIONS

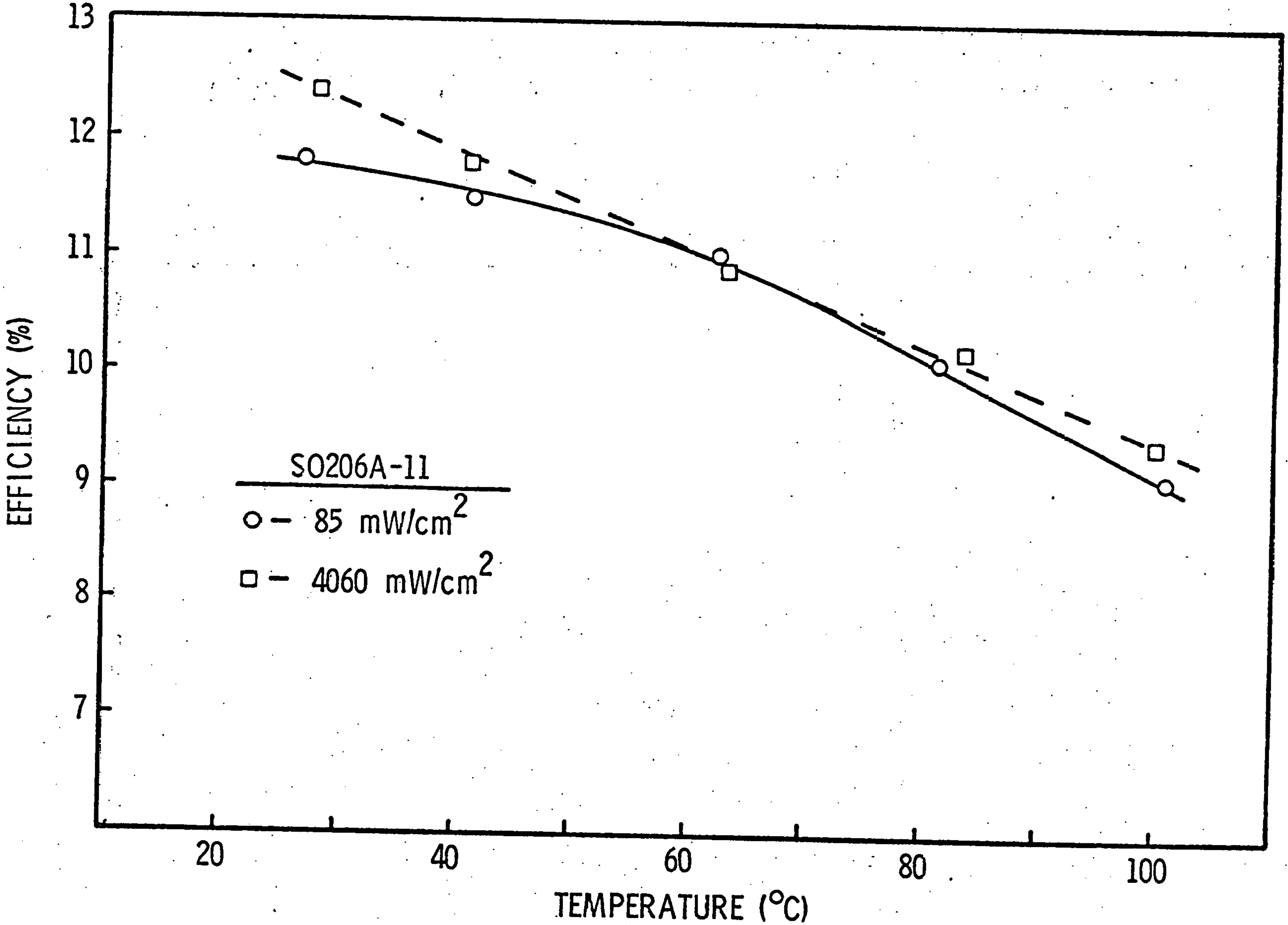
- THEORETICAL
  - 1-D NUMERICAL DEVICE SIMULATION
  - 2-D CURRENT-VOLTAGE CALCULATIONS
- MORPHOLOGICAL
  - $N_A \sim 10^{17}$ CM^{-3}
  - JUNCTION DEPTH $\sim$ 3000 Å
  - P^+ BACK CONTACT
  - AL-AG METALLIZATION
- FABRICATION
  - P^+ IMPLANT (BORON)
  - N^+ DIFFUSION (PHOSPHOROUS)
  - PHOTOLITHOGRAPHY
  - AR COATING



PERFORMANCE OF SANDIA 1X2 cm HIGH INTENSITY SILICON SOLAR CELLS AT 27°C



PERFORMANCE OF SANDIA TWO INCH DIAMETER WAFER HIGH INTENSITY SILICON SOLAR CELLS AS A FUNCTION OF ILLUMINATION INTENSITY



TEMPERATURE PERFORMANCE OF SANDIA TWO INCH DIAMETER WAFER HIGH INTENSITY SOLAR CELLS

SILICON SOLAR CELLS FOR MULTIPLE-SUN, HIGH TEMPERATURE APPLICATIONS

FUTURE WORK

- BACK SURFACE FIELD CELLS (N^+-P-P^+)

  OPEN CIRCUIT VOLTAGE ENHANCEMENT

- IMPLANTED JUNCTIONS (ARSENIC OR PHOSPHORUS)

  IMPROVED EMITTER EFFICIENCY

- EPITAXIAL JUNCTION FORMATION

  IMPROVED EMITTER EFFICIENCY

1 KW PROTOTYPE CONCENTRATOR ARRAY

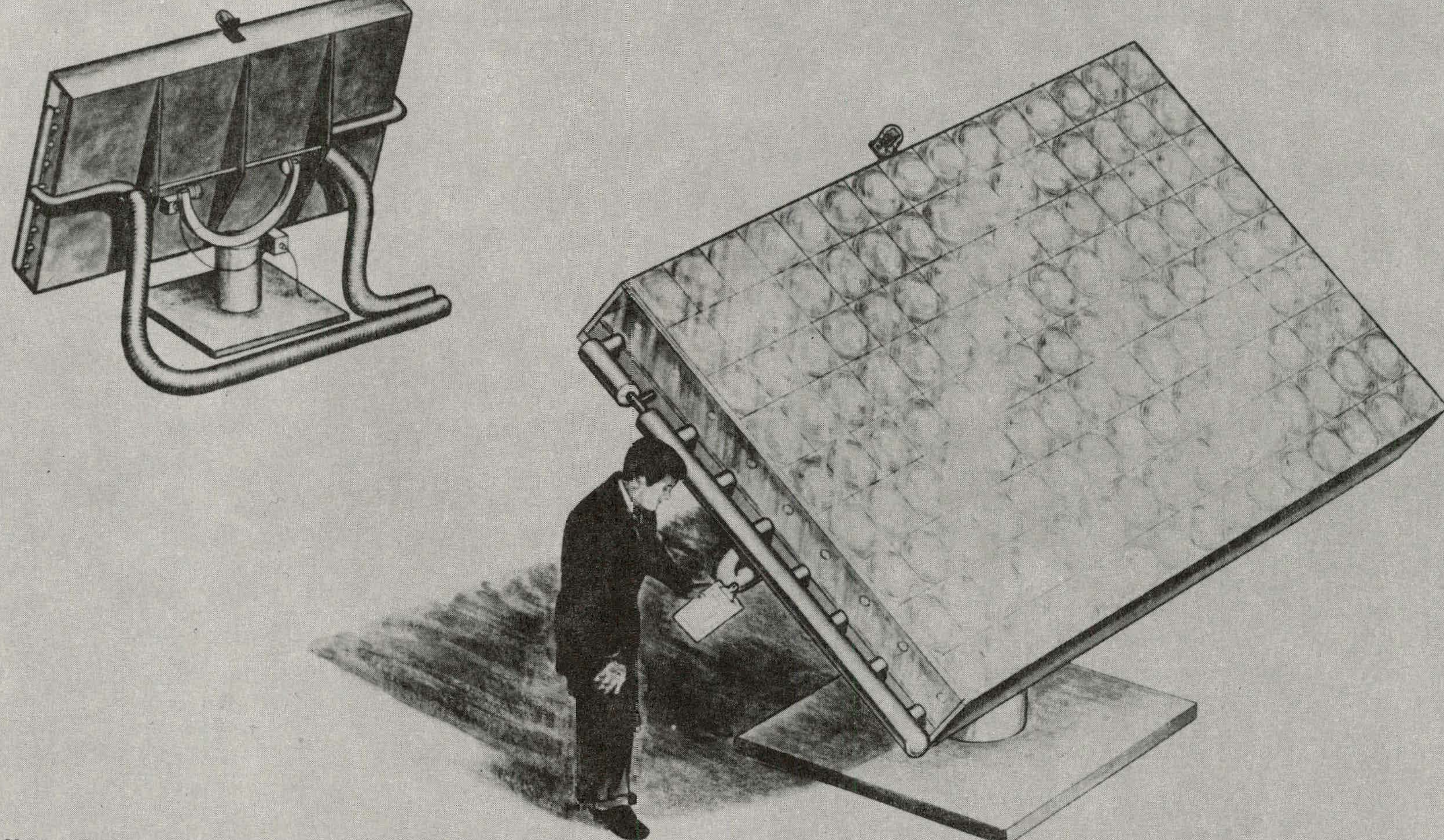
SANDIA LABORATORY - E. L. BURGESS

OBJECTIVE -

DESIGN, CONSTRUCT, AND EVALUATE A 1 KW PHOTOVOLTAIC CONCENTRATOR ARRAY HAVING VARIOUS CELL COOLING OPTIONS

STATUS -

ARRAY AND TRACKING STRUCTURES COMPLETE, PROTOTYPE FRESNEL LENS DELIVERED, FIRST PRODUCTION OF SOLAR CELLS COMPLETE, SYSTEM OPERATIONAL BY 9/76



1 KW_e PHOTOVOLTAIC TEST BED

1 KW_E PHOTOVOLTAIC CONCENTRATOR SUBSYSTEM

-DESIGN SPECIFICATIONS-

ELECTRICAL

PEAK ELECTRICAL POWER	1000 W
NUMBER CELLS (SERIES CONNECTED)	135
CELL EFFICIENCY, η_c	
AT 27°C	0.140
At 100°C	0.118
PEAK POWER PER CELL	7.4 W
CELL AREA	15.2 cm^2

OPTICAL SYSTEM

SQUARE FRESNEL LENS CONCENTRATORS	
30.5 cm FOCAL LENGTH (f 1.0) POINT FOCUSING	
GEOMETRIC CONCENTRATION RATIO	60 X
ESTIMATED OPTICAL EFFICIENCY, η_o	0.80
ACTUAL CONCENTRATION RATIO	48 X

MECHANICAL

DIMENSIONS	2.95 x 4.98 x 0.46 m
COLLECTOR AREA	14.7 m^2
LENS PACKING EFFICIENCY, η_p	0.86

COOLING OPTIONS

PASSIVE (INCLUDING EXTENDED SURFACES)
FORCED AIR
WATER LOOP

ARRAY EFFICIENCY

ELECTRICAL, $\eta_A = \eta_p \eta_o \eta_c$	
AT 27°C	0.096
AT 70°C	0.090
THERMAL (COMBINED SYSTEM), η_T	
AVE T = 70°C, 1 GLAZING	0.40
2 GLAZINGS	0.49

PHOTOVOLTAIC-CONCENTRATOR DEVELOPMENT

CONTRACTORS

SOLAR DATA-ESTIMATION OF DIRECT SOLAR RADIATION
AEROSPACE CORPORATION

SUBSYSTEM ANALYSIS AND EXPERIMENTAL EVALUATION
ARIZONA STATE UNIVERSITY
SPECTROLAB INC.

LOW CONCENTRATION CPC PROTOTYPE ARRAYS
ARGONNE NATIONAL LAB

HIGH CONCENTRATION PROTOTYPE SILICON ARRAYS
RCA LABORATORIES

INTERDIGITATED BACK CONTACT SILICON CELLS
PURDUE UNIVERSITY*

HIGH PERFORMANCE GALLIUM ARSENIDE CELLS
HUGHES RESEARCH LABS*
VARIAN ASSOCIATES*

* CONTRACT IN NEGOTIATION

SOLAR RADIATION AND WEATHER DATA TAPES

AEROSPACE CORPORATION - C. RANDALL

PERIOD: 9 MONTHS FUNDING: $45K

OBJECTIVE -

ADD ESTIMATED DIRECT-NORMAL RADIATION VALUES TO THE HOURLY SOLAR AND WEATHER DATA BASE BEING RESERECTED BY ERDA/NOAA

STATUS -

ESTIMATION TECHNIQUE BEING REFINED, DATA TAPES FOR ~30 U.S. LOCATIONS AVAILABLE BY 3/77

TERRESTRIAL PHOTOVOLTAIC POWER SYSTEMS WITH SUNLIGHT CONCENTRATION

ARIZONA STATE UNIVERSITY - C. E. BACKUS

PERIOD: 12 MONTHS FUNDING: $156K

SPECTROLAB INC. - J. A. CASTLE

PERIOD: 6 MONTHS FUNDING: $85K

OBJECTIVES -

- RECOMMEND CONCENTRATOR TECHNOLOGY TO BE DEVELOPED FOR ACHIEVEMENT OF $2000/KW GOAL
- CONTINUE EXPERIMENTAL TESTING OF CONCENTRATOR SYSTEMS
- PERFORM SUBSYSTEM SIMULATION STUDIES
- CONTINUE THERMAL ANALYSIS AND EXPERIMENTS OF SOLAR CELL COOLING METHODS
- HIGH INTENSITY SOLAR CELL DEVELOPMENT

EVALUATION CRITERIA

1. ENERGY GENERATION COSTS
2. TECHNICAL RISK
3. MAINTENANCE REQUIREMENTS
4. LIFE EXPECTANCY
5. DEGRADATION OF PERFORMANCE DUE TO DIRT
6. POTENTIAL FOR REDUCED COSTS
7. SITE PREPARATIONS
8. SUITABLE FOR IMPLEMENTATION IN SMALL UNITS

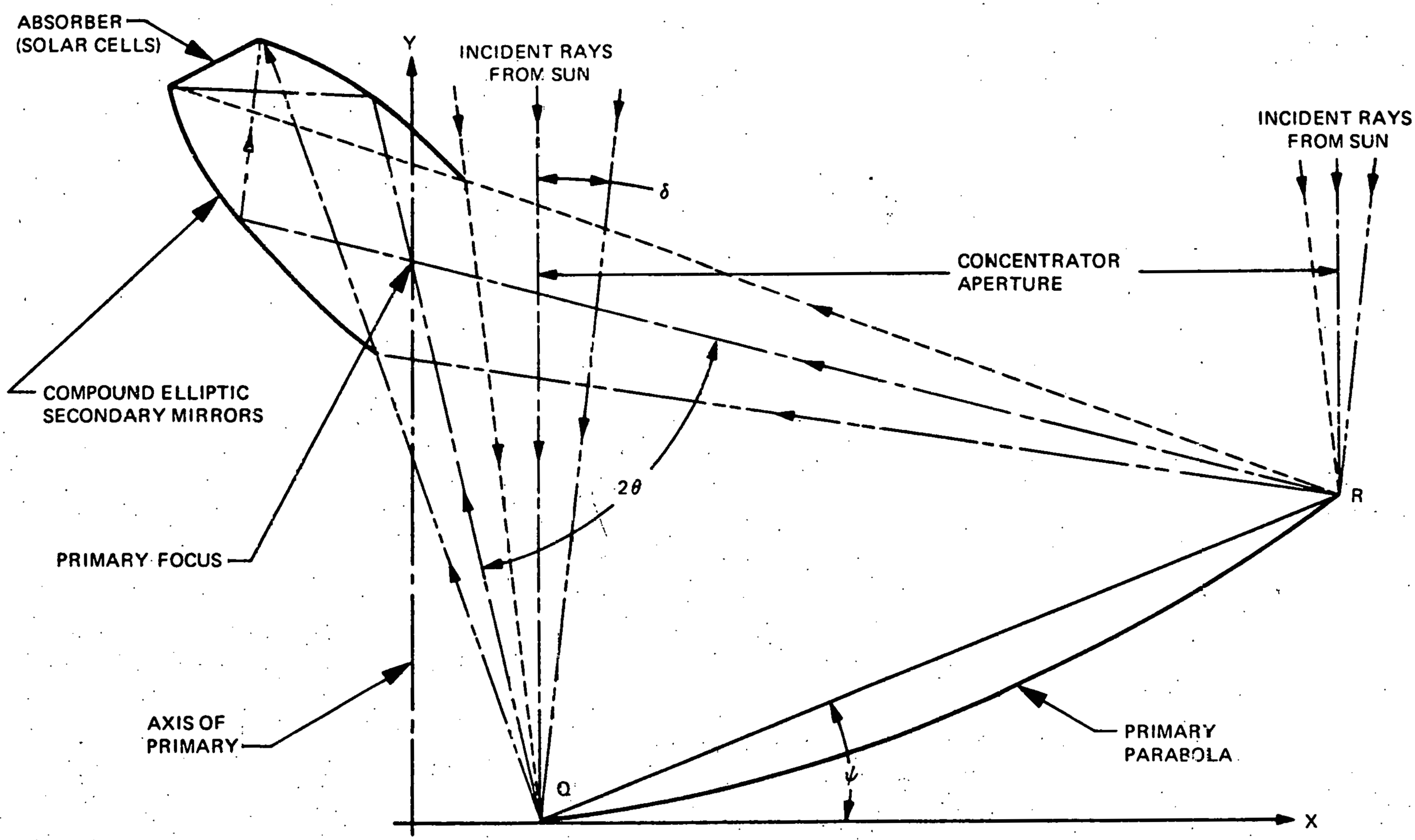
MOST PROMISING CONCENTRATOR SYSTEMS
FOR NEAR-TERM DEVELOPMENT

- PARABOLIC TROUGH - CEC SECONDARY, VARIOUS TRACKING MODES
  CONCENTRATION RATIO = 19-25

- LINEAR FRESNEL LENS, TWO AXIS TRACKING
  CONCENTRATION RATIO = 18

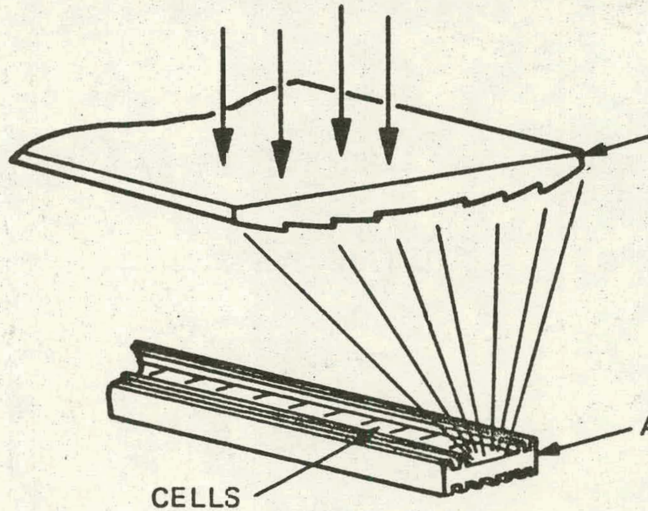
- CIRCULAR FRESNEL LENS, TWO AXIS TRACKING
  CONCENTRATION RATIO = 82

OFF-AXIS PTCEC RAY TRACE DIAGRAM

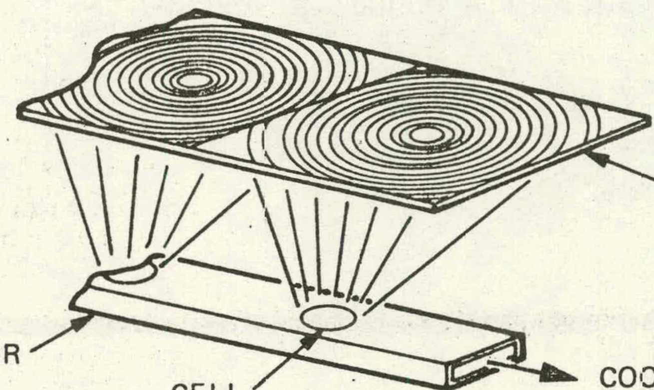


METHODS OF OPTICAL CONCENTRATION - CONTD.

METHOD NO. 3 - LINEAR FRESNEL



METHOD NO. 4 - CIRCULAR FRESNEL



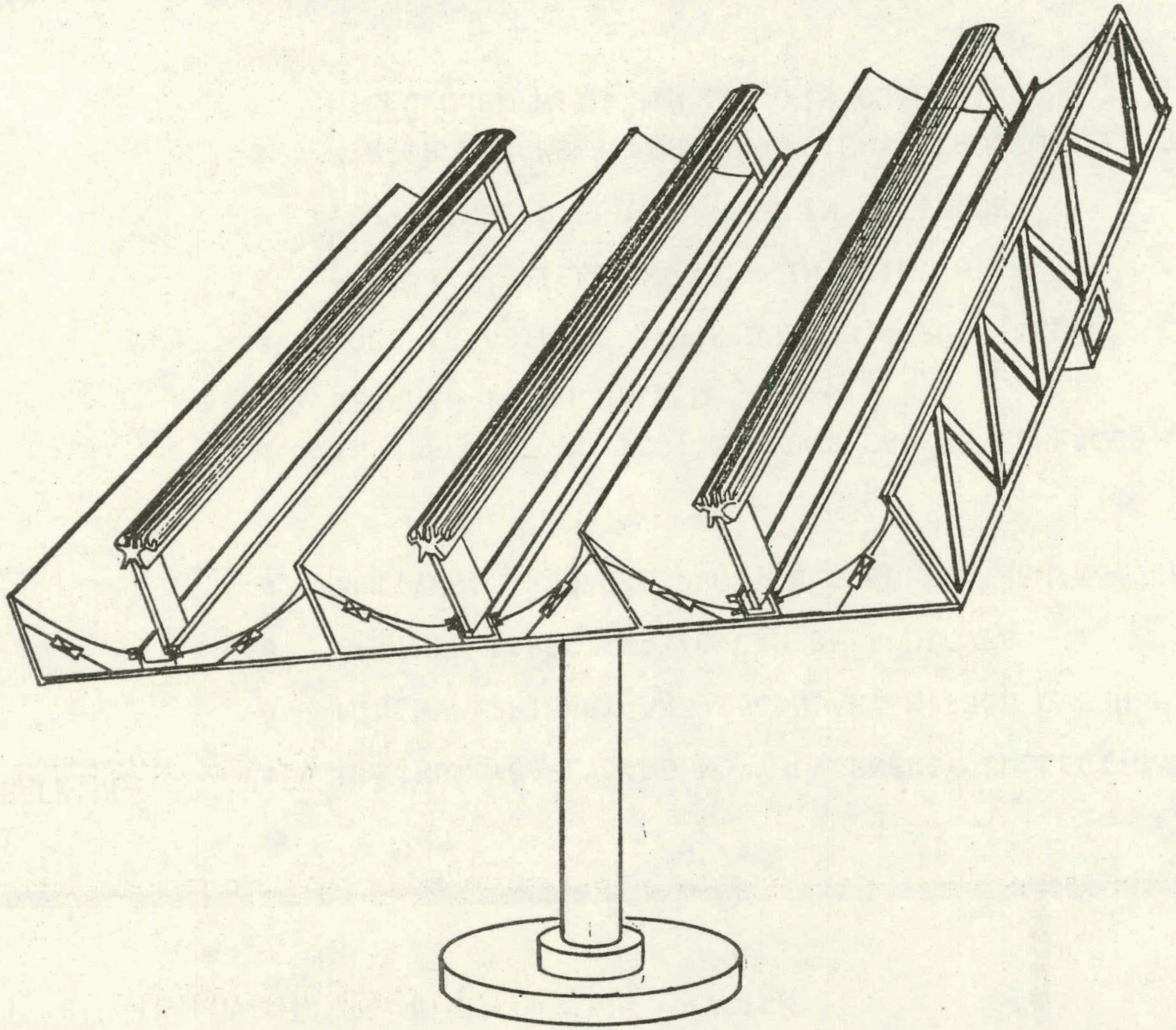
RECOMMENDED CONCENTRATOR SYSTEM

GENERAL SYSTEM DATA

TRACKING:	2 AXIS (ONE AXIS VERTICAL)
OPTICS:	PARABOLIC TROUGH WITH COMPOUND ELLIPTICAL CONCENTRATOR (PTCEC)
COOLING:	PASSIVE
CONCENTRATION:	25
SIZE:	65 M^2 CLEAR APERTURE
PEAK POWER RATING:	6.74 kW PER UNIT

PARABOLIC TROUGH WITH COMPOUND ELLIPTICAL SECONDARY

(FOR ONE OR TWO AXIS TRACKING)



INTRINSIC ADVANTAGES OF RECOMMENDED SYSTEM

2 AXIS TRACKING:

- MAXIMUM YEARLY AND MONTHLY ENERGY COLLECTION
- MINIMUM PRIMARY AND SECONDARY MIRROR OVERHANG
- OPTIMUM ASPECT RATIO CAN BE ACHIEVED
- ALTITUDE AXIS CAN PROVIDE SELF FEATHERING FEATURE

PTCEC:

- INEXPENSIVE OPTICS; MIRRORS CAN BE REPLACED OR RETAPED IN THE FIELD
- GOOD IRRADIANCE DISTRIBUTION ACROSS CELLS
- $\sim \pm 1.5°$ FIELD OF VIEW IN AZIMUTH
- VERY LARGE FIELD OF VIEW IN ALTITUDE
- MIRROR ASSEMBLY MORE EFFICIENT STRUCTURALLY THAN PTCEC USED WITH SINGLE AXIS CONCEPTS

PASSIVE COOLING:

- NO POWER REQUIRED FOR BLOWERS OR PUMPS
- LESS EXPENSIVE THAN ACTIVE COOLED SYSTEMS

IMPORTANT OBSERVATIONS ASSOCIATED WITH PHOTOVOLTAIC CONCENTRATOR SYSTEMS

- MIRROR DISTORTIONS CAN SIGNIFICANTLY AFFECT SYSTEM EFFICIENCY
- SHADING OF ANY PORTION OF CELL CIRCUITS BY STRUCTURE SHOULD BE AVOIDED
- DISTRIBUTION OF RADIATION ACROSS CELLS IS IMPORTANT
- GOOD ALIGNMENT & RIGIDITY ARE REAL REQUIREMENTS
- SELF FEATHERING STRUCTURES ARE DESIRABLE

APPLICATION OF THE COMPOUND PARABOLIC CONCENTRATOR TO SOLAR PHOTOVOLTAIC CONVERSION

ARGONNE NATIONAL LABORATORY - ROLAND WINSTON

PERIOD: 6 MONTHS FUNDING: $144K

OBJECTIVE -

DESIGN, FABRICATE, AND DELIVER 4x4 FOOT NON-TRACKING ARRAYS EMPLOYING HOLLOW TROUGH AND SOLID DIELECTRIC COMPOUND PARABOLIC CONCENTRATORS AS A MEANS OF OVERALL COST REDUCTION

STATUS -

DESIGNS COMPLETE, SOLAR CELLS PROCURED, SUB-ARRAYS TESTED BY 9/76

100 WATT PHOTOVOLTAIC ENERGY CONVERTER WITH HIGH SOLAR CONCENTRATION AND PRECISION TRACKING

RCA LABORATORIES - L. S. NAPOLI

PERIOD: 12 MONTHS FUNDING: $273K

OBJECTIVE -

DESIGN, FABRICATE, AND DELIVER SIX 100 WATT PASSIVELY COOLED SILICON ARRAYS EMPLOYING HIGH SOLAR CONCENTRATION TO ACHIEVE COST REDUCTION

STATUS -

SECOND-GENERATION DESIGN BEING FABRICATED

INTERDIGITATED BACK CONTACT SILICON CELLS FOR CONCENTRATOR APPLICATIONS

PURDUE UNIVERSITY - R. J. SCHWARTZ

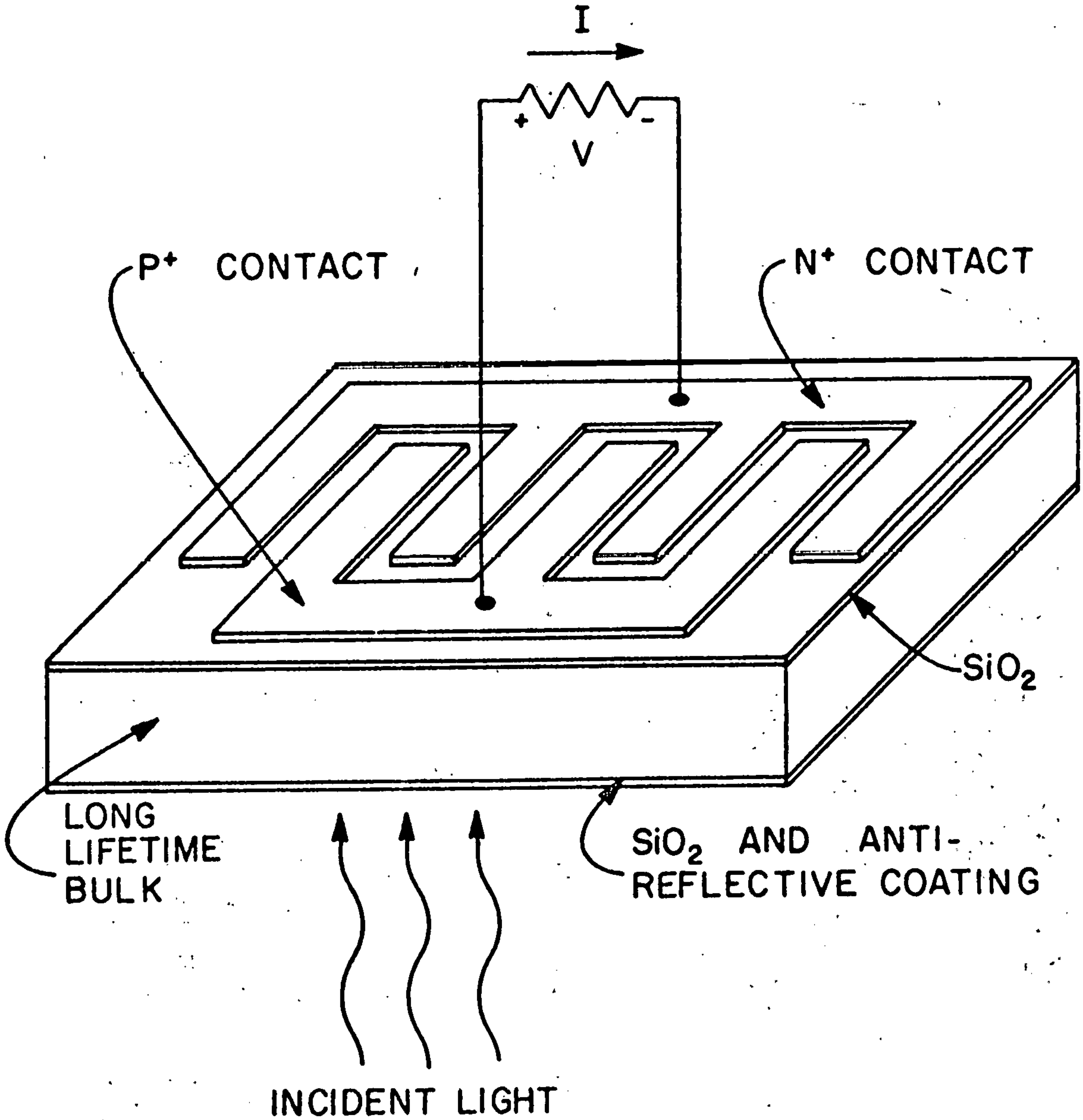
PERIOD: 12 MONTHS FUNDING: $76K

OBJECTIVE -

ACHIEVE 18% OR GREATER POWER CONVERSION EFFICIENCY AT 100 SUNS INTENSITY

STUDY TASKS -

- CELL DESIGN OPTIMIZATION
- HEAT SINK DESIGN
- CELL FABRICATION AND CHARACTERIZATION
- DELIVERY OF PROTOTYPE CELLS



AN INTERDIGITATED BACK CONTACT PHOTOVOLTAIC CELL

HIGH PERFORMANCE GALLIUM ARSENIDE SOLAR CELLS FOR CONCENTRATOR APPLICATIONS

HUGHES RESEARCH LABS - R. C. KNECHLI

VARIAN ASSOCIATES - R. L. BELL

OBJECTIVE -

ACHIEVE 20% OR GREATER POWER CONVERSION EFFICIENCY AT 1000 SUNS INTENSITY

STUDY TASKS -

- CELL DESIGN OPTIMIZATION
- CELL FABRICATION AND CHARACTERIZATION
- LIFETESTING AND RELIABILITY ASSESSMENT
- DELIVERY OF PROTOTYPE CELLS

PHOTOVOLTAIC-CONCENTRATOR DEVELOPMENT

PLANS - NEXT SIX MONTHS

- EVALUATE PROTOTYPE CONCENTRATOR ARRAYS
- CONTINUE SYSTEM AND ECONOMIC ANALYSIS
- INITIATE COMBINED PHOTOVOLTAIC/THERMAL EXPERIMENTS
- ISSUE RFP FOR 10 KW CONCENTRATOR SUBSYSTEM

HIGH ENERGY DENSITY PHOTOVOLTAIC CONVERTERS

Grant or Contract Number: None

Author: David H. Navon

Principal Investigator: David H. Navon
Professor
Electrical & Computer
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University of Massachusetts
Amherst, Massachusetts 01002

Presented at the National Solar Photovoltaic Program Review Meeting

August 3 - 6, 1976

University of Maine at Orono

Orono, Maine 04473

Abstract

A program is proposed to investigate theoretically the optimum design of semiconductor photovoltaic converters under high energy density irradiation conditions. The work is prompted by the trend toward using mirrors and lenses to focus the incident solar energy onto relatively small solar cell devices. This trend results from the present high cost of semiconductor single-crystal materials and the relatively inefficient performance of deposited thin film cells. The proposed research will be directed toward calculating the current density and temperature distributions in a two-dimensional model of a semiconductor photovoltaic cell, as well as the power output under intense illumination. Due to the highly nonlinear nature of the electrical carrier flow and heat flow equations describing the device operation, a difference equation computer analysis of the problem will be employed. This will facilitate investigation of a variety of device structures incorporating heterotaxial layers, arbitrary impurity distributions, different electrode configurations, unusual cell geometries, etc. Effects such as the impurity concentration, temperature, and field dependence of the carrier mobilities, the temperature dependence of the thermal conductivity, the various surface and bulk recombination mechanisms, etc., can be readily included in this computer-aided two-dimensional, high current density level, nonisothermal model.

PROPOSED RESEARCH

1. THE OPERATION OF SOLAR CELLS UNDER HIGH LEVEL, CONCENTRATED ILLUMINATION CONDITIONS, INCLUDING TEMPERATURE EFFECTS.

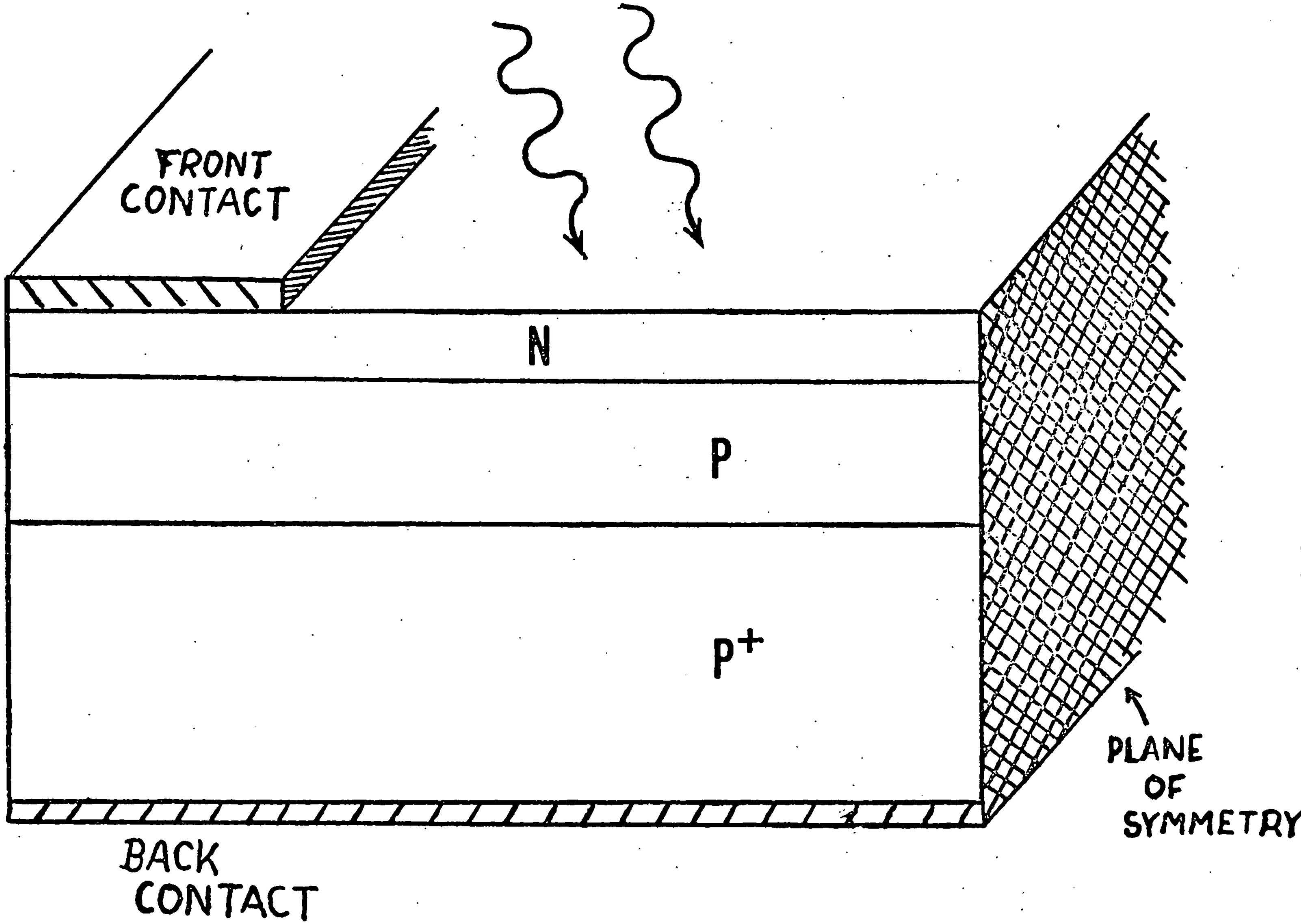
2. THE DETERMINATION OF THE MOST EFFICIENT CELL GEOMETRY AND ELECTRODE STRUCTURE FOR OPTIMUM ENERGY CONVERSION, USING A TWO-DIMENSIONAL ANALYSIS.

3. THE MODELING OF ALL VARIETIES OF HETEROJUNCTION-TYPE STRUCTURES AS WELL AS HOMOJUNCTION TYPES.

4. THE INCORPORATION OF ALL OF THE KNOWN CARRIER RECOMBINATION PROCESSES IN THE TREATMENT, AND THE INCLUSION OF BOTH BULK AND SURFACE REACTIONS.

5. THE STUDY OF HEAVY DOPING EFFECTS WHICH CAUSE ENERGY BAND GAP ALTERATION, AS WELL AS THE POSSIBLE UTILIZATION OF FERMI STATISTICS.

6. THE CALCULATION OF SOLAR CELL POWER OUTPUT UNDER A VARIETY OF ELECTRICAL LOADING CONDITIONS.



CROSS SECTION

643

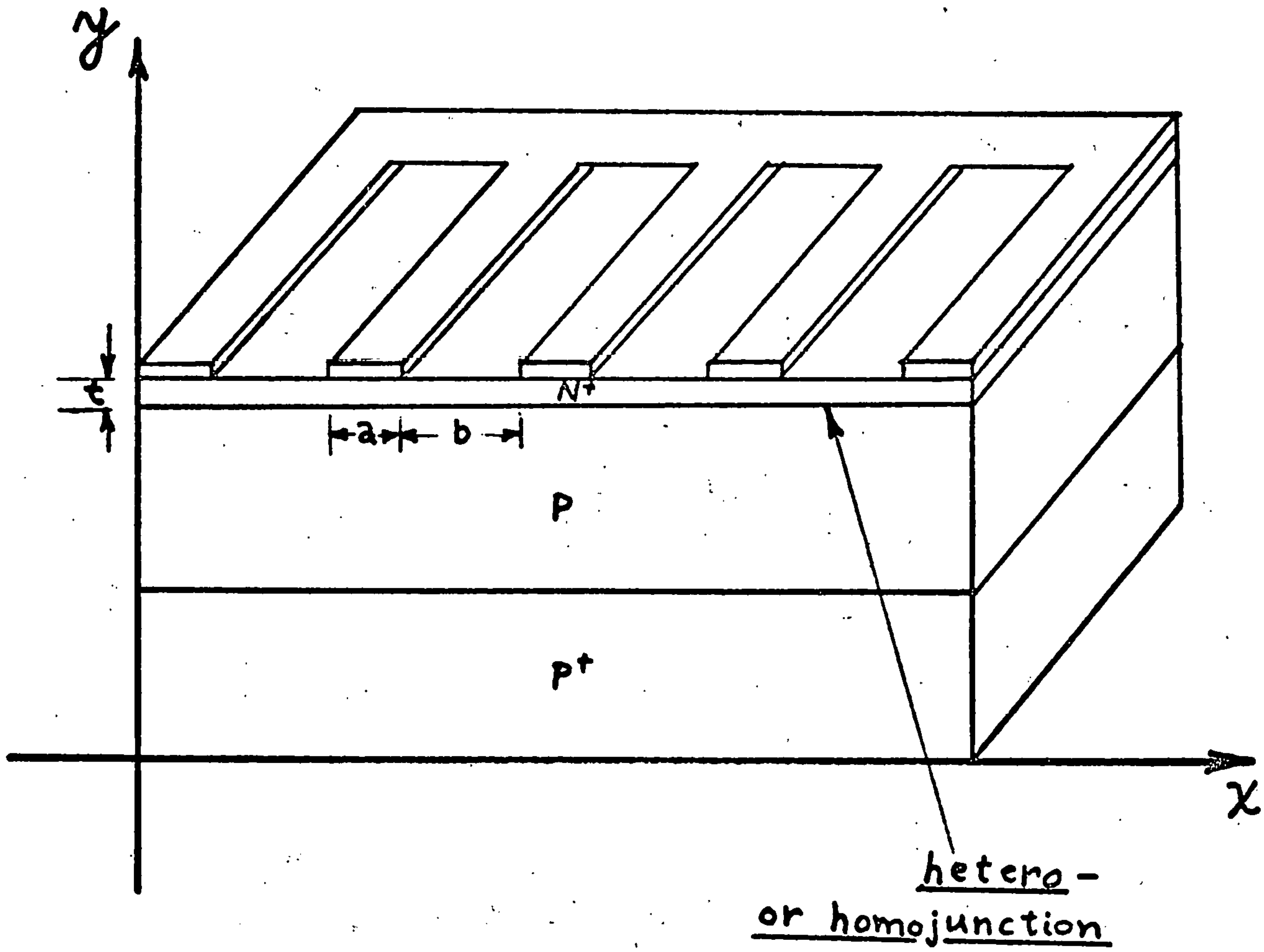
1. $$\nabla^2 \psi = -\frac{q}{\epsilon}(p - n + N)$$

2. $$\nabla \cdot J_p = -q(R - G)$$

3. $$\nabla \cdot J_n = q(R - G)$$

4. $$\nabla^2 T = -\frac{Q}{K}$$

5. $$G(x) = \sum_{\lambda} T(\lambda) N_{ph}(\lambda) \eta(\lambda) e^{-\alpha(\lambda) \cdot x}$$


y
t
N+
a
b
P
P+
x
hetero-
or homojunction

TIME AND TEMPERATURE DEPENDENT TRANSPORT EQUATIONS FOR THE 2-D TRANSISTOR MODEL

$$\nabla^2 \psi = \frac{-q}{\epsilon}(p - n + N)$$ POISSON'S EQ.

$$\nabla \cdot J_p = -q\frac{\partial p}{\partial t} - qR$$

CONTINUITY EQS.

$$\nabla \cdot J_n = q\frac{\partial n}{\partial t} + qR$$

$$\nabla^2 T = -\frac{Q}{K} + \frac{\rho C_p}{K}\frac{\partial T}{\partial t}$$ HEAT FLOW EQ.

$$J_p = -q\mu_p p \nabla\psi - qD_p \nabla p - qpD_p^T \nabla T$$

$$J_n = -q\mu_n n \nabla\psi + qD_n \nabla n + qnD_n^T \nabla T$$

$$J_T = J_p + J_n + \epsilon \frac{\partial E}{\partial t}$$

$$Q = (J_p + J_n) \cdot E$$

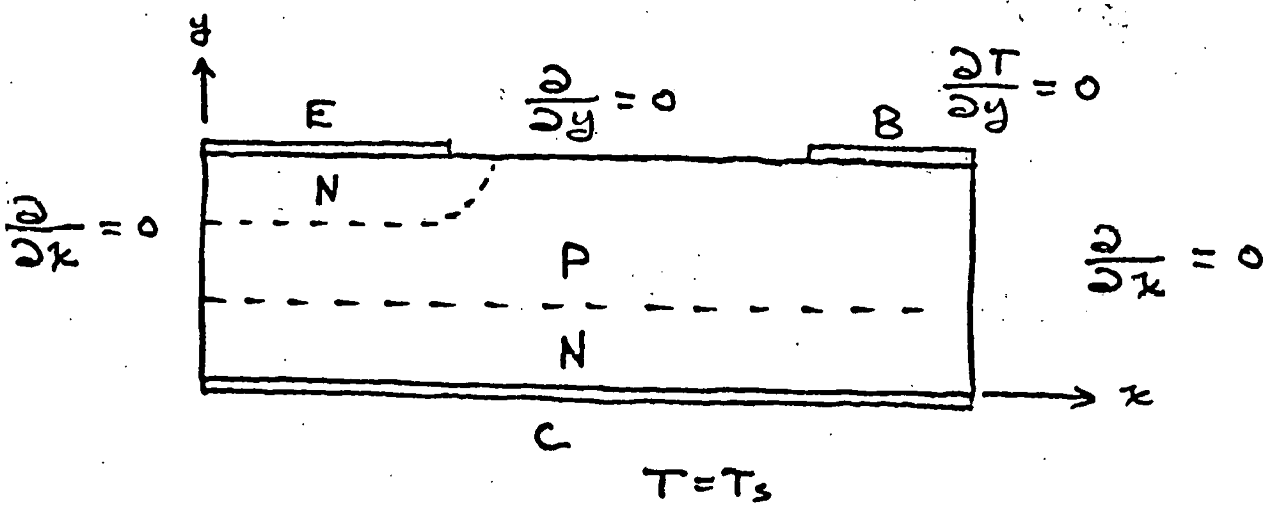
WHERE

$$D_p^T = \frac{k\mu_p}{2q}$$

$$D_n^T = \frac{k\mu_n}{2q}$$

(STRATTON)

BOUNDARY CONDITIONS



AT E, B AND C

CONTACTS ARE ASSUMED TO BE IDEAL OHMIC CONTACTS. SEMICONDUCTOR IS IN THERMODYNAMIC EQUILIBRIUM AND THE CHARGE NEUTRALITY CONDITIONS ARE VALID

THUS: φ_p, φ_n, AND ψ ARE SPECIFIED AT THE CONTACTS

ASSUMPTIONS

BOLTZMAN APPROXIMATION OF FERMI STATISTICS

$$p = n_i(T)\, e^{\frac{q(\varphi_p - \psi)}{kT}}$$

$$n = n_i(T)\, e^{\frac{q(\psi - \varphi_n)}{kT}}$$

EINSTEIN RELATION

$$D_p = \frac{kT}{q}\mu_p \quad , \quad D_n = \frac{kT}{q}\mu_n$$

HALL-SHOCKLEY-READ RECOMBINATION MODEL

$$R = \frac{pn - n_i^2}{\tau_{po}(n+n_i) + \tau_{no}(p+n_i)}$$

τ_{po} AND τ_{no} ASSUMED CONSTANT

SOLUTION TECHNIQUE

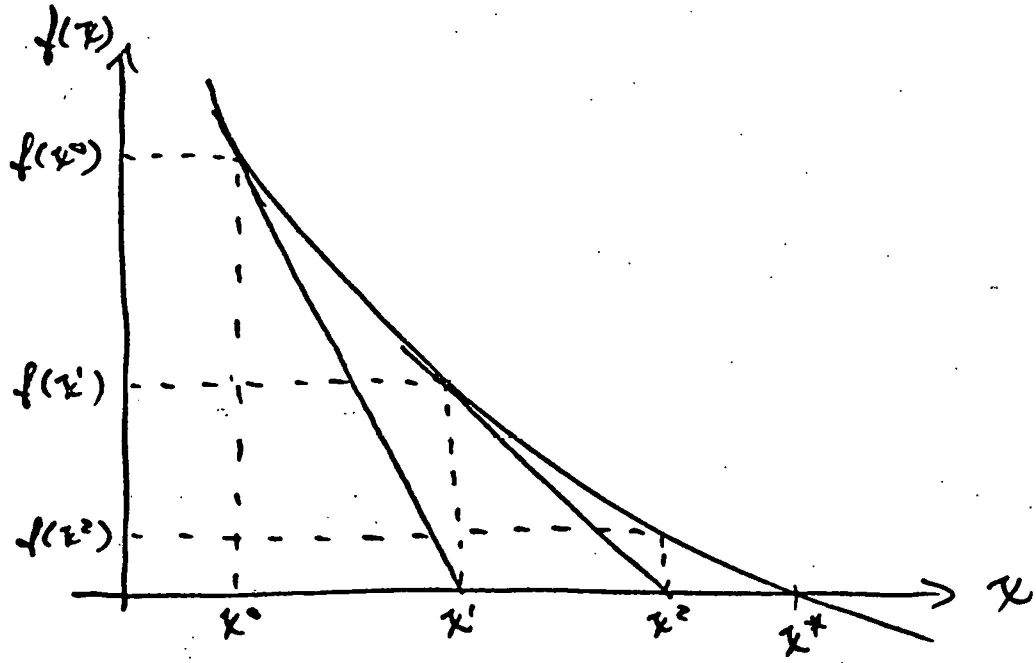
APPROXIMATE REGION BY AN ARRAY OF N x M DISCRETE POINTS ON A NON UNIFORM GRID.

DISCRETIZE EQUATIONS IN THE TIME AND SPACE VARIABLES.

SOLVE THE 4 x N x M EQUATIONS SIMULTANEOUSLY BY NEWTON'S ITERATIVE METHOD.

NEWTON'S ITERATIVE TECHNIQUE

CONSIDER A NONLINEAR FUNCTION OF A SINGLE VARIABLE x. WE WISH TO FIND x^* SUCH THAT $f(x^*) = 0$.



NEWTON'S ITERATIVE TECHNIQUE FOR SOLVING $f(x^*) = 0$.

$$x^{k+1} = x^k - \left[f'(x^k) \right]^{-1} f(x^k)$$

WITH x^0 = INITIAL "GUESS"

OR:

$$f'(x^k)\,\delta^{k+1} = -f(x^k)$$

AND:

$$x^{k+1} = x^k + \delta^{k+1}$$

PROCESS IS REPEATED UNTIL $\delta^m \approx 0$

AT WHICH TIME $f(x^m) \approx 0$

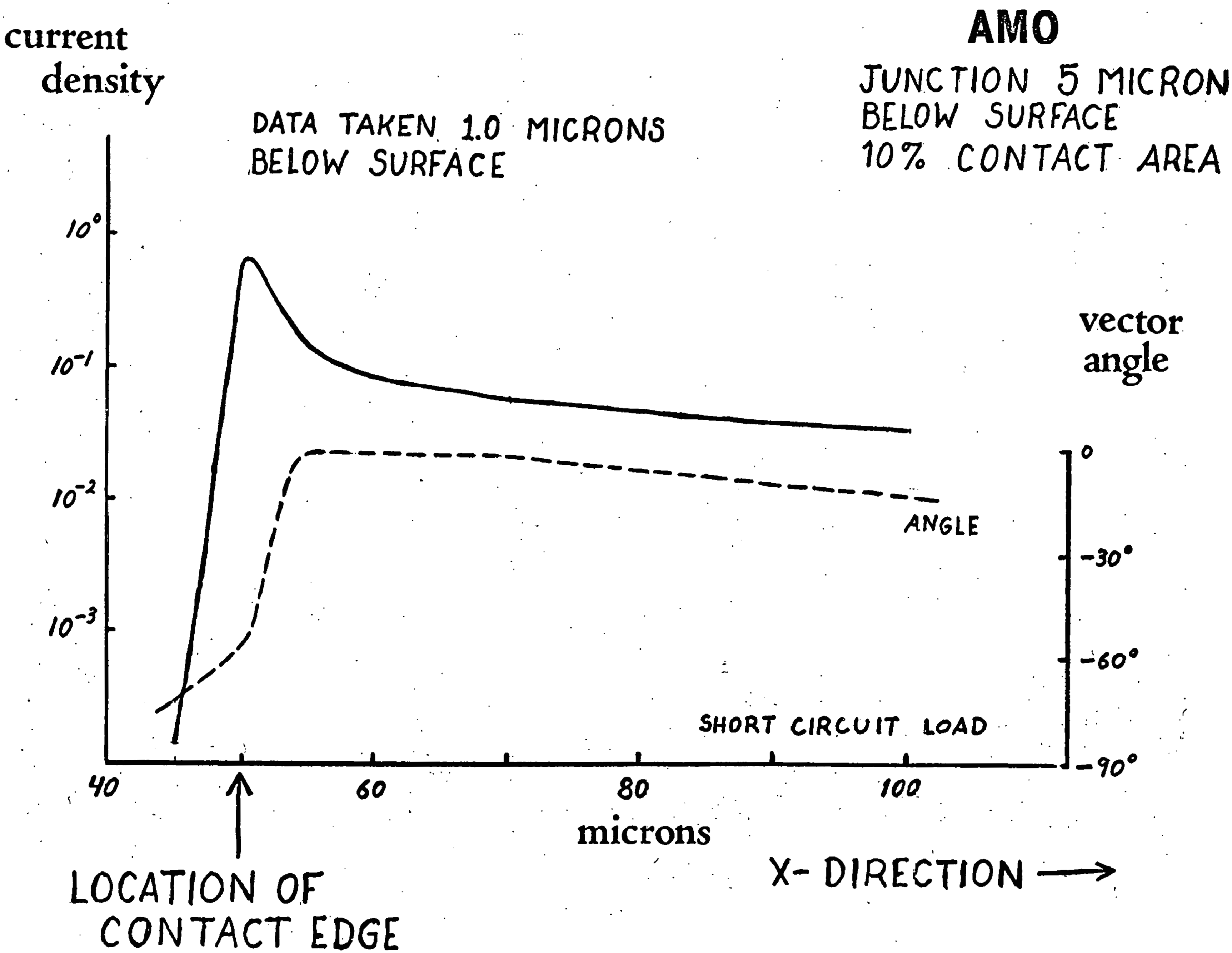
AND $x^m \approx x^*$

ADVANTAGES OF NEWTON'S TECHNIQUE

1) SUITABLE FOR SOLVING SIMULTANEOUS NONLINEAR EQS.
2) EXHIBITS QUADRADIC CONVERGENCE
3) CAN BE EXTENDED TO INCLUDE t AS AN INDEPENDENT VARIABLE

DISADVANTAGES

1) NECESSARY TO INVERT A LARGE (SPARSE) MATRIX
2) MUST EVALUATE $f'(x^k)$



current density
DATA TAKEN 1.0 MICRONS BELOW SURFACE
AMO
JUNCTION 5 MICRON BELOW SURFACE
10% CONTACT AREA
10°
10-1
10-2
10-3
vector angle
0
ANGLE
-30°
-60°
SHORT CIRCUIT LOAD
-90°
40
60
80
100
microns
LOCATION OF CONTACT EDGE
X- DIRECTION →

653

HIGH-EFFICIENCY THIN-FILM GaAs SOLAR CELLS

NSF GRANT AER 76-01823

DECEMBER 1, 1975 — NOVEMBER 30, 1976

$230,000

PRINCIPAL INVESTIGATOR: RICHARD J. STIRN
GUIDANCE AND CONTROL RESEARCH GROUP
JET PROPULSION LABORATORY

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

AUGUST 3-6, 1976
UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE 04473

High-Efficiency Thin-Film GaAs Solar Cells

Richard J. Stirn

Jet Propulsion Laboratory
Pasadena, California 91103

ABSTRACT

A program to investigate the feasibility of growing large grain polycrystalline GaAs by chemical vapor deposition on recrystallized Ge films, to fabricate AMOS (Antireflection-Coated Metal-Oxide-Semiconductor) solar cells on the films, and to further investigate the physics of AMOS cells on single crystals began in January, 1976. Concepts of the device structure and processing, material availability and cost considerations, and a brief description of the planned approaches were given at the first and second Semiannual Review meetings and in the first Interim Report (April, 1976).

During the last six months, four of which were devoted to rebuilding the vacuum evaporation system for very fast pump-down times and establishing a clean bench environment for all processing steps, considerable progress has been made in obtaining reproducibly high open-circuit voltages on oxidized single crystal GaAs before contacting with grids or depositing AR coatings. In contrast to earlier results before the above modifications, the two thermal oxidation processes using ozone and oxygen in the presence of a resin epoxy now give very similar results: (1) increasing the Au-GaAs barrier height from 0.90 to 1.03-1.06eV, (2) reduced reverse saturation current densities (I_o), and (3) lowered values of the empirical n-factor in the dark forward current-voltage (I-V) characteristics. In addition, a marked difference was found between several GaAs surfaces having different crystallographic orientation. In particular, one obtains about 100mV higher value V_{oc} when using the (111) Ga-rich surface as compared to the $(\overline{1}\overline{1}\overline{1})$ As-rich surface. The difference is mainly due to a much higher value of I_o with the $(\overline{1}\overline{1}\overline{1})$ surface even though the measured barrier heights are about equal. Values of V_{oc} on (100) surfaces are intermediate.

Chemical characterization of the different oxidized surfaces using X-ray Photoelectron Spectroscopy shows that the oxidation of the As atoms seems to be one of the key processes required for proper film preparation. Significant amounts of Ga_2O_3 are observed in the film and the ratio of oxidized gallium to oxidized Arsenic in the film seems to be most important. A ratio of GaO_x/AsO_x of about 1:1 appears to give higher V_{oc}. Degradation of unprotected cells exposed to water vapor is caused by conversion of As_2O_5 to As_2O_3 and to increased oxide thickness causing high series resistance. Application of gold to the oxide film results in gold reaction with the film and apparent modification of the relative amounts of As^{+3} to As^{+5} in the oxide. Preparation of thick-film grid contacts or AR coatings usually reduce the enhanced V_{oc} from the 0.70-0.75 volt to the 0.60-0.65 volt range without affecting the fill factor. This too may be due to loss of As_2O_5 caused by latent heat of condensation. Modification of the equipment is underway to allow cooling of the sample during the grid and AR depositions.

A third oxidation process using RF-generated oxygen plasmas looks promising because of its potential for very fast oxide growths at room temperature with high uniformity over the surface. Anodized oxidation processes investigated to date have not given results as good as the dry thermal or plasma processes, perhaps because of the rapid conversion of As_2O_5 to As_2O_3 in the presence of water, and modifications of the amount of gallium enrichment of the oxide.

Baseline and AMOS Schottky barrier solar cells have been fabricated on polished wafers of polycrystalline GaAs with relatively high doping levels. Except for the high doping effects which lower the effective barrier heights, the cells on the poly-GaAs showed no apparent effects from the grain boundaries. Grains averaged 100-500μm in size as shown by SEM/EBIC photographs. These experiments also showed that the 5μm wide grain boundaries had reduced currents locally by about 20% at most, leading to an overall reduction of about 2% from that expected from equivalent material in the single crystal form. Open-circuit voltages of AMOS-treated poly-GaAs wafers were about 600-630 millivolts, comparable to that obtained on single crystal GaAs with similar carrier concentration ($2 \times 10^{17} - 2 \times 10^{18} cm^{-3}$).

Germanium films to be used eventually as an interlayer between low cost metal substrates and GaAs deposited by CVD were found to have a (111) preferred orientation in increasing amounts for increasing substrate temperatures during deposition. Ge films recrystallized to date with focused IR line heaters melted over too large an area for zone recrystallization. Consequently the solidified Ge films, though having very large grain structure, showed dendritic growth regions and an irregular surface morphology. A 10-watt CW Nd/YAG laser has been ordered in order to accomplish much finer zones of melting by line focusing with a cylindrical mirror.

OBJECTIVES

- DEMONSTRATE THE FEASIBILITY OF A LOW-COST THIN-FILM GALLIUM ARSENIDE SOLAR CELL

  - RECRYSTALLIZE GE FILMS ON LOW-COST SUBSTRATES

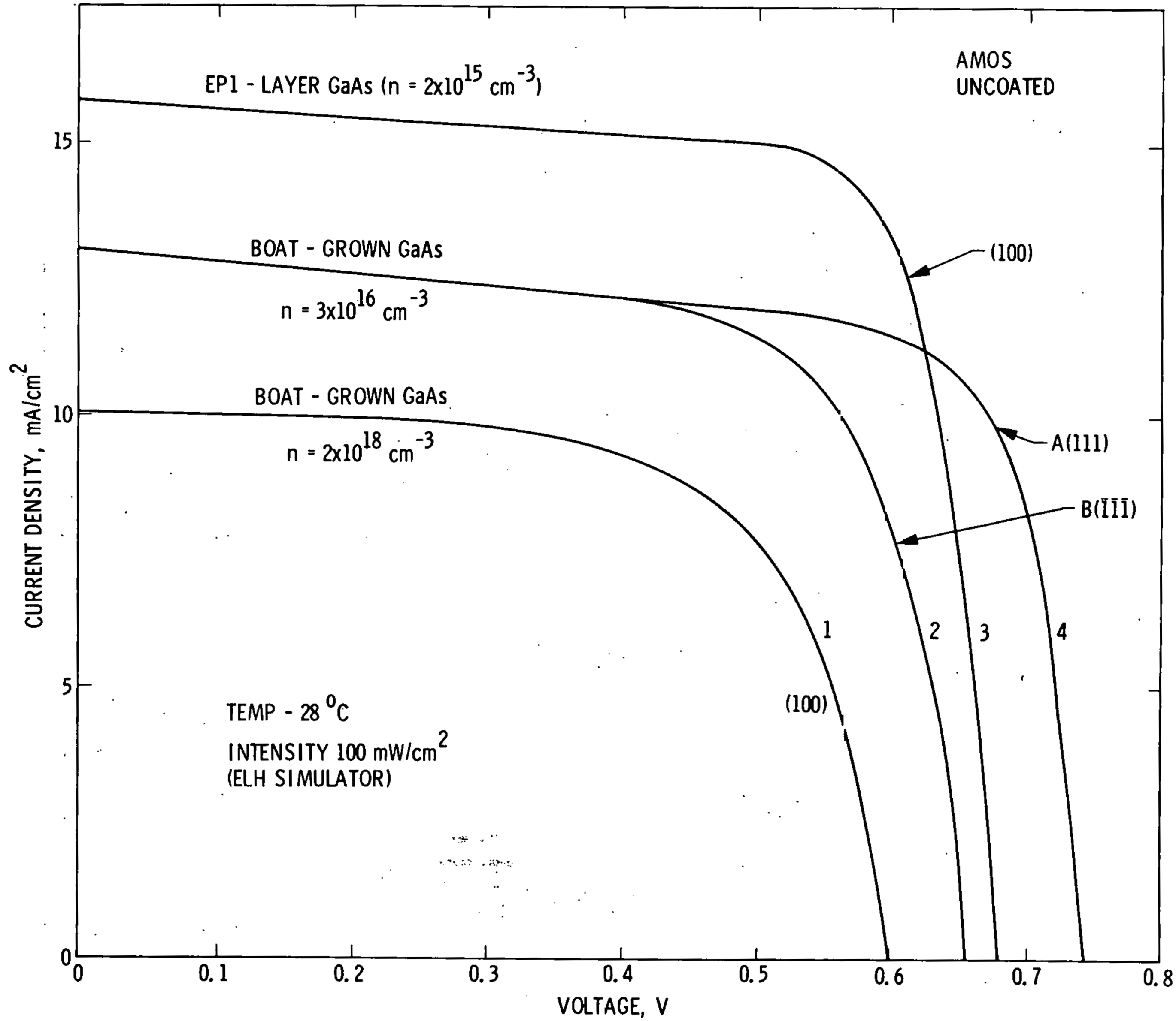
  - OPTIMIZE GaAs GROWTH BY CVD ON GE FILMS

  - FABRICATE OPTIMUM AMOS SOLAR CELL STRUCTURES ON THE GaAs CVD FILMS

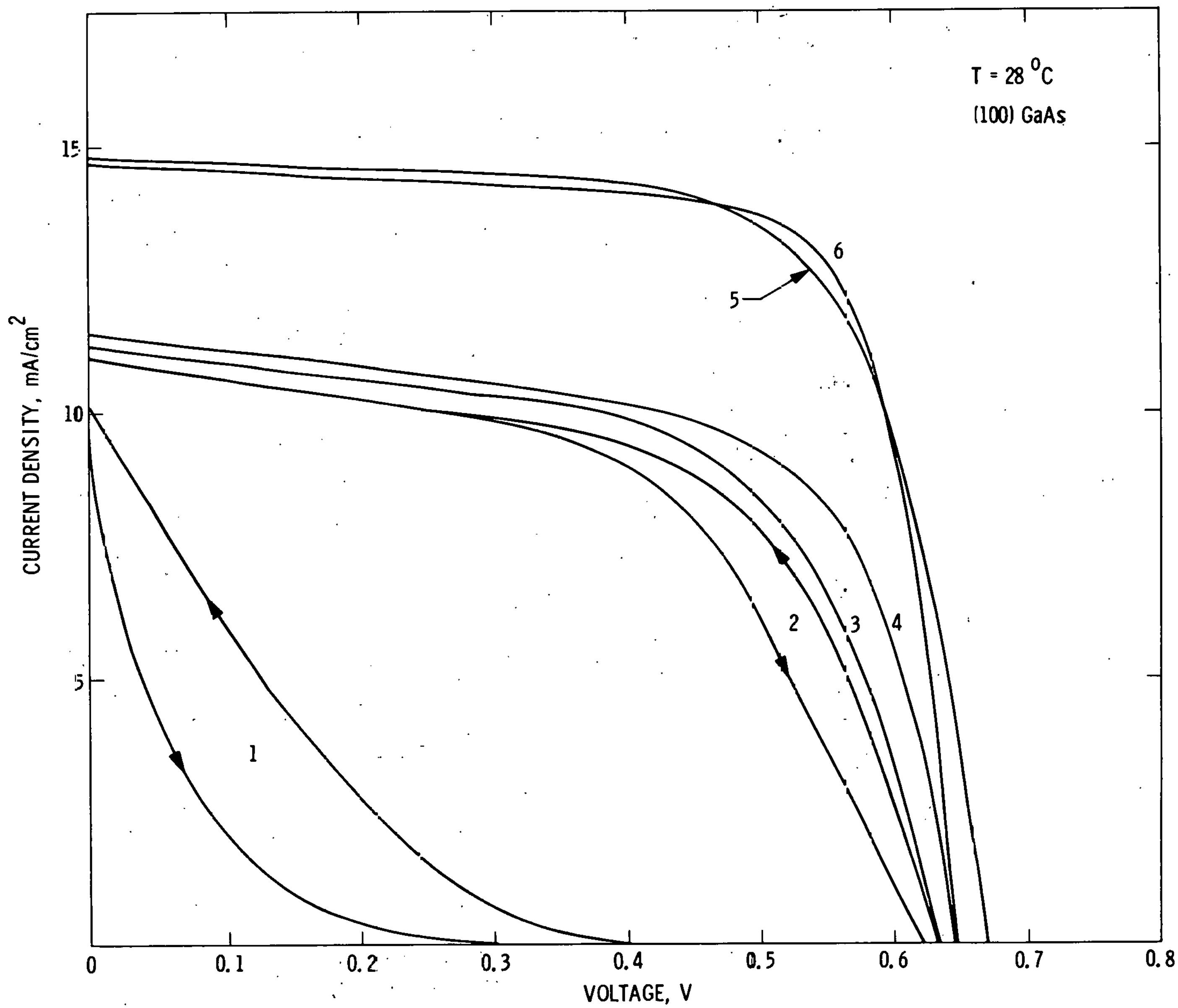
  - INVESTIGATE INTERFACE PHYSICS AND CHEMISTRY

PLANNED ACTIVITY FOR LAST SIX MONTHS

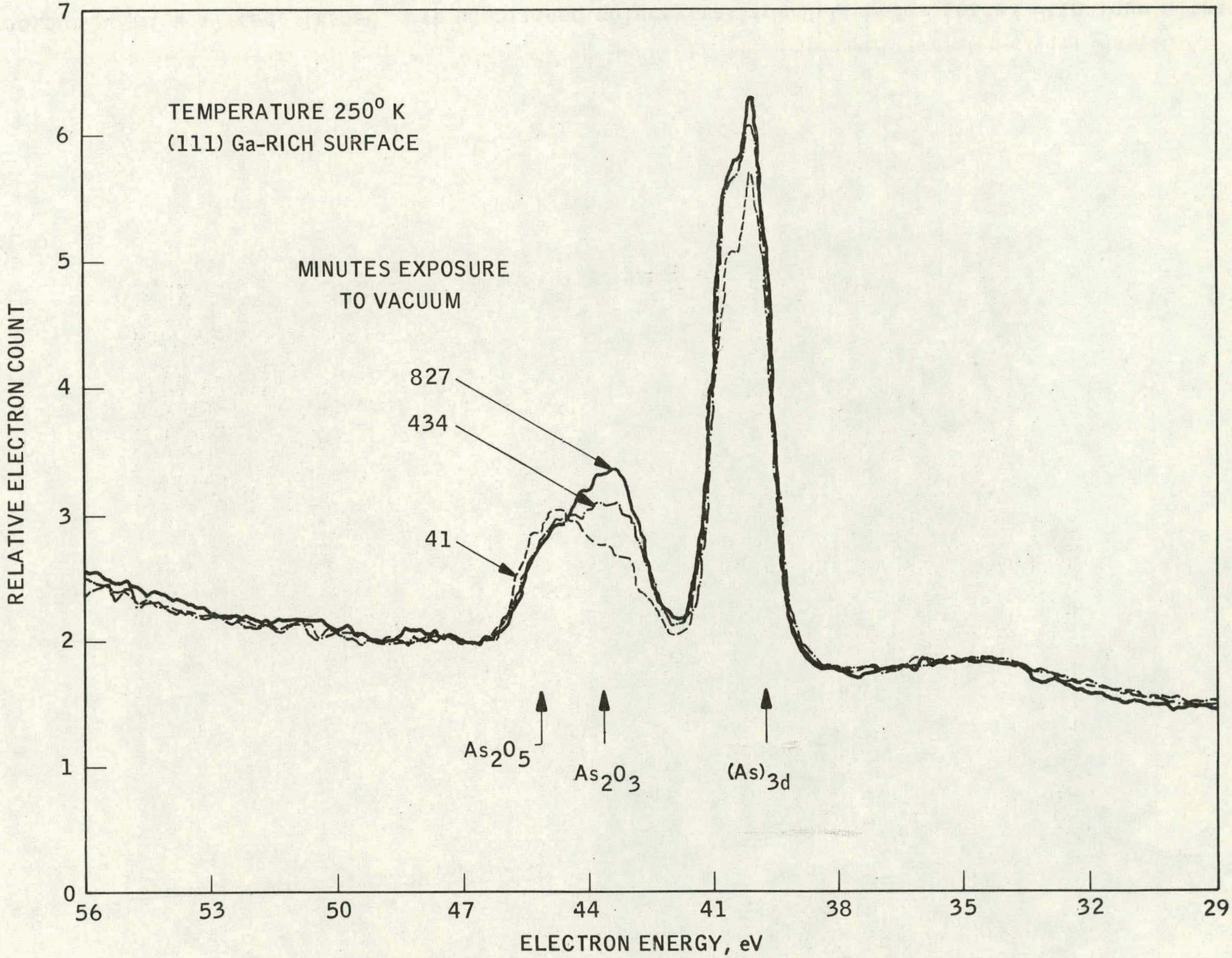
- FABRICATE AMOS AND BASELINE SOLAR CELLS ON VPE-GaAs LAYERS GROWN ON POLYCRYSTALLINE GaAs WAFERS
- LET SUB-CONTRACT TO PENNSYLVANIA STATE UNIVERSITY FOR STUDIES ON ELECTRONIC CHARACTERIZATION OF INTERFACE REGION
- CONTINUE XPS (ESCA) STUDIES ON CHEMICAL CHARACTERIZATION OF GaAs SURFACES OXIDIZED BY OZONE, HYDROGEN PEROXIDE AND OTHER OXIDANTS FOUND TO BE DESIRABLE
- INITIATE FABRICATION OF APPARATUS FOR LASER SPOT OR LINE SCANNING OF GERMANIUM THIN FILMS, AND CHOOSE APPROPRIATE LASER



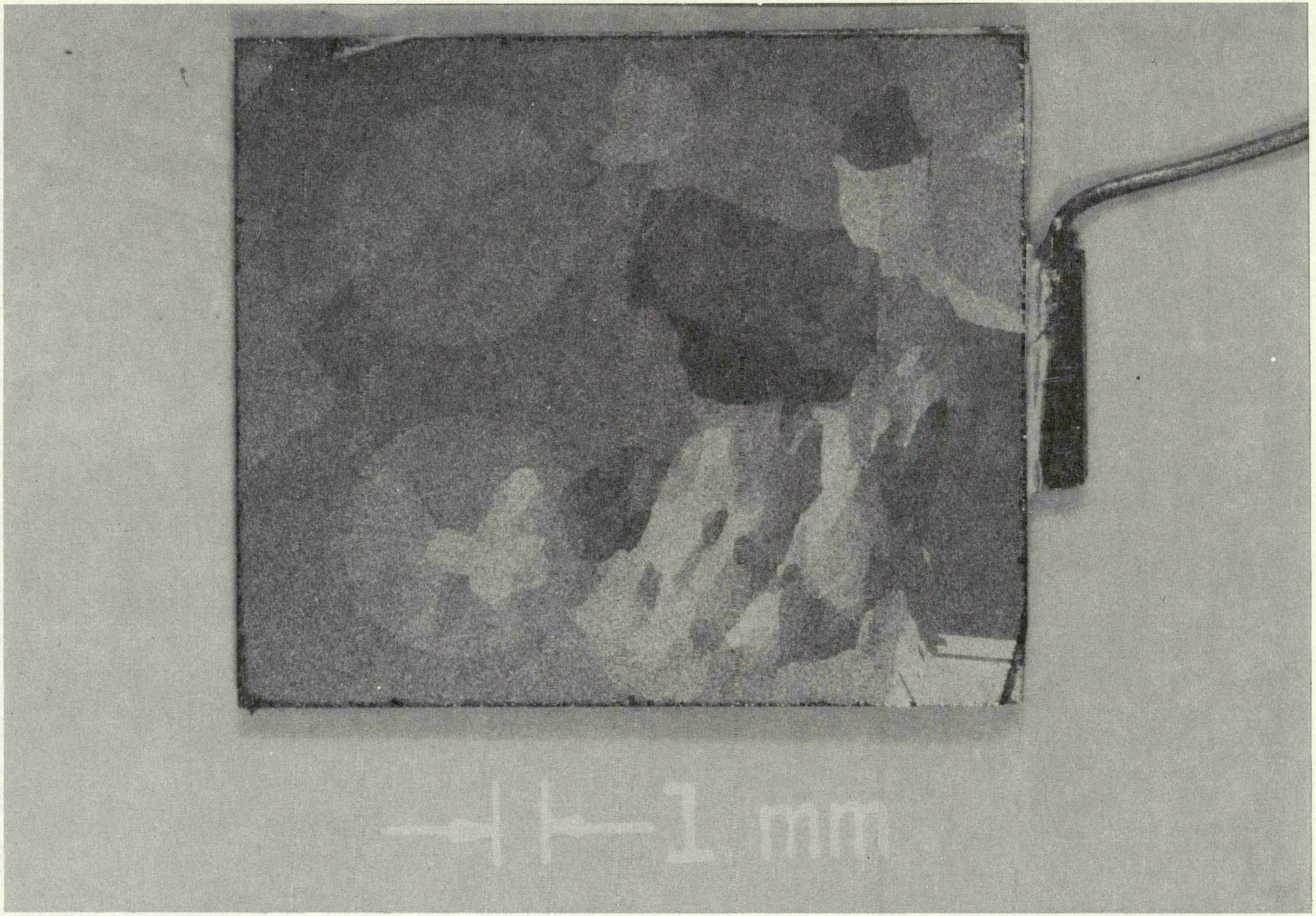
Light I-V characteristics for 60 Å gold on ozone-treated GaAs with no grid nor antireflection coatings for several orientations and carrier concentrations.



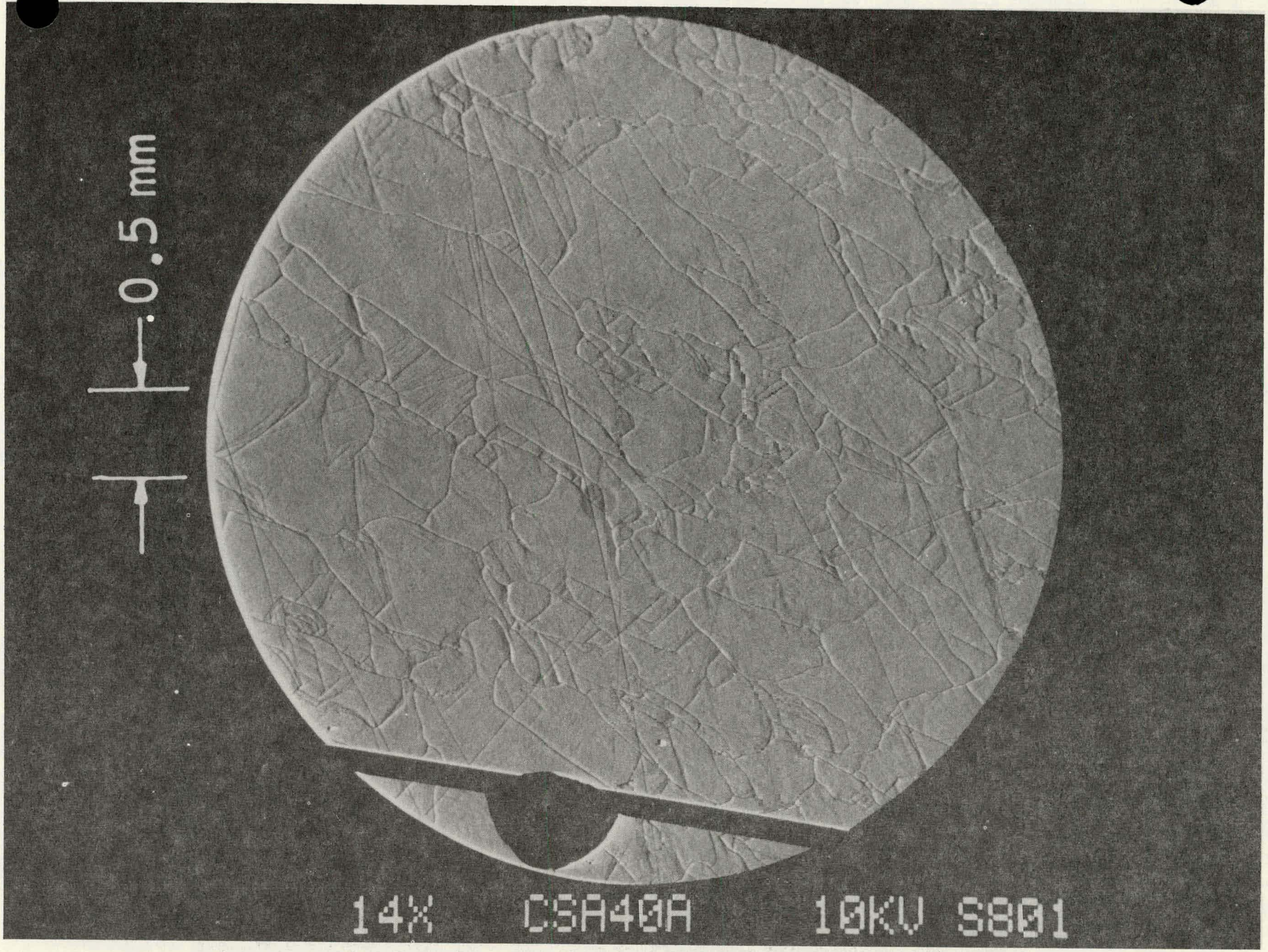
Light I-V characteristics for AMOS solar cells with the oxide formed in an RF generated oxygen plasma. Curves 1-4 are for lower current output GaAs wafers. Oxide thickness increasing with decreasing curve number.



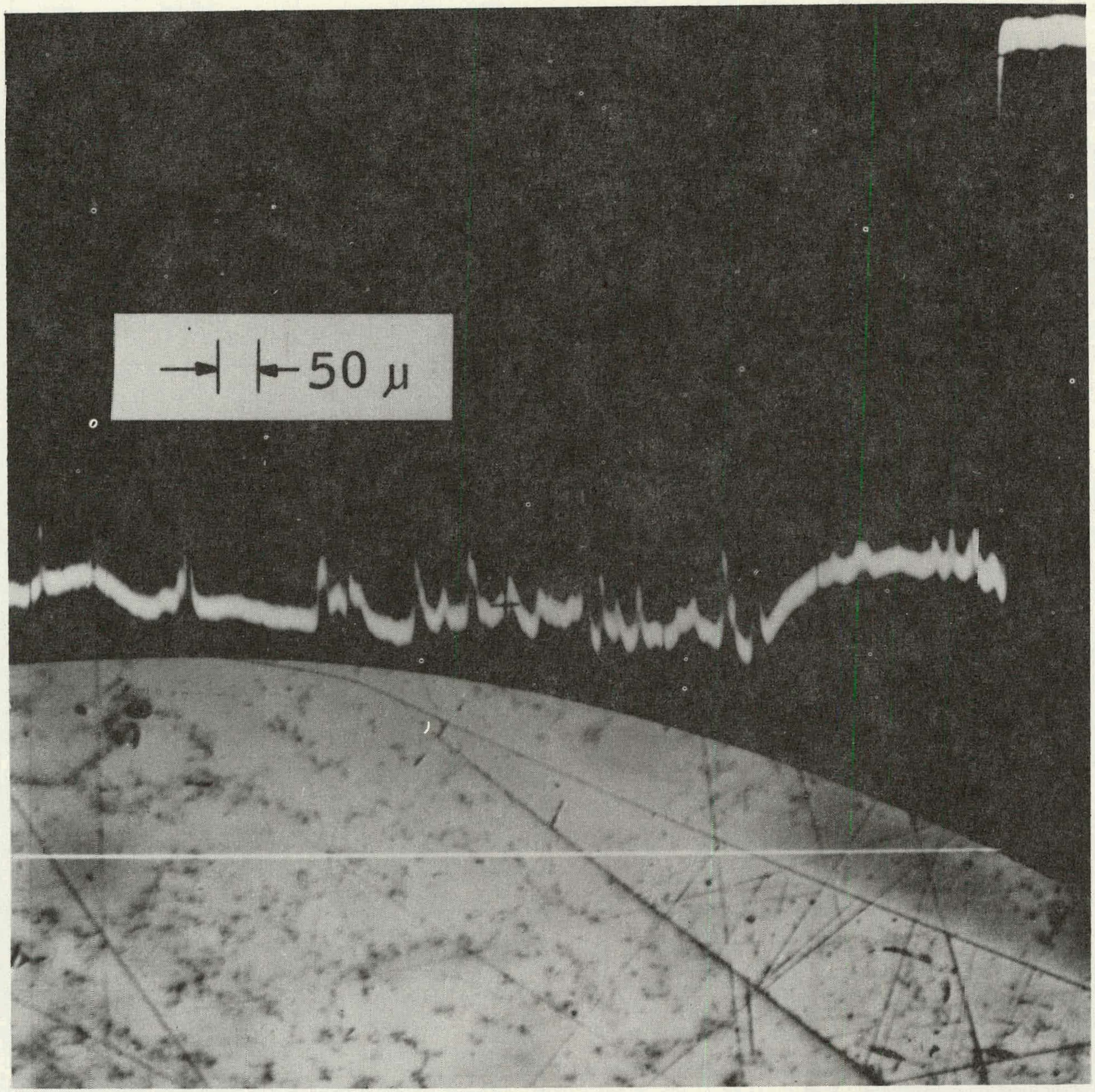
ESCA scan of arsenic line and its associated oxide showing oxygen desorption with time in high vacuum.



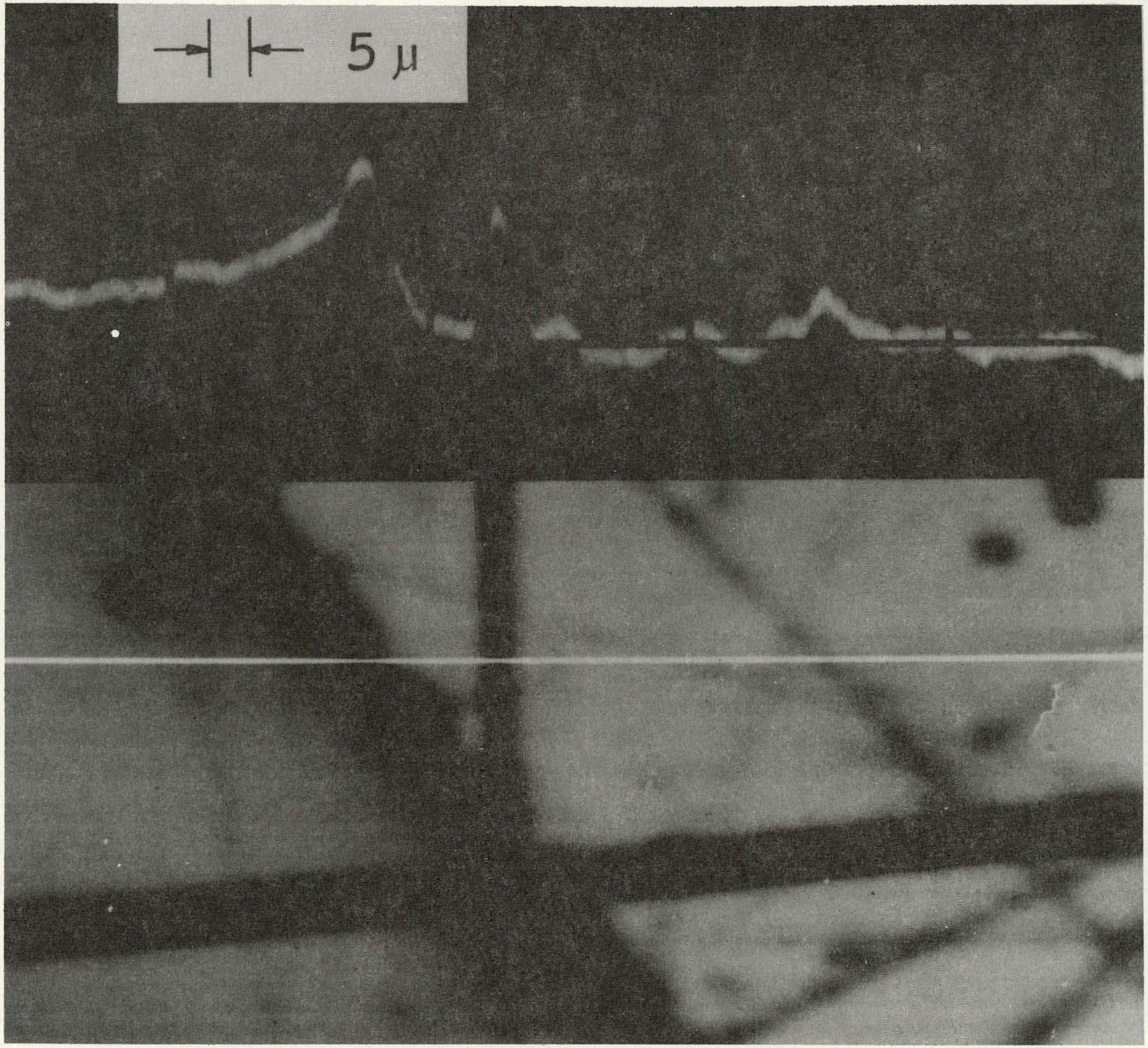
Optical photograph of a sliced, lapped, but unpolished polycrystalline GaAs wafer coated with four ultra-thin films of evaporated gold.



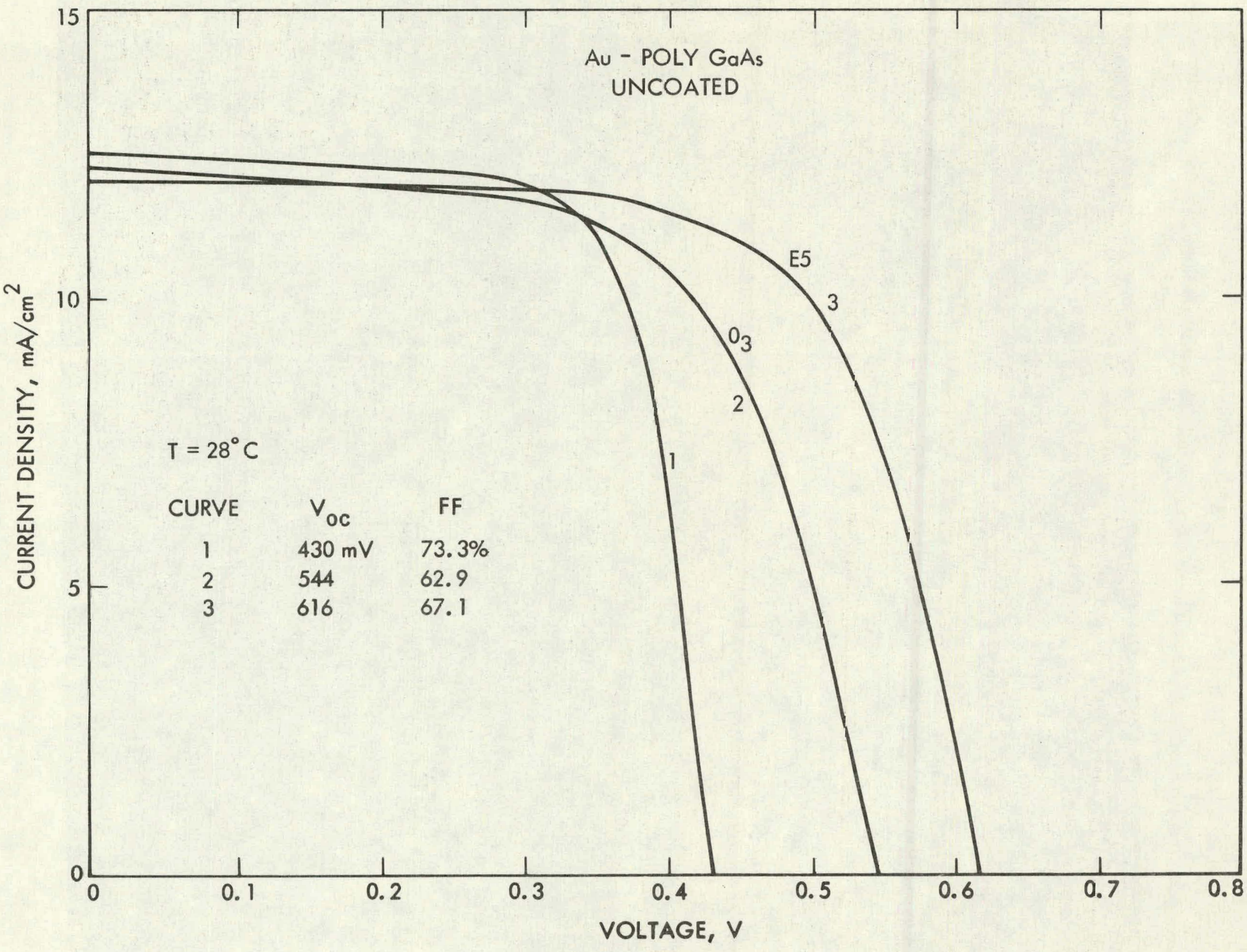
EBIC picture of sample area in lower right hand portion of wafer in previous figure.



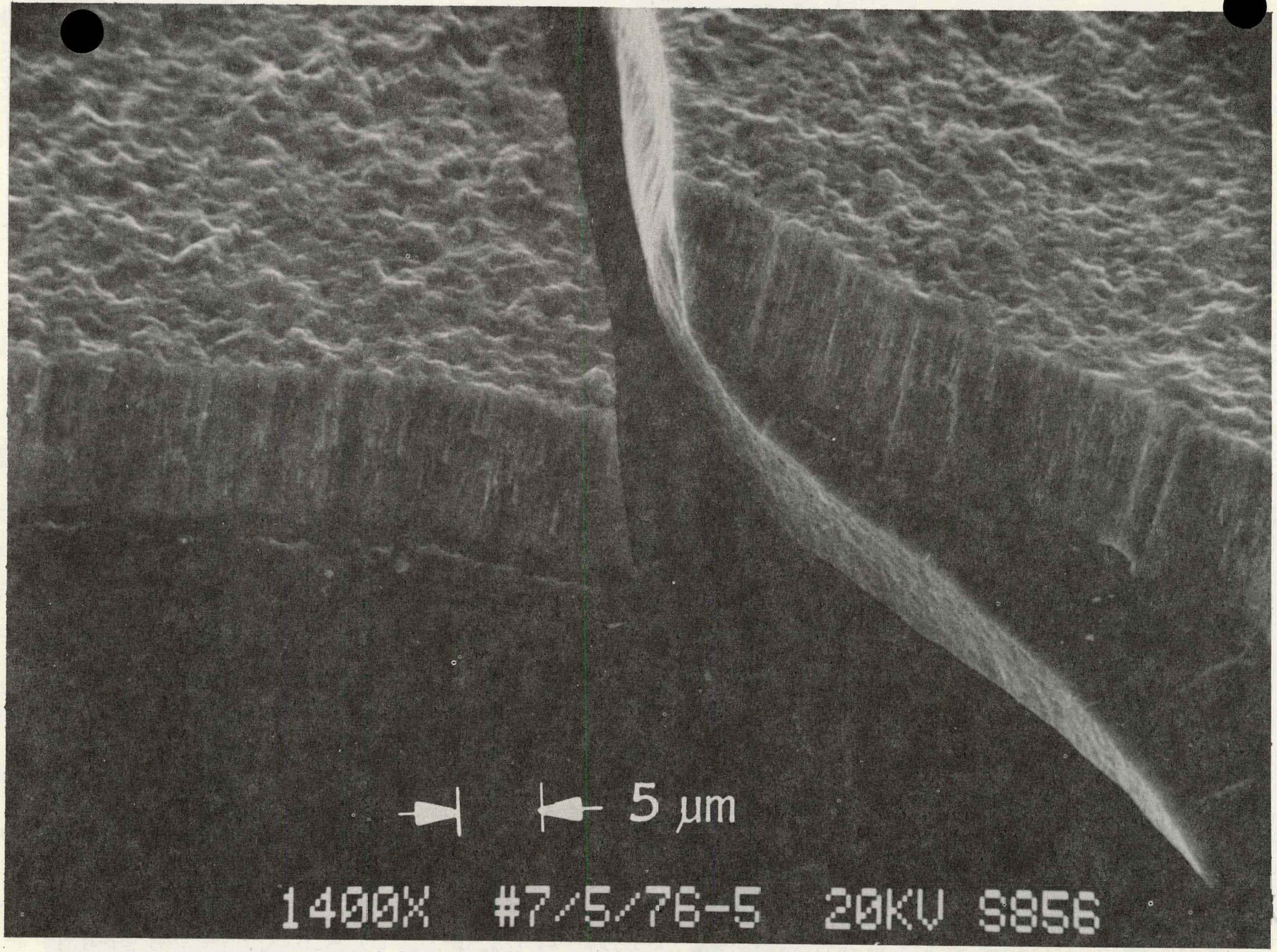
EBIC picture and amplitude modulated signal from one line scan across Schottky barrier solar cell made on a polycrystalline GaAs wafer.



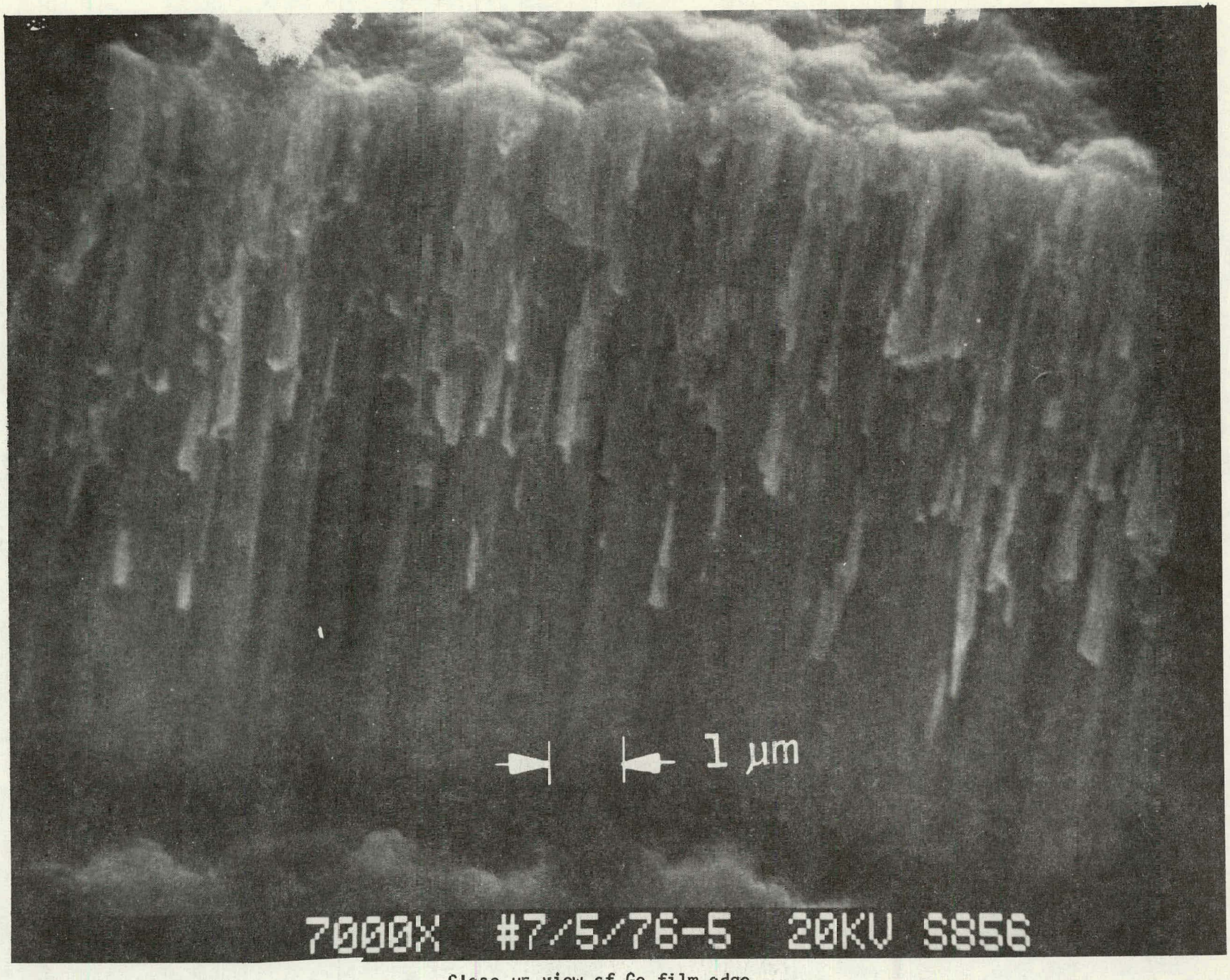
Same as last figure but magnified ten times.



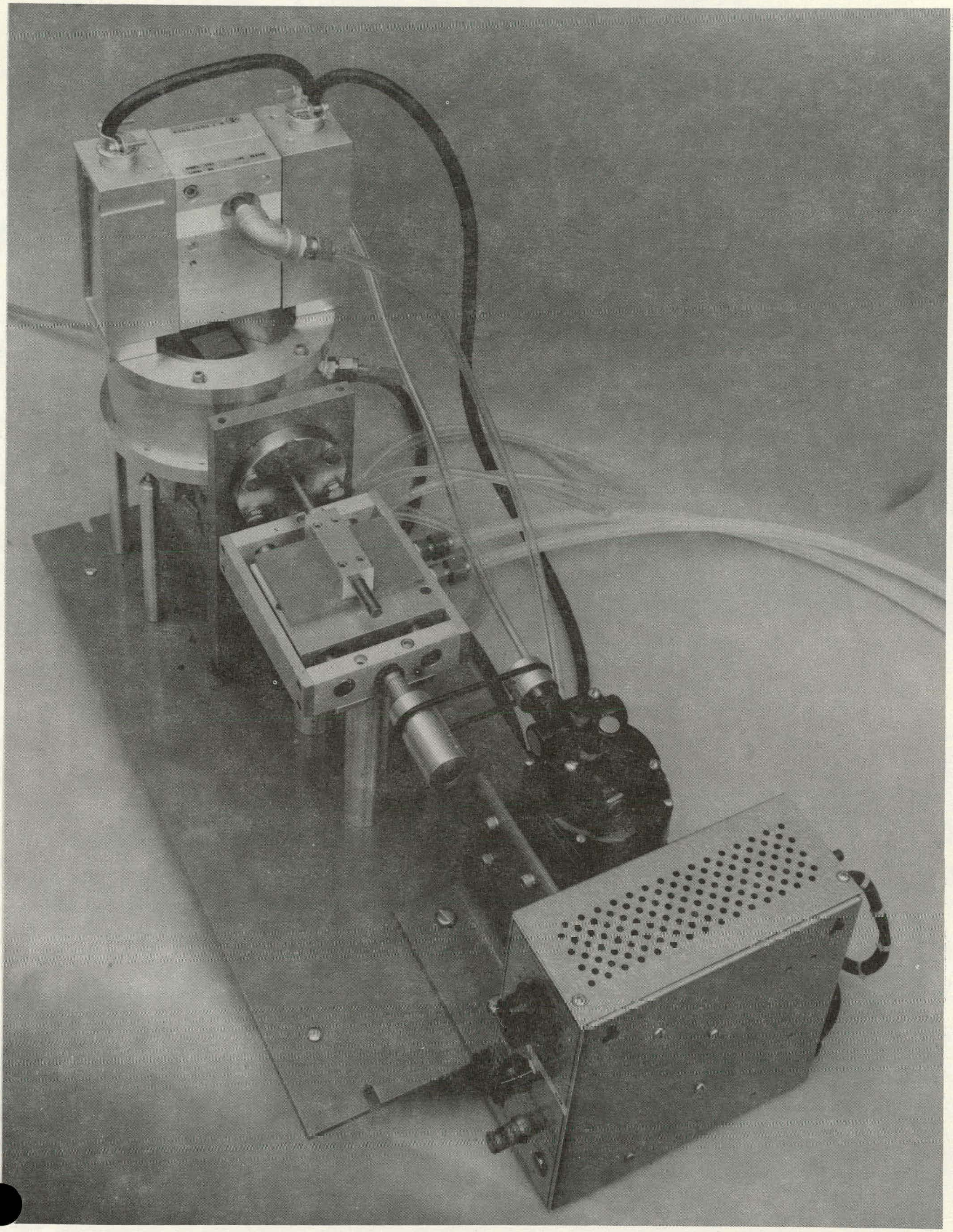
Light I-V characteristics for 60Å gold on polycrystalline GaAs wafers with $1\text{-}3 \times 10^{17}\ cm^{-3}$ doping.



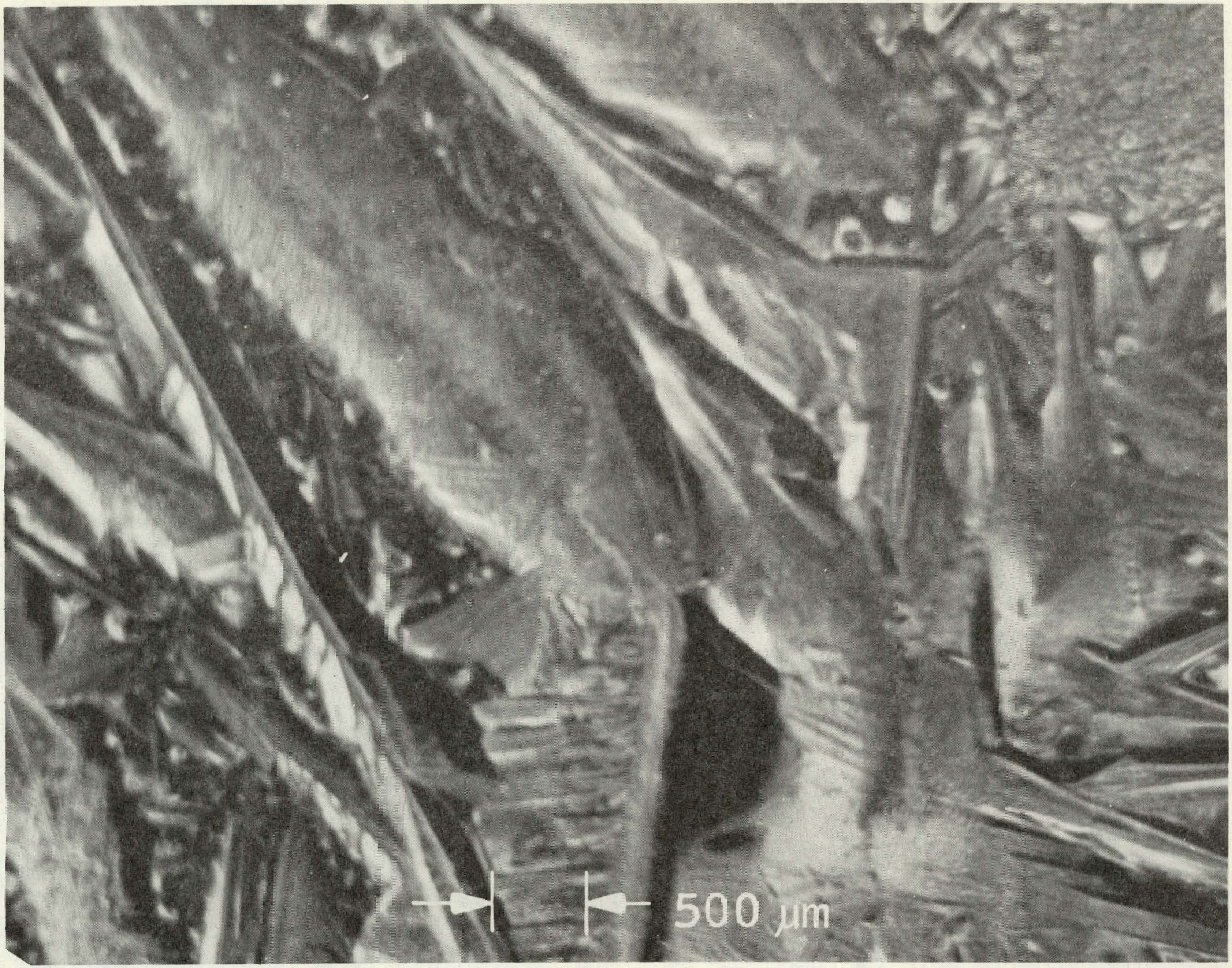
SEM photograph of fractured evaporated Ge film showing columar-type growth.



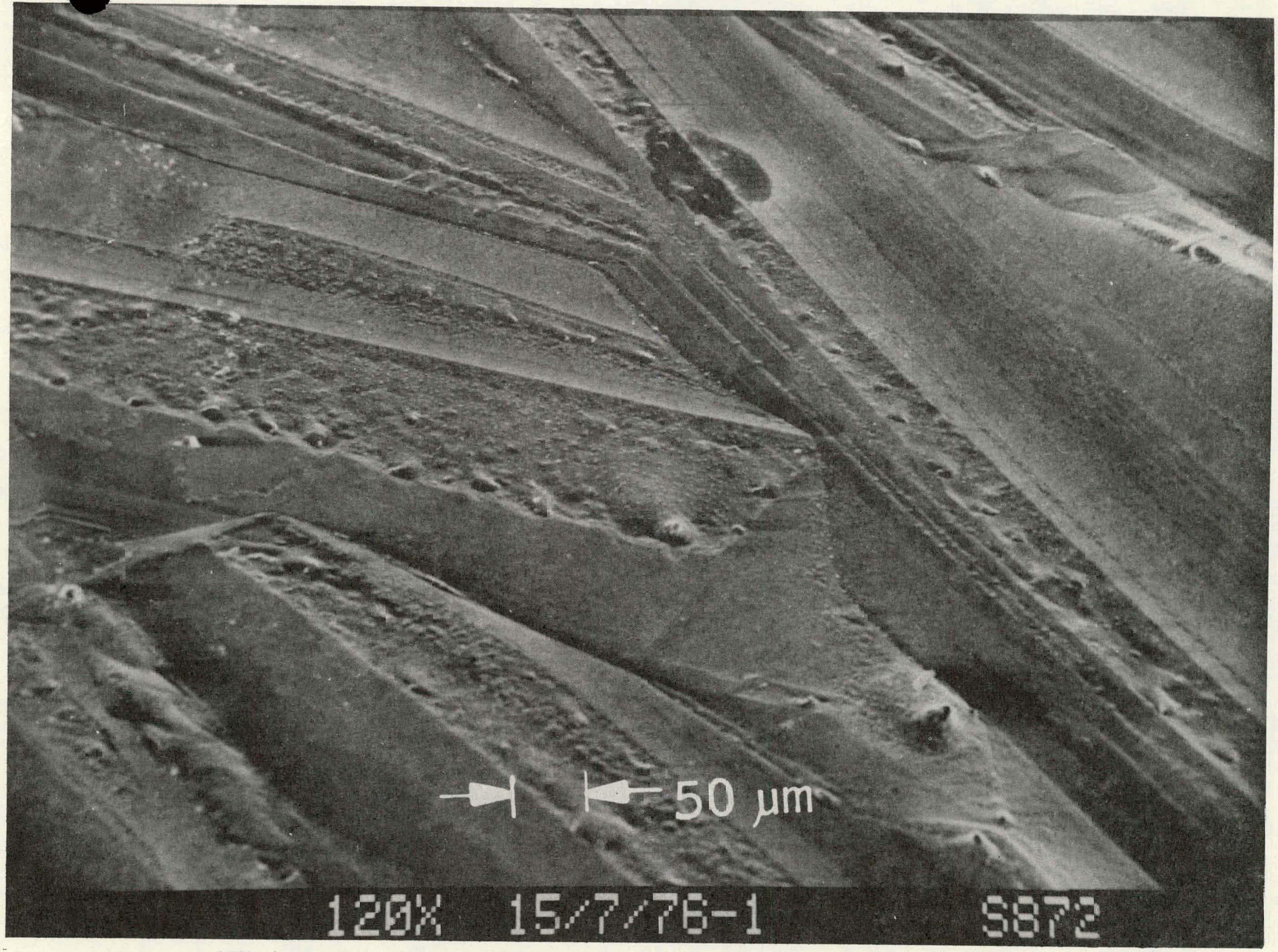
Close up view of Ge film edge.



Photograph of Ge recrystallization chamber with two Q-I tungsten lamps in place.



Optical photograph of region of Ge film on tungsten melted under the line heater.



SEM photograph of same film as in last figure with tilt angle of 50°.

SUMMARY OF KEY RESULTS

- REPRODUCIBLE IMPROVED OPEN-CIRCUIT VOLTAGES OBTAINED
- MAJOR EFFECT ON VOLTAGE IN AMOS CELLS DUE TO CRYSTALLOGRAPHIC ORIENTATION
- RF PLASMA OXIDATION PROCESS IS VIABLE CANDIDATE
- GRAIN BOUNDARIES FOUND TO HAVE NO NOTICEABLE EFFECT ON BASELINE OR AMOS SOLAR CELLS FOR RELATIVELY **LARGE-GRAIN** SLICED POLYCRYSTALLINE GaAs WAFERS
- EVAPORATED GE FILMS SHOW PREFERRED ORIENTATION AND GOOD BONDING ON SEVERAL METAL SUBSTATES
- IR LINE HEATER DOES NOT PROVIDE SUFFICIENT LOCALIZED MELTING FOR ZONE RECRYSTALLIZATION

MAJOR PROBLEMS

- NEED TO ELIMINATE DECREASE IN VOLTAGE UPON GRID CONTACTING OR AR COATING DEPOSITION

- DEVELOP MULTI-LAYER AR COATING WITH WHICH TO FURTHER DECREASE REFLECTION LOSSES

- NEED TO FURTHER LOCALIZE GE MELTING FOR PROPER RECRYSTALLIZATION OF FILMS

PLANNED ACTIVITY FOR NEXT SIX MONTHS

- OPTIMIZE RF PLASMA OXIDATION PROCESS AND FURTHER INVESTIGATE CRYSTALLOGRAPHIC ORIENTATION EFFECT ON OPEN-CIRCUIT VOLTAGE
- CONTINUE XPS (ESCA) STUDIES ON OXIDIZED GaAs SURFACES, PARTICULARLY ON PLASMA OXIDES
- INVESTIGATE DEGRADATION EFFECT WHEN AR COATING IS APPLIED AND MEANS TO ELIMINATE IT
- RECRYSTALLIZE GE FILMS WITH LINE FOCUSSED ND/YAG LASER BEAMS, CHEMICALLY VAPOR DEPOSIT GaAs AND FABRICATE AMOS SOLAR CELLS ON SUCH FILMS
- SELECT MOS TECHNIQUES WHICH CAN PROVIDE ELECTRICAL PARAMETERS OF INTERFACE STATES AND OXIDE CHARGES

RENEWAL REQUEST

- MAJOR GOALS
  - 8% EFFICIENCY ON POLY-GaAs BY DEC. 1977
  - 10% EFFICIENCY ON POLY-GaAs BY DEC. 1978
  - ALL MATERIALS AND PROCESSES AMENDABLE TO 30 CENTS PER PEAK WATT GOAL OR LESS
- DURATION
  - DECEMBER 1, 1976 TO NOVEMBER 30, 1978
- ESTIMATED COSTS
  - $550,000 (24 MONTHS)

TITLE

DEPOSITION OF GALLIUM ARSENIDE BY LIQUID PHASE EPITAXIAL GROWTH ON OXIDE SUBSTRATE MATERIALS

GRANT TITLE

THIN FILM GALLIUM ARSENIDE FOR LOW COST PHOTOVOLTAIC ENERGY CONVERSION

GRANT NO. AER 74-13036

DURATION OF GRANT
9/1/75 to 2/28/77

VALUE OF GRANT
67,200

AUTHORS

D. A. STEVENSON, A. G. ELLIOT AND B. L. MATTES
Department of Materials Science and the Center
for Materials Research, Stanford University

PRINCIPLE INVESTIGATORS

D. A. STEVENSON AND B. L. MATTES

Presented at the National Solar Photovoltaic Program Review Meeting
August 3-6, 1976
University of Maine at Orono
Orono, Maine 04473

ABSTRACT

A. OBJECTIVE

The objective of this program is to deposit gallium arsenide (GaAs) thin films on inexpensive substrate materials by liquid phase epitaxial (LPE) growth techniques for solar cell applications. The motivation for this work is based on the thickness of GaAs required for solar energy photovoltaic conversion (∿ 1 μm), the availability and cost of Ga and the expense of GaAs single crystals.

The major aspects of this program include: a study of nucleation and growth of GaAs thin films by the LPE growth process on oxide substrates, the selection of suitable substrates and their preparation, the structural and elemental characterization of substrate surfaces and epitaxial films, and the analysis of the film's electrical properties. The program goals can be divided into three phases: (I) fundamental studies of nucleation and growth on single crystal oxide substrates; (II) growth on low cost substrates, particularly fused quartz; and (III) optimization of the growth process and thin films for solar cell device studies.

B. PREVIOUS ACTIVITIES

The design and construction of an LPE growth system for the study of steady state and transient growth of GaAs thin films on oxide substrates was completed in the first six months of the program. During this period structural analyses of the spinel ($MgAlO_4$) and sapphire (Al_2O_3) substrates were undertaken to study surface preparations and atom bond arrangements.

C. CURRENT EFFORTS

In the second six months of the program, GaAs was deposited on these substrates to determine the liquid-solid interfacial conditions necessary to control nucleation and growth. These conditions are influenced by temperature, cooling rate, temperature gradient, and substrate preparation. In addition, substrate surface degradation was studied in the scanning electron microscope by x-ray energy

analysis to determine the composition of interfacial layers and anomalous growths.

In the past few weeks, growths on fused quartz substrates were pursued, utilizing the information and techniques gained from growths on oxide single crystals.

D. SUMMARY OF KEY RESULTS

The most significant result of our studies is that highly oriented GaAs films can be grown on fused quartz. The films at present appear to arise from a coalescence of (111)B hillocks. These have a surface configuration with the lowest interfacial energy. In order to achieve heteroepitaxial nucleation and growth the As super-saturation at the substrate surface must exceed that found in single crystal GaAs. Nucleation and growth is not limited to lattice parameter matching. Nucleation and growth are related to the type of available bonds on the substrate surface. Surface replication studies have shown microfacet arrays on the substrate for different orientations. These arrays can be related to atom and/or bond arrangements existing at the surface. When these are matched against similar facets found on GaAs, heteroepitaxial growth orientations can be deduced.

F. FUTURE PLANS

Contingent on future funding, Phase II and III will be pursued over the next two years. However, without funding our effort will be scaled down over the next six months to achieve a better understanding of our results for publication.

GRANT NO. AER 74-13036

"THIN FILM CALLIUM ARSENIDE FOR LOW COST
PHOTOVOLTAIC ENERGY CONVERSION"

STANFORD UNIVERSITY
THE CENTER FOR MATERIALS RESEARCH
AND
THE DEPARTMENT OF MATERIALS SCIENCE

9/1/75 to 2/28/77

67,200

D. A. STEVENSON AND B. L. MATTES

<u>PROJECT OBJECTIVE</u>

DEPOSITION OF GaAs THIN FILMS BY LIQUID PHASE EPITAXIAL GROWTH ON FUSED QUARTZ FOR SOLAR CELL APPLICATIONS

PROJECT PERSONNEL

D. A. STEVENSON, PROFESSOR OF MATERIALS SCIENCE

B. L. MATTES, SENIOR RESEARCH ASSOCIATE, CENTER FOR MATERIALS RESEARCH

A. G. ELLIOT, RESEARCH ASSOCIATE, CENTER FOR MATERIALS RESEARCH

E. D. JONES, GRADUATE STUDENT, DEPARTMENT OF MATERIALS SCIENCE

G. M. POUND, PROFESSOR OF MATERIALS SCIENCE

R. S. FEIGELSON, DIRECTOR OF CRYSTAL TECHNOLOGY, CENTER FOR MATERIALS RESEARCH

SYNOPSIS OF OVERALL PLAN

PHASE I: FUNDAMENTAL STUDY OF NUCLEATION AND GROWTH BY HETEROEPITAXIAL DEPOSITION ON A VARIETY OF OXIDE SUBSTRATES

1. GROWTH SYSTEM DESIGN AND CONSTRUCTION
2. SELECTION OF SUBSTRATES AND DEVELOPMENT OF SURFACE PREPARATION TECHNIQUES FOR SUBSTRATES
3. DEVELOPMENT OF GROWTH PROCEDURES
4. STRUCTURAL CHARACTERIZATION OF SUBSTRATE SURFACES AND DEPOSITED LAYERS BY TRANSMISSION AND SCANNING ELECTRON MICROSCOPY
5. ELECTRICAL PROPERTY CHARACTERIZATION OF GaAs FILMS

PHASE II: EMPHASIS ON LOW COST SUBSTRATES, PARTICULARLY FUSED QUARTZ

1. SUBSTRATE SURFACE TREATMENTS
2. EXTENSION OF GROWTH STUDIES AND FILM CHARACTERIZATION
3. PRELIMINARY STUDIES FOR SOLAR CELL APPLICATIONS

PHASE III. OPTIMIZATION OF PROCESS AND GaAs THIN FILMS FOR SOLAR CELL APPLICATIONS

1. OPTIMIZATION OF DEPOSITION PROCESS, WITH EMPHASIS ON FILM QUALITY AND EFFICIENCY OF DEPOSITION
2. FILM SUBSTRATE BONDING STUDIES
3. OPTIMIZATION OF GaAs THIN FILMS FOR SOLAR CELLS

PLANNED ACTIVITY FOR LAST SIX MONTHS

1. OPERATION OF NEW GROWTH SYSTEM

2. GROWTH ON SINGLE CRYSTAL SUBSTRATES ($MgAl_2O_4$, Al_2O_3)

3. DEVELOPMENT OF PRETREATMENT PROCEDURES FOR SUBSTRATES (MECHANICAL AND CHEMICAL TECHNIQUES)

4. STRUCTURAL ANALYSIS OF SUBSTRATES AND GROWN FILMS (TRANSMISSION AND SCANNING ELECTRON MICROSCOPY)

5. PRELIMINARY GROWTH STUDIES ON FUSED QUARTZ

PROGRESS

1. GROWTH SYSTEM HAS DEMONSTRATED VERSATILITY AND YIELDED CONTROLLED GROWTH CONDITIONS.

2. SUBSTRATE SURFACES HAVE BEEN ANALYZED BY TEM, SEM FOR STRUCTURE AND ELEMENTAL IDENTIFICATION.

3. GROWTH STUDIES HAVE BEEN MADE ON GaAs, $MgAl_2O_4$, Al_2O_3, GRAPHITE AND FUSED QUARTZ SUBSTRATES.

RESULTS

1. HOMO- AND HETEROEPITAXIAL NUCLEATION AND GROWTH IS LIMITED TO HIGH As SUPERSATURATIONS AT THE LIQUID-SOLID INTERFACE.

2. NUCLEATION AND GROWTH DOES NOT APPEAR TO BE LIMITED TO LATTICE PARAMETER MATCHING -- BUT TO THE TYPE OF AVAILABLE BONDS ON THE SUBSTRATE SURFACE. THE BONDS CHANGE WITH SUBSTRATE SURFACE ORIENTATION AND CAN BE RELATED TO MICROFACETS.

3. HIGHLY ORIENTED CONTINUOUS GaAs LAYERS HAVE BEEN GROWN ON FUSED QUARTZ.

MAJOR PROBLEMS

FUNDING!

TABLE II (Revised August 1975)

APPROXIMATE PROGRAM SCHEDULES AND EXPENSES
3 Year Program - Total Expenditure $237.0
(all figures in thousands of dollars)

OBJECTIVES	FY 76	FY 77*	FY 78	TOTAL EXPENDITURES
GaAs Films on Single Crystal Oxide Substrates	($47.0)	($30.0)		$77.0
Heteroepitaxial Interface and Structure Studies	($15.0)	($15.0)	($15.0)	$45.0
Electrical and Optical Evaluation of GaAs Films	($5.0)	($10.0)	($10.0)	$25.0
GaAs Films on Fused Quartz		($25.0)	($45.0)	$70.0
Optimization of Thin Film GaAs Growth on Fused Quartz			($10.0)	$10.0
Heterostructure Growth and Evaluation Studies of GaAs Films for Solar Cells			($10.0)	$10.0
(Total Cost)	($67.0)	($80.0)	($90.0)	$237.0

*FY ncludes an increased overhead charge from 47% to 58%.

COMPETITIVE FACTORS FOR GaAs

I. AVAILABILITY

Gallium

Source	Reserve	Recovery	Amount
Al and Zn Ores			
U.S.	2.2×10^6 Kg	10%	0.27×10^6 Kg
World	25×10^6		2.5×10^6
Coal			
U.S.	9.6×10^9	18%	1.7×10^9
World	22×10^9		4.0×10^9
Ocean	6.9×10^{12}	1%	6.9×10^{10}

Arsenic

Copper Ores			
U.S.	1.7×10^9 Kg	10%	0.17×10^9 Kg
World	3.8×10^9		0.38×10^9

II. COST OF GALLIUM ARSENIDE

GaAs Substrates (500 μm thick @ $4.00/g)	$1,000/ft^2
1 μm thick GaAs Crystal	$2/ft^2
Ga and As	23¢/ft^2
Fused Quart Substrates (100 μm thick)	36¢/ft^2

III. REQUIREMENTS

Low Cost Growth Process

High Recoverability of Ga

Thin GaAs Films on Cheap Substrates

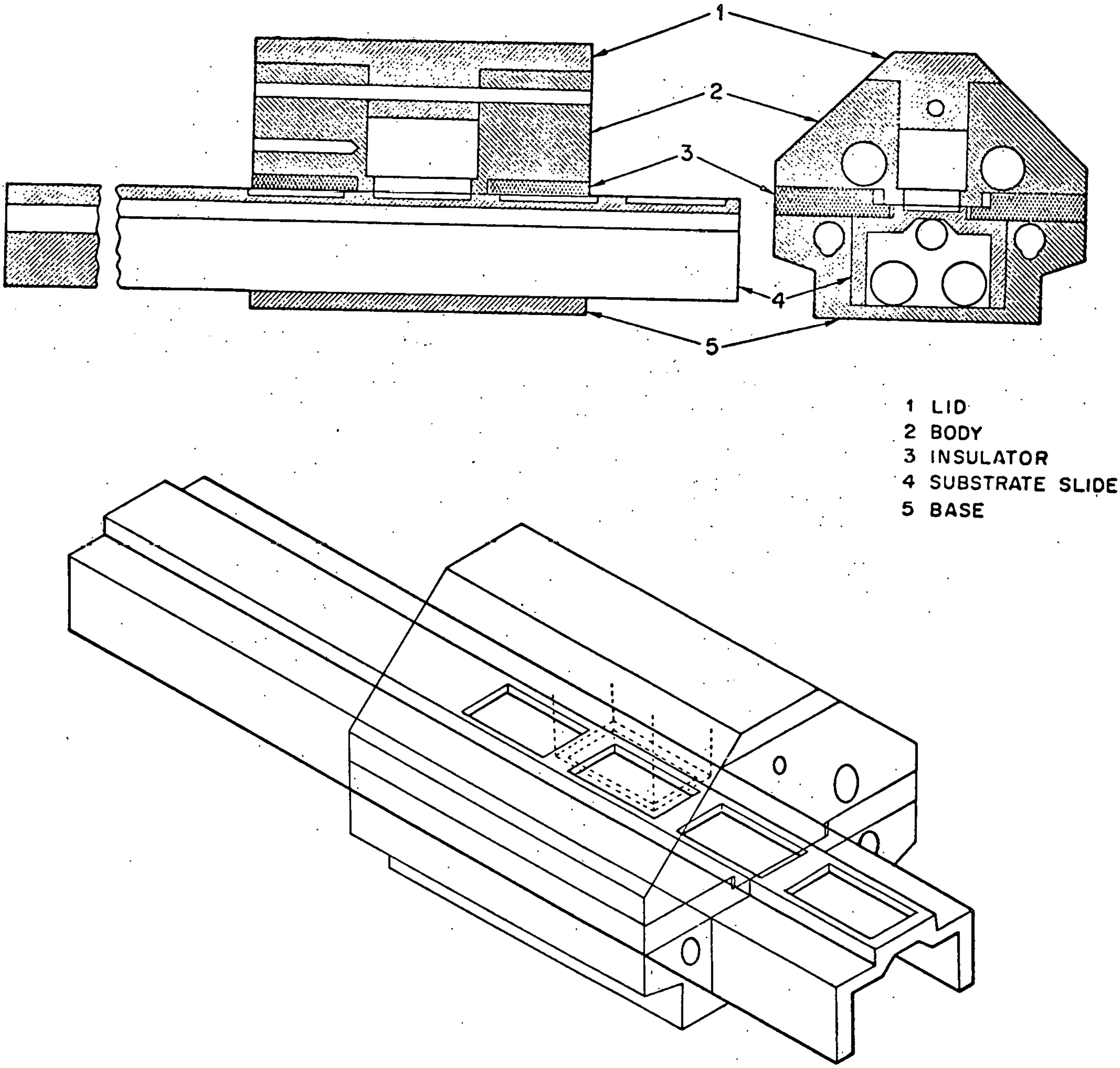
LPE vs. VPE

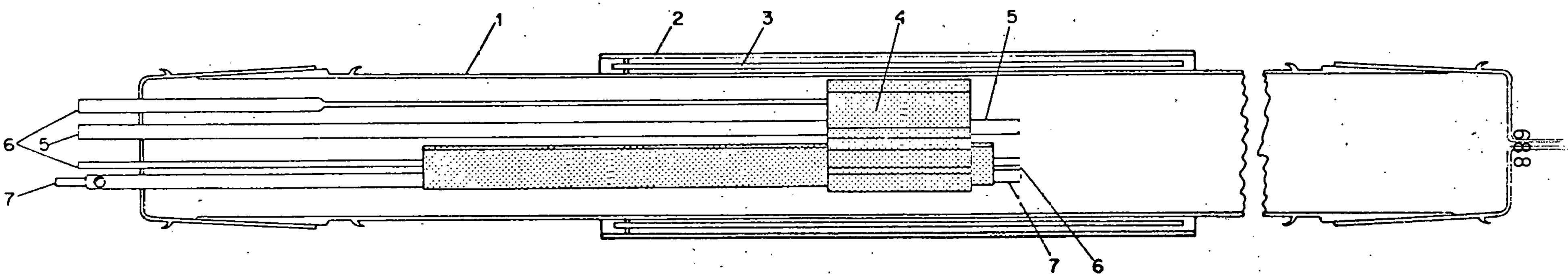
1. Ga AND As CAN BE USED IN ELEMENTAL FORM

2. Ga AND As LOSS ARE LOWER

3. GROWTH SYSTEM COST IS LOWER

4. LIQUID Ga SEGREGATES IMPURITIES FROM THE EPITAXIAL LAYER


1
2
3
4
5
1 LID
2 BODY
3 INSULATOR
4 SUBSTRATE SLIDE
5 BASE



1 QUARTZ REACTOR
2 GOLD COATED REFLECTOR
3 KANTHAL HEATER
4 LPE GROWTH CELL
5 INTERNAL KANTHAL HEATERS
6 THERMOCOUPLES
7 HEAT EXCHANGER

FIGURE CAPTIONS

Figure 1. GaAs growth formations on a (111) spinel substrate. (a) and (b) by SEM. (c) and (d) by replication and TEM.

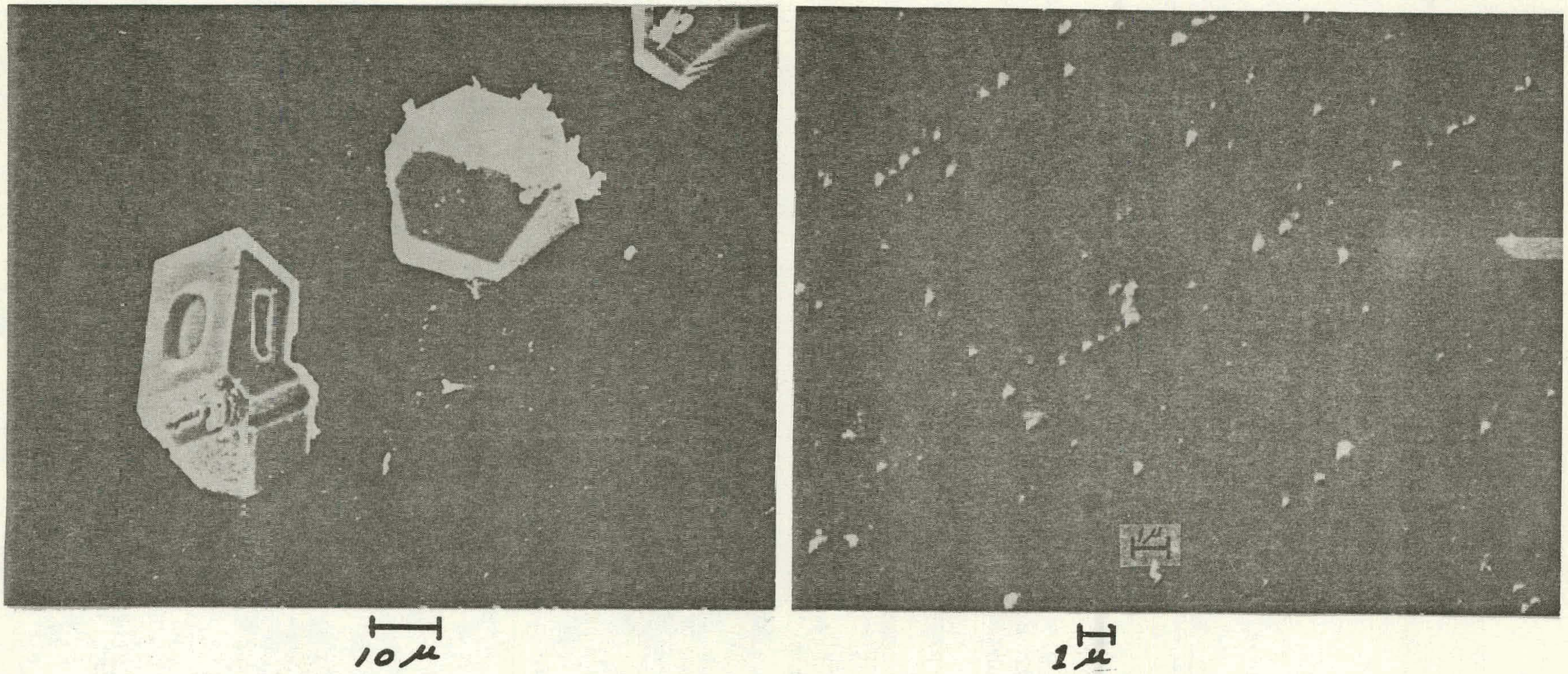
Figure 2. SEM/X-ray energy analysis of growths on a (100) spinel substrate. "A" shows a GaAs + Al and "B" shows a Mg + Al composition.

Figure 3. GaAs growths on $(1\bar{1}02)$ sapphire substrates. Note that growth appears primarily on treated area (right side of substrate).

Figure 4. GaAs growth on fused quartz. (a) top and (b) side views.

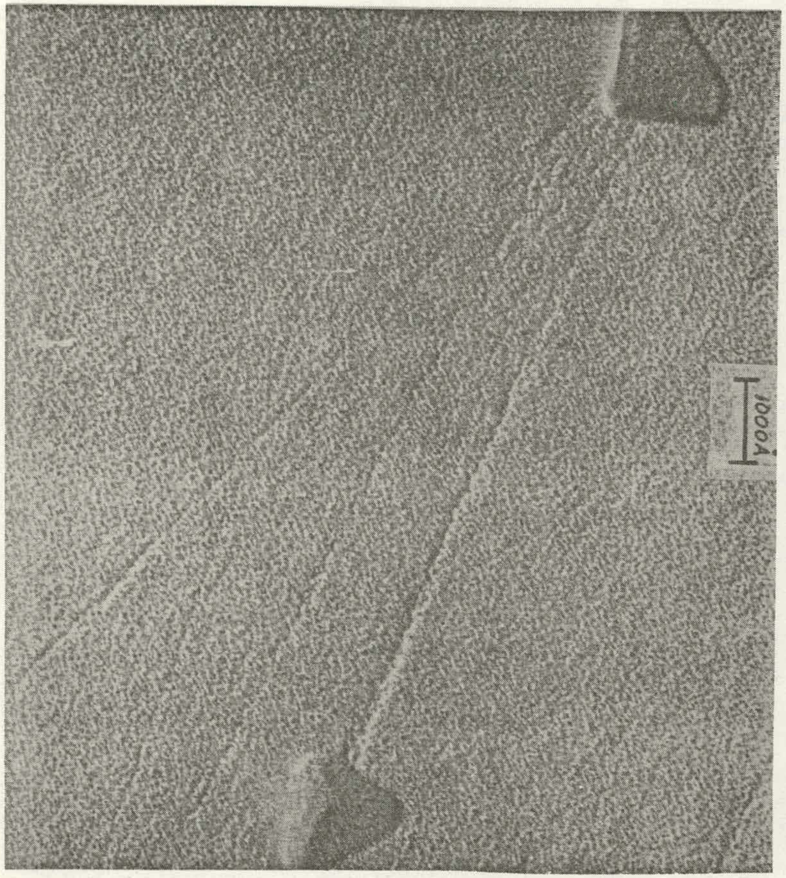
Figure 5. GaAs growth on fused quartz. Optical view of layer over treated surface (a) and at two angles through the quartz (b,c).

Figure 6. GaAs growth on fused quartz. SEM view of (111)B hillocks (a,b) and bottom of spalled-off layer (c,d).

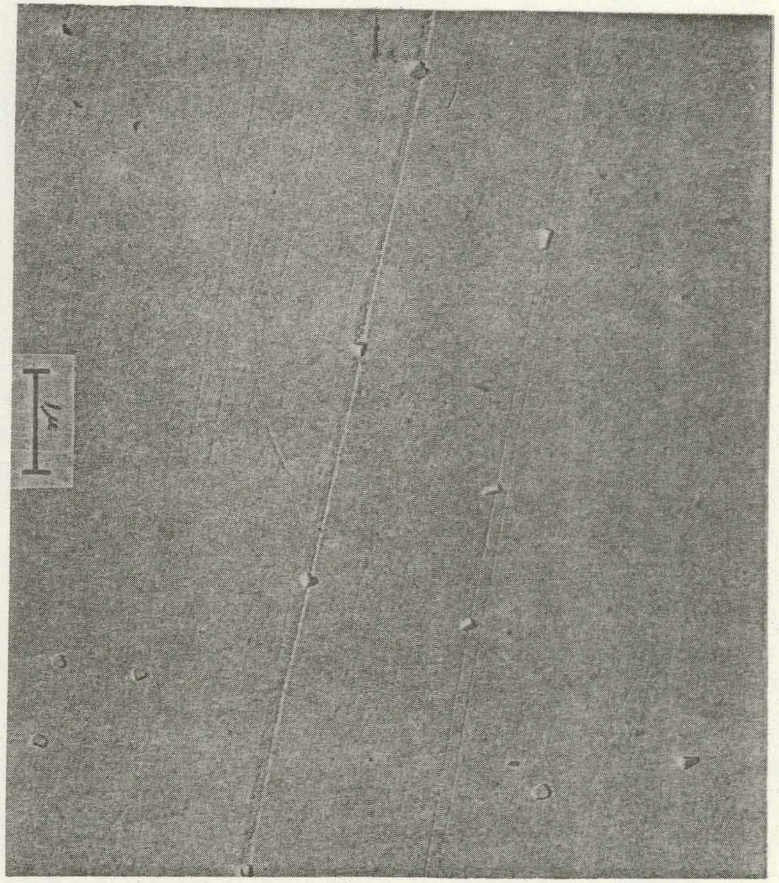


(a) (b)

Fig. 1



(c)



(d)

Fig. 1 (Continued)

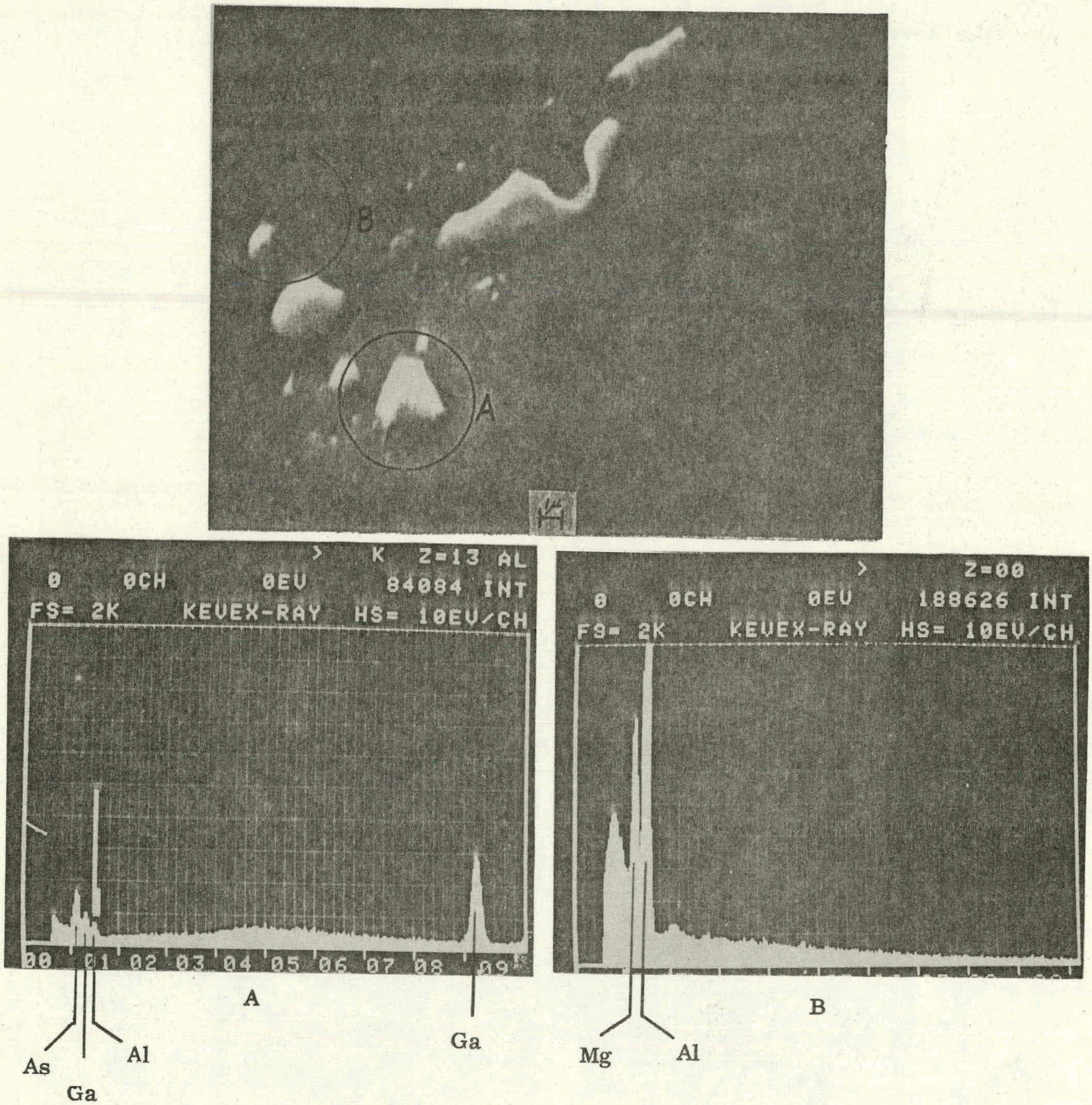
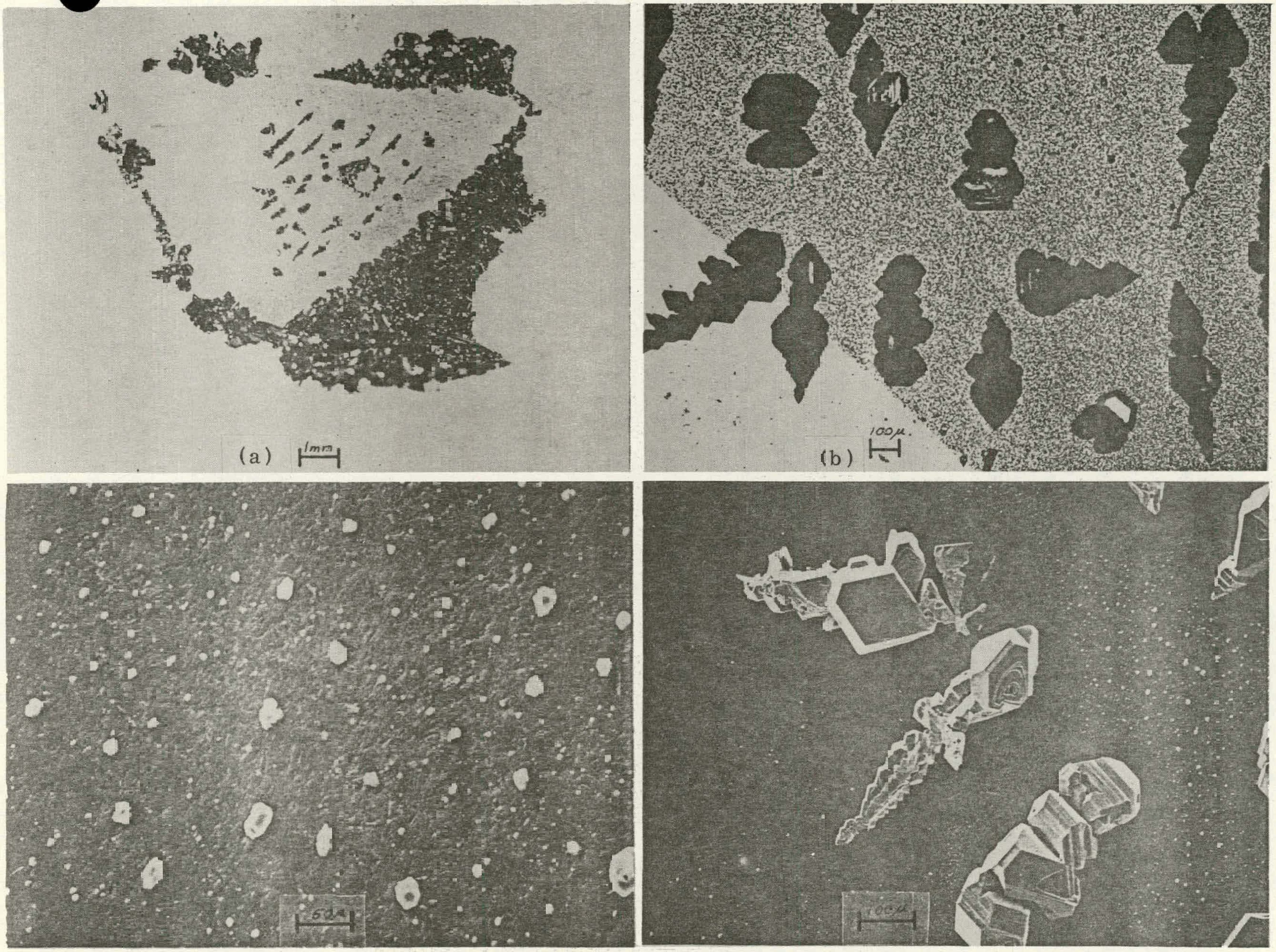
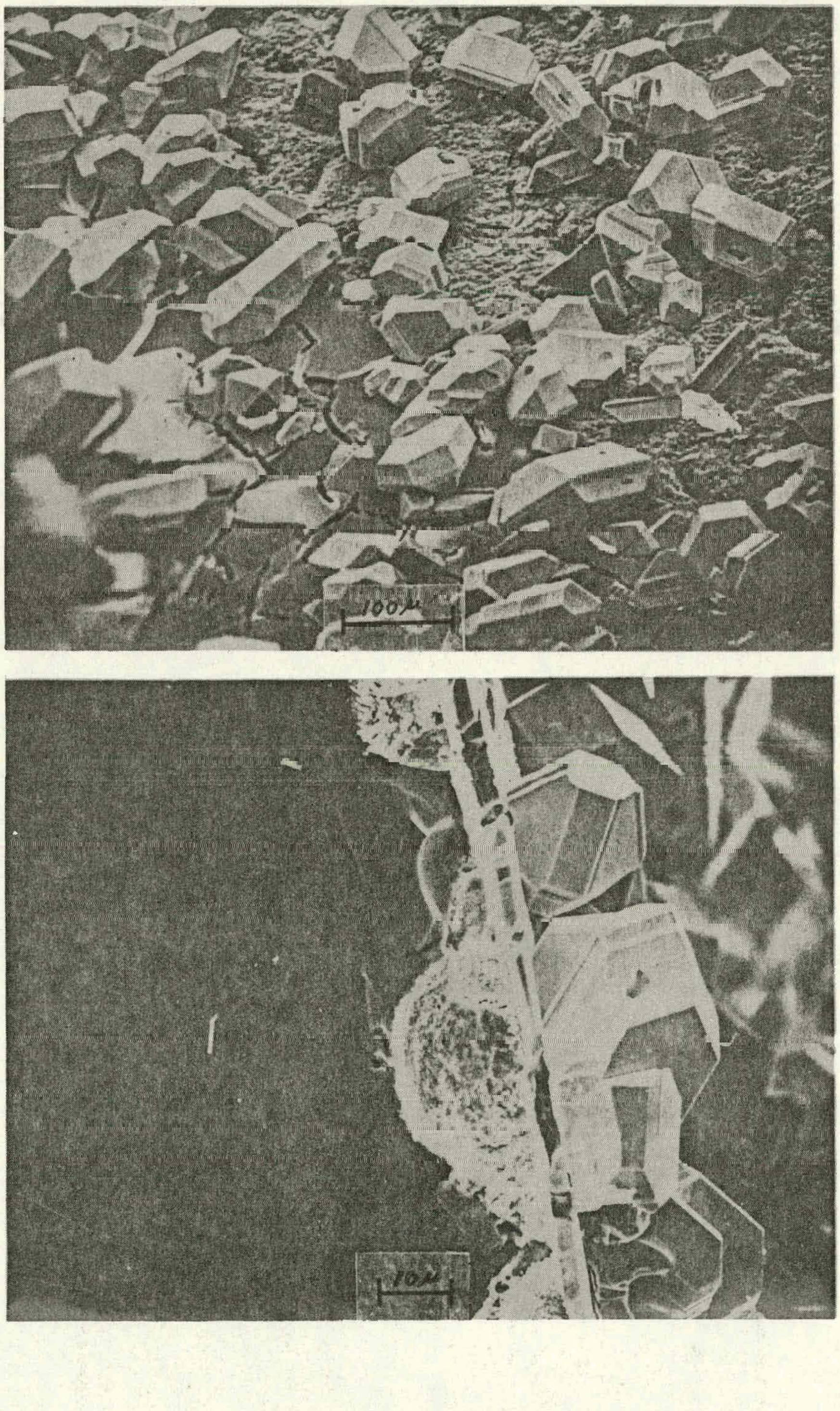

B
A
> K Z=13 AL
0 0CH 0EV 84084 INT
FS= 2K KEVEX-RAY HS= 10EV/CH
00 01 02 03 04 05 06 07 08 09
A
As
Ga
Al
Ga
> Z=00
0 0CH 0EV 188626 INT
FS= 2K KEVEX-RAY HS= 10EV/CH
B
Mg
Al

Fig. 2



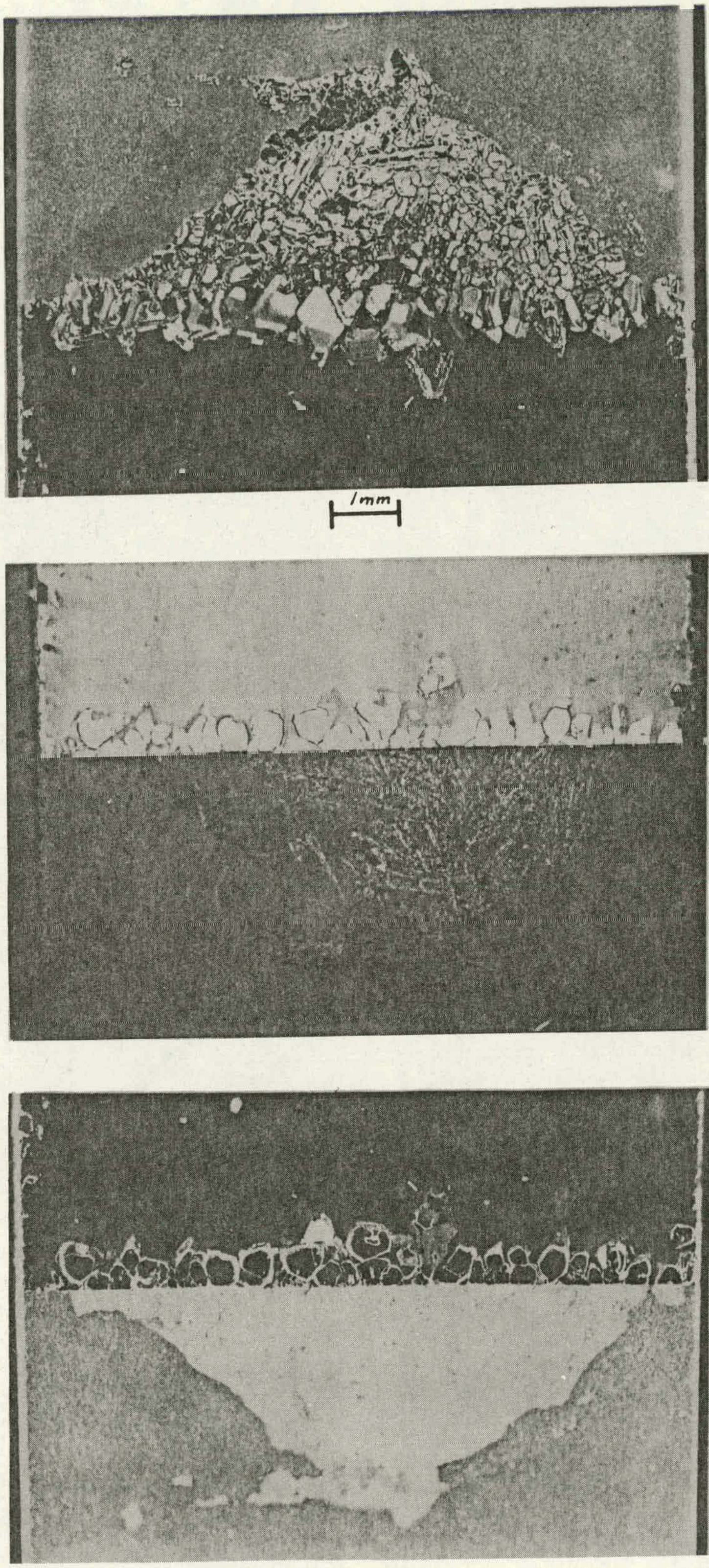
(c) Fig. 3 (d)



(a)

(b)

Fig. 4

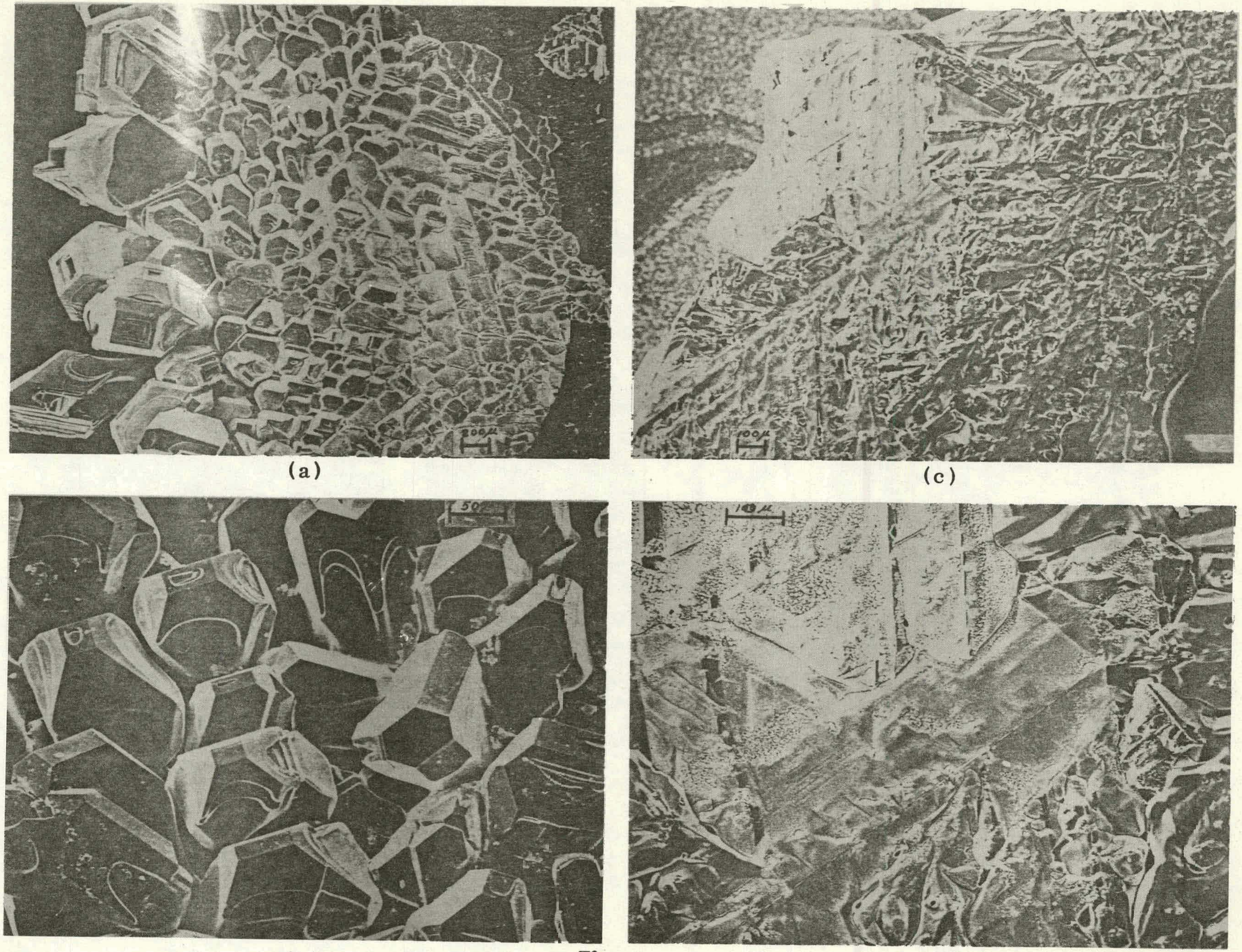


(a)

(b)

(c)

Fig. 5



(a) (b) (c) (d)

Fig. 6

POLYCRYSTALLINE THIN FILM GALLIUM ARSENIDE SOLAR CELLS

NATIONAL SCIENCE FOUNDATION

GRANT NO.: AER76-06186
PERIOD OF GRANT: 4/1/76 - 9/30/78
PROGRAM INITIATED: 6/1/76
TOTAL AWARD (2 YEARS): $140,000

CO-PRINCIPAL INVESTIGATORS:
J. M. BORREGO AND S. K. GHANDHI
RENSSELAER POLYTECHNIC INSTITUTE
TROY, NEW YORK 12181

PRESENTED AT THE NATIONAL SOLAR
PHOTOVOLTAIC PROGRAM REVIEW MEETING
AUGUST 3 - 6, 1976
UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE 04473

POLYCRYSTALLINE THIN GALLIUM ARSENIDE PHOTOVOLTAIC CELLS

Objectives

The objective of this program is to investigate a new approach to photovoltaic energy conversion, based on the use of thin films of III-V compound semiconductors. The initial effort will be conducted on single crystal layers of GaAs for the purpose of developing the device physics; however, polycrystalline layers will be used in the final cell structures. A highly conductive transparent layer of degenerate tin-oxide will be evaluated as the upper contact for this structure.

This program of materials and device development will be conducted simultaneously with one of device characterization. This is a newly-initiated program.

Discussion

Figure 1 shows the concept for the proposed approach. Details are as follows:

1. A molybdenum or tungsten substrate will be used, for good thermal expansion match. High temperature treatments will be used to enhance its grain structure, and to remove surface oxides. An in-situ HCl etch will prepare the surface for the deposition of semiconductor layers.

2. Interface layers of degenerate GaAs, InAs, or graded GaInAs will be used, followed by the working layers of GaAs. The function of this interface layer is to provide a low resistance contact to the working layer. Metalorganic processes for vapor deposition are proposed for all layers. These result in exothermic reactions, with high efficiency of chemical conversion. In addition, adherent films can be grown on metallic substrates using these materials. All of the components (trimethylgallium, triethylindium, and arsine) can be readily transported to the reaction chamber without previous equilibrating of the sources. Thus, it is possible to grow both successive as well as graded layers with rapid turn-around time by this method.

3. Both thermal and anodic methods will be investigated for growth of the interface oxide layer on the GaAs surface.

4. The upper layer of doped tin-oxide will be grown by the oxidation of tetramethyltin and phosphine gas. Arsine will be considered as an alternative doping source. A N_2/H_2 heat treatment will be used to increase the electrical conductivity of the tin-oxide layer.

5. Evaporated contacts will be used during this program. Possibilities available to us are aluminum, gold, palladium, and chromium. A cover layer of phosphosilicate glass may be eventually used for an anti-reflective coating. The composition of this layer can be adjusted to minimize thermal mismatch with GaAs.

6. Cell characterization will be conducted initially on single crystal substrates. Emphasis will be placed on measurement of the interface state density so that techniques can be developed for its control. Work characterization will be extended to polycrystalline substrates as the program advances.

Previous Activities

Figure 2 shows the reactor system currently in use at Rensselaer. Evidence of our capability for growth of 3/5 compounds is shown in Figs. 3-5. Figures 3 and 4 show mobility vs. carrier concentration of GaAs and InAs respectively, achieved by us in this system (Refs. 1,2). Material quality, as judged by this data, is comparable to that obtained by the halide process. Figure 5 shows the composition of $GaIn_xAs$ which have been grown in our system (Ref. 3). Note that the full range $0 \leq x \leq 1$ can be achieved.

Growth and properties of the doped tin-oxide layer are shown in Figs. 6-7. Figure 6 shows the conductivity vs. PH_3/TMT ratio obtained in our system (Ref. 5). Figure 7 shows the conductivity of doped and undoped SnO_2 as a function of annealing temperature. Resistivities as low as .003 ohm-cm have been achieved by us (Ref. 5).

Phosphosilicate glass layers have been grown with a full range of expansion coefficients to match that of GaAs. Measured data on our films is shown in Fig. 8 (Ref. 6), to show the compositional range we have achieved.

Schottky structures on GaAs have been made with gold and aluminum gates at Rensselaer. Figure 9 shows the guard ring structure used to avoid surface leakage, as well as the test circuit. Evidence of our diode quality is shown in Fig. 10. Figure 11 shows interface state density data for this diode, and establishes our ability to perform these measurements (Ref. 7).

Relevant Rensselaer Publications

1.	GaAs:	J. Crys. Growth, 26, 314 (1974).
2.	InAs:	JECS, 121, 1642 (1974).
3.	GaInAs:	JECS, 122, 683 (1975); JAPS, 46, 3941 (1975).
4.	In-situ Etch:	JECS, 122, 1378 (1975).
5.	SnO_2:	JECS, 123, 941 (1976).
6.	SiO_2 and P_2O_5-SiO_2:	JAP, 44, 990 (1973); IEEE PGED, ED-21, 410 (1974).
7.	Interface States:	SSE, 19 (accepted) (1976).

Current Efforts and Future Plans

1. A new reactor has been designed and is presently under construction.

2. Equipment is being set up for deep level transient spectroscopy measurements.

3. A simple solar simulator has been set up for laboratory use.

4. Preliminary diode structures of SnO_2-GaAs have been fabricated during the past two months. These are being characterized both electrically and optically. Experiments are under way to determine the manner in which the oxide interface should be formed, together with its effect on the properties of the cells.

5. Experiments have begun on the growth of polycrystalline films of GaAs.

Future plans are to extend the work along the above lines.

July 29, 1976

700

COVER LAYER	250° C	$P_2O_5 \cdot SiO_2$
CONTACT GRID		(Al, Pd, Cr/Au)
HEAT TREATMENT	300° C	(N_2/H_2)
UPPER LAYER	450° C	(P - SnO_2)
OXIDE INTERFACE		(Thermal, Anodic)
WORKING LAYER	700° C	(GaAs)
INTERFACE LAYER		(GaAs, InGaAs)
IN-SITU ETCH	900° C	(HCl)
HEAT TREATMENT	1100° C	(H_2)
SUBSTRATE		(Mo, W)

Fig. 1

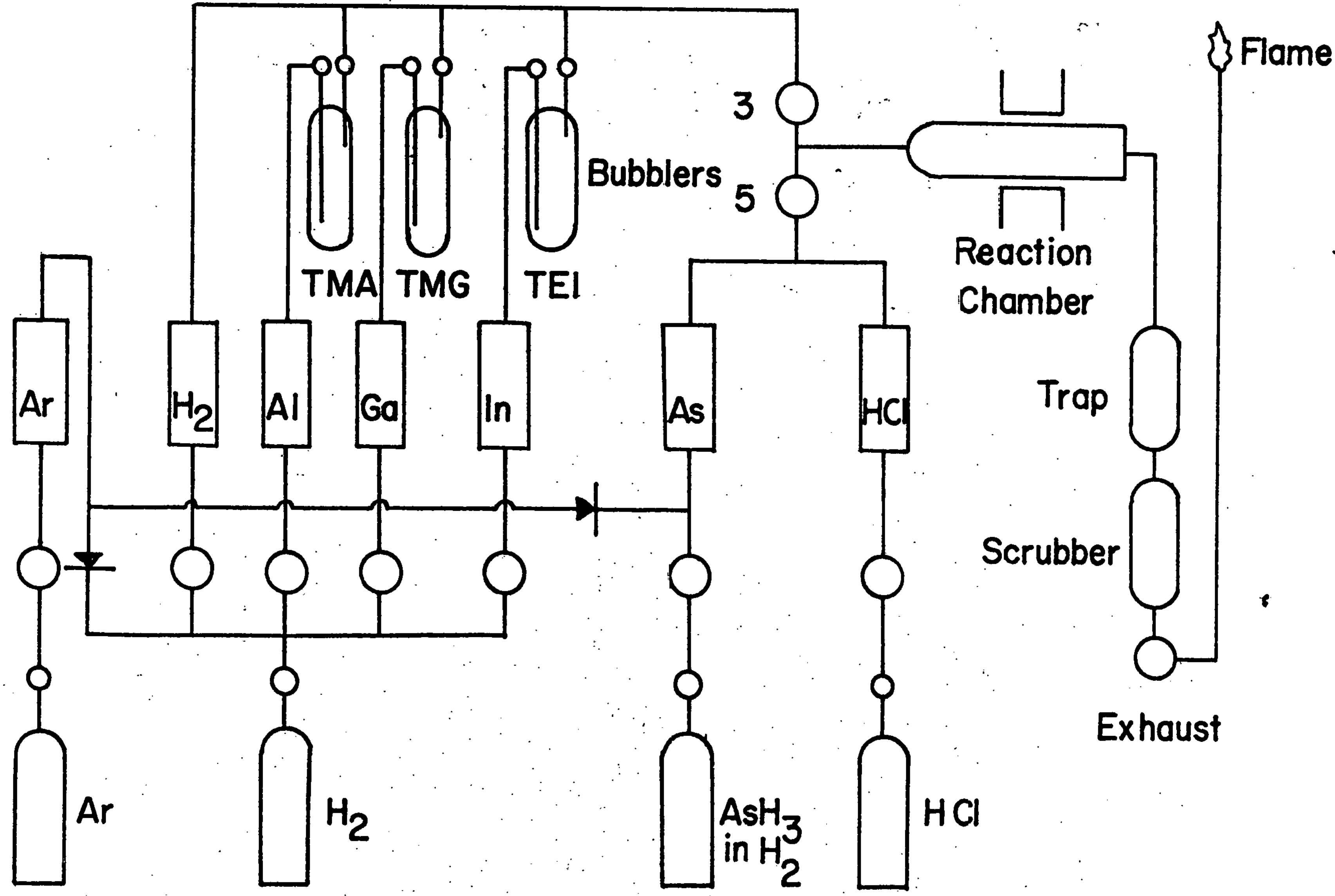

Flame
3
5
Bubblers
Reaction
Chamber
TMA
TMG
TEI
Ar
H2
Al
Ga
In
As
HCl
Trap
Scrubber
Exhaust
Ar
H2
AsH3
in H2
H Cl

Fig. 2

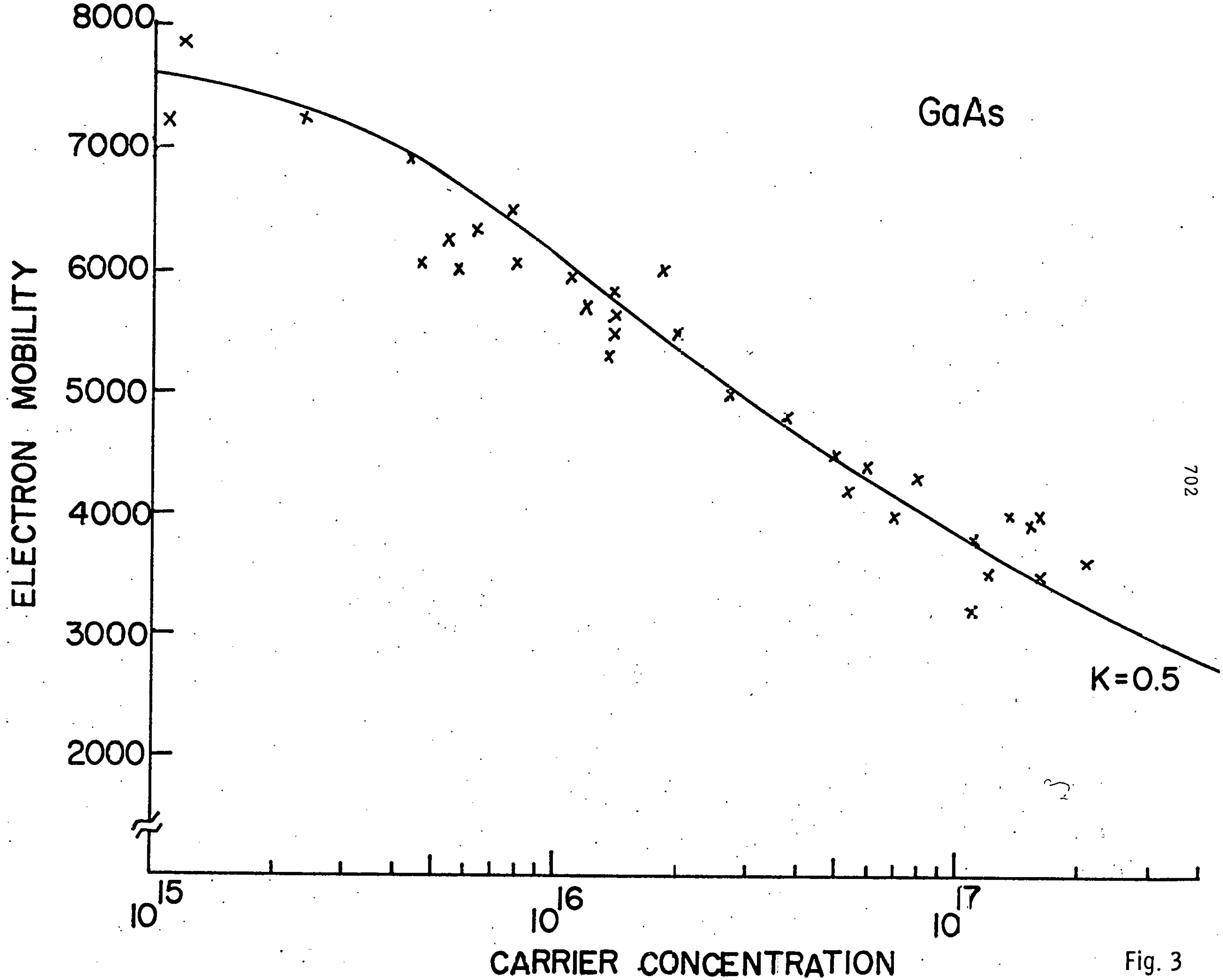

GaAs
ELECTRON MOBILITY
8000
7000
6000
5000
4000
3000
2000
K=0.5
10^{15}
10^{16}
10^{17}
CARRIER CONCENTRATION

Fig. 3

702

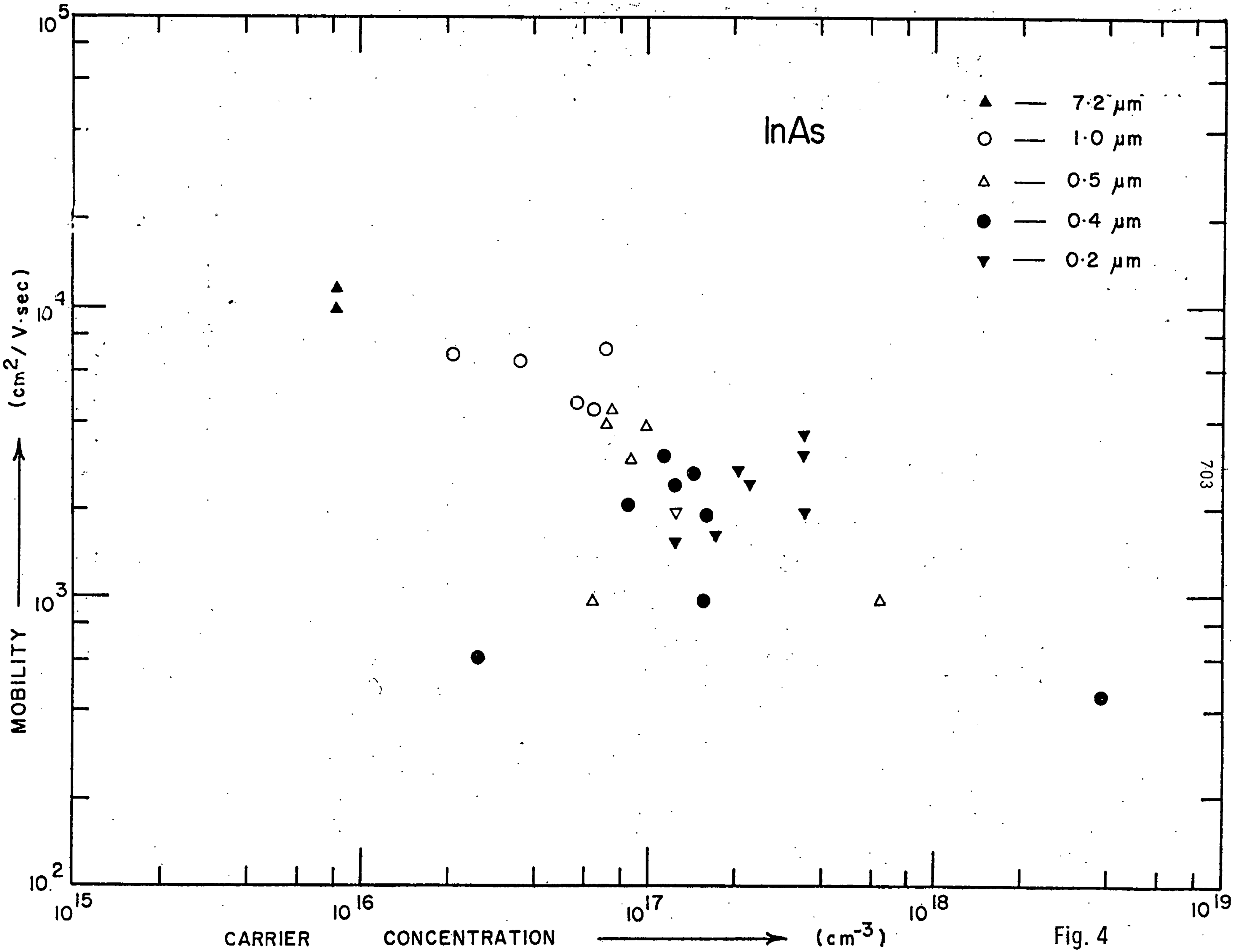

InAs
7·2 μm
1·0 μm
0·5 μm
0·4 μm
0·2 μm
MOBILITY (cm²/V·sec)
CARRIER CONCENTRATION (cm⁻³)
10^5
10^4
10^3
10^2
10^15
10^16
10^17
10^18
10^19

Fig. 4

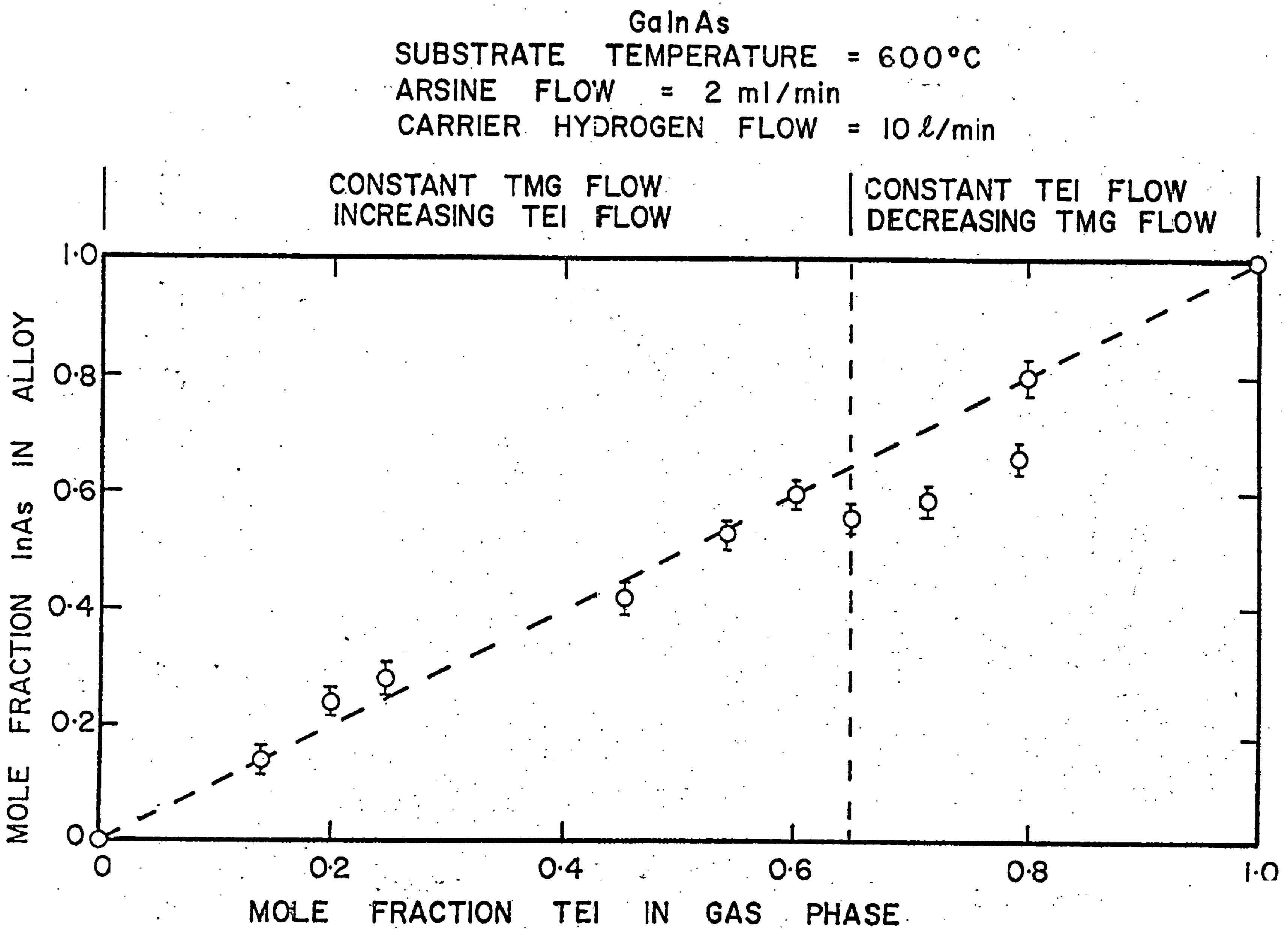

GaInAs
SUBSTRATE TEMPERATURE = 600°C
ARSINE FLOW = 2 ml/min
CARRIER HYDROGEN FLOW = 10 ℓ/min
CONSTANT TMG FLOW
INCREASING TEI FLOW
CONSTANT TEI FLOW
DECREASING TMG FLOW
1·0
0·8
0·6
0·4
0·2
0
0
0·2
0·4
0·6
0·8
1·0
MOLE FRACTION InAs IN ALLOY
MOLE FRACTION TEI IN GAS PHASE

Fig. 5

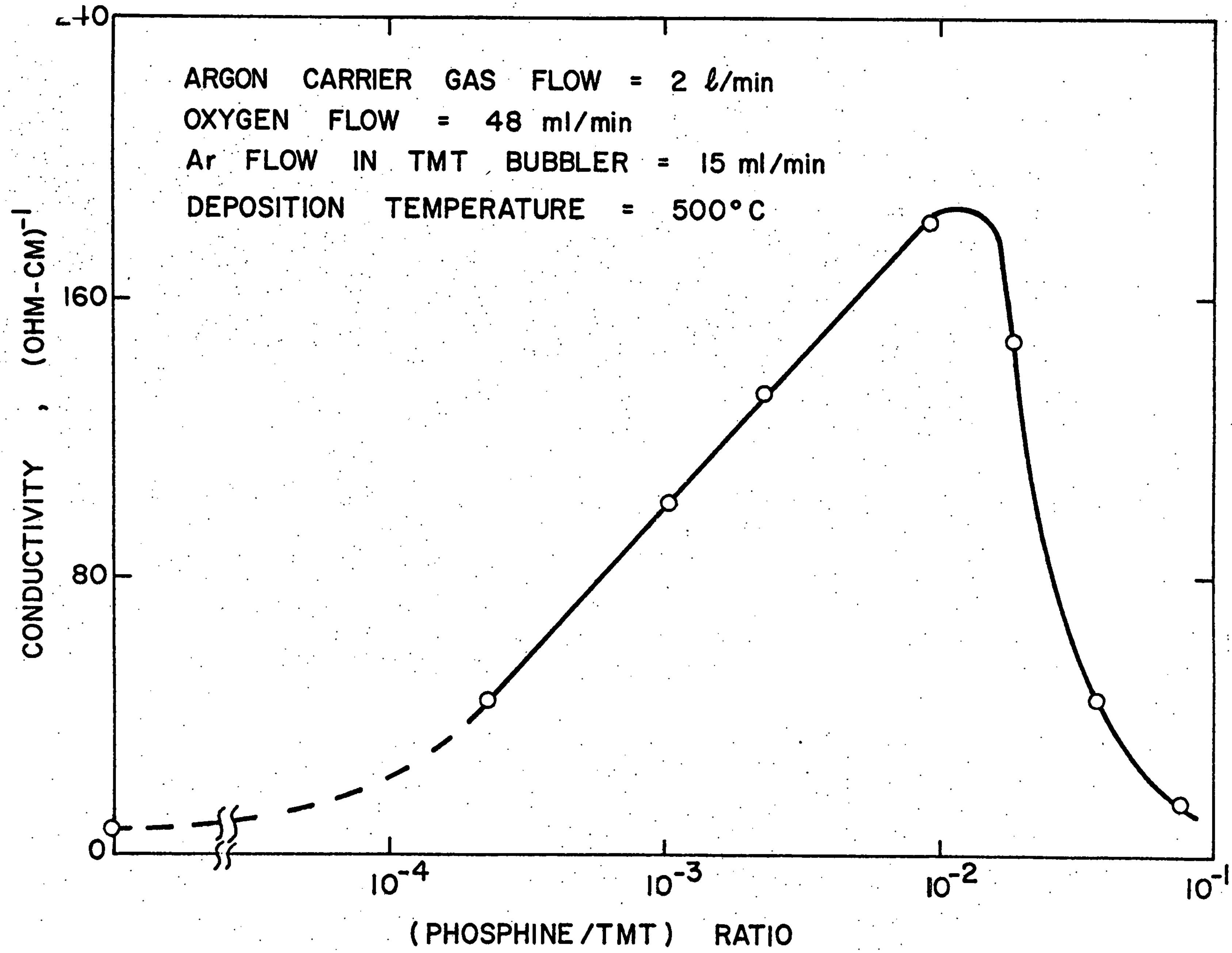

ARGON CARRIER GAS FLOW = 2 ℓ/min
OXYGEN FLOW = 48 ml/min
Ar FLOW IN TMT BUBBLER = 15 ml/min
DEPOSITION TEMPERATURE = 500°C
CONDUCTIVITY , (OHM-CM)$^{-1}$
160
80
0
10^{-4}
10^{-3}
10^{-2}
10^{-1}
(PHOSPHINE/TMT) RATIO

Fig. 6

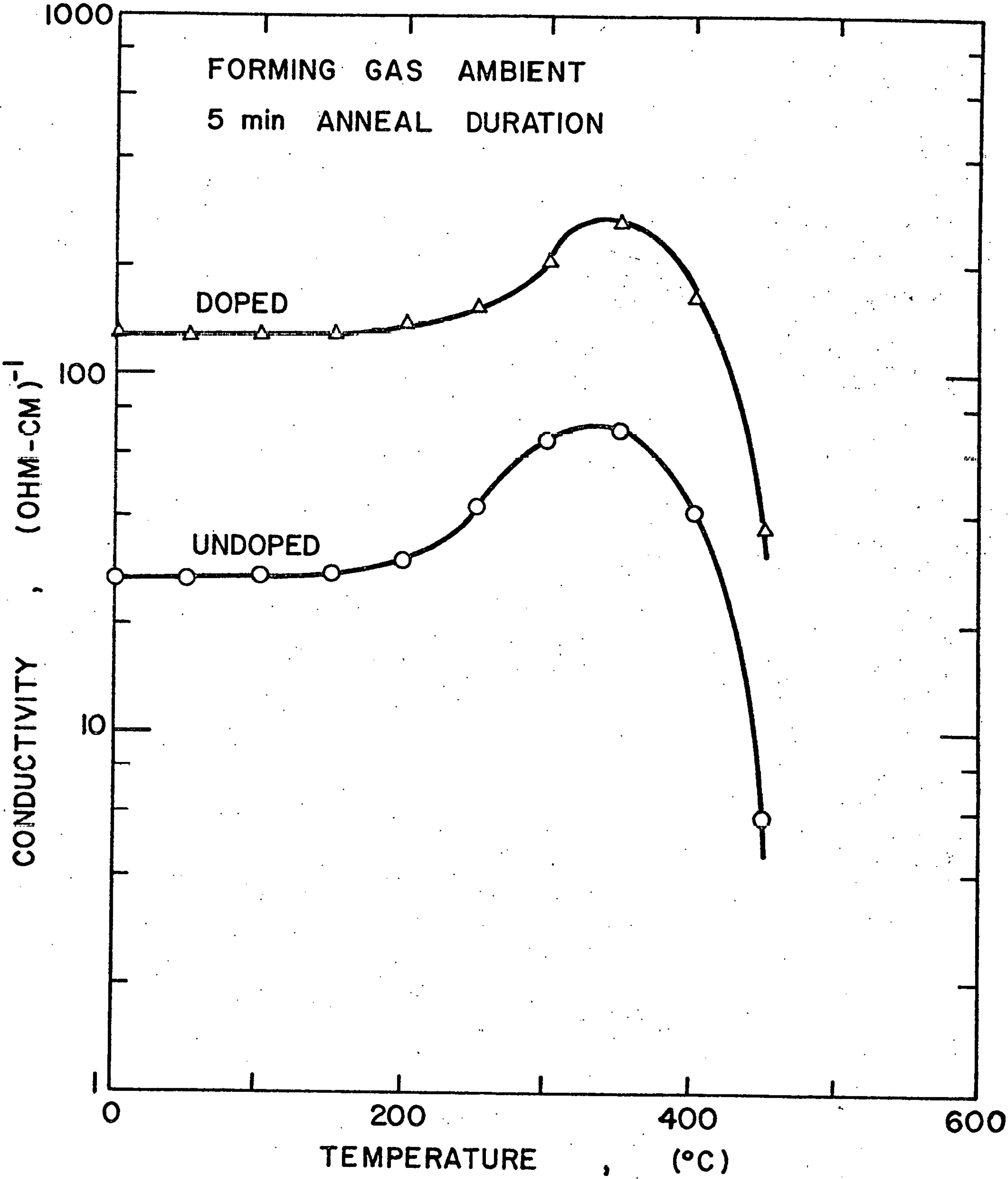

FORMING GAS AMBIENT
5 min ANNEAL DURATION
DOPED
UNDOPED
CONDUCTIVITY , (OHM-CM)$^{-1}$
1000
100
10
1
0
200
400
600
TEMPERATURE , (°C)

Fig. 7

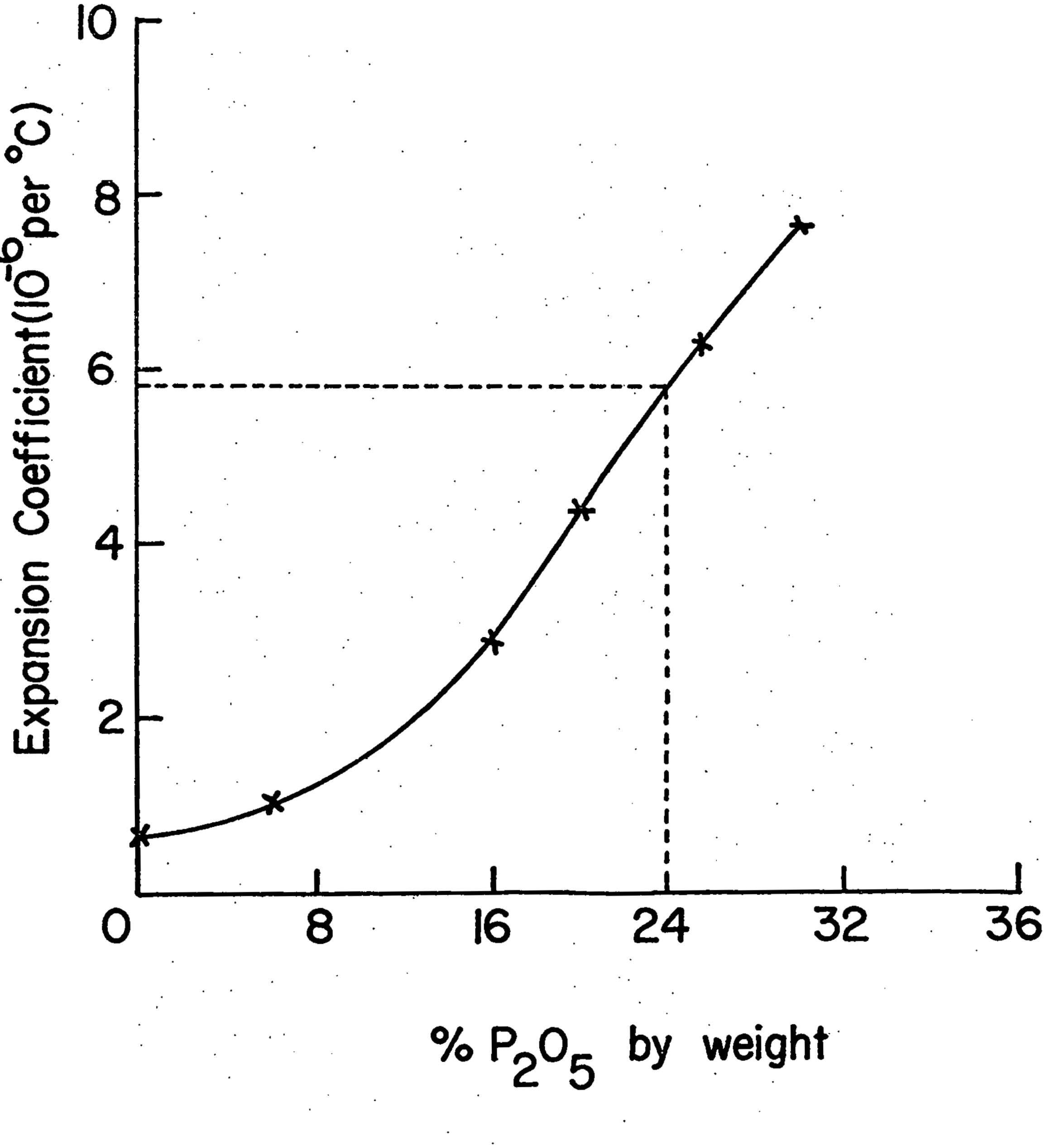
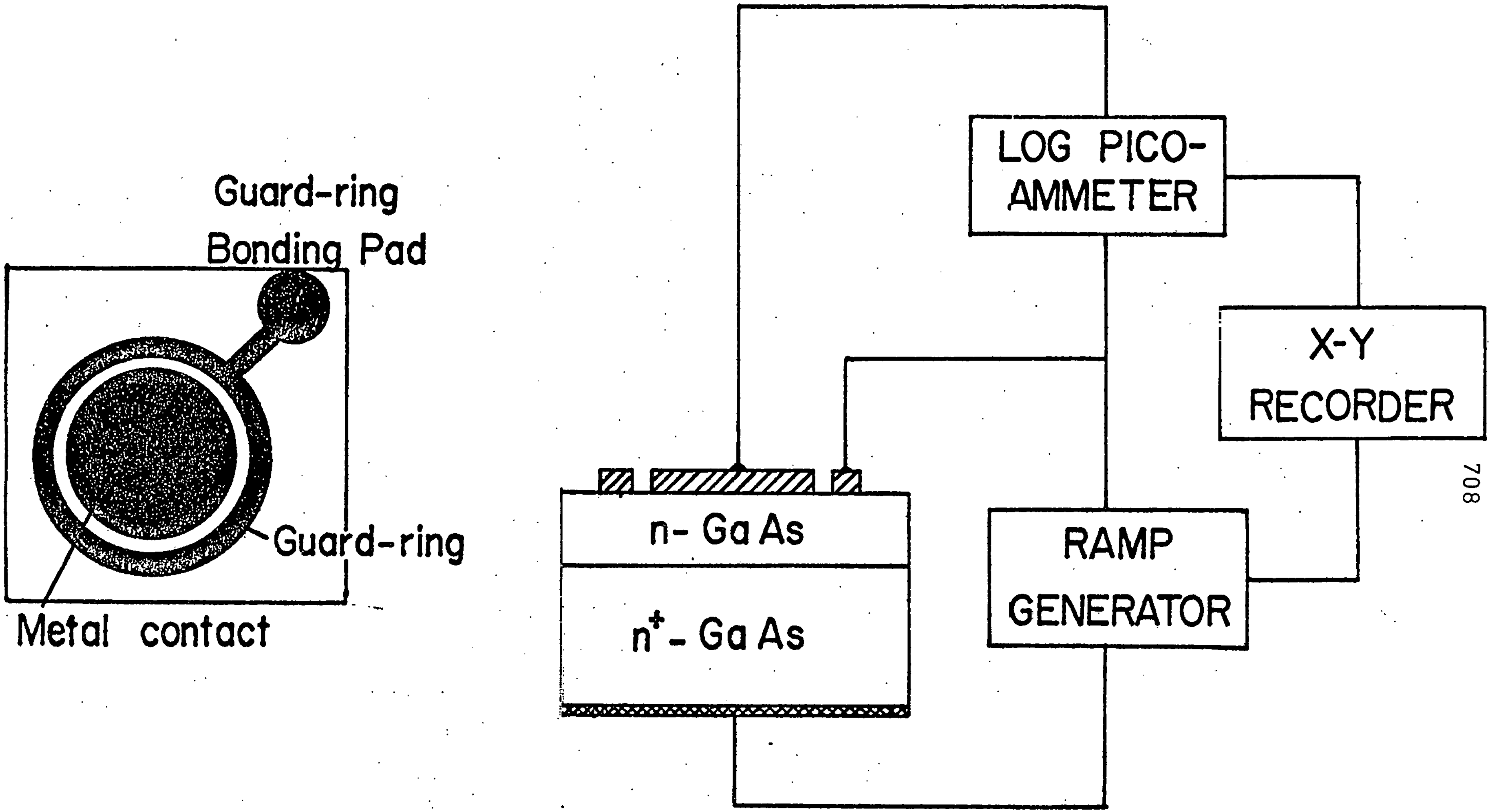

10
8
6
4
2
Expansion Coefficient (10^-6 per °C)
0
8
16
24
32
36
% P2O5 by weight

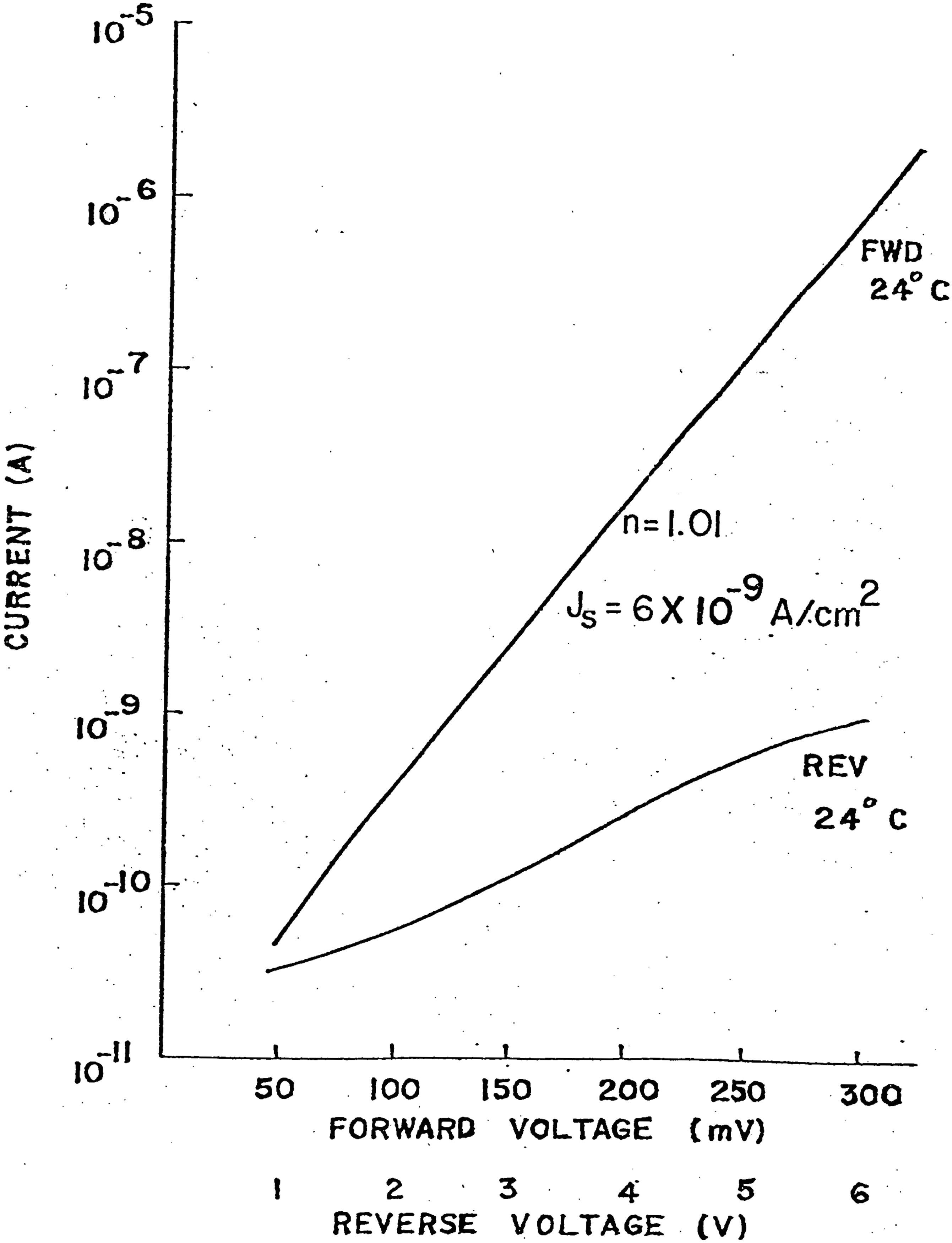
Fig. 8



708

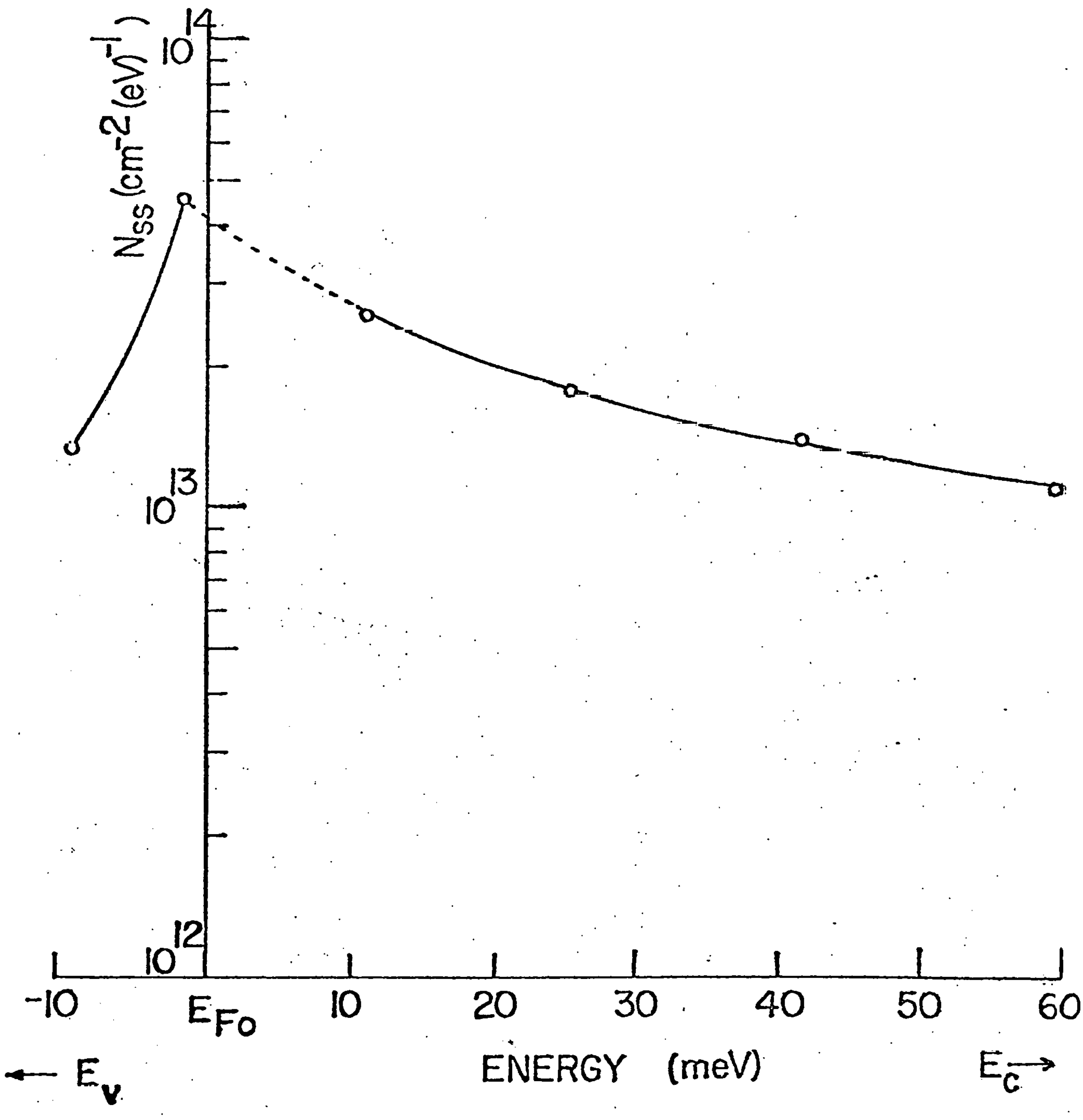
DIODE STRUCTURE AND MEASUREMENT CIRCUIT

Fig. 9



CURRENT (A)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
FWD
24° C
n=1.01
$J_s = 6 \times 10^{-9}$ A/cm^2
REV
24° C
50
100
150
200
250
300
FORWARD VOLTAGE (mV)
1
2
3
4
5
6
REVERSE VOLTAGE (V)

Fig. 10



N_{ss} (cm^{-2}(eV)$^{-1}$)
10^{14}
10^{13}
10^{12}
-10
E_{Fo}
10
20
30
40
50
60
ENERGY (meV)
← E_v
E_c →

Fig. 11

THIN FILMS OF GaAs ON LOW COST SUBSTRATES

U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Contract Number: E(04-3)-1202

Period of Grant: July 5, 1976 to September 4, 1976

Value of Grant: $226,634

P. D. Dapkus

Principal Investigator

ROCKWELL INTERNATIONAL
Electronics Research Division
3370 Miraloma Avenue
Anaheim, California 92803

Presented at the National Solar Photovoltaic Program Review Meeting

August 3-6, 1976

University of Maine at Orono

Orono, Maine 94473

ABSTRACT

A program to apply the metalorganic chemical vapor deposition technique (MO-CVD) to the growth of thin films of GaAs and GaAℓAs on low cost substrates is being pursued at Rockwell ERD Division. The objective of this program is to develop deposition techniques on selected low cost substrates and improve the properties of these films so that heterojunction thin film solar cells with AM1 efficiency of 10% can be fabricated. Five main areas of investigation have been identified and are being pursued to achieve these goals. They are: 1) selection, evaluation and development of substrate materials, 2) development of the CVD process for these substrates, 3) evaluation of the properties of these films, 4) fabrication and evaluation of experimental devices, and 5) analysis and projection of cell fabrication costs.

Several candidate substrates have been identified and potential suppliers have been contacted. The candidate substrates fall into four major categories: 1) single crystal substrates to be used for establishing present capability of the MO-CVD, e.g., GaAs, Ge and $A\ell_2O_3$, 2) polycrystalline aluminas, 3) metals and metal films, e.g., Kovar, Mo, W, 4) glasses and glazed ceramics. In addition, composites of these categories will be considered is necessary.

Initial results indicate that doping of p-type GaAs over the range 5×10^{16} to $10^{19} cm^{-3}$ can be achieved with diethylzinc as the dopant. Methods are being investigated to ensure good control of the doping.

Depositions of GaAs on Kovar (Fe,Ni,Co) alloy have been performed at 730°C, 610°C, and 536°C. At the two higher temperatures considerable interaction between the film and substrate are observed. The film growth appears to contain large crystallites ($\sim 5 \mu m$) of GaAs interspersed with another phase of Ni-rich material. At 536°C, only "hair like" filamentary growth occurs on Kovar.

Work during the next period will include the growth fabrication and evaluation of single crystal heterojunction solar cells to establish present capabilities of MO-CVD for producing high efficiency solar cells.

Activity will continue on substrate material selection and development and film growth on promising substrates will be pursued. The growth process will be modified as necessary to ensure optimal growth on the various substrates. Once optimal conditions have been achieved on a promising substrate materials thin film solar cells will be fabricated to assess the ultimate suitability of the film/substrate composite for energy conversion applications.

THIN FILMS OF GaAs ON LOW COST SUBSTRATES
ERDA CONTRACT No. E(04-3)-1201

ROCKWELL INTERNATIONAL
ELECTRONICS RESEARCH DIVISION
ANAHEIM, CA 92803

PERIOD OF CONTRACT:

JULY 5, 1976 TO SEPTEMBER 4, 1976

VALUE OF AWARD: $226,634

P. D. DAPKUS, PRINCIPAL INVESTIGATOR

OVERALL OBJECTIVE OF PROGRAM

TO INVESTIGATE THE DEPOSITION OF THIN FILMS OF GaAs AND GaAlAs BY THE METALORGANIC CHEMICAL VAPOR DEPOSITION TECHNIQUE (MO-CVD) ON LOW COST SUBSTRATES AND TO PERFECT THE PROPERTIES OF THESE FILMS TO THE POINT THAT 10 PERCENT AM1 EFFICIENCY HETEROJUNCTION SOLAR CELLS CAN BE CONSTRUCTED.

AREAS OF ACTIVITY TO MEET PROJECT OBJECTIVE

1. SELECTION, EVALUATION AND DEVELOPMENT OF SUBSTRATE MATERIALS
2. CVD EXPERIMENTS AND PARAMETER STUDIES
3. FILM PROPERTY EVALUATION
4. FABRICATION AND EVALUATION OF EXPERIMENTAL DEVICES
5. ANALYSIS AND PROJECTION OF CELL FABRICATION COST

PLANNED ACTIVITY TO DATE

I. SUBSTRATE SELECTION, EVALUATION AND DEVELOPMENT

A. IDENTIFY POTENTIALLY USEFUL LOW COST SUBSTRATE MATERIALS

B. CONTACT SUPPLIERS TO SOLICIT THEIR COOPERATION IN SUBSTRATE SUPPLY AND DEVELOPMENT

C. ESTABLISH EVALUATION AND SCREENING PROCEDURES FOR SUBSTRATE MATERIALS

II. CVD EXPERIMENTS AND PARAMETER STUDIES

A. BEGIN CONSTRUCTION OF DEDICATED REACTOR

B. BEGIN DOPING STUDIES OF N AND P TYPE GaAs AND $Ga_{.1}Al_{.9}As$

C. BEGIN DEPOSITION EXPERIMENTS ON LOW COST SUBSTRATES

III. FILM PROPERTY EVALUATION

A. IDENTIFY POTENTIALLY USEFUL CHARACTERIZATION TECHNIQUES AND ACCUMULATE APPARATUS WHERE NECESSARY

B. BEGIN STRUCTURAL AND ELECTRICAL EVALUATION OF FILMS

IV. FABRICATION AND EVALUATION OF EXPERIMENTAL DEVICES

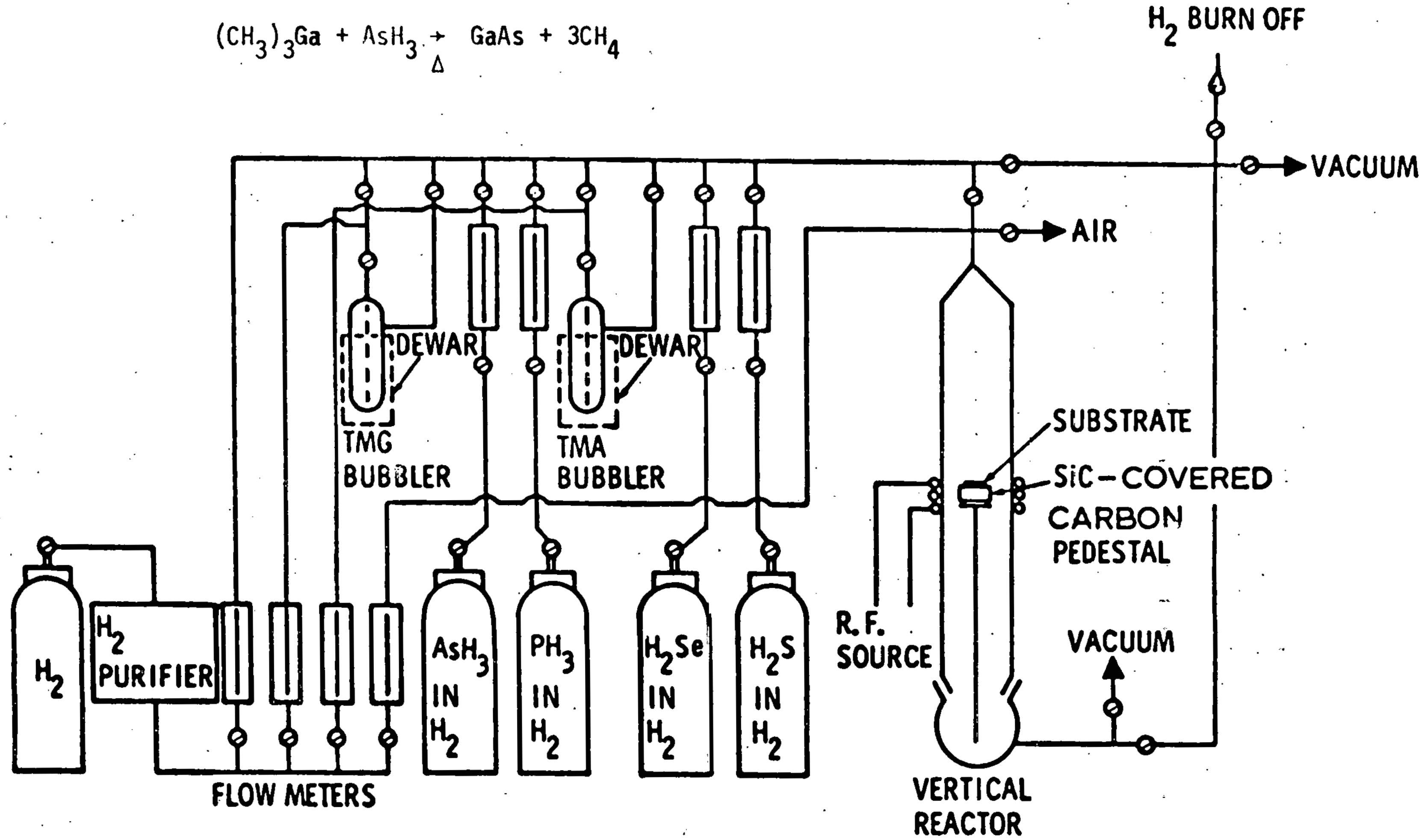
A. IDENTIFY USEFUL DEVICE STRUCTURES

B. IDENTIFY USEFUL CHARACTERIZATION TECHNIQUES AND ACQUIRE NECESSARY APPARATUS

V. ANALYSIS AND PROJECTION OF CELL FABRICATION COST

BEGIN PRELIMINARY ESTIMATES OF COSTS BASED ON OPTIMISTIC ASSUMPTION OF CELL PERFORMANCE AND MATERIALS COST.

$$(CH_3)_3Ga + AsH_3 \xrightarrow{\Delta} GaAs + 3CH_4$$

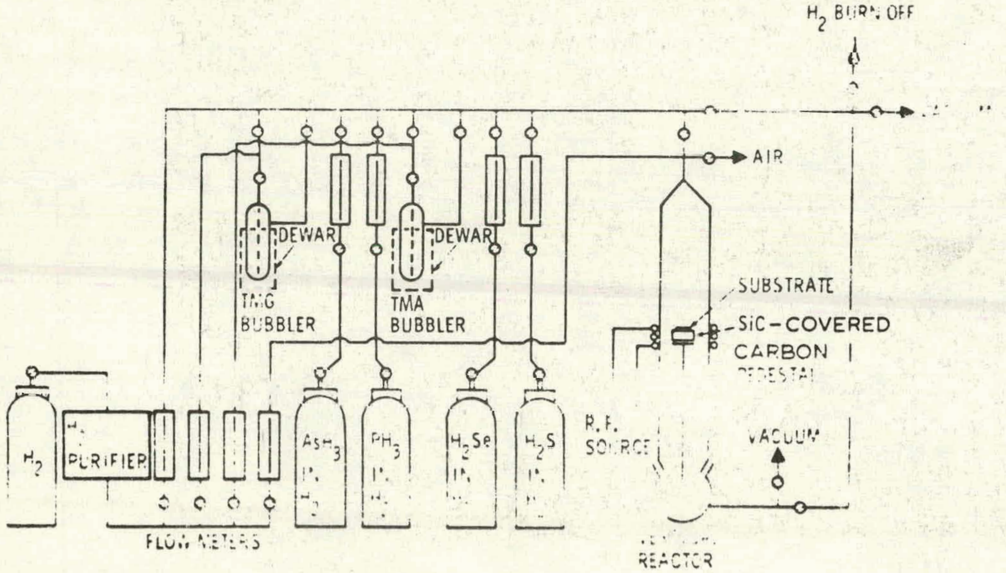


Schematic of Deposition Apparatus

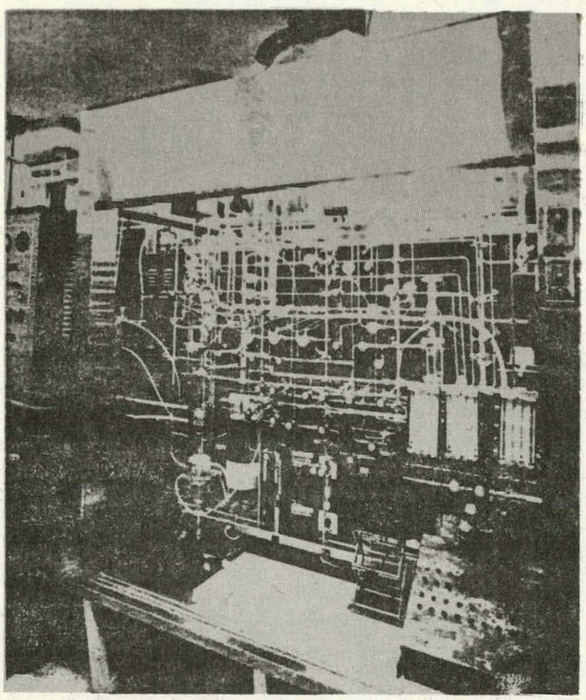
SUBSTRATE SELECTION CRITERIA

1. AVAILABLE AT LOW COST OR POTENTIALLY SO
2. AVAILABLE IN LARGE SHEET FORM OR POTENTIALLY SO
3. MECHANICALLY COMPATIBLE WITH FILM OVER WIDE TEMPERATURE RANGE
4. CHEMICALLY COMPATIBLE WITH FILM GROWTH TECHNIQUE AND PROVIDE NO CONTAMINATION OF FILM
5. PROVIDE LOW RESISTANCE CONTACT TO FILM

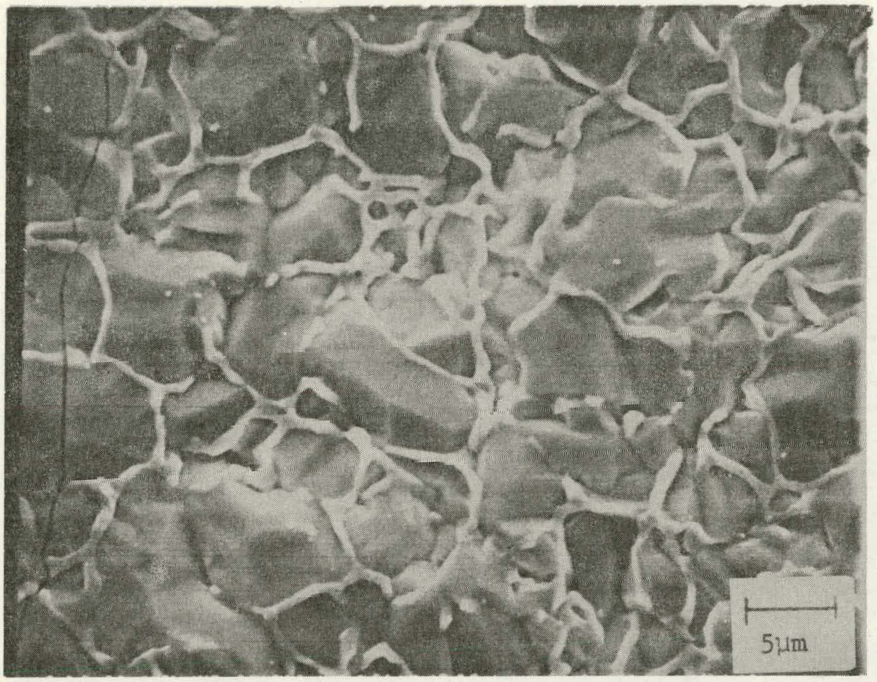
SUBSTRATE IDENTIFICATION	MATERIAL/TYPE	THERMAL EXPANSION COEFF (TEMP RANGE) (10^{-6} PER DEG C)	SURFACE ROUGHNESS	NOMINAL PURITY (%)	REPRESENTATIVE APPROXIMATE COST FOR RELATIVELY LARGE QUANTITIES
Corning 0221	Lime Borosilicate	7.4(0-300 C)	< 1 Microinch	–	$0.031/in.^{2} (12" x 14" sheet) as drawn
0317	Alumina Soda Lime	8.7(0 300 C)	~0.5 Microinch	–	$0.22/in.^{2} (10,000 4" x 4") as drawn
1723	Aluminosilicate	5.4(25-670 C)	< 0.5 Microinch	–	–
7059	Barium Alumino-Borosilicate	4.6(0-300 C)	< 0.5 Microinch	(Alkali-free)	$0.11/in.^{2} (144 sq in.) polished $0.04/in.^{2} (168 sq in.) as drawn
Coors ADS96F	Alumina	8.1(25-1000 C)		96	
ADS995	Alumina	7.7(25-1000 C)	8–10	99.5	
Vistal	Alumina	8.3(25-1200 C)		99.9	
MRC Superstrate	Alumina	7.3(25-800) C)	4–5 Max	99.6	
3M ASM614	Alumina	7.9(25-900 C)		96	$0.06/in.^{2} (40 x 10^3 in.^{2})
ASM772	Alumina	7.7(25-900 C)		99.5	$0.08/in.^{2} (40 x 10^3 in.^{2})
ASM624 W/743 Glaze	Lead Borosilicate on Alumina	~6.5(40-540 C)	~1 Microinch		$0.13/in.^{2} (40 x 10^3 in.^{2})
ASM805	Alumina	7.7(25-900 C)	<1–2 Microinch	99.9	$0.50/in.^{2} (40 x 10^3 in.^{2})
ASM665	Steatite	7.8(25-700 C)			
Tungsten	W Sheet or Foil	5.0(25-700 C)			$~40/lb
Molybdenum	Mo Sheet or Foil	6.0(25-700 C)			$ ~35/lb
Kovar	Ni-Co-Fe Alloy Foil or Sheet	8.1(25-700 C)			$0.06-0.09/in.^{2} ($5.50-$8/lb)
Ge	Single Crystal Slice	6.6(300 650 C)			$2.25/in.^{2} (3000 in.^{2})
GaAs	Single Crystal Slice	6.9(62 2000 C)			$5 8/in.^{2}
Sapphire	Single Crystal Ribbon	8.4(25 800 C)			$1/in.^{2}(1/2 in. wide ribbon) $2.39/in.^{2} (10,000 sq in. with Grains)



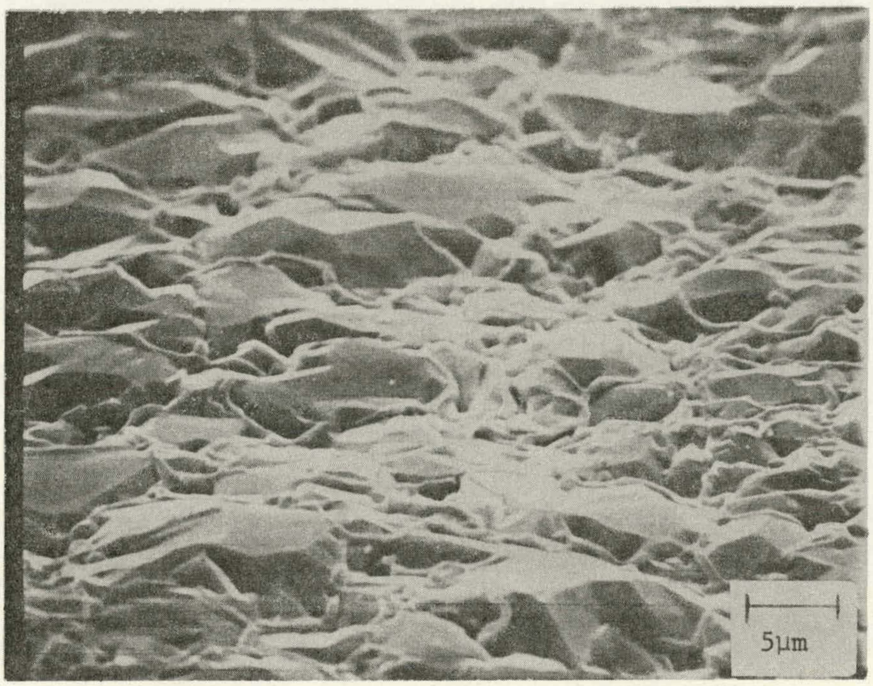
Schematic of Deposition Apparatus

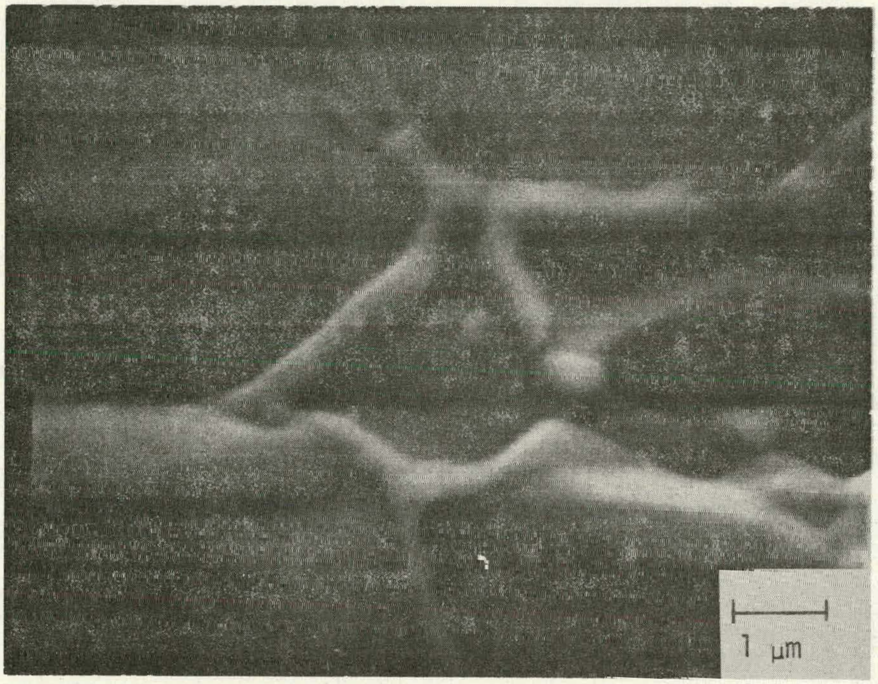


Research Reactor for MO-CVD Growth of III-V Semiconductors



GaAs FILM ON RODAR (KOVAR)
$730^{o}C$

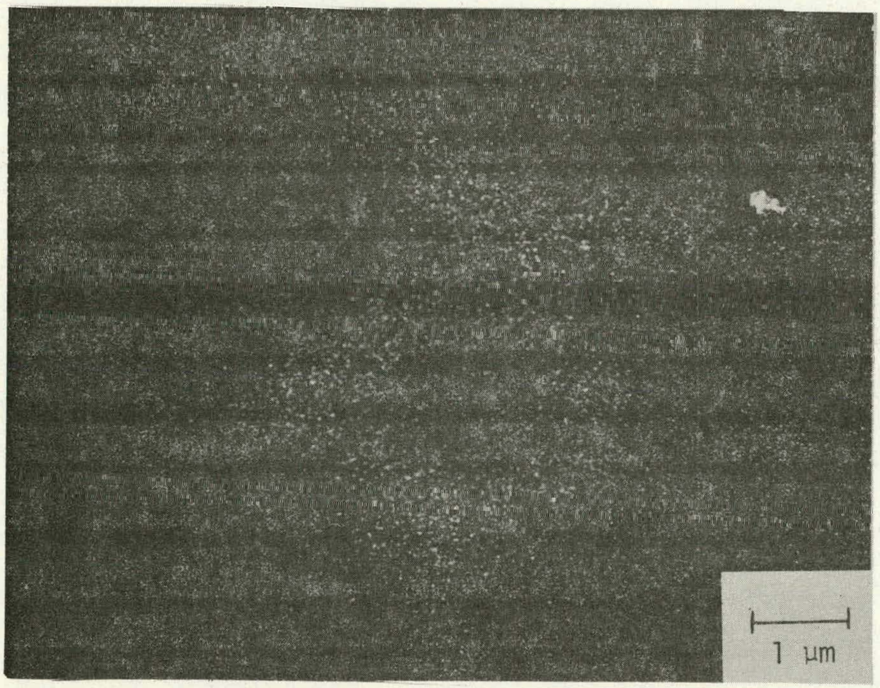


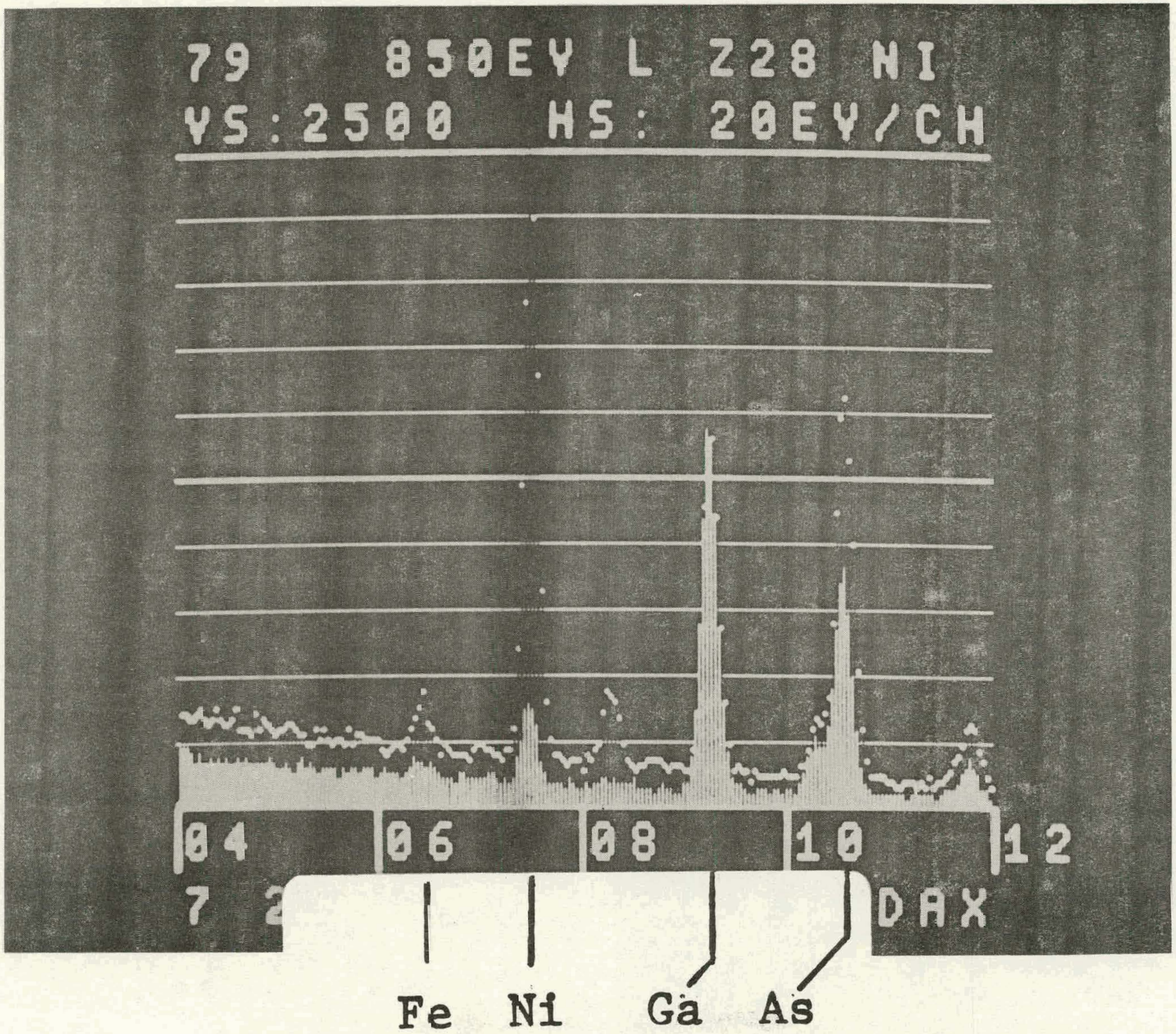


GaAs/RODAR(730°C)

↑ SECONDARY ELECTRON IMAGE

↓ Ni Kα XRAY IMAGE





XRAY ANALYSIS OF GaAs ON RODAR FILM

PLANNED ACTIVITY FOR 8/5/76 TO 2/5/77

I. SUBSTRATE MATERIAL SELECTION, EVALUATION AND DEVELOPMENT

A. CONTINUE TO IDENTIFY MATERIALS AND CONTACT POTENTIAL SUPPLIERS

B. INVESTIGATE EFFECT OF SUBSTRATE PREPARATION AND PURITY ON FILM PROPERTIES

II. CVD EXPERIMENTS AND GROWTH PARAMETERS

A. CONSTRUCT DEDICATED REACTOR FOR PROGRAM

B. FINISH DOPING STUDIES

C. GROW N ON P AND P ON N SINGLE CRYSTAL HETEROSTRUCTURE SOLAR CELLS

D. CONTINUE TO INVESTIGATE FILM GROWTH ON LOW COST SUBSTRATES

E. GROW THIN FILM HETEROSTRUCTURE SOLAR CELLS ON PROMISING SUBSTRATES

III. EVALUATION OF FILM PROPERTIES

A. CONTINUE APPLYING AVAILABLE STRUCTURAL AND ELECTRICAL MEASUREMENT TECHNIQUES AS NEEDED TO DETERMINE FILM PROPERTIES

B. INVESTIGATE DOPING DEPENDENCE OF MINORITY CARRIER DIFFUSION LENGTH IN SINGLE CRYSTAL GaAs USING THE SPECTRAL DEPENDENCE OF THE PHOTOCURRENT OF SCHOTTKY BARRIERS AND EBIC MODE

C. INVESTIGATE MINORITY CARRIER PROPERTIES OF POLY-CRYSTALLINE FILMS

SUMMARY

1. SEVERAL POTENTIAL SUBSTRATE MATERIALS HAVE BEEN IDENTIFIED AND SUPPLIERS HAVE BEEN CONTACTED TO SOLICIT THEIR COOPERATION IN THIS PROGRAM

2. CVD EXPERIMENTS TO DETERMINE DOPING CALIBRATION OF SYSTEM HAVE BEGUN WITH THE GOAL OF PRODUCING "BASELINE" HETERO-STRUCTURE SINGLE CRYSTAL SOLAR CELLS. P-TYPE DOPING OF GAAS OVER THE RANGE 5×10^{16} CM^{-3} TO 2×10^{19} CM^{-3} USING DIETHYL ZINC AS A DOPANT SOURCE HAS BEEN DEMONSTRATED

3. CVD EXPERIMENTS HAVE BEGUN TO GROW GAAS ON KOVAR AS A FIRST SUBSTRATE CHOICE. INITIAL RESULTS INDICATE SUBSTANTIAL INTERACTION BETWEEN CONSTITUENTS OF FILM AND SUBSTRATE

4. ALL NECESSARY APPARATUS FOR CHARACTERIZATION AND ALL NECESSARY PARTS FOR DEDICATED CVD REACTOR ARE ON HAND OR WILL BE SHORTLY.

IV. FABRICATION AND EVALUATION OF EXPERIMENTAL DEVICES

A. DEVELOP FABRICATION TECHNIQUES FOR THIN FILM POLYCRYSTALLINE HETEROSTRUCTURE CELLS
B. CONSTRUCT AND EVALUATE SINGLE CRYSTAL HETEROSTRUCTURE SOLAR CELLS (η, V_{OC}, I_{SC}, FF, SPECTRAL RESPONSE)
C. CONSTRUCT AND EVALUATE POLYCRYSTALLINE HETEROSTRUCTURE SOLAR CELLS

V. ANALYSIS AND PROJECTION OF CELL COST

COMPLETE INITIAL OPTIMISTIC EVALUATION OF CELL COST.

THIN FILMS OF GALLIUM ARSENIDE ON LOW-COST SUBSTRATES

Energy Research and Development Administration
Contract Number: E(04-3)-1284

Period of Contract

September 1, 1976 - October 31, 1977

Value of Contract: $129,100

Shirley S. Chu, Principal Investigator
Associate Professor, Southern Methodist University
Dallas, Texas 75275

Presented at the National Solar Photovoltaic Program Review Meeting

August 3-6, 1976
University of Maine at Orono
Orono, Maine 04473

I. Objective

The objective of this program is to conduct intensive studies concerning thin films of gallium arsenide on low cost substrates as an initial step for the fabrication of low cost solar cells of relatively high efficiency. The areas of studies are: (1) the selection and the preparation of low cost substrates, (2) the deposition of gallium arsenide films on the substrates, (3) the characterization of the gallium arsenide films, (4) the control of conductivity type and carrier concentration in gallium arsenide films, and (5) the preparation, characterization, and optimization of gallium arsenide p-n junctions and solar cells.

II. Program Plan

The initial phase of this work will be directed to the selection of substrates and the deposition of gallium arsenide films.

1. Selection of Substrates. The requirements of the electrical, chemical, and mechanical properties of foreign substrates for the deposition of gallium arsenide films are fairly well established. Since it is desirable to have large crystallites in gallium arsenide films, the crystal symmetry, lattice parameters, and crystallite size in the substrate are also important factors. Germanium has the same crystal symmetry as gallium arsenide, and the lattice parameter and thermal expansion coefficient of germanium (5.657 Å, 5.9×10^{-6} °C^{-1}) are very similar to those of gallium arsenide (5.654 Å 6.8×10^{-6} °C^{-1}). Thus, germanium is a suitable substrate for the deposition of gallium arsenide films. Although germanium is not a low cost substrate, polycrystalline germanium films can be deposited on a low cost support, such as graphite and metallurgical silicon, by the thermal reduction of germanium tetrachloride. The deposited germanium films can then be recrystallized to yield large crystallites.

In addition to recrystallized germanium films, the use of tungsten films on a low cost support (graphite or steel) as a substrate for the deposition of gallium arsenide will also be investigated. Tungsten crystallized in the body-centered cubic structure with a lattice parameter of 3.165Å and thermal expansion coefficient of 4.5×10^{-6} °C^{-1}. Gallium arsenide films with a high degree of orientation has been deposited on single crystalline tungsten substrates. Tungsten can be readily deposited by the thermal reduction of tungsten hexafluoride with hydrogen at about 500°C.

2. Deposition of Gallium Arsenide Films. Gallium arsenide films will be deposited by the chemical vapor deposition technique using the reaction between gallium, hydrogen chloride, and arsine in a gas flow system. A two-zone, resistance-heated furnace will be used to maintain gallium at 800-900°C and the substrates at about 50°C lower. Two reactions are involved: the formation of gallium monochloride at the high temperature zone, and the reaction of gallium monochloride and arsine at the substrate surface.

$$2\ Ga(\ell) + 2\ HCl(g) \longrightarrow 2\ GaCl(g) + H_2(g)$$
$$GaCl(g) + AsH_3(g) \longrightarrow GaAs(s) + HCl(g) + H_2(g)$$

The conductivity type and carrier concentration in the deposited film will be controlled by using hydrogen sulfide as the n-type dopant and zinc or diethylizinc as the p-type dopant. It is believed that this process will permit the preparation of large area gallium arsenide films of uniform thickness and properties and controlled dopant concentration.

The structural and electrical properties of gallium arsenide films will be characterized by the conventional techniques. During the early stage of this program, emphasis will be directed to the microstructure of the gallium arsenide films. When gallium arsenide films of reasonable microstructure can be prepared reproducibly, the structural properties of gallium arsenide films will be evaluated in more detail, and their electrical properties such as dopants concentration, uniformity of dopant distribution, and Hall mobility will be measured. The characterization work will be closely coordinated with the material preparation task to optimize the properties of gallium arsenide films.

Subsequent to the development of gallium arsenide films of reasonable structure and electrical properties, the preparation and characterization of p-n junctions and solar cells will be formulated.

THIN FILMS OF GALLIUM ARSENIDE ON LOW-COST SUBSTRATES

ERDA Contract E(04-3)-1284

Work to be performed at Southern Methodist University

Period of Contract

September 1, 1976 - October 31, 1977

Value of Contract $129,100

Principal Investigator: Shirley S. Chu

THIN FILMS OF GALLIUM ARSENIDE ON LOW-COST SUBSTRATES
INTRODUCTION

- OBJECTIVE: To conduct intensive studies of gallium arsenide films on low cost substrates as an initial step for the fabrication of low cost solar cells of relatively high efficiency.

- APPROACHES

  - Selection and preparation of substrates.

  - Deposition of gallium arsenide films.

  - Characterization of structural, electrical, and mechanical properties of gallium arsenide films.

  - Control of conductivity type and carrier concentration in gallium arsenide films.

  - Preparation and characterization of thin films gallium arsenide p-n junctions and solar cells.

THIN FILMS OF GALLIUM ARSENIDE ON LOW COST SUBSTRATES
SELECTION OF SUBSTRATES

- REQUIREMENTS: Compatible with gallium arsenide in chemical, electrical, mechanical, and structural properties

- PROPOSED SUBSTRATES:
  - Germanium (recrystallized)/low cost support (graphite, metallurgical silicon, etc.)
  - Large grain tungsten/low cost support (steel, etc.)

THIN FILMS OF GALLIUM ARSENIDE ON LOW COST SUBSTRATES
SELECTION OF SUBSTRATES

- MATERIAL PROPERTIES:

	GaAs	Ge	W
Crystal Structure	Zincblende	Diamond	Body-Centered Cubic
Lattice Parameter, Å	5.654	5.657	3.165
Interatomic Distance, Å	2.448	2.449	2.741
Thermal Expansion Coeff., °C^{-1}	6.8×10^{-6}	5.9×10^{-6}	4.5×10^{-6}
Chemical Reactivity		GeAs 737°C $GeAs_2$ 732°C continuous solid solution with Ga	WAs_2, W_4As_5, W_2As inert toward Ga
Electrical Property		donor in GaAs ionization energy: 40 meV	

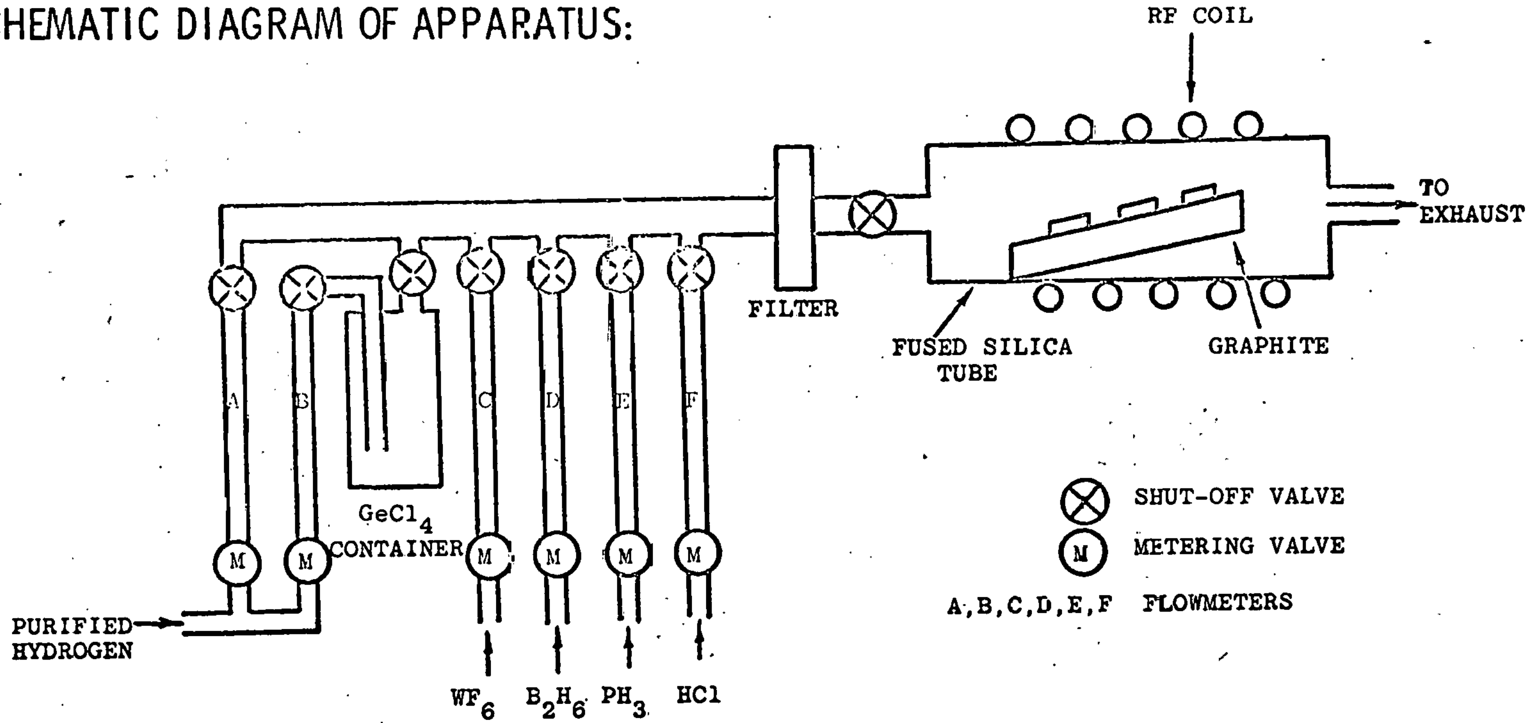
THIN FILMS OF GALLIUM ARSENIDE ON LOW COST SUBSTRATES
PREPARATION OF SUBSTRATES

- DEPOSITION OF GERMANIUM AND TUNGSTEN ON LOW COST SUPPORTS:

$$GeCl_4(g) + 2H_2(g) \rightarrow Ge(s) + 4HCl(g)$$

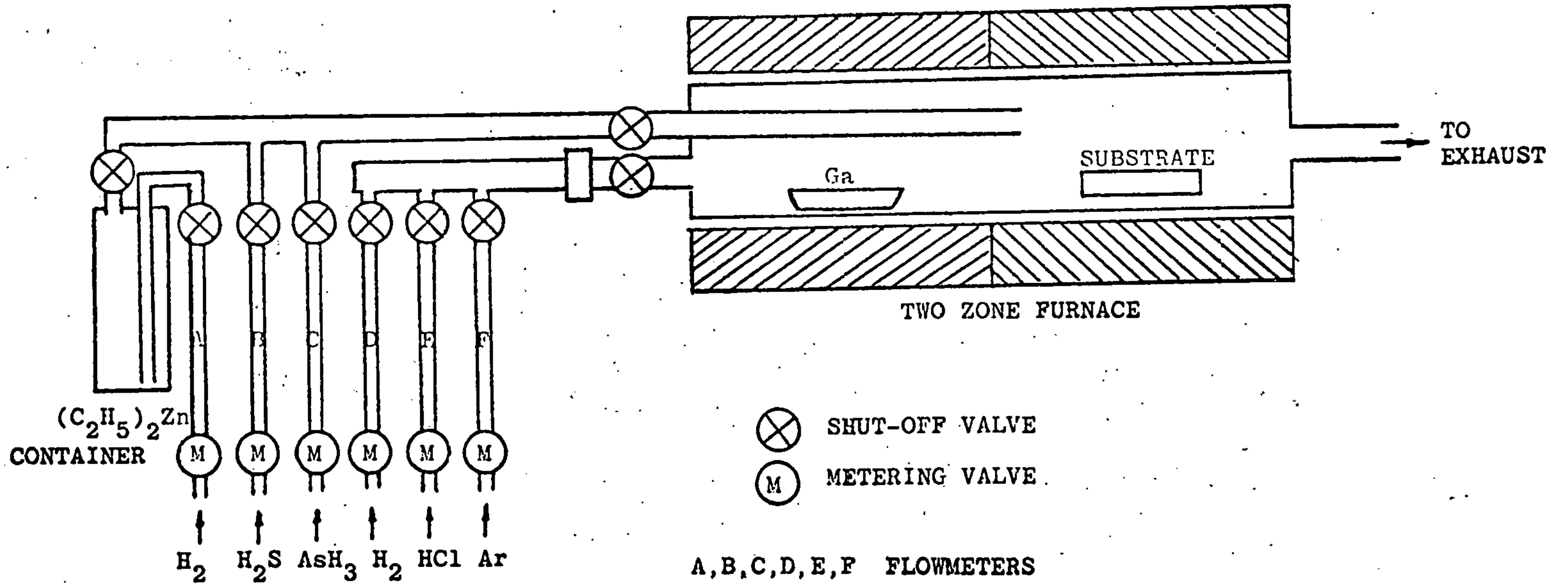
$$WF_6(g) + 3H_2(g) \rightarrow W(s) + 6HF(g)$$

- SCHEMATIC DIAGRAM OF APPARATUS:



THIN FILMS OF GALLIUM ARSENIDE ON LOW COST SUBSTRATES
DEPOSITION OF GALLIUM ARSENIDE FILMS

- SCHEMATIC DIAGRAM:



- REACTIONS:

$$2Ga(\ell) + 2HCl(g) \rightarrow 2GaCl(g) + H_2(g)$$

$$GaCl(g) + AsH_3(g) \rightarrow GaAs(s) + HCl(g) + H_2(g)$$

THIN FILMS OF GALLIUM ARSENIDE ON LOW COST SUBSTRATES
CHARACTERIZATION OF GALLIUM ARSENIDE FILMS

- STRUCTURAL CHARACTERIZATION:
  - Chemical etching and optical microscopy
  - X-ray diffraction
  - Scanning electron microscopy

- ELECTRICAL CHARACTERIZATION:
  - Carrier mobility and concentration by Hall measurements
  - Dopant profile by differential capacitance measurements

THIN FILMS OF GALLIUM ARSENIDE ON LOW COST SUBSTRATES
PLANNED ACTIVITY FOR NEXT SIX MONTHS

- Deposition of germanium on graphite and metallurgical silicon and the recrystallization of germanium films.
- Deposition of tungsten films on steel.
- Deposition of gallium arsenide films on germanium (recrystallized)/support and tungsten/steel substrates.
- Characterization of structural and electrical properties of gallium arsenide films.

SILICON SCHOTTKY PHOTOVOLTAIC DIODES FOR SOLAR ENERGY CONVERSION

NATIONAL SCIENCE FOUNDATION
GRANT AER73-03197
PERIOD OF GRANT: JUNE 1, 1976-MAY 31, 1978
VALUE: $69,200.00

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PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING
AUGUST 3-6, 1976
UNIVERSITY OF MAINE AT ORONO
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SILICON SCHOTTKY PHOTOVOLTAIC DIODES FOR SOLAR ENERGY CONVERSION

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Schottky barrier solar cells (SBSC) on <100>, p-type silicon are fabricated by thermal evaporation with an Al ohmic contact and 40-50 Å Cr Schottky metal. A 10-20 Å oxide between Si and Cr makes this a MIS device in which tunneling occurs through the oxide. Current research is directed towards achieving a 12% efficiency on 2-6 cm^2 cells by increasing fill factor from 0.65 to 0.75 and short circuit current density from 22 mA/cm^2 to 28 mA/cm^2.

Open-circuit voltage can be consistently designed for 0.52-0.58 V by controlling Cr deposition parameters (Figures 1 and 2). Illuminated solar cells now give I-V data showing promising values of V_{oc}, J_{sc}, and F (Figure 3). Experimental data now conform well to the theoretical equations

$$V_{oc} = n(\phi_B - 0.515) \qquad (1)$$

and

$$\phi_m = 4.95 - 0.21\,n - V_{oc} \qquad (2)$$

such that experimental and measured values of ϕ_b are in good agreement (Figure 4). Furthermore, ϕ_m for Cr is calculated to range from

4.01 to 4.24 eV which is significantly less than the bulk value of 4.55 eV. This lowered ϕ_m contributes to a high V_{oc}, and is controlled by deposition procedures as well as the oxide substrate. The diode n-factor value agrees well with that predicted from oxide thickness (δ) and surface state factor (D_s) as given by

$$n = 1 + \frac{q\delta D_s}{\varepsilon_i \varepsilon_o} \tag{3}$$

(Figure 5).

SBSC's on Tyco silicon exhibit promising values of J_{sc} and F (Figure 6). Tests at NASA agree well with AM1 data obtained on the same cells at Rutgers (Figure 7). Auger analysis (Figure 8) shows that the Cu conductive metal does not penetrate the Cr barrier metal for a >30 Å Cr film thickness. Environmental studies, by continuous operation of SBSC's in sunlight do not yet show evidence of junction degradation (Figure 9). The voltage is expected to decrease by 2.3 mV/°C at higher temperatures which has been observed by tests during the warmer months. Optical constants have been calculated for thin films of Ag, Cr, Cu, and SiO on glass based on experimental values of reflectance and transmittance (Figures 10-13). These constants may then be used in a computer program to predict spectral response in good agreement with experimental results.

OBJECTIVE OF THE PROJECT

THE OVERALL OBJECTIVE IS TO PRODUCE A 12% EFFICIENT SCHOTTKY SOLAR CELL USING ECONOMICAL SILICON AND FABRICATION METHODS. THIS IS TO BE ACCOMPLISHED THROUGH OPTIMIZATION OF CURRENT BY USE OF NEW AR COATINGS, VOLTAGE BY INTERFACE STUDIES, AND FILL FACTOR BY DEPOSITION STUDIES. FURTHER STUDIES INCLUDE ENVIRONMENTAL EFFECTS, THIN EPITAXIAL SILICON FILMS, SURFACE EFFECTS, NEW SOURCES OF SILICON, AND CORRELATION OF DATA FROM ELECTRICAL MEASUREMENTS.

PLANNED ACTIVITY FOR LAST 6 MONTHS

1. EXPAND C AND G MEASUREMENTS AS FUNCTIONS OF F, T, AND V.

2. CONTINUE ION BACKSCATTERING AND SEM SURFACE ANALYSIS.

3. FABRICATE 10% SOLAR CELLS.

4. COMPUTER CALCULATION OF N AND K FOR THIN METAL FILMS USING MEASUREMENT OF R AND T VS. λ.

5. SEND CELLS TO NASA FOR TESTING.

6. CALIBRATE THE ELH SOLAR SIMULATOR.

7. CONTINUE STUDIES OF BONDING, ENCAPSULATION, ENVIRONMENTAL EFFECTS AND CONCENTRATION.

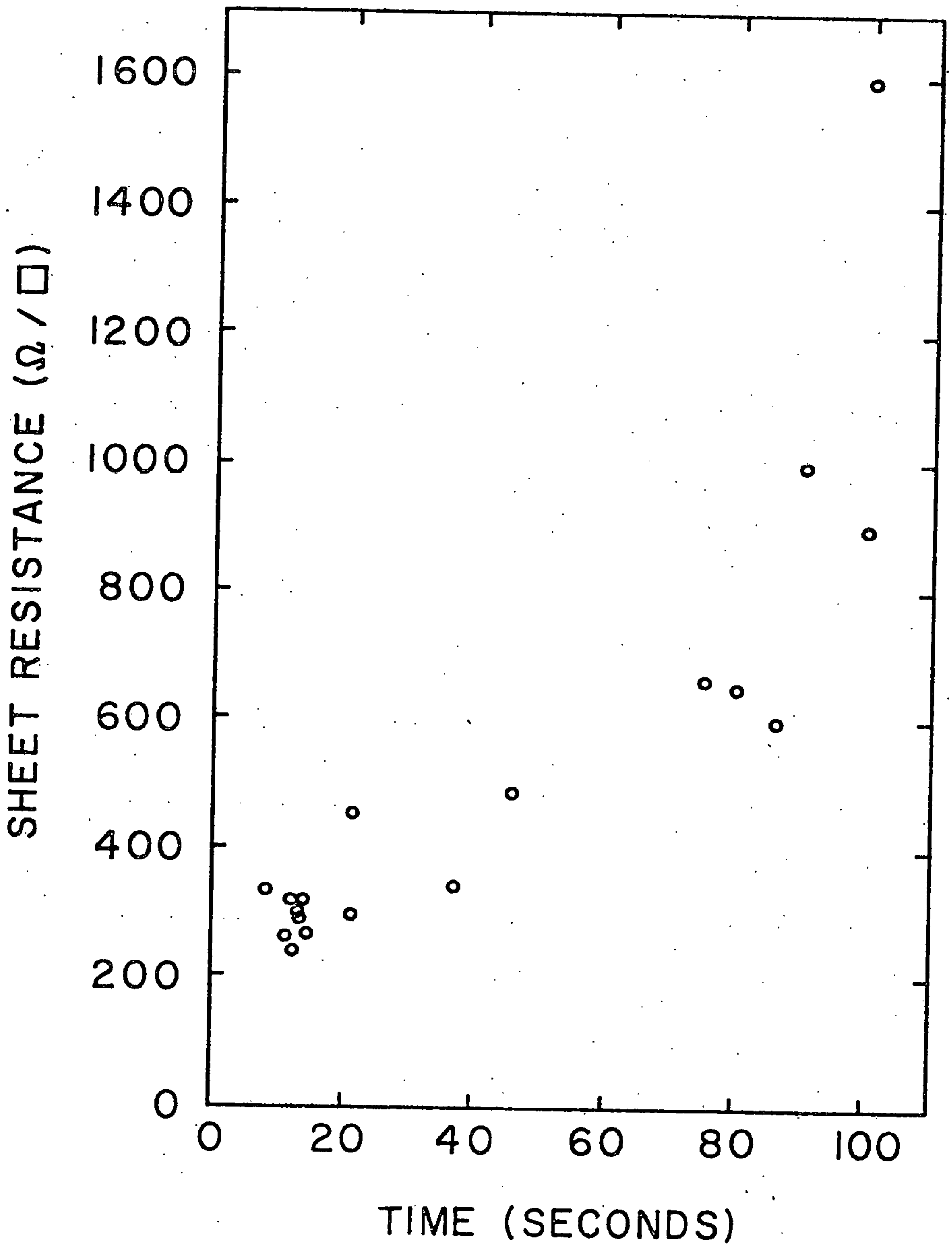


FIG. 1-SHEET RESISTANCE OF 50 Å EVAPORATED CR ON GLASS AS A FUNCTION OF DEPOSITION TIME.

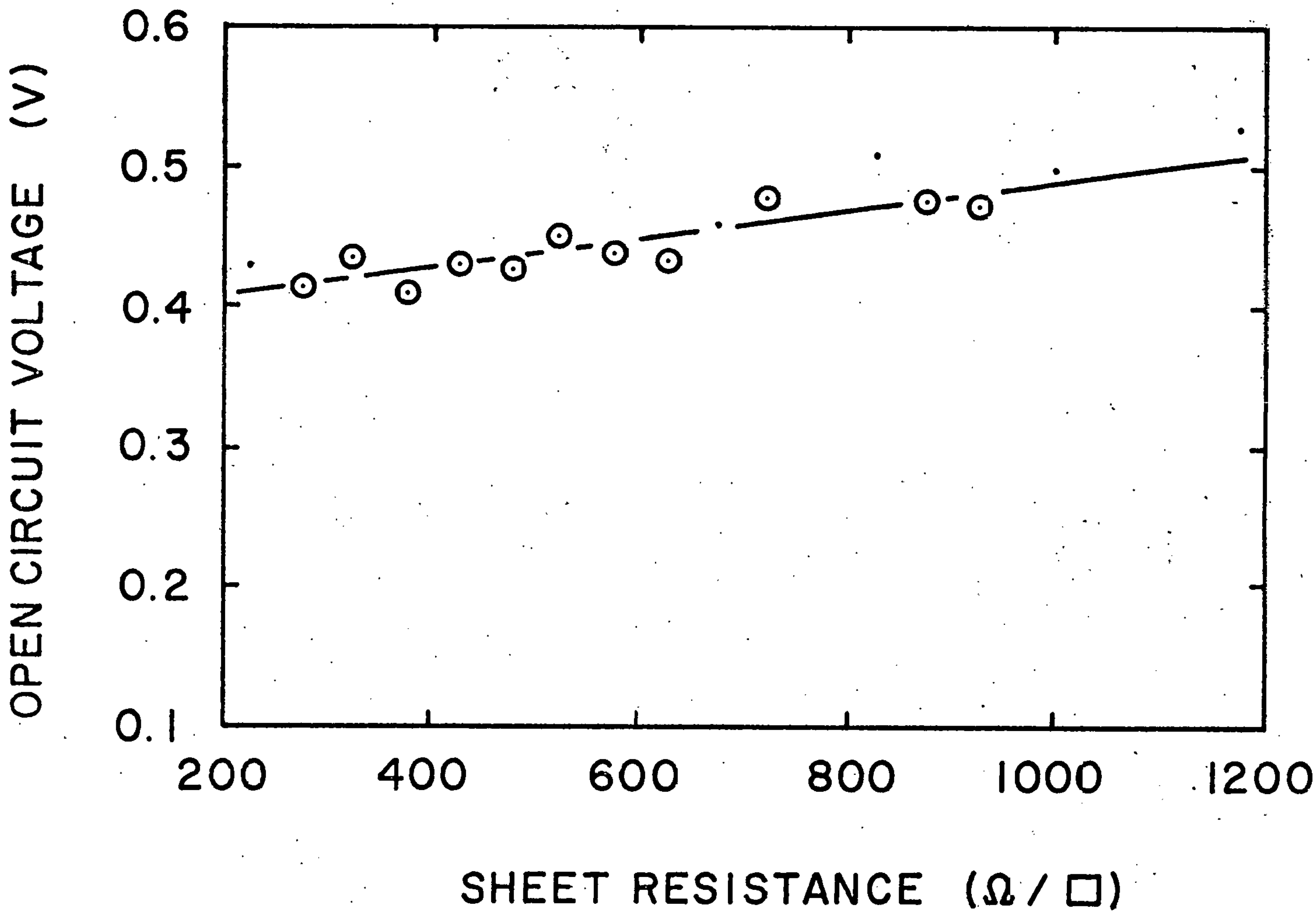
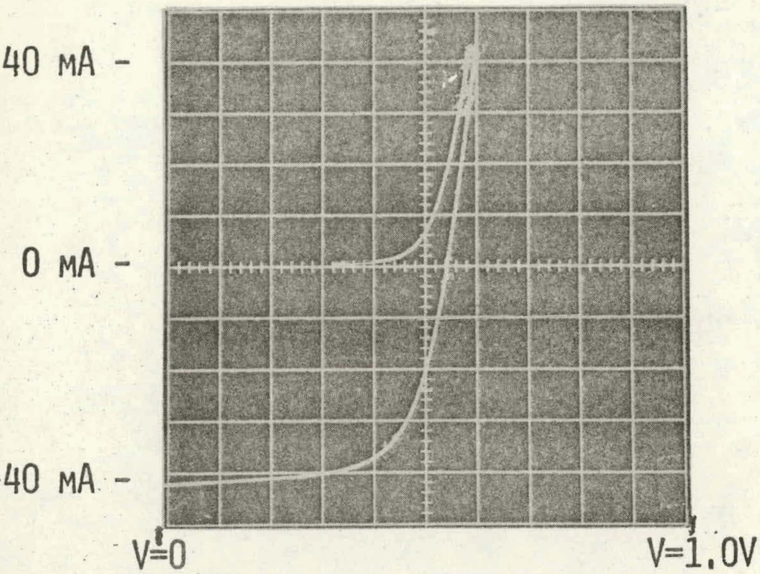


FIG. 2-OPEN-CIRCUIT VOLTAGE AS A FUNCTION OF CR SHEET RESISTANCE.



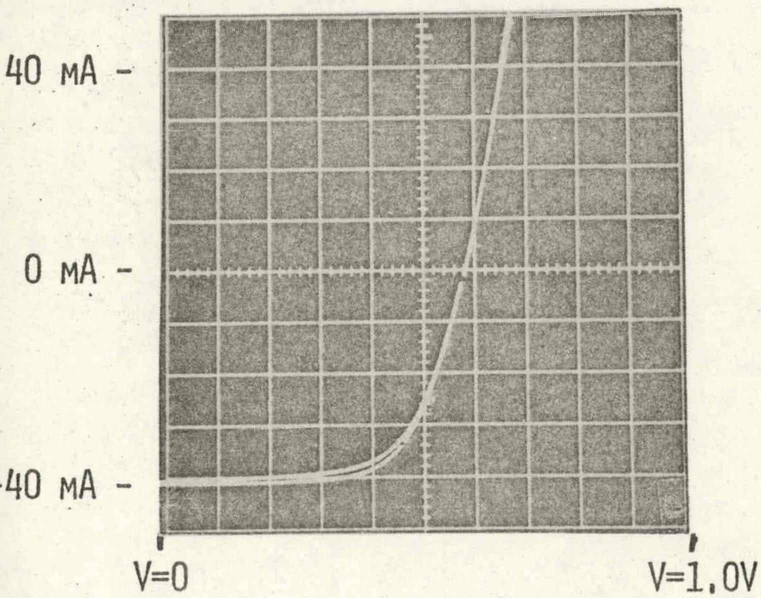
Cell 245

Area = 1.77 cm^2

V_{oc} = 0.54 V

J_{sc} = 24.2 mA/cm^2

F = 0.67



Cell 262

Area = 1.61 cm^2

V_{oc} = 0.58 V

Fig. 3-I-V data with AM1 illumination.

FIGURE 4

BARRIER HEIGHT AND WORK FUNCTION DATA FOR SCHOTTKY (MIS) SOLAR CELLS

$$V_{OC} = N\phi_B + 0.026\ N\ \ln\left(\frac{J_{SC}}{A^*T^2}\right)$$

$J_{SC} = 25\ \text{MA/CM}^2,\ A^* = 32,\ T = 298^oK$

THEN $V_{OC} = N\ (\phi_B - 0.515)$ (1)

$\phi_B = \gamma(E_G + X_S - \phi_M) + (1 - \gamma)\ \phi_0$

$\gamma \approx \frac{1}{N},\ \phi_0 = 0.30,\ E_G + X_S = 5.25$ FOR SI

THEN $\phi_M = 4.95 - 0.21\ N - V_{OC}$ (2)

SAMPLE	V_{OC} (V)	N	ϕ_B(EV) CV	ϕ_B(EV) IV	ϕ_B(EV) USING (1)	ϕ_M(EV) USING (2)
247	0.38	1.96	0.78	0.69	0.71	4.16
182B	0.41	1.45	0.63	0.77	0.79	4.24
185A	0.46	1.50	0.73	0.83	0.82	4.18
234	0.52	1.81	--	0.80	0.80	4.05
242	0.53	1.41	0.98	0.89	0.89	4.12
252	0.54	1.35	0.90	0.90	0.92	4.13
264	0.56	1.83	1.20	0.88	0.84	4.01
262	0.57	1.34	1.17	0.97	0.94	4.10

V_{OC} = OPEN CIRCUIT VOLTAGE

N = DIODE QUALITY FACTOR

ϕ_B = BARRIER HEIGHT

ϕ_M = METAL WORK FUNCTION

FIGURE 5

RELATIONSHIP BETWEEN N-FACTOR, SURFACE STATE FACTOR (γ), SURFACE STATE DENSITY (D_S), AND OXIDE THICKNESS (δ)

$$N = 1 + \frac{\delta}{\varepsilon_I \varepsilon_O}\left[\frac{\varepsilon_S \varepsilon_O}{W} + QD_S\right]$$

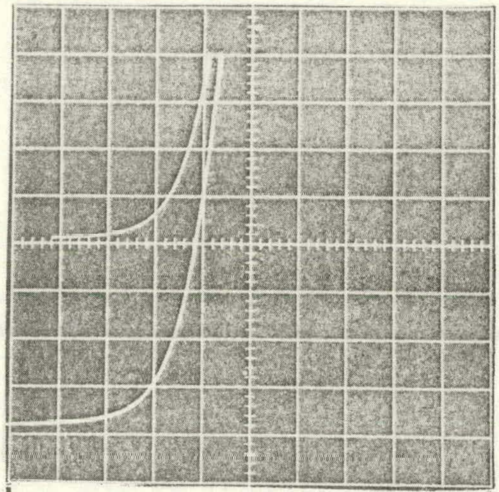
$$N \approx 1 + \frac{Q\delta D_S}{\varepsilon_I \varepsilon_O} = \frac{1}{\gamma}$$

PREDICTED DEPENDENCE OF N AND (γ) ON δ AND D_S

δ(Å) ↓, D_S(STATES/CM^3) ⟶	5×10^{12}	1×10^{13}	1.5×10^{13}	2×10^{13}
10	1.26 (0.783)	1.52 (0.658)	1.78 (0.562)	2.04 (0.491)
15	1.39 (0.719)	1.78 (0.562)	2.17 (0.462)	2.56 (0.391)
20	1.52 (0.658)	2.04 (0.491)	2.56 (0.391)	3.08 (0.325)

BY EXPERIMENT

DIODE NO.	N	D_S	δ	COMMENT
262	1.34	5.6×10^{12}	12.8 Å	<100>, 15 MIN H.T.
264	1.82	5.3×10^{12}	32.6 Å	<100>, 30 MIN H.T.
248	1.91	24×10^{12}	8 Å	<110>, TYCO USING SHORT H.T.



CELL 242
TYCO SILICON
AREA = 1.87 cm^2
V_{OC} = 0.38 V
J_{SC} = 20.3 mA/cm^2
F = 0.62

AM1 DATA ON SCHOTTKY CELLS USING
TYCO SILICON

V_{OC}(V)	$J_{SC}(\frac{mA}{cm^2})$	FILL FACTOR	POWER $(\frac{mW}{cm^2})$	ϕ_B^*(eV)	N-FACTOR*
0.38	21.1	0.60	4.8	0.69	1.96
0.38	20.3	0.62	4.8	0.69	2.03

* FROM I-V ANALYSIS

THE HIGH N-FACTOR COULD BE CAUSED BY A HIGH D_S.

FIG. 6-DATA ON SCHOTTKY CELLS MADE FROM TYCO SILICON

FIGURE 7

SOLAR ENERGY DATA COMPARED FOR RUTGERS AND NASA

	#226		#234		#245	
	R.U.[A]	NASA[B]	R.U.[A]	NASA[B]	R.U.[A]	NASA[B]
V_{OC}(V)	0.51	0.48	0.52	0.49	0.54	0.531
I_{SC}(mA)	28.0	29.5	36.5	36.6	43.0	41.5
F	0.64	0.66	0.72	0.69	0.67	0.63
P_{MAX}(mW)	14.3	14.2	19.0	17.9	23.2	22.0
P_O(mW)	9.2	9.4	13.7	12.4	15.5	13.9
Area(cm^2)[C]	1.46	2.26	1.65	2.26	1.77	2.18
P_{O1}(mW/cm^2)	6.3	4.2	8.3	5.5	8.76	6.44

$P_{MAX} = I_{SC}V_{OC}$

$P_O = F\ P_{MAX}$

$P_{O1} = P_O/A$

A) Tested in New Jersey sunlight @ < 25°C.

B) Tested using 100 mW Xenon simulator @ 28°C.

C) Our calculations exclude the grid area which will be significantly decreased in the future.

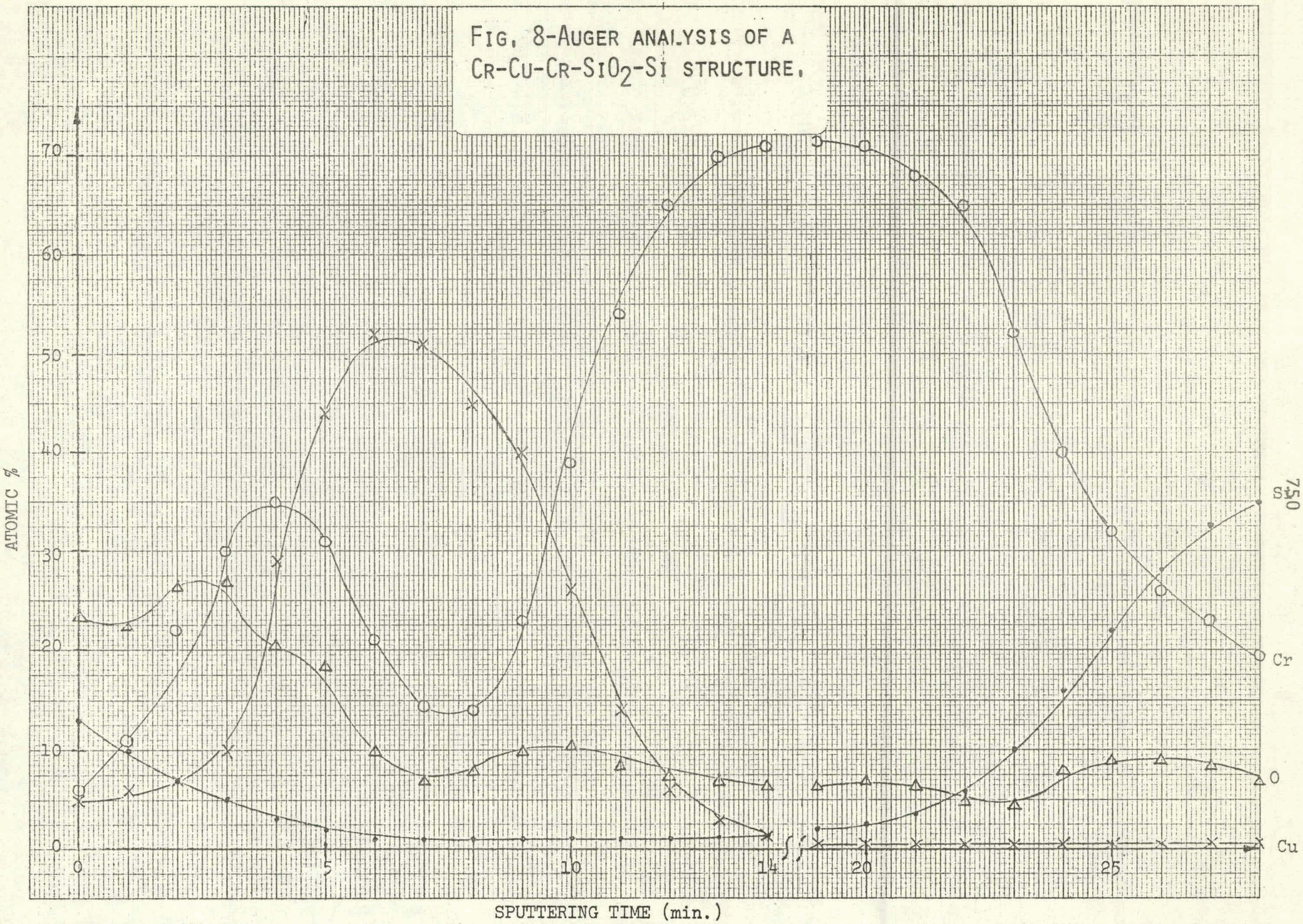


FIG. 8-AUGER ANALYSIS OF A Cr-Cu-Cr-SiO_2-Si STRUCTURE.

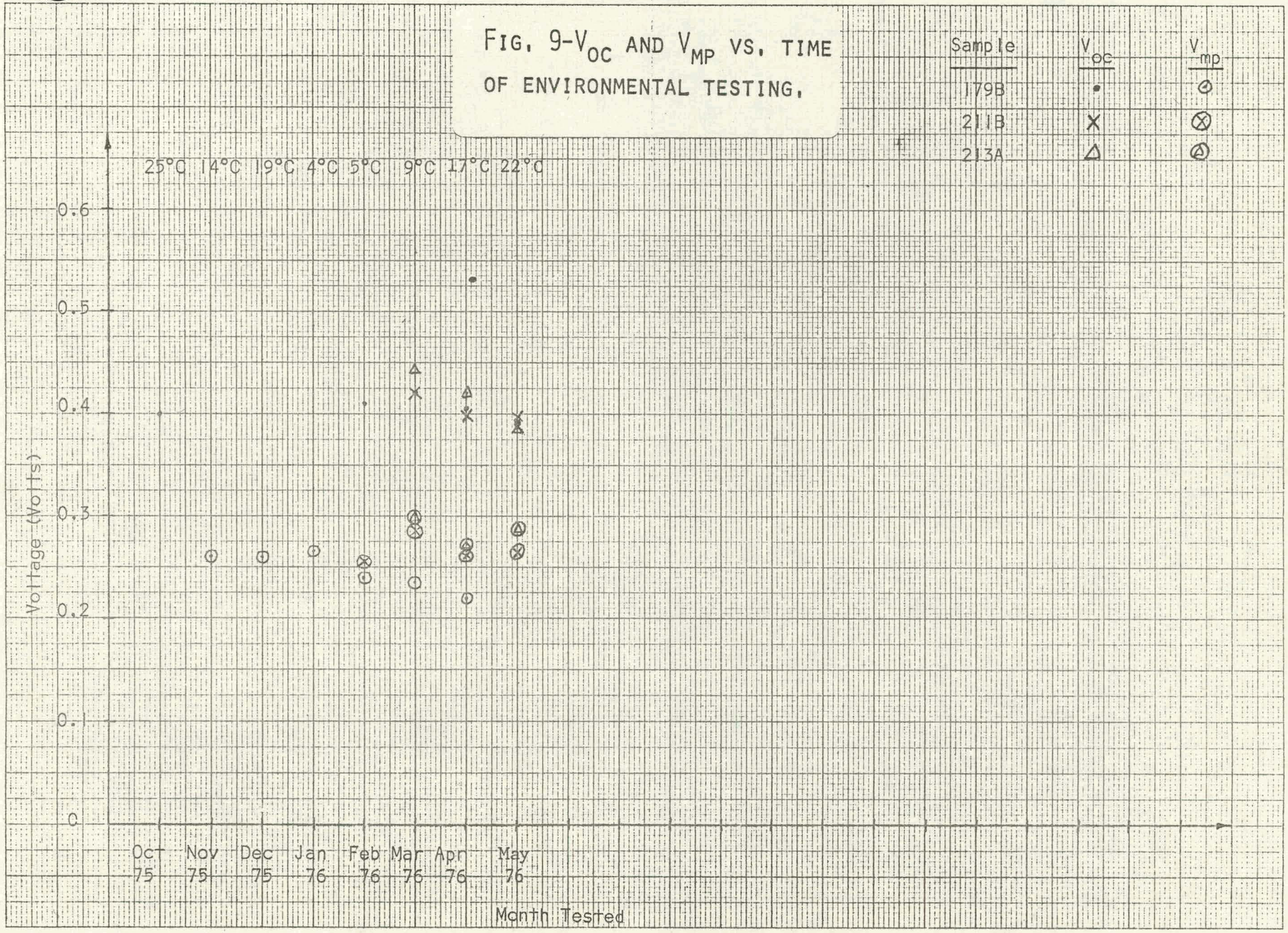


FIG. 9-V_{OC} AND V_{MP} VS. TIME OF ENVIRONMENTAL TESTING.

FIG. 10-REFRACTIVE INDEX OF THIN AG FILMS.

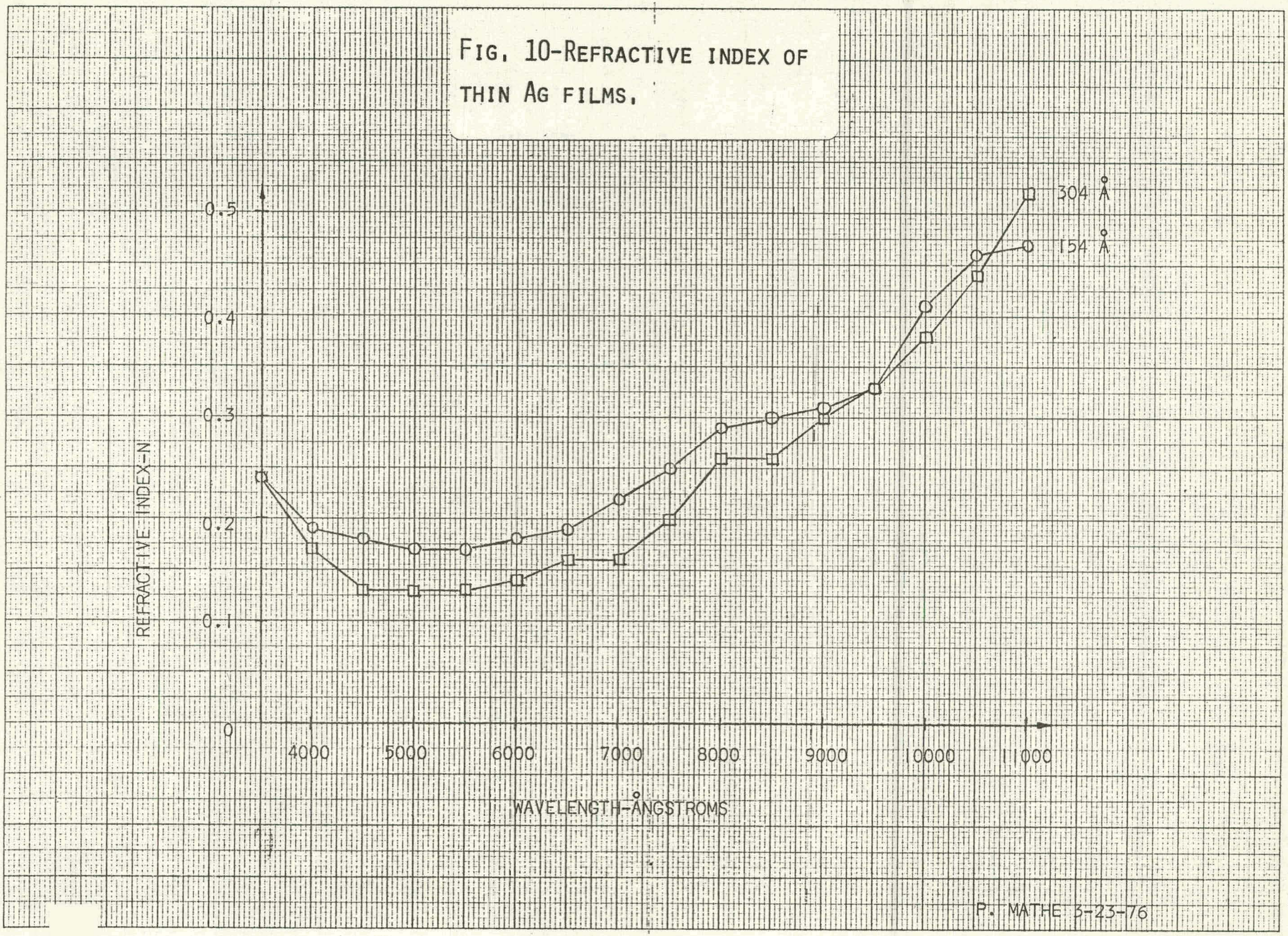


FIG. 11-EXTINCTION COEFFICIENT OF THIN AG FILMS.

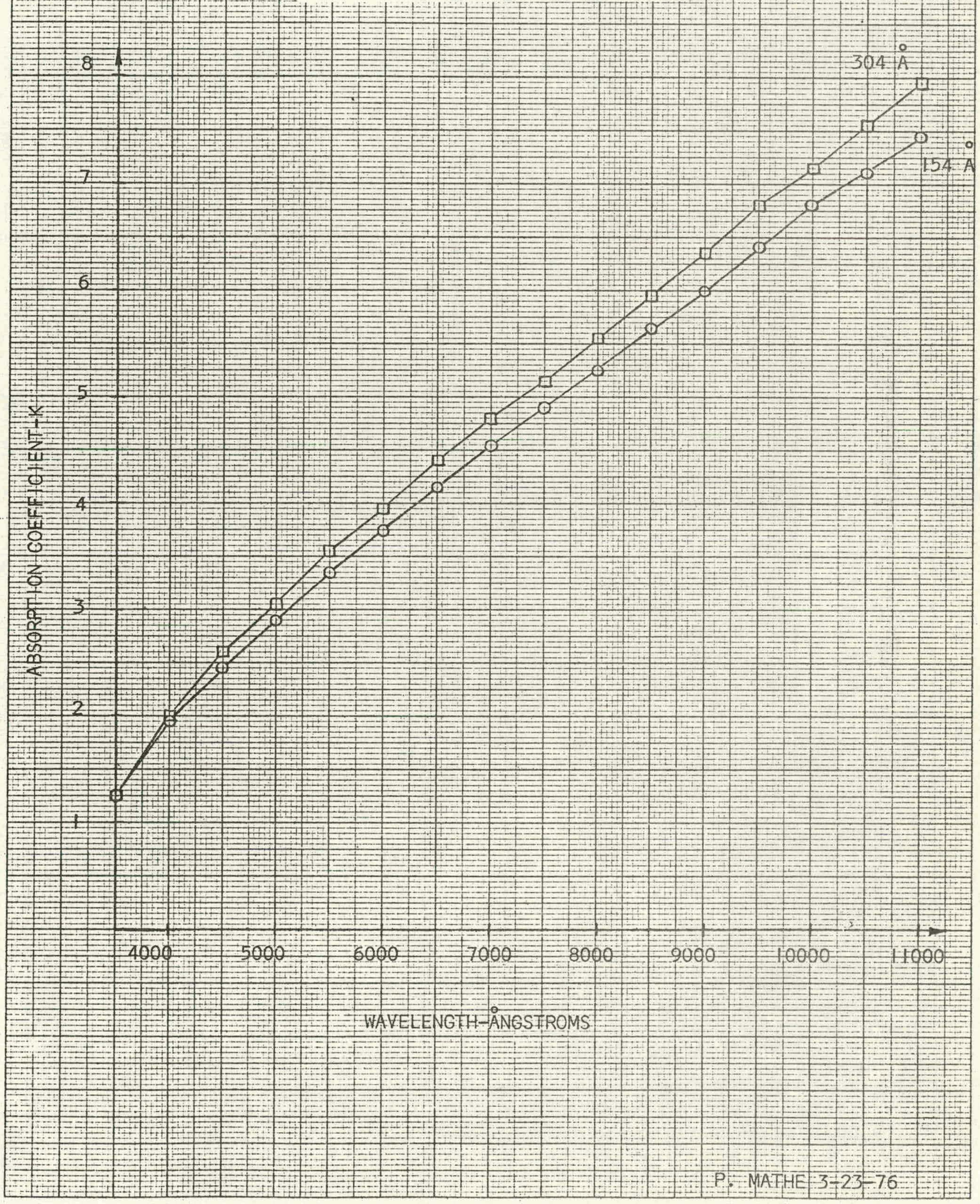
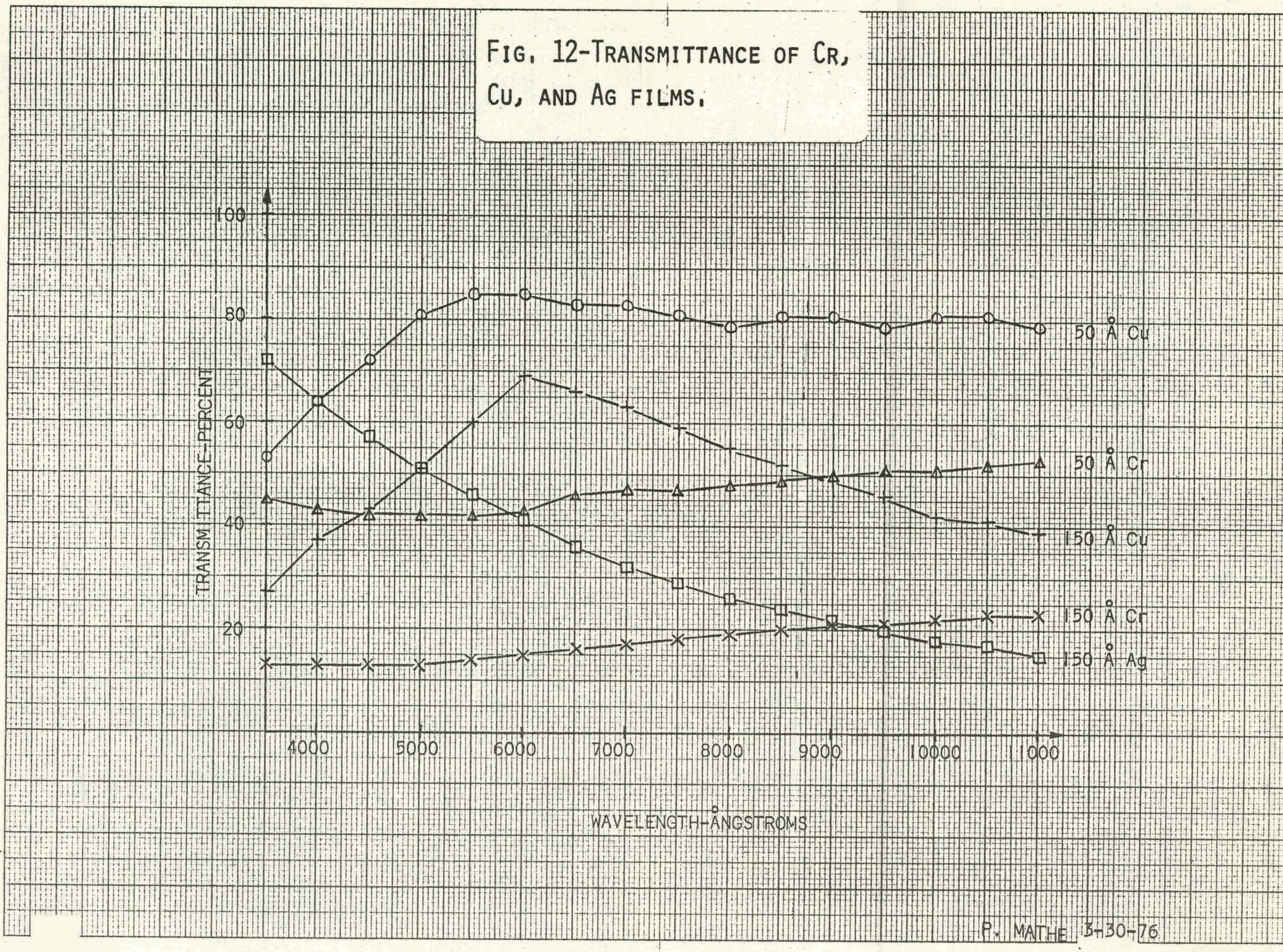


FIG. 12-TRANSMITTANCE OF CR, CU, AND AG FILMS.



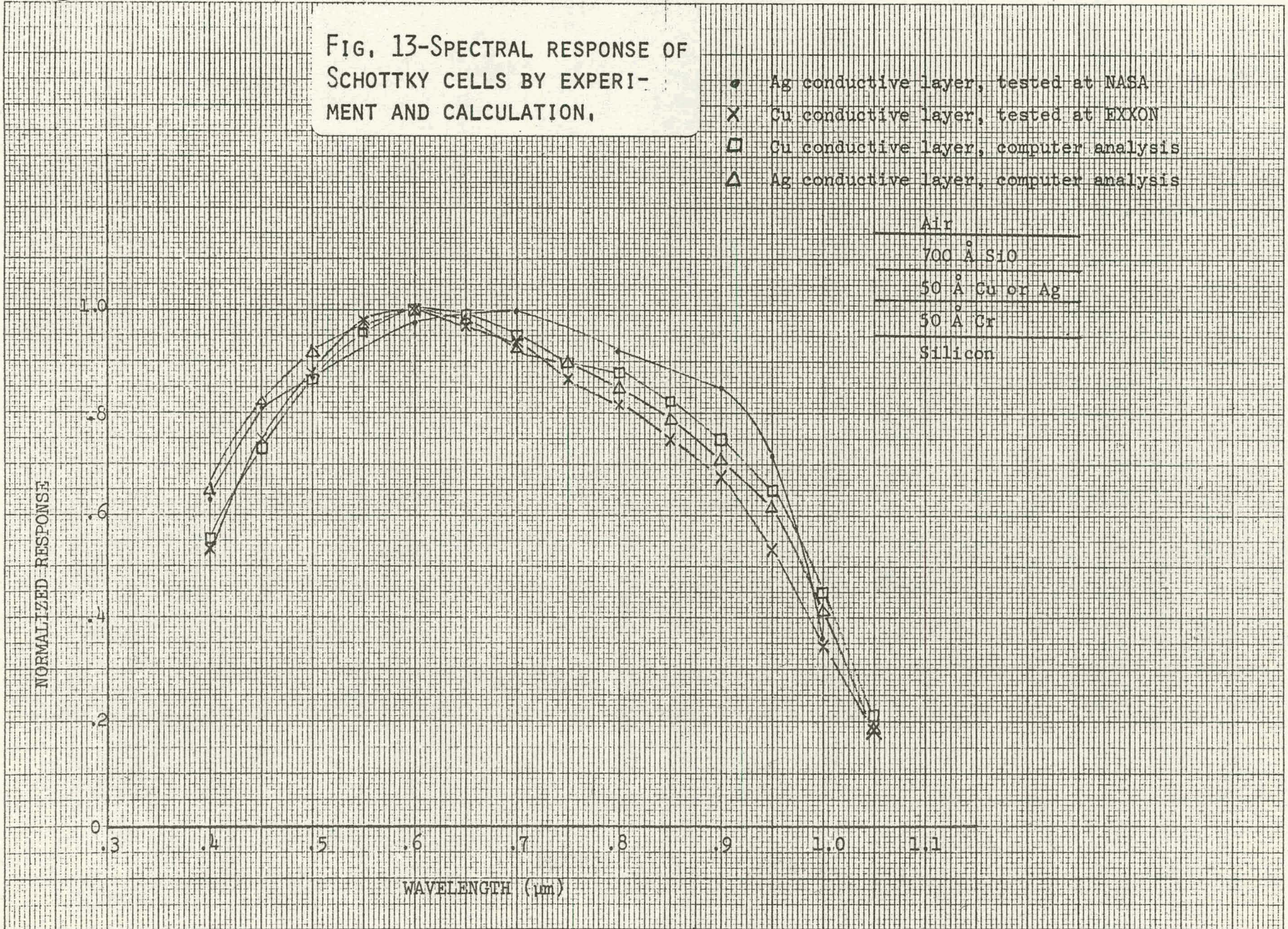


FIG. 13-SPECTRAL RESPONSE OF SCHOTTKY CELLS BY EXPERIMENT AND CALCULATION.

SUMMARY OF KEY RESULTS

1. V_{OC} MAY BE CONTROLLED BY CR DEPOSITION RATE.

   V_{OC} MAX = 0.58 V

2. DATA SATISFY $V_{OC} = N(\phi_B - 0.515)$

   THE EQUATION $V_{OC} = 4.95 - 0.215N - \phi_M$ PREDICTS THAT LOW N AND $\phi_M \rightarrow$ HIGH V_{OC}.

   ϕ_M IS < BULK VALUE FOR CR AND DEPENDS ON OXIDE INTERFACE AND DEPOSITION RATE.

3. DATA SATISFY $N = 1 + \frac{Q \delta D_S}{\epsilon_I \epsilon_O}$

4. SCHOTTKY CELLS ON TYCO SILICON EXHIBIT GOOD V_{OC} AND F.

5. AUGER ANALYSIS SHOWS CU TO NOT PENETRATE CR.

6. ENVIRONMENTAL TESTS DO NOT YET SHOW JUNCTION DEGRADATION.

7. OPTICAL CONSTANTS ARE NOW AVAILABLE FOR CR, CU, AG, AND SIO.

8. THERE IS GOOD AGREEMENT BETWEEN EXPERIMENTAL AND CALCULATED SPECTRAL RESPONSE DATA.

PLANNED ACTIVITY FOR NEXT 6 MONTHS

1. IMPROVE THE GRID DESIGN TO GIVE F=0.75.

2. EXAMINE CONDUCTIVE AR COATINGS.

3. CORRELATE V_{OC}, ϕ_M, ϕ_B, N, δ, AND D_S WITH PROCESS VARIABLES.

4. STUDY NEW TYPES OF SILICON.

5. STUDY OTHER SCHOTTKY METALS.

6. CONTINUE STUDIES OF BONDING, ENCAPSULATION, AND ENVIRONMENTAL EFFECTS.

RESEARCH PARTICIPANTS

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PLANNED RENEWAL REQUESTS

Plans are not yet formulated.

ACKNOWLEDGMENT

Dr. Brown Williams of RCA-Princeton has been helpful in arranging for Auger analysis studies.

Dr. K. Ravi of Mobil-Tyco has supplied silicon samples for our evaluation.

HETEROJUNCTION SOLAR CELLS

NSF
AER 76-04168

PERIOD OF GRANT: JUNE 1, 1976-MAY 31, 1978

VALUE: $99,900

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AUGUST 3 - 6, 1976

UNIVERSITY OF MAINE AT ORONO

ORONO, MAINE 04473

ABSTRACT

I. OBJECTIVE

The objective of this research is to investigate the material systems which may be useful for the fabrication of low cost, efficient heterojunction solar cells. The active substrate of principal interest is Si, in both single crystalline and polycrystalline form. Because SnO_2/Si cells of 10% efficiency at AM1 have been fabricated, this system appears to hold promise, although degradation of the cells has been observed. Major objectives of this effort are to determine the maximum theoretical conversion efficiency of SnO_2/Si HJSC's and to determine if the observed degradation is inherent to these cells or if it can be avoided.

II. PREVIOUS ACTIVITIES

In a previous Grant (August 1, 1974 to July 30, 1975) with INNOTECH Corporation as a subcontractor, we demonstrated the validity of the heterojunction solar cell (HJSC) concept using Si as substrate and In_2O_3 and SnO_2 films as windows. In the In_2O_3/Si system, AM1 conversion efficiencies of 5 - 6% were achieved, with a theoretical maximum of 11 - 13% predicted. In the SnO_2/Si system efficiencies as high as 10% were achieved, but the system was not sufficiently understood to predict the maximum theoretical efficiency. Degradation effects were also observed in the SnO_2/Si HJSC's.

Between August 1, 1975 and June 1, 1976, this effort was not funded. Although work did continue, it was at an appreciably reduced level and was confined to investigation of those cells fabricated on the previous NSF grant.

III. CURRENT ACTIVITIES

We are currently investigating the stability of cells on hand with respect to the nature of the substrate (monocrystalline or polycrystalline), the type of stress (optical, thermal, or ambient). We are also investigating the effects on electrical characteristics and on conversion efficiency of the thin interfacial layer between window and substrate.

IV. SUMMARY OF KEY RESULTS

A) A thin insulating (I) layer between window and substrate can increase conversion efficiency, (η), by the reduction of the dark saturation current, (I_o), through carrier reflection at the interface. The presence of bound interface charge (Q_{ss}) can also affect I_o and thus V_{oc} and η through its effect on the Si interface potential (ϕ_s). In the system studied, this interface charge appears to be positive. As a consequence the V_{oc} of HJSC's using p-type Si substrates is enhanced while that for cells using n-type Si substrates is reduced.

B) This I layer also impedes the transfer of photo-generated carriers across the junction region, thus increasing recombination at the expense of the photocurrent. This photocurrent suppression increases with light intensity and may preclude the use of these cells in systems using concentration.

C) HJSC's with In_2O_3 and SnO_2 windows using good quality (float zone) polycrystalline Si substrates were compared to those using single crystal Si substrates from the same run and with similar processing. Those with polycrystalline substrates (poly-cells) consistently have larger (2 - 7 times) series resistance than those with monocrystalline substrates (mono-cells). The In_2O_3/p-Si poly-cells had consistently larger V_{oc} than the mono-cells while the SnO_2/n-Si poly-cells had consistently smaller V_{oc} than mono-cells. These effects are attributed to an increased I-layer thickness in the poly-cells and a positive Q_{ss}.

D) No time variation in the I-V characteristics was observed for In_2O_3/Si HJSC's exposed to ambient laboratory conditions. Degradation was observed, however, at elevated temperatures (400°C).

Many SnO_2/Si HJSC's do degrade on the shelf at room temperature, and all degrade at elevated temperatures. The series resistance increases with time, and the V_{oc} may decrease or increase. This degradation is attributed to an increase in the width of the I-layer. Illumination of the cells tends to decrease the series resistance and decrease V_{oc}.

After an initially small (10-15 mV) change in V_{oc}, the I-V characteristics of unstressed SnO_2/Si HJSC's from certain runs have remained constant for the past year. Both encapsulated and unencapsulated cells show this stability, although some poly-cells from these runs show degradation. These relatively stable cells are also those with high efficiency.

V. FUTURE PLANS

Becuase of the relative stability observed for some SnO_2/Si HJSC's, we believe that stable cells are feasible and we plan to concentrate on fabrication processes to produce such cells reproducibly. Coupled with this we will model SnO_2/Si cells in terms of physical and chemical parameters such that the characteristics, including stability, can be explained. We also plan to use other appropriate window materials.

THE OBJECTIVE OF THIS RESEARCH IS TO INVESTIGATE THE MATERIAL SYSTEMS WHICH MAY BE USEFUL FOR THE FABRICATION OF LOW-COST EFFICIENT HETEROJUNCTION SOLAR CELLS. THE SPECIFIC OBJECTIVES ARE:

1) TO FABRICATE AND EVALUATE HETEROJUNCTION SOLAR CELLS OF SNO_2/SI STRUCTURE;

2) TO ELUCIDATE THE PHYSICAL AND CHEMICAL PROCESSES OCCURRING AT THE INTERFACIAL LAYERS IN THE HETEROJUNCTION SOLAR CELLS;

3) TO DEVELOP ACCELERATED LIFE TEST STANDARDS;

4) TO EVALUATE THE STABILITY OF THE CELLS;

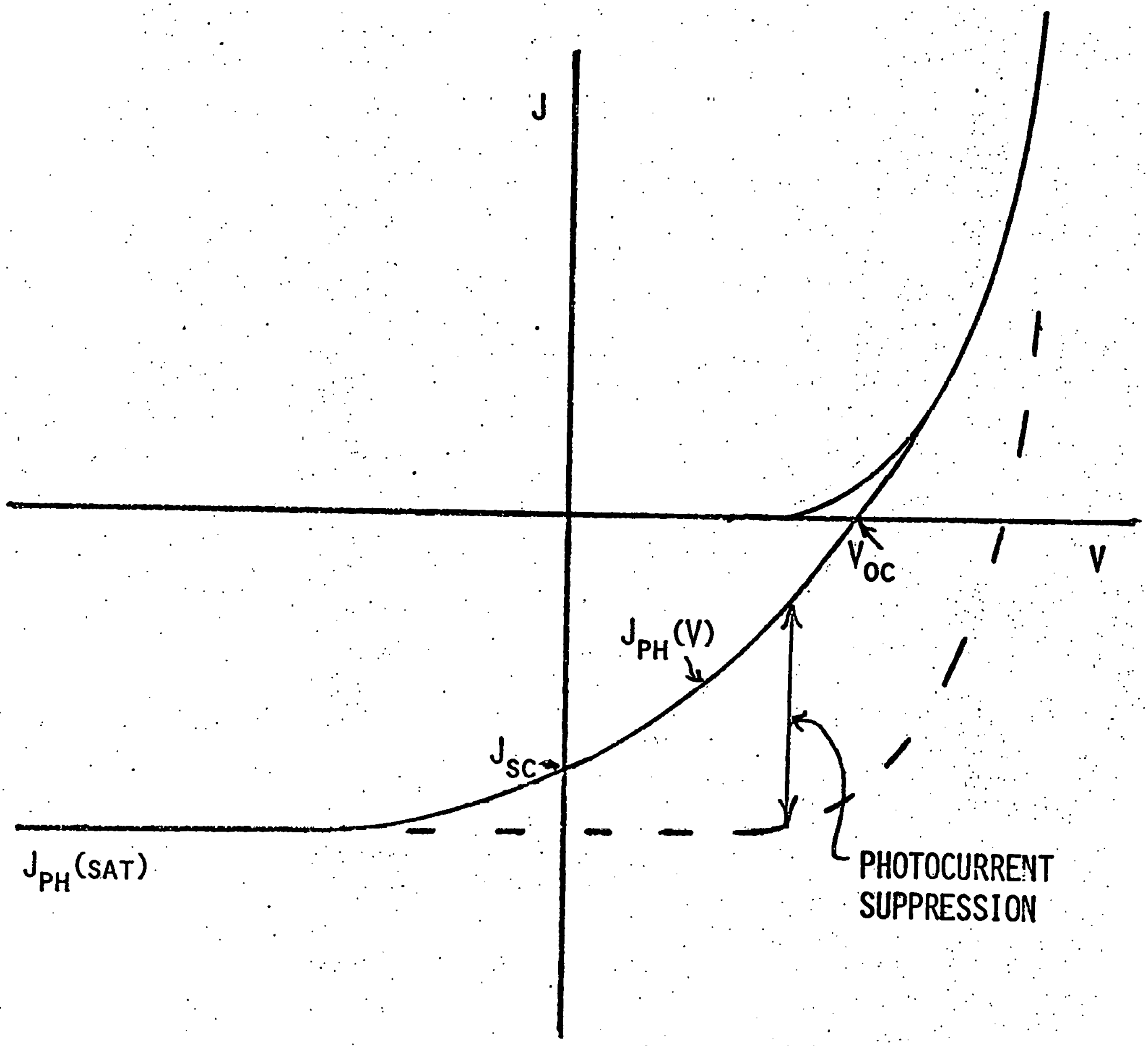
5) TO REFINE THE THEORY OF HETEROJUNCTIONS TO BE APPLICABLE TO SNO_2/SI SOLAR CELLS.

PLANNED ACTIVITY TO DATE:

I FABRICATION AND EVALUATION OF METAL OXIDE/SI HJSC STRUCTURES

II COMPARISON OF HJSC's USING MONOCRYSTALLINE AND POLYCRYSTALLINE SUBSTRATES

III INVESTIGATE STABILITY OF CELLS



DEFINITION OF J_{PH}, J_{SC}, V_{OC} AND PHOTOCURRENT SUPPRESSION

FABRICATION:

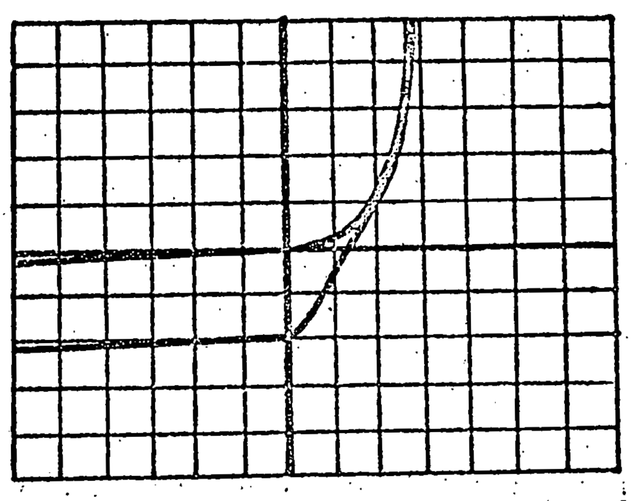
A) SPRAY-ON (AT ~ 500°C)

$SnCl_4:SbCl_3$ SOLUTION

RESULTS: SEVERE PHOTOCURRENT SUPPRESSION

DARK

AM1



500 μA/DIV

200 mV/DIV

V_{OC} = 280 mV

J_{PH} = 15 mA/cm^2

DARK AND AM1 CHARACTERISTICS OF SPRAY-ON SnO_2/n-Si HJSC

B) E-BEAM EVAPORATION OF SnO_2 FOLLOWED BY HEAT TREATMENT

RESULTS:

J_{PH} : 15 - 25 mA/cm^2
V_{OC} : 300 - 400 mV
R_S : HIGH
PHOTOCURRENT SUPPRESSION

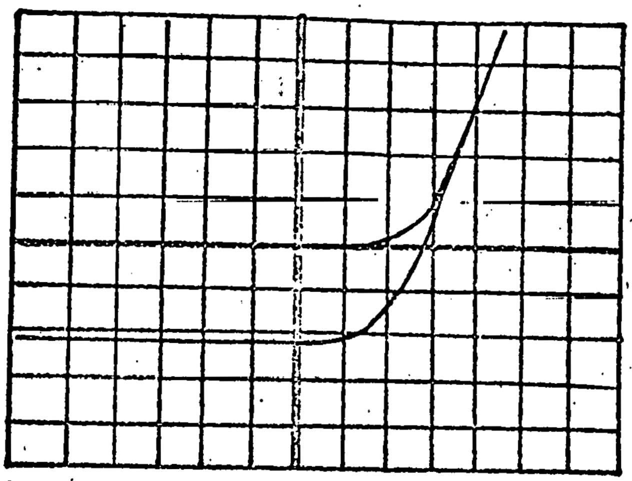
C) R.F. SPUTTERING OF $In_2O_3:SnO_2$ IN AR (AFTER BACK-SPUTTERING)

J_{PH} : 10 - 20 mA/cm^2
V_{OC} : 120 - 140 mV

NO APPARENT PHOTOCURRENT SUPPRESSION

HJSC'S USING POLY-Si SUBSTRATES COMPARED TO SINGLE CRYSTAL Si SUBSTRATES

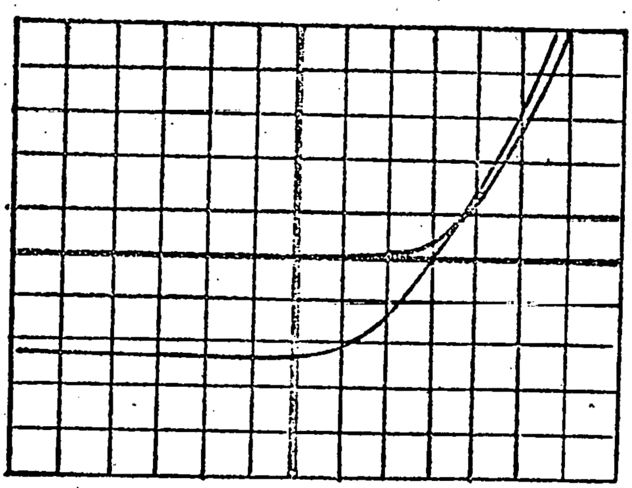
	In_2O_3/p-Si	SnO_2/n-Si
R_S	LARGER	LARGER
V_{OC}	LARGER	SMALLER
J_{SC}	SMALLER (SLIGHTLY)	SMALLER (SLIGHTLY)
J_{PH}(SAT)	SMALLER (SLIGHTLY)	SMALLER (SLIGHTLY)
F.F.	SMALLER	SMALLER
	SMALLER	SMALLER
PHOTO-CURRENT SUPPRES-SION	LARGER	LARGER
DEGRA-TION	——	FASTER



10 mA
100 mV

V_{OC} = 280 mV
J_{SC} = 23.0 mA/cm^2
F.F. = .50
η = 3.2%
R_S = 1.4 Ω
ρ_{SUB} = 1.5 Ω-cm

SINGLE CRYSTAL Si

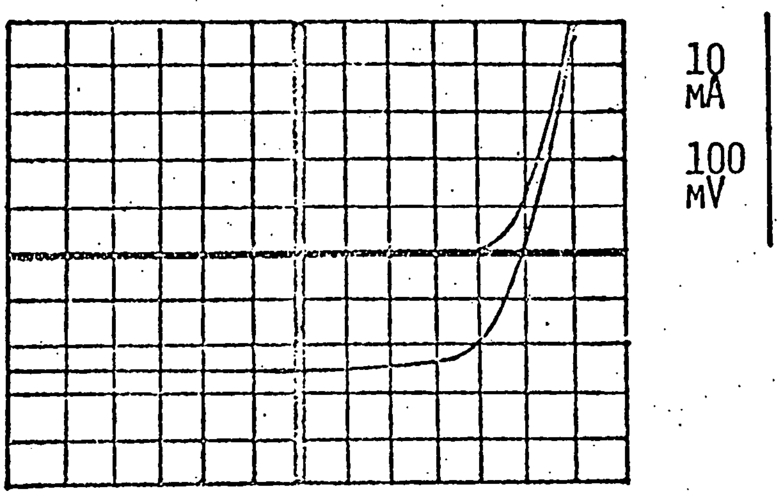


10 mA
100 mV

V_{OC} = 317 mV
J_{SC} = 22.5 mA/cm^2
F.F. = .41
η = 2.9%
R_S = 2.7 Ω
ρ_{SUB} = 3.8 Ω-cm

POLYCRYSTAL Si

In_2O_3/p-Si HJSC's (1 cm^2) FROM THE SAME RUN



SINGLE CRYSTAL SI

V_{OC} = 500 mV

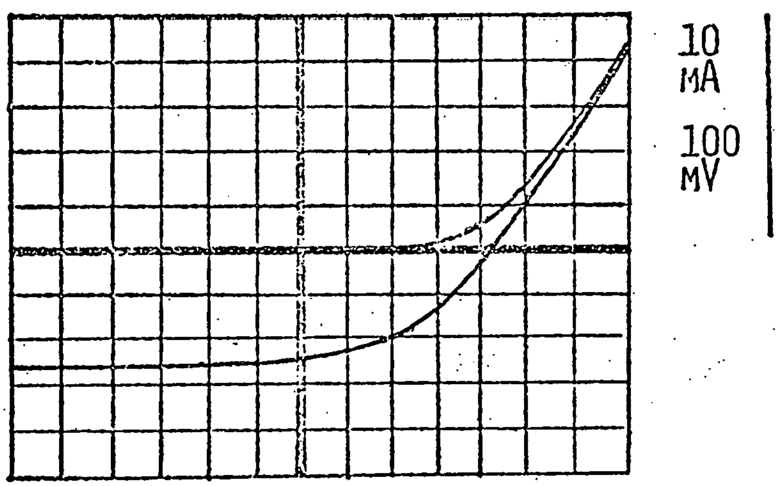
J_{SC} = 24.5 mA/cm^2

F.F. = 0.61

η = 7.5%

R_S = 2.1 Ω

ρ_{SUB} = 1.5 Ω-cm



POLYCRYSTAL SI

V_{OC} = 430 mV

J_{SC} = 23.5 mA/cm^2

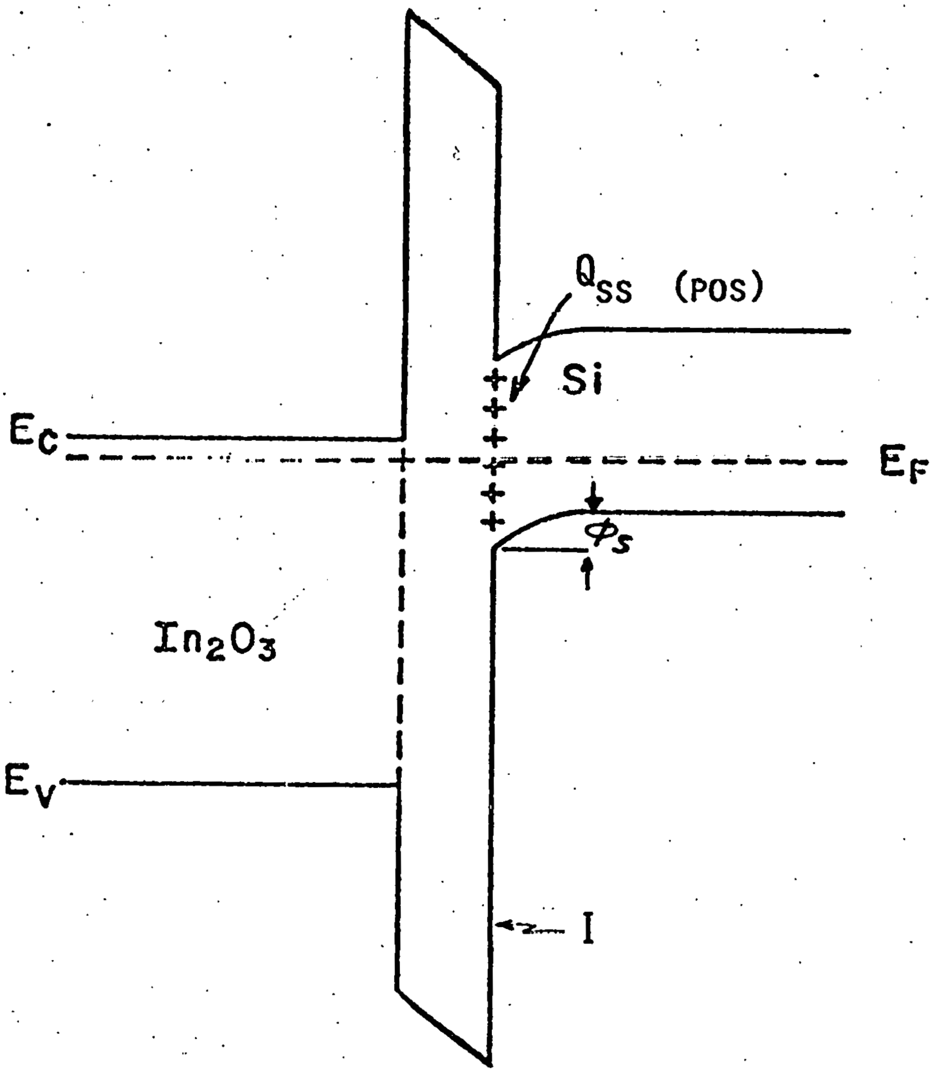
F.F. = 0.38

η = 3.9%

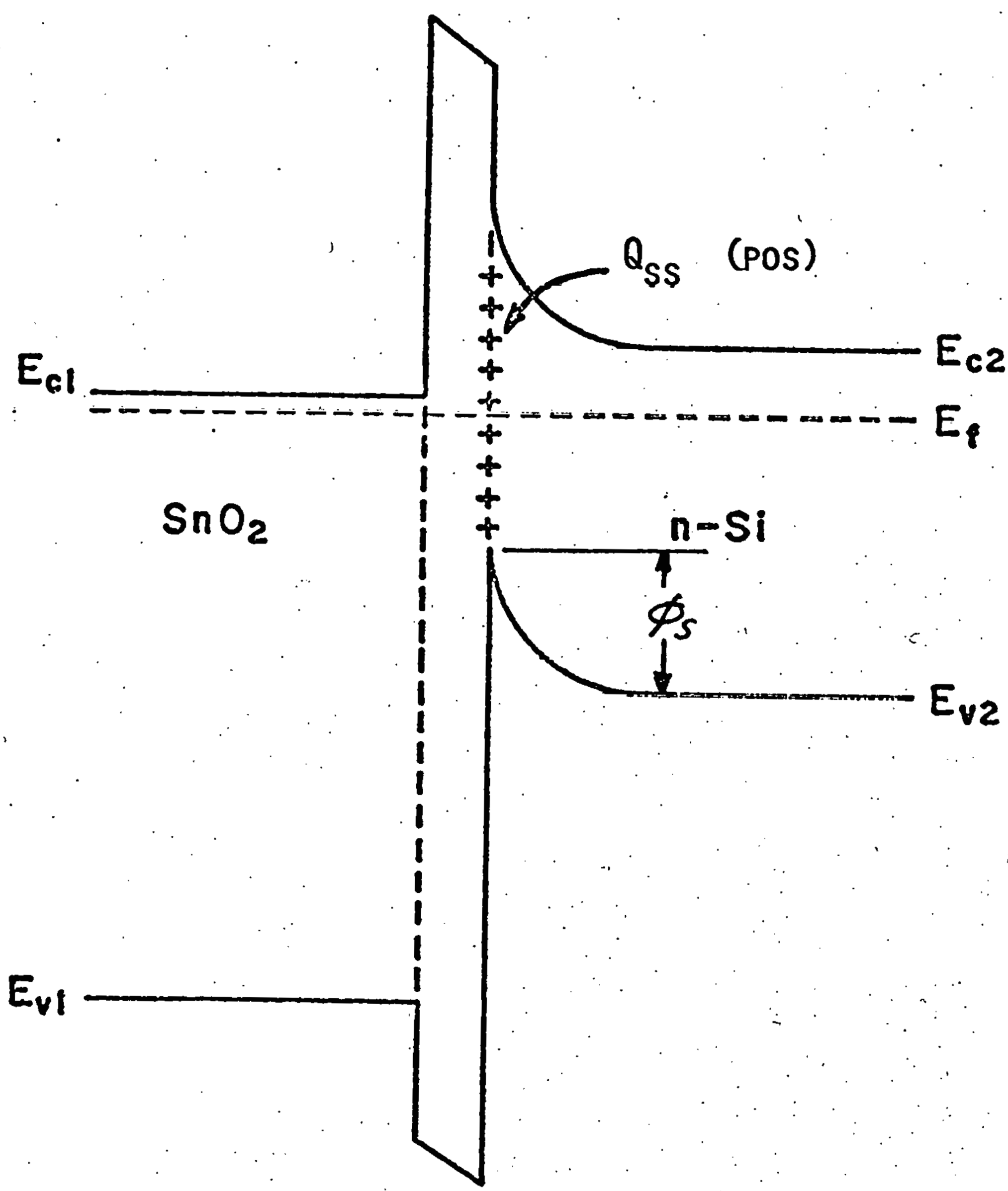
R_S = 7.0 Ω

ρ_{SUB} = 2 Ω-cm

SnO_2/ n -Si HJSC's (1 cm^2) FROM SAME RUN



ENERGY BAND DIAGRAM OF NIP HJSC STRUCTURE



ENERGY BAND DIAGRAM OF NIN HJSC STRUCTURE

IF

$$J = J_O \ \mathrm{EXP}\left[\frac{Q(V - IR)}{M\ KT} - 1\right] - I_{PH}(V)$$

THEN

$$V_{OC} = \frac{M\ KT}{Q}\ \mathrm{LN}\left[\frac{J_{PH}\ (V_{OC})}{J_O} + 1\right]$$

WHERE

J_O = FN OF I THICKNESS
(THROUGH ϕ_S AND REFLECTION)

J_{PH} (V_{OC}) = FN OF I THICKNESS
(THROUGH PHOTOCURRENT SUPPRESSION)

SO V_{OC} IS A FUNCTION OF I THICKNESS (AND Q_{SS})

DEGRADATION:

In_2O_3/Si HJSC'S:

NO DEGRADATION ON SHELF

DEGRADATION AT ELEVATED TEMPERATURE ($\sim 400^{\circ}C$)

SnO_2/Si HJSC'S:

A) DEGRADATION ON SHELF

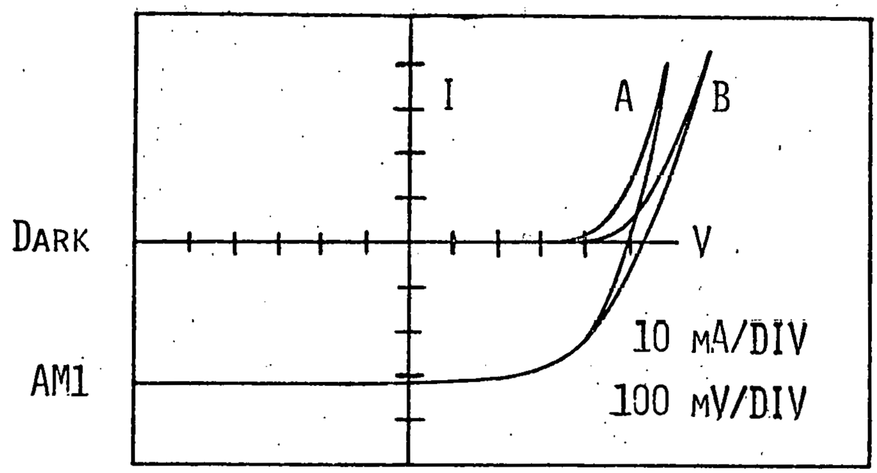
B) ENHANCED DEGRADATION AT ELEVATED TEMPERATURES

R_S (NON-LINEAR) INCREASES

V_{OC} CAN INCREASE OR DECREASE

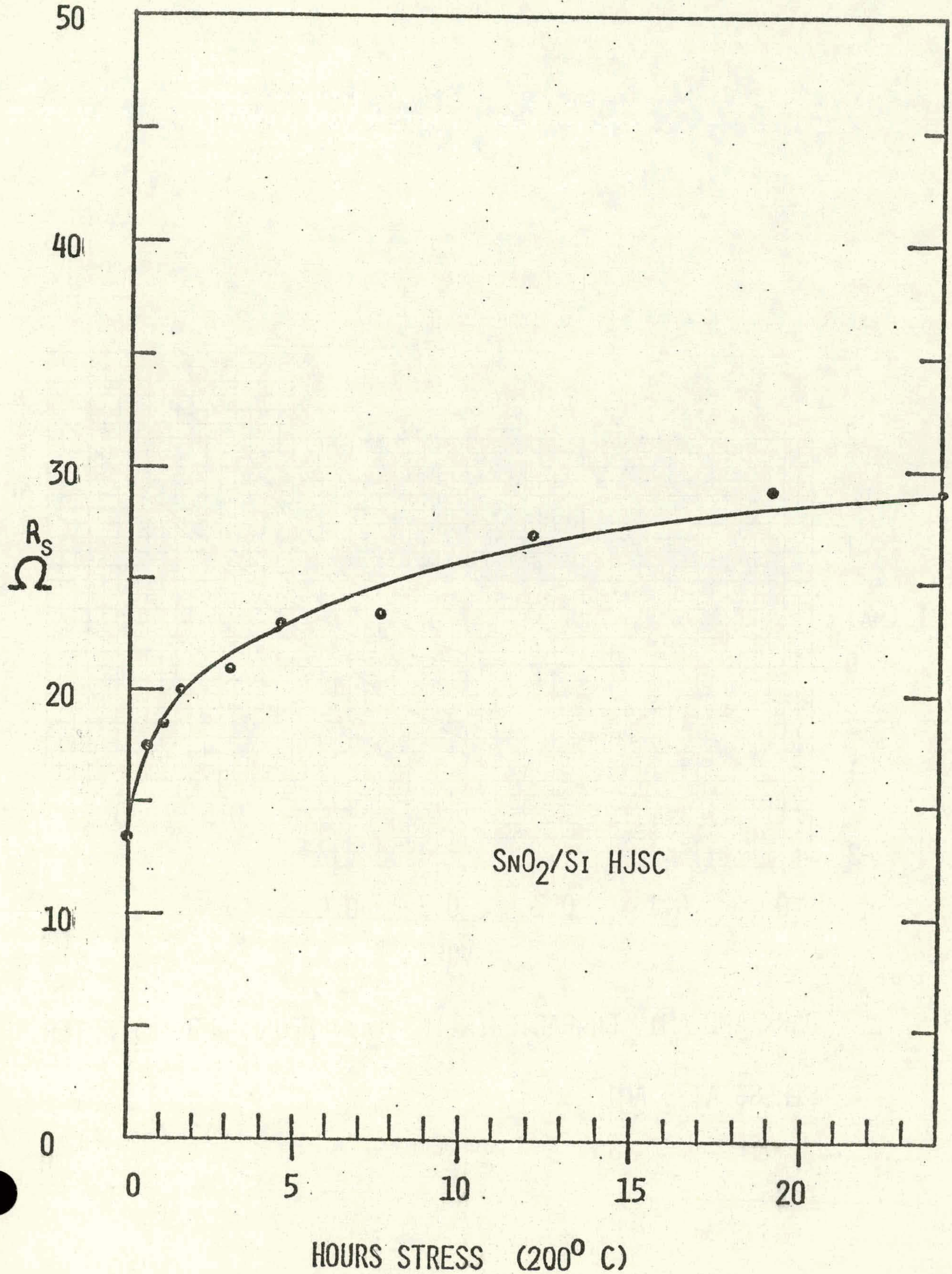
C) WITH ILLUMINATION, R_S DECREASES SLOWLY

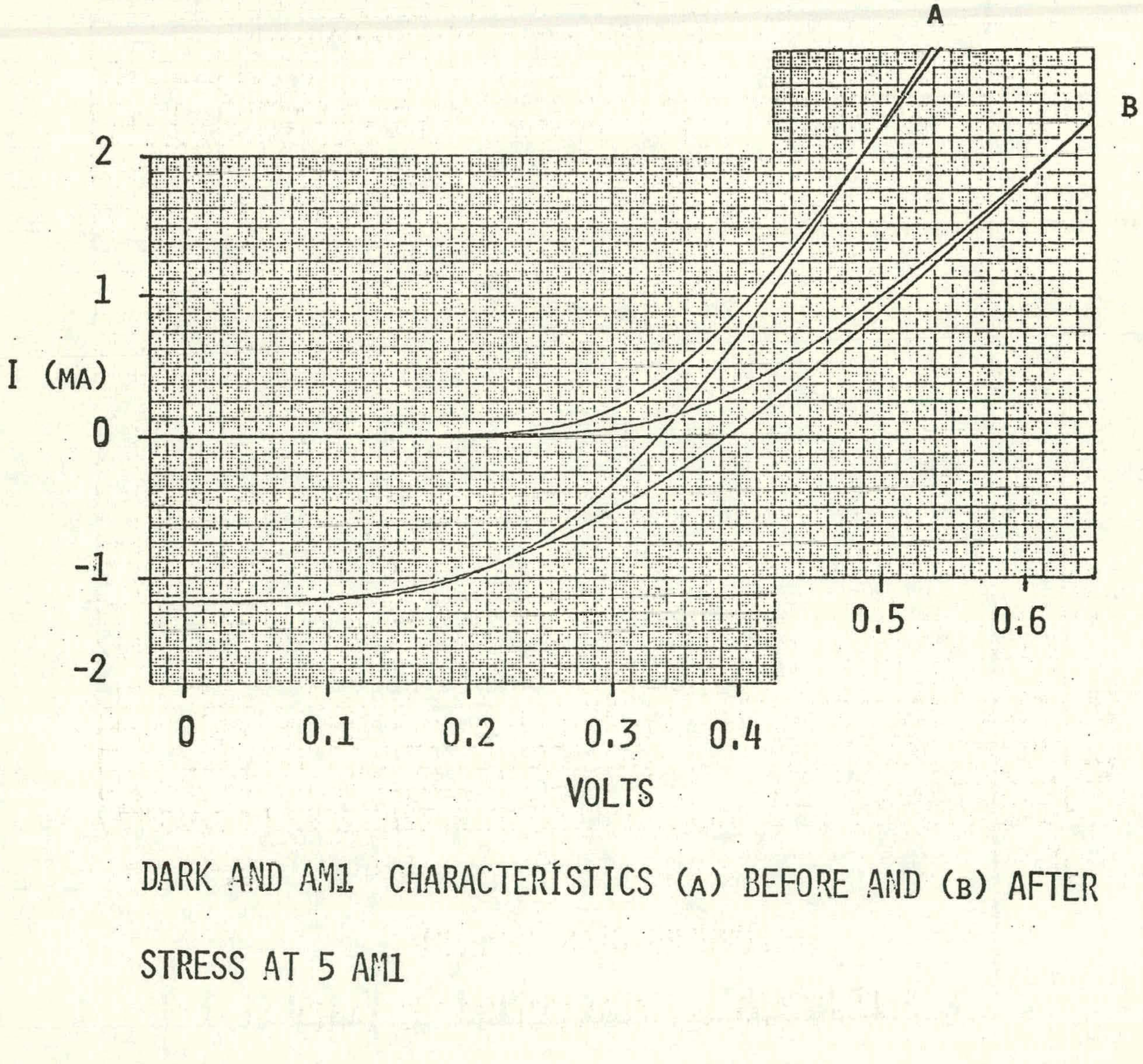
V_{OC} USUALLY DECREASES, BUT CHARACTERISTICS RELAX BACK IN HOURS OR DAYS



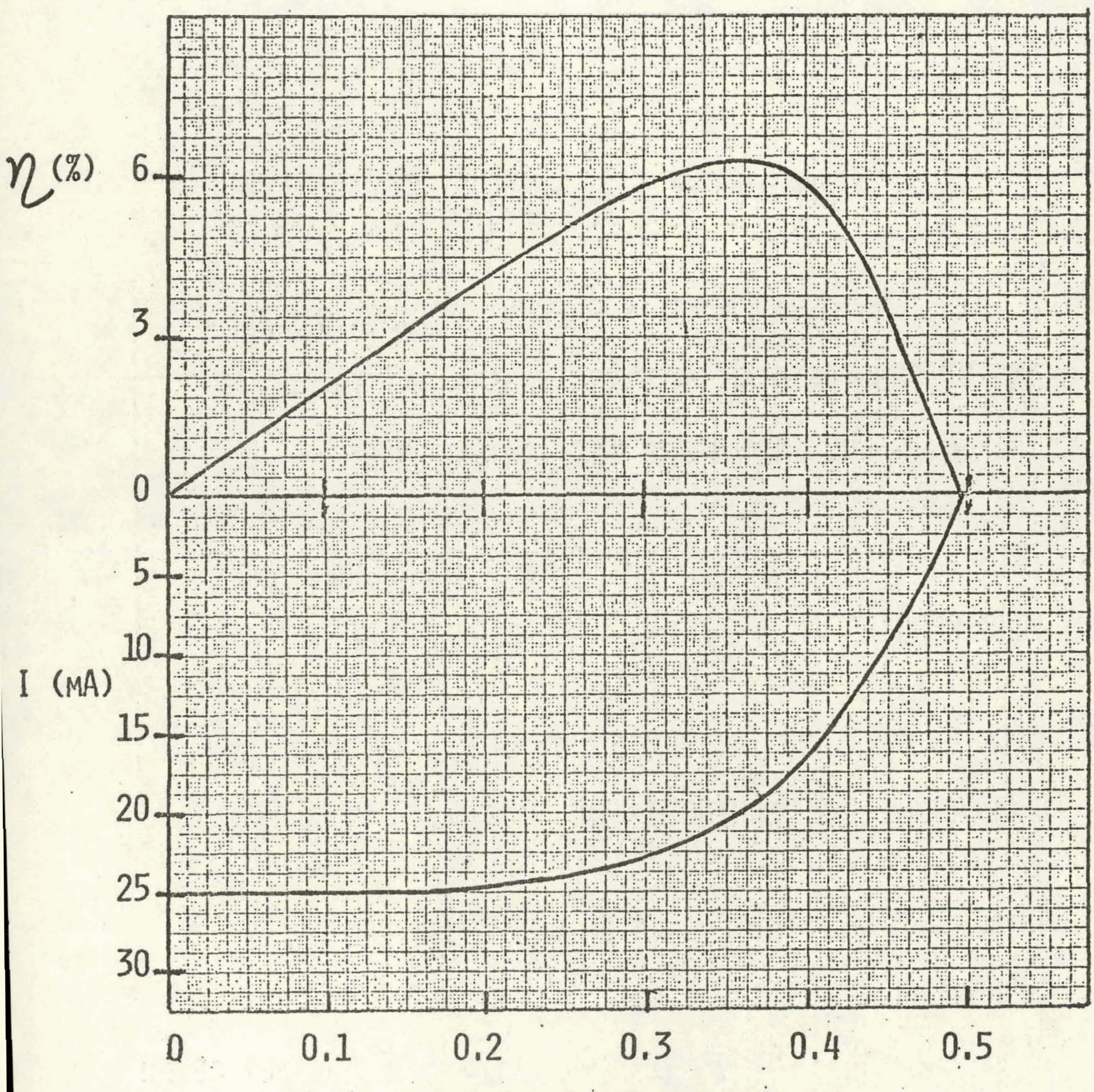
1cm^2 SnO_2/n-Si HJSC

I-V characteristics in (b) were taken 3 months later than (a).


50
40
30
20
10
0
R_S
Ω
SnO_2/Si HJSC
0
5
10
15
20
HOURS STRESS (200° C)



DARK AND AM1 CHARACTERÍSTICS (A) BEFORE AND (B) AFTER STRESS AT 5 AM1



η-V AND I-V CHARACTERISTIC (AM1)

FOR "STABLE" SnO_2/Si HJSC (1 cm^2)

SUMMARY OF KEY RESULTS

A) A THIN I (SiO_2?) LAYER IS PRESENT BETWEEN WINDOW AND Si SUBSTRATE AND A FIXED (POSITIVE) INTERFACE CHARGE IS PRESENT AT THE I/Si INTERFACE.

B) THIS I LAYER INCREASES THE SERIES RESISTANCE AND THUS REDUCES FILL FACTOR.

C) THIS I LAYER AND INTERFACE CHARGE CAN INCREASE OR DECREASE V_{OC} DEPENDING ON THE SYSTEM.

D) AN EXCESSIVELY THICK I LAYER CAN CAUSE PHOTO-CURRENT SUPPRESSION.

SUMMARY OF KEY RESULTS (CONT.)

E) THE I LAYER IS LARGER ON HJSC'S USING POLYCRYSTALLINE SI SUBSTRATES. THIS INCREASES R_S AND AFFECTS V_{OC}.

F) In_2O_3/SI HJSC'S DEGRADE ONLY AT ELEVATED TEMPERATURES

G) MOST SnO_2/SI HJSC'S TESTED DEGRADE ON-SHELF. THE DEGRADATION IS ENHANCED AT ELEVATED TEMPERATURES. THIS DEGRADATION IS THOUGHT TO BE ASSOCIATED WITH THE GROWTH OF AN INSULATING INTERFACE LAYER.

H) SnO_2/SI HJSC'S FROM SOME RUNS ARE STABLE ON-SHELF.

PLANNED ACTIVITY FOR NEXT SIX MONTHS

1. PUT E-BEAM SYSTEM INTO OPERATION AND FABRICATE SnO_2/Si HJSC'S
2. CONTINUE STUDIES ON STABILITY OF SnO_2/Si HJSC'S
3. INVESTIGATE CHARACTERISTICS OF INTERFACE LAYERS
4. CONTINUE DEVELOPMENT OF HJSC THEORY INCLUDING INTERFACE LAYER WITH PARTICULAR EMPHASIS ON SnO_2/Si CELLS

TWELVE PERCENT EFFICIENT INDIUM TIN OXIDE ON SILICON HETEROSTRUCTURE SOLAR CELLS

Professor Joel DuBow

Electrical Engineering Department

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Presented at the National Solar Photovoltaic Program Review Meeting

August 3 - 6, 1976

University of Maine at Orono

Orono, Maine 04473

I. Objectives

Even though oxide semiconductor on silicon (OSOS) solar cells began receiving serious attention only 2 years ago, two laboratories, Syracuse University[1] and Colorado State University[2] have reported OSOS solar cells with greater than ten percent efficiency. The Syracuse cells consisted of tin oxides evaporated onto single crystal n-type silicon and the Colorado State cells consisted of indium-tin oxides sputter deposited onto single crystal p-type silicon.

The major objective of this program is to fabricate, test and package 2 cm x 2 cm OSOS solar cells of at least 12 percent efficiency in a manner consistent with continuous, low cost manufacturing techniques. Another major objective will be to evaluate the films and solar cells made during this program through an extensive series of measurements to determine an accurate model of device performance. A third objective is to use this model to evaluate (fabrication cost)/(device performance) tradeoffs to optimize the cell fabrication from the viewpoint of near term practical viability as a photovoltaic energy source. Testing under temperature and bias stress will be made to estimate degradation mechanisms. A final objective will be to quantitatively estimate the cost/watt of producing 500 MW/yr of OSOS cells and the sensitivity of these costs to variations in fabrication techniques, materials costs, labor costs and economic conditions.

II. Previous Activities

We have fabricated 0.07 cm^2 indium-tin oxide on silicon solar cells with 12 percent conversion efficiency and measured properties of the cells and of films deposited on glass slides. Figure 1 shows a cross section of the cell. More recent devices use an indium dot in place of an aluminum dot and have a 4000 Å thick oxide layer instead of a 2000 Å thick layer. The silicon dioxide serves only to delineate devices on a wafer and reduce any junction edge effects and is not an essential fabrication feature. Figure 2 outlines the device fabrication procedure. The silicon dioxide is sputter etched through a stainless steel mask and the indium tin oxide is sputter deposited on the wafer. Contacts are made with aluminum evaporated on the back of the wafer and on aluminum or indium dot deposited on the front. When a stylus contact is used, no front contact dots are utilized.

Corning 7059 glass slides are included in each run for film evaluation. As sputtered resistivities range from 2 to 5 x 10^{-4} ohm-cm. Oxide composition was varied from 10 percent tin oxide to 70 percent tin oxide in indium oxide. Figure 3 depicts the transmission of 4000 Å thick films over the visible and near infrared spectral region. The net transmission for the 10% tin oxide film, weighted by the sun's spectrum, is 0.86, whereas for the 70% film it is 0.77. Galvanomagnetic measurements taken over the temperature range 77°K to 350°K indicate that the films have a relatively temperature independent carrier concentration of about 10^{21} cm^{-3} and a mobility of 12cm^2/v-sec. The films therefore appear to be transparent, degenerate semiconductors.

Figure 4 shows the I-V characteristics of a typical 10% tin oxide, 90% indium oxide solar cell. This particular composition displays a fill factor of 0.7, an open circuit voltage of 0.53 volts, a short circuit current of 32ma/cm^2 and a ser resistance of 20 ohms (for a 0.07 cm^2 device).

The compositional dependence of the solar cell parameters is shown in Figure 5. There is little change in the open circuit voltage, suggesting that the barrier height is nearly independent of composition. This is consistent with extrapolated c-v measurements, which consistently suggest a flat-band voltage of 1.0 $\pm$ 0.1 V. Figures 5(b) and 5(c) indicate that both the short circuit current and the fill factor decrease with increasing tin concentration. The series resistance increases with increasing tin concentration. This is primarily caused by increasing resistivity of the films. The combined effect is a decrease in efficiency with increasing tin concentration shown in Figure 5(e).

Conventional current flows from the oxide to the silicon. The combined film, and solar cell data point to a p-type Schottky barrier model for the device, which may be represented by the band structure shown in Figure 6. The barrier height is relatively constant with composition, indicating that the Fermi level is pinned at the interface. This structure is similar to that proposed by Anderson for SnO_2:Si solar cells.(3) However, the interface region is not well characterized and can complicate device structure. The sputter deposition process can cause a shallow damage layer in the silicon. There is also quite likely a thin S_1O_2 layer between the oxide semiconductor and the silicon. In addition, the initial few layers of the deposited film, because of nucleation and lattice accommodation[1] effects, may not be completely stoichiometric. Figure 7 shows an Auger spectra of a cell. Although resolution in the few Angstroms around the interface is not yet well defined, the composition throughout the bulk of the film appears uniform.

The insulating layer points to an MIS model for the cell,(4,5) which significantly affects analysis of the results and fabrication procedures.

III. Future Plans

We plan to fabricate 2 cm x 2 cm cells and evaluate their optical and electronic properties. The solar cell parameters, solar cell spectral response. film spectral response, film resistivity, Auger spectra of films and cells, x-ray diffraction patterns of the films, and temperature and voltage stress measurements, will be made. These measurements will be correlated with MIS device models being developed by John Shewchun. Finally, an estimate of the cost to manufacture OSOS cell array, using differentially pumped, continuous fabrication procedures will be estimated using cost estimates and the computer models previously developed for solar thermal power systems at CSU.

References

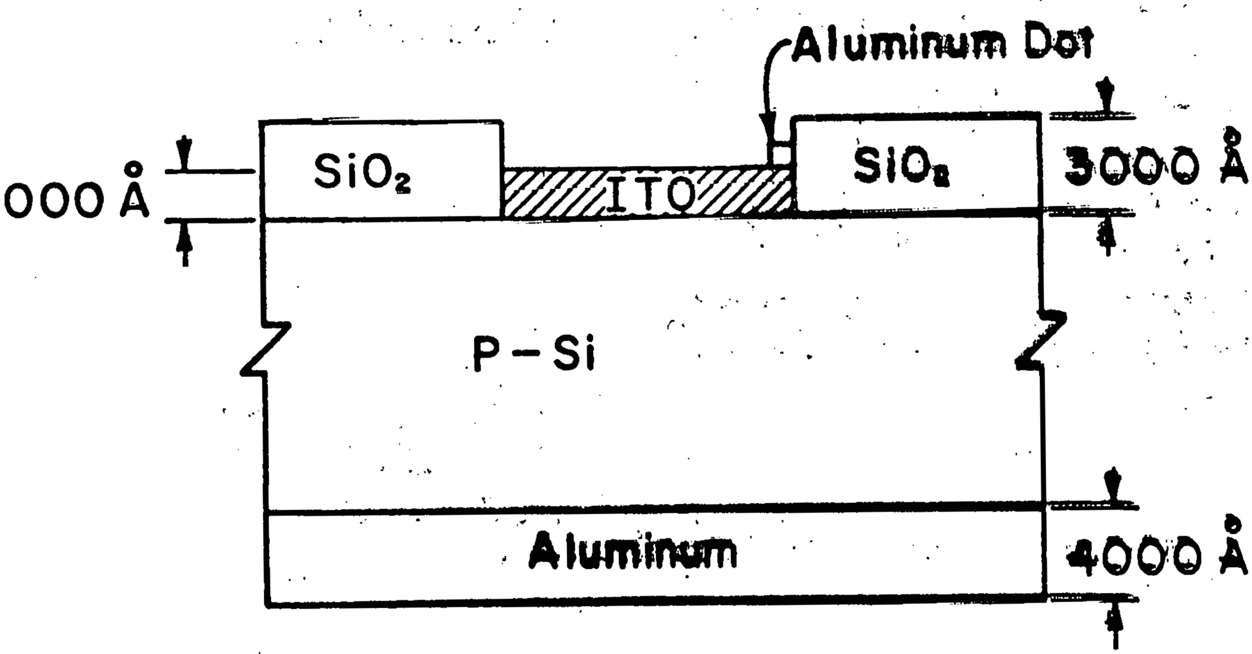
1) R. L. Anderson, NSF/RANN Report AER 74-17631 (1975).

2) J. B. DuBow, D. E. Burk and J. R. Sites. To be published in Applied Physics Letters.

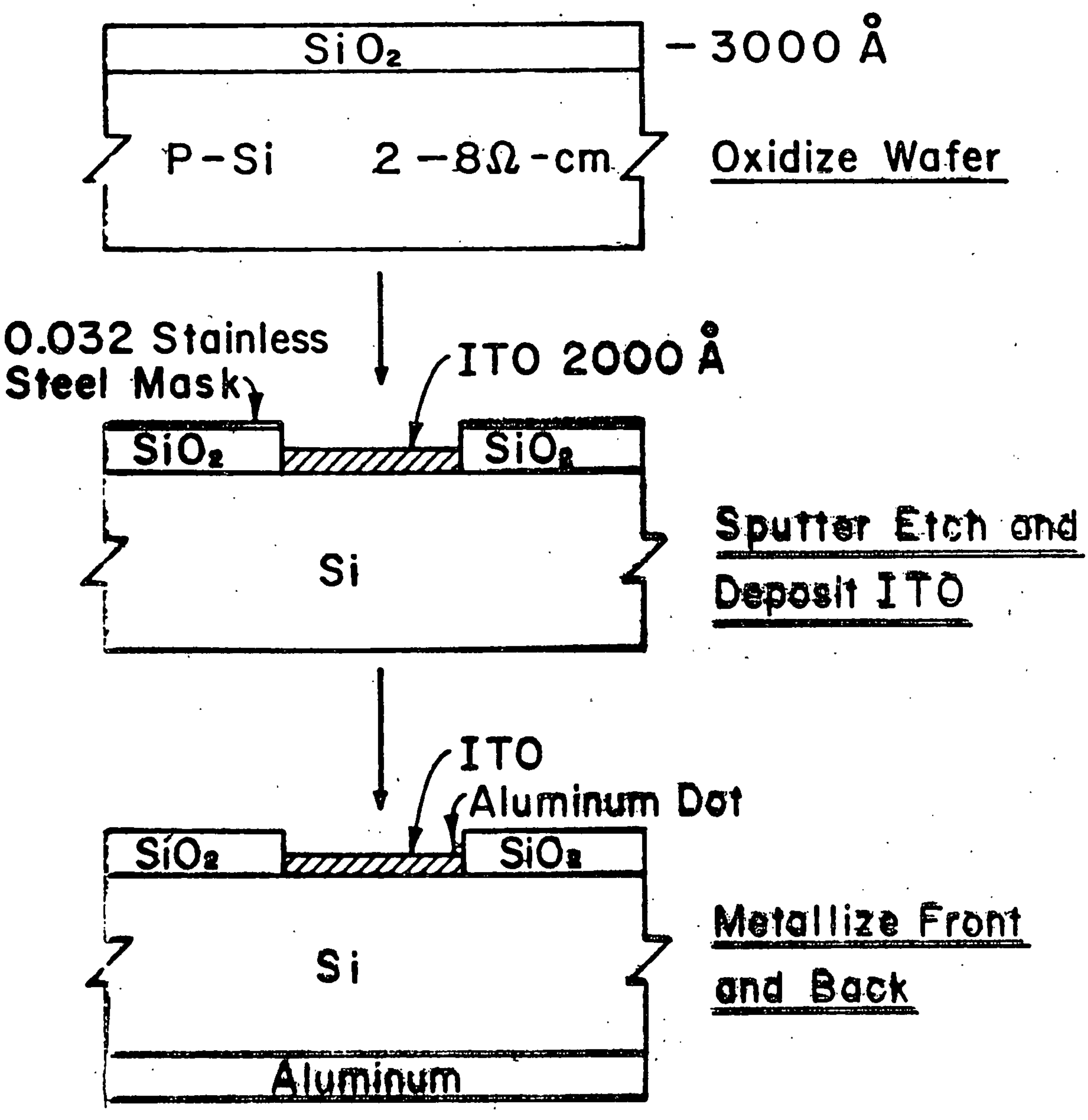
3) R. L. Anderson, Applied Physics Letters, 27, 691 (1975).

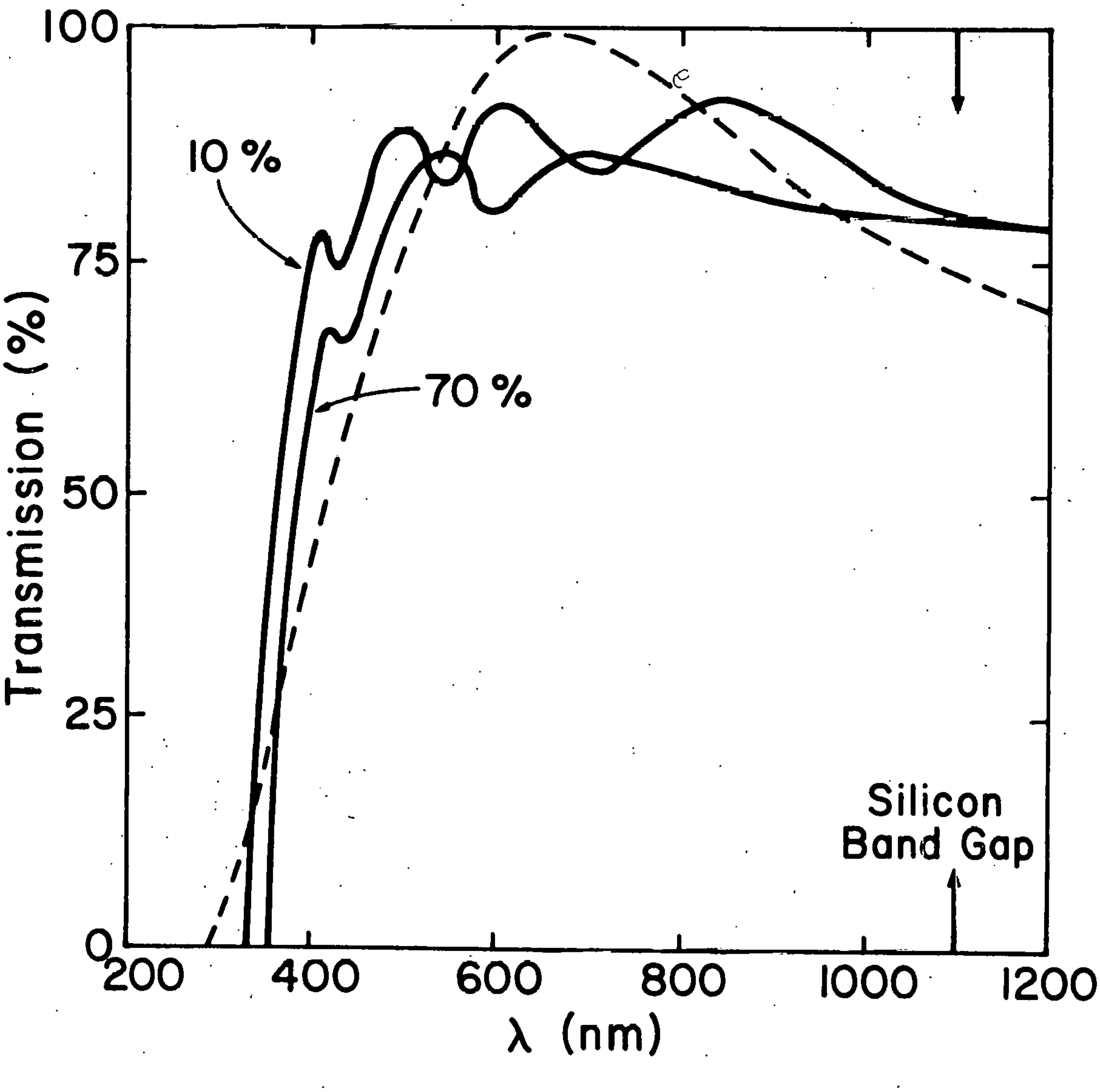
4) R. Singh and J. Shewchun, Applied Physics Letters, 28, 512 (1976).

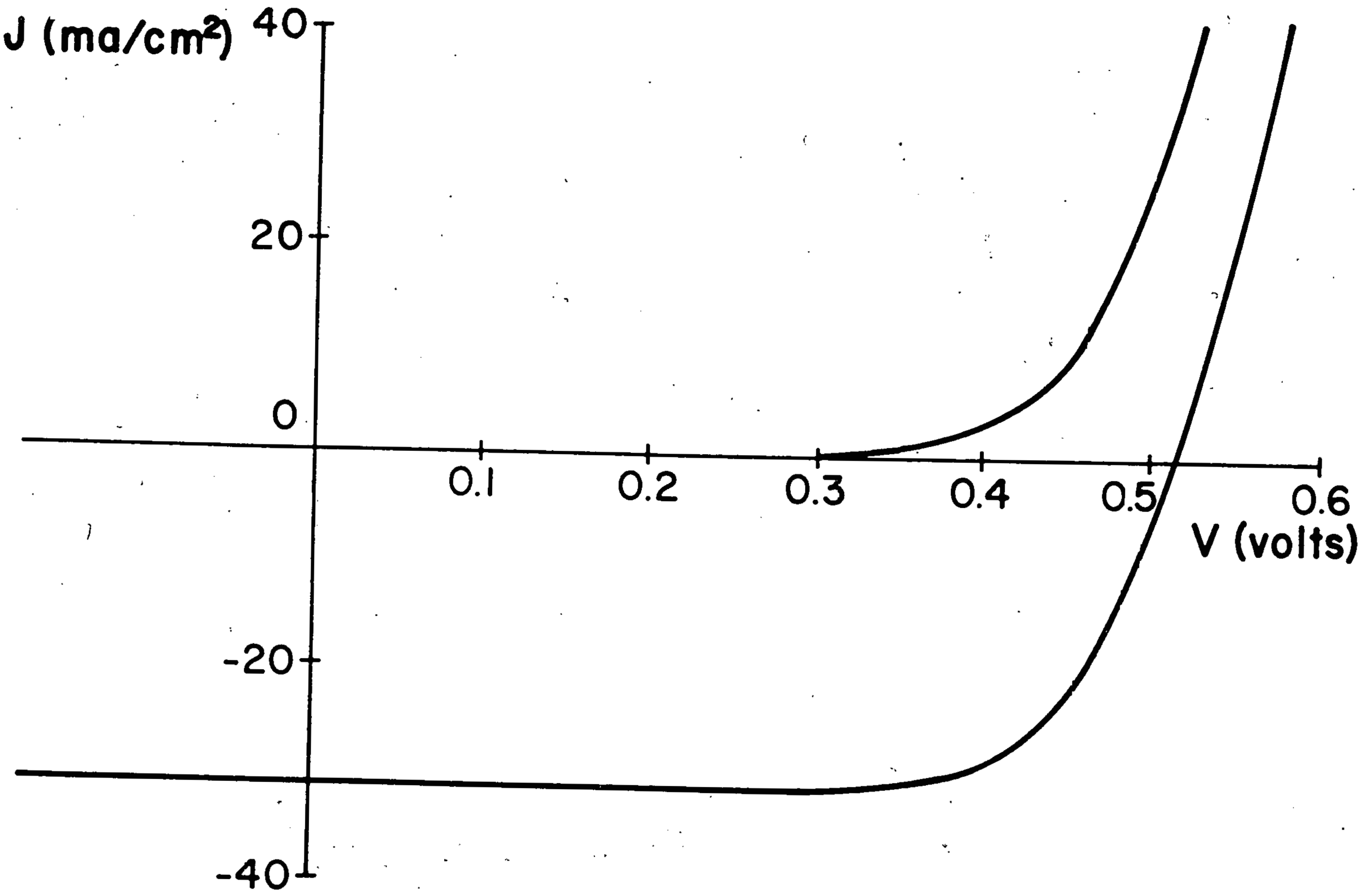
5) S. J. Fonash, J. Appl. Phys., 45, 1286 (1975).

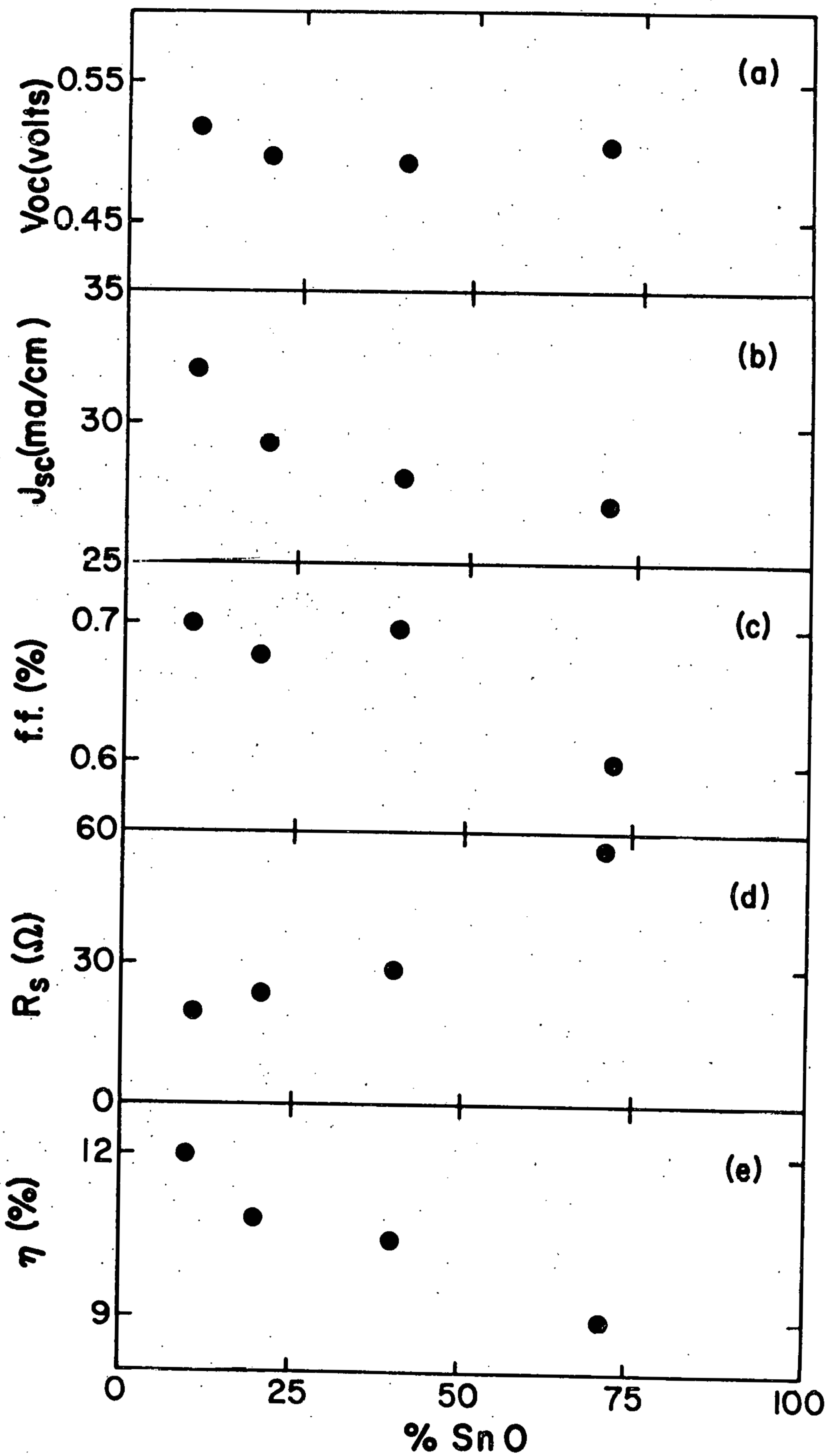


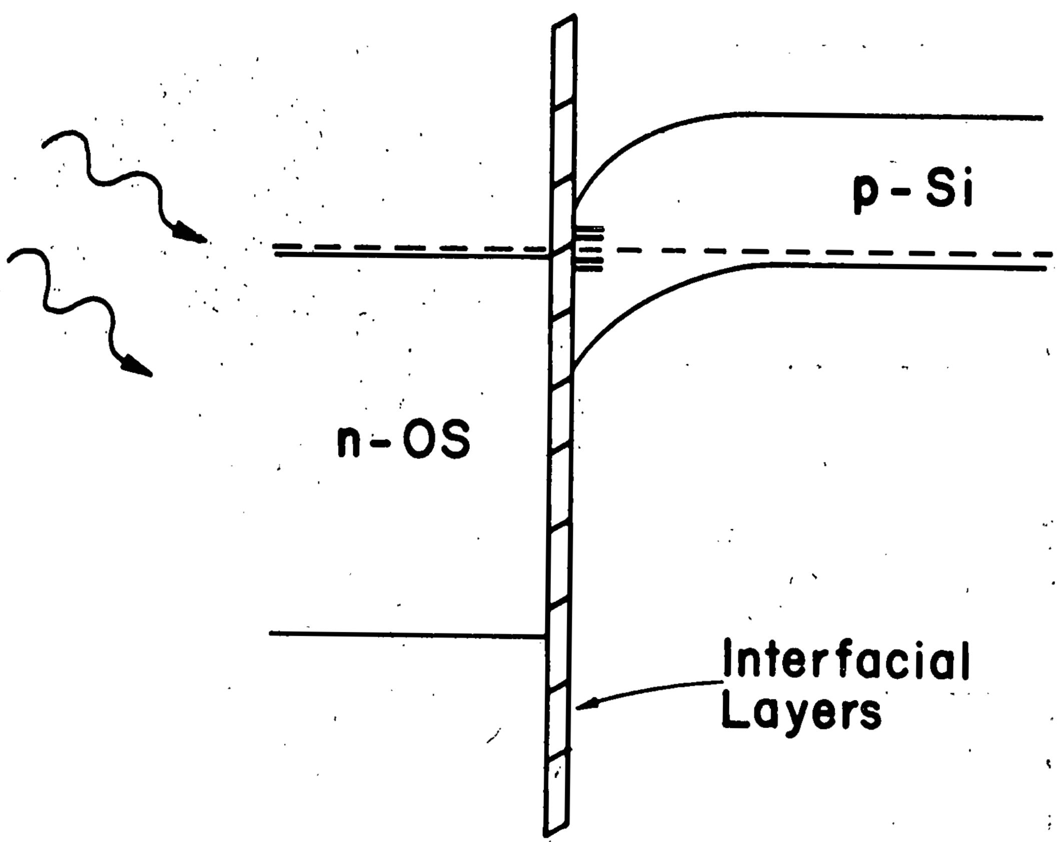
Aluminum Dot
000 Å
SiO2
ITO
SiO2
3000 Å
P - Si
Aluminum
4000 Å

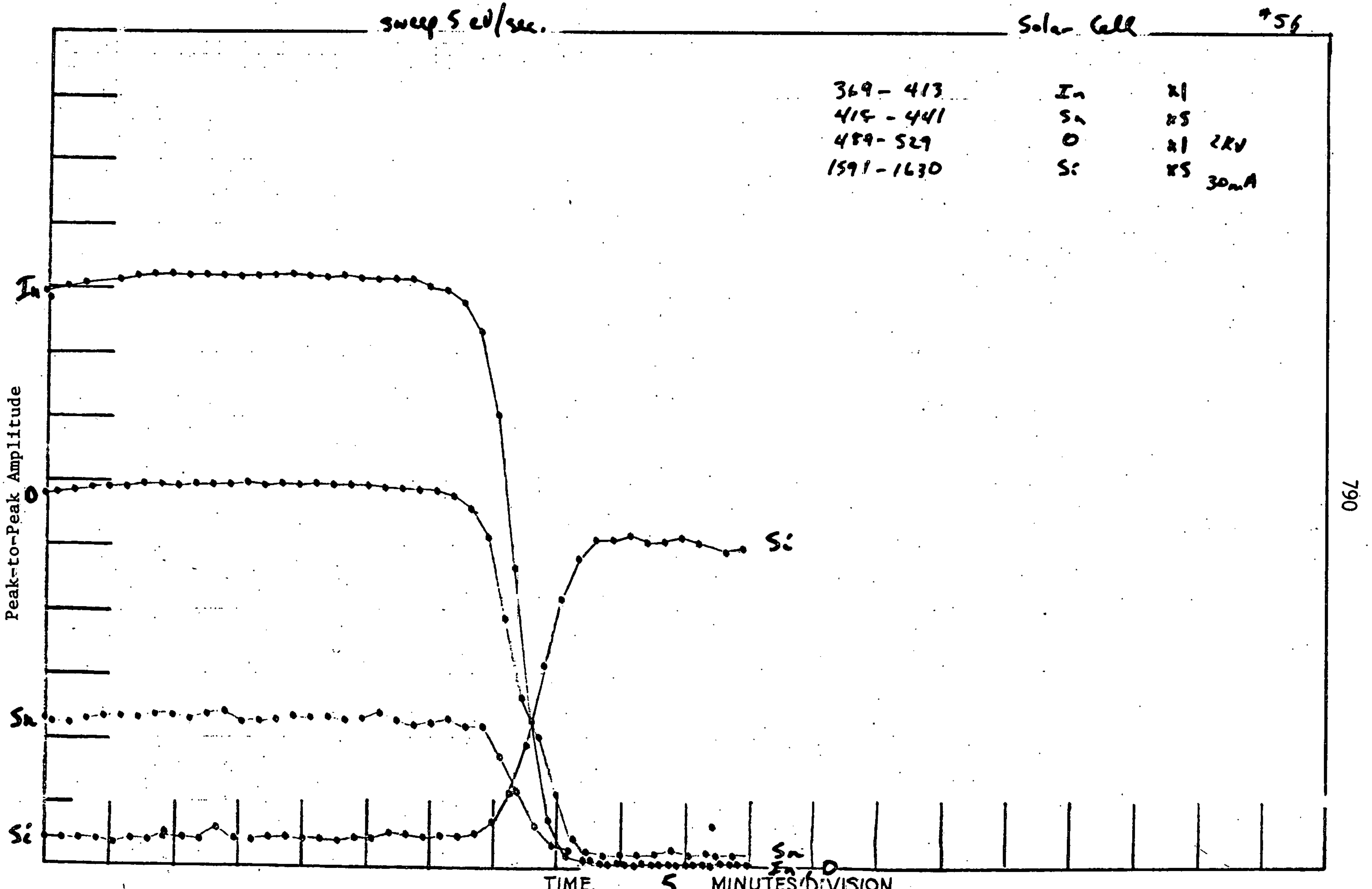

SiO2
- 3000 Å
P-Si
2-8Ω-cm
Oxidize Wafer
0.032 Stainless
Steel Mask
ITO 2000 Å
SiO2
SiO2
Si
Sputter Etch and
Deposit ITO
ITO
Aluminum Dot
SiO2
SiO2
Si
Metallize Front
and Back
Aluminum


100
75
50
25
0
Transmission (%)
10 %
70 %
Silicon
Band Gap
200
400
600
800
1000
1200
λ (nm)


J (ma/cm²)
40
20
0
-20
-40
0.1
0.2
0.3
0.4
0.5
0.6
V (volts)


Voc(volts)
0.55
0.45
(a)
35
Jsc(ma/cm)
30
25
(b)
f.f. (%)
0.7
0.6
(c)
60
Rs (Ω)
30
0
(d)
η (%)
12
9
(e)
0
25
50
75
100
% SnO


p - Si
n - OS
Interfacial
Layers



Ep= 5kV Ip= 33 μA Vmod= 3eV RC= .03 Vmult = 580 SENS= x10 NEUT. N/A DATE 7/20/76 BY rwk

HETEROSTRUCTURE SINGLE CRYSTAL SILICON PHOTOVOLTAIC SOLAR CELLS (TYPE A, SEMICONDUCTOR HETEROJUNCTION SILICON DEVICES)

Funding Agency - ERDA

Grant or Contract Number - Pending

Period of Grant: Pending

Value: $K 247

Robert F. Shaw
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Presented at the National Solar Photovoltaic Program Review Meeting

August 3 - 6, 1976

University of Maine at Orono

Orono, Maine 04473

OBJECTIVE OF PROJECT

FABRICATE AND STUDY SnO_2/Si TYPE DEVICES AND WORK ON THEORY OF DEVICE PERFORMANCE AND DEGRADATION WITH A VIEW TO IMPROVE EFFICIENCY AND STABILITY.

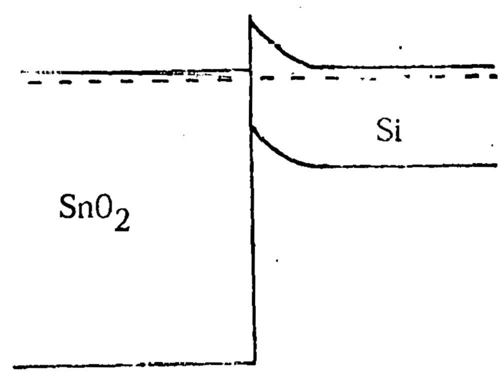
PLANNED TECHNICAL ACTIVITY

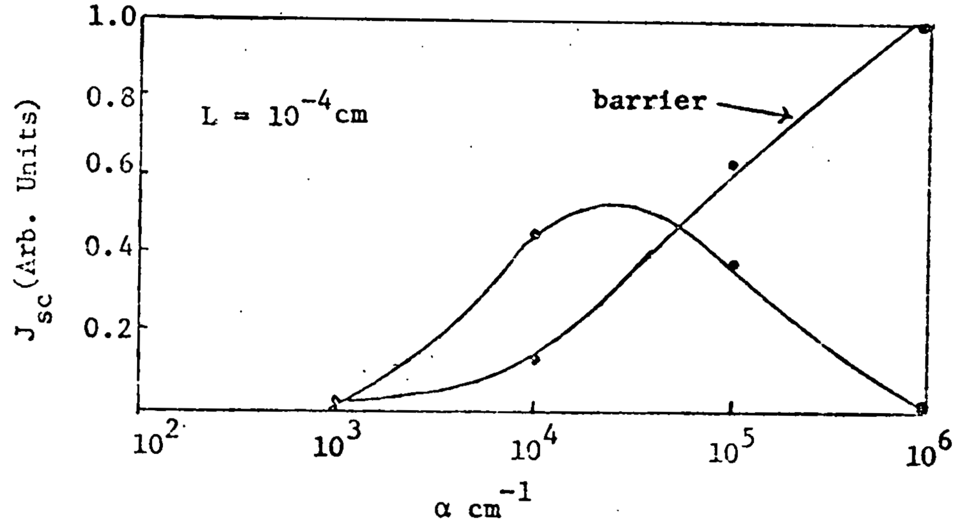
1. ANALYZE DEVICES MADE BY INNOTECH AND PRESENTLY OWNED BY EMDEX CORP.

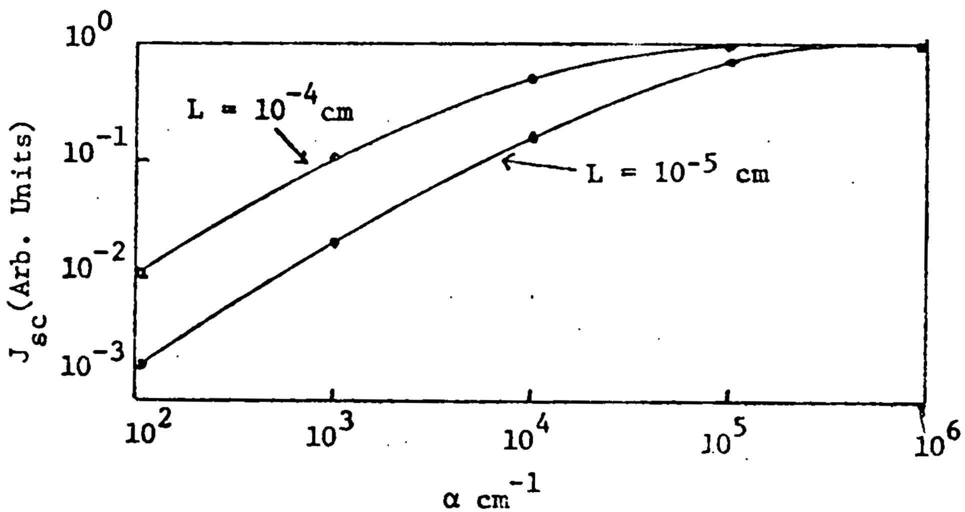
2. FABRICATE REPRODUCIBLE DEVICES.

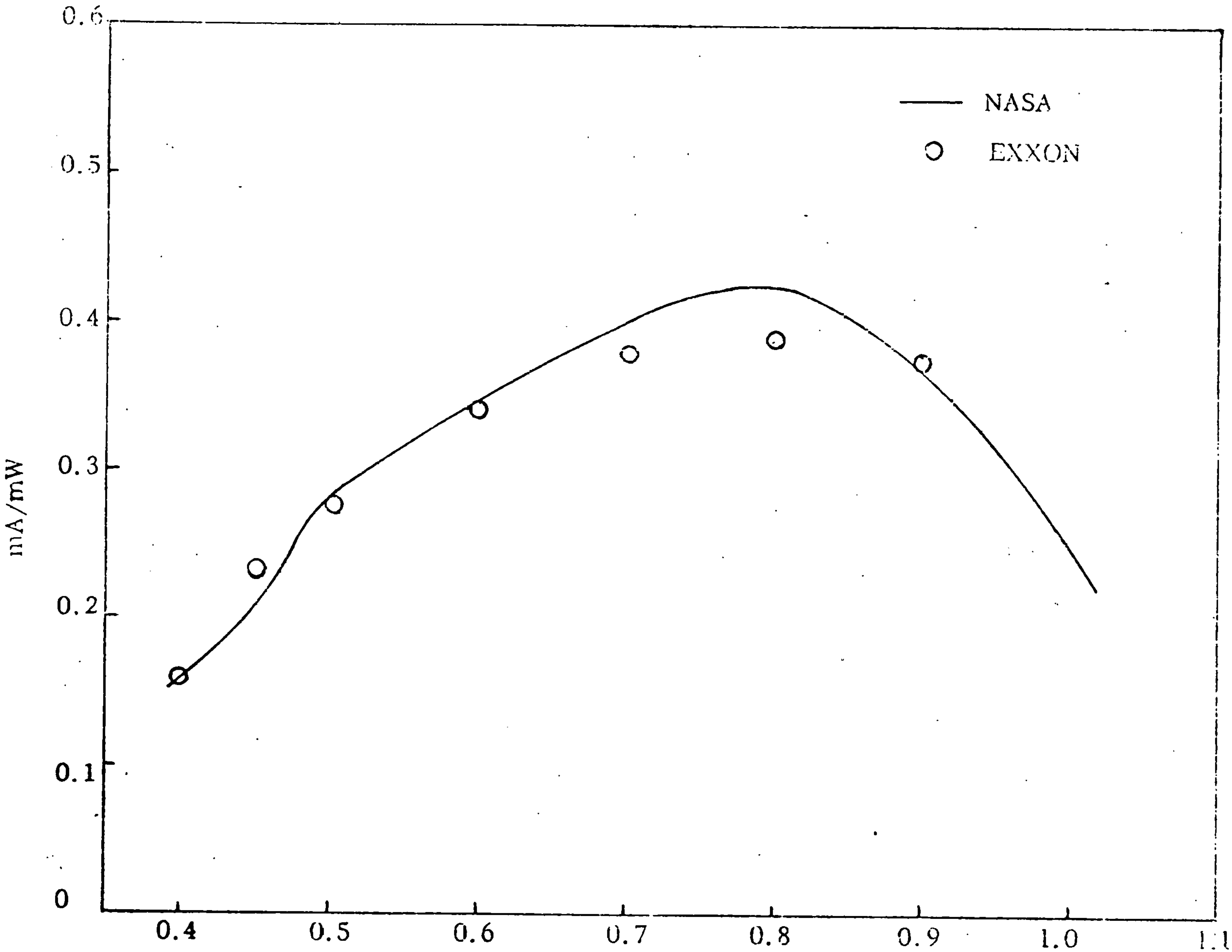
3. THEORETICAL AND PHENOMENOLOGICAL ANALYSIS OF DATA.

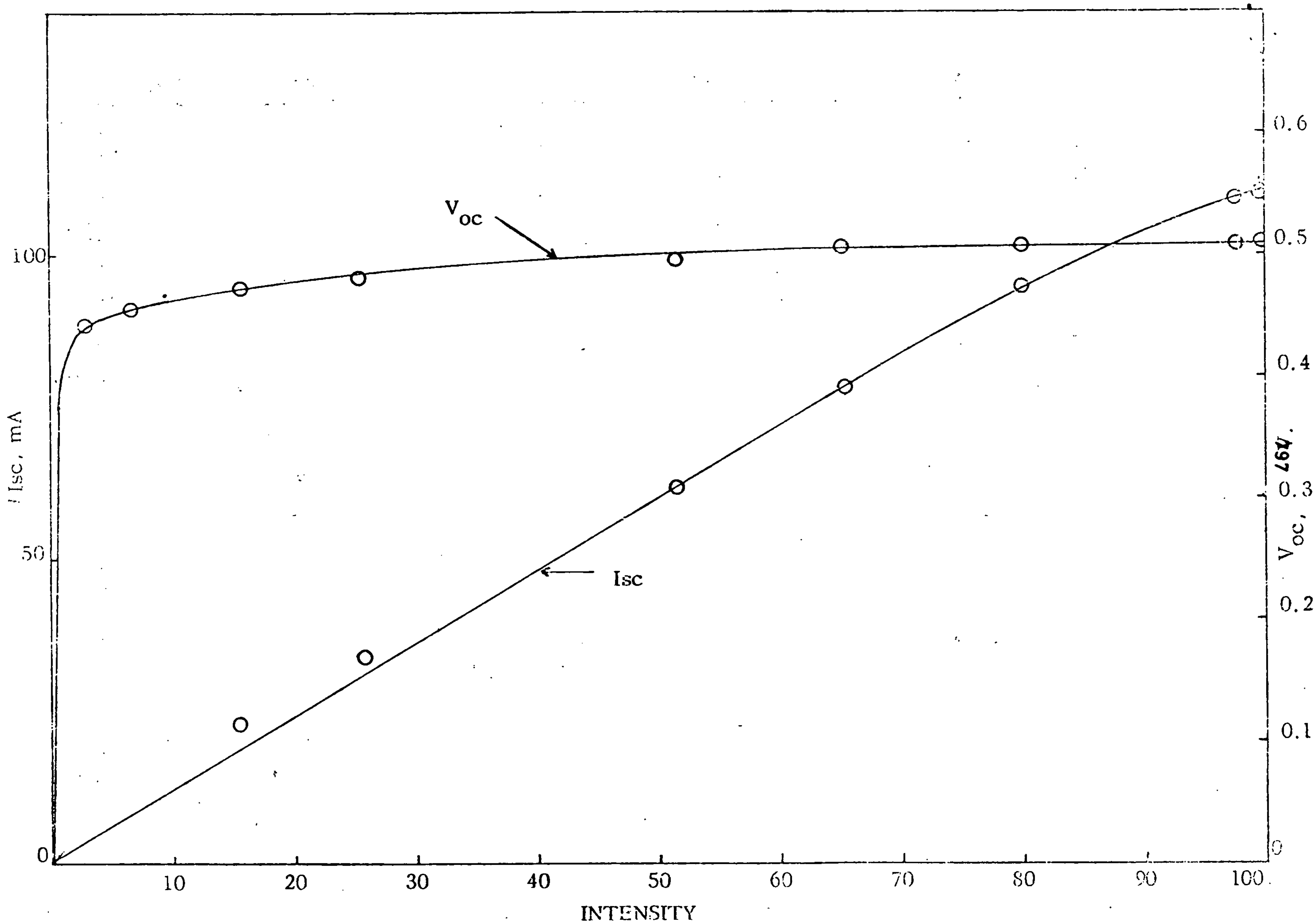
4. STUDY DEVICE DEGRADATION MECHANISM.

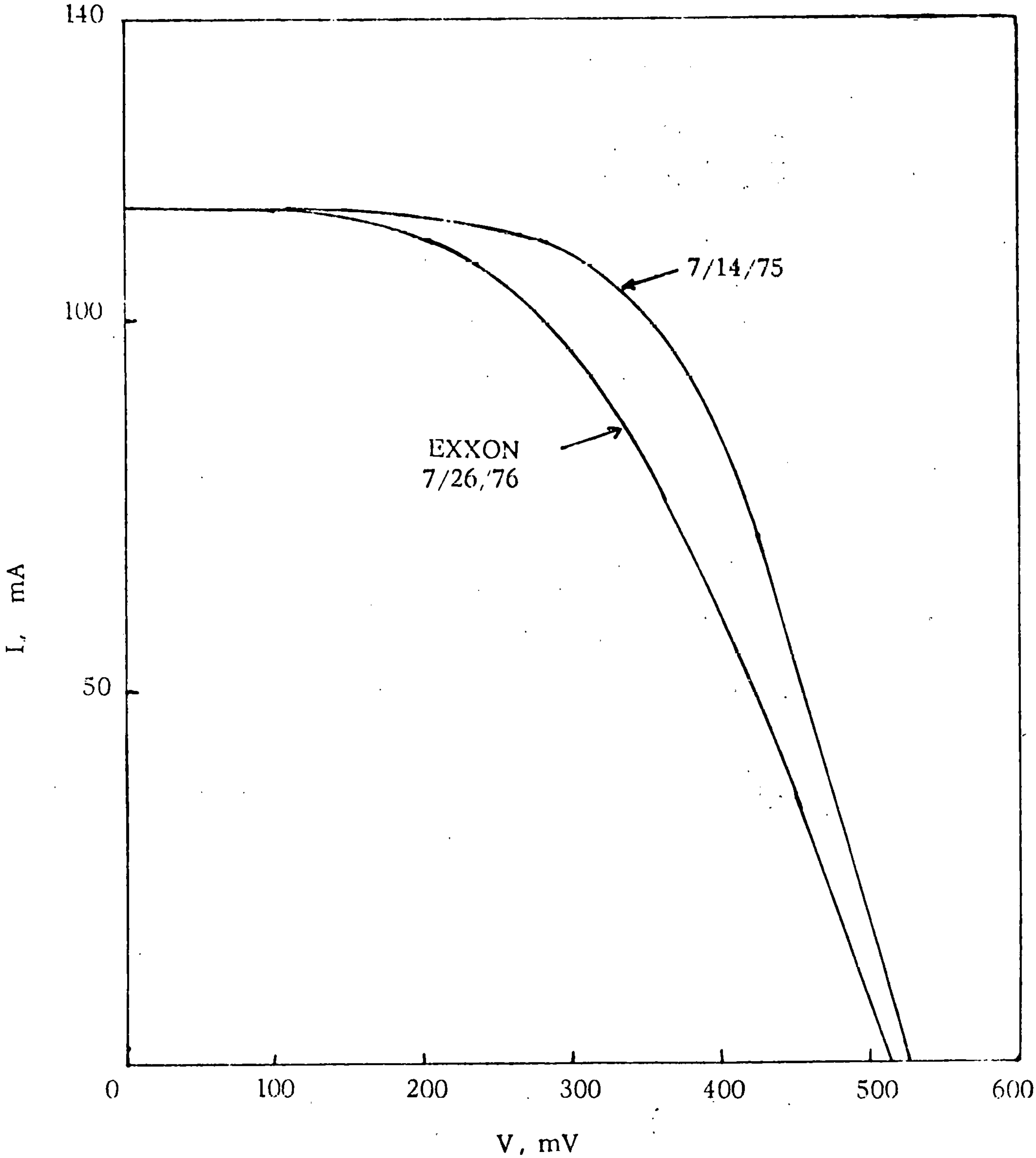

Si
SnO_2


1.0
0.8
0.6
0.4
0.2
L = 10^-4 cm
barrier
J_sc (Arb. Units)
10^2
10^3
10^4
10^5
10^6
α cm^-1


10^0
10^-1
10^-2
10^-3
L = 10^-4 cm
L = 10^-5 cm
J_sc (Arb. Units)
10^2
10^3
10^4
10^5
10^6
α cm^-1


NASA
EXXON
mA/mW
0.6
0.5
0.4
0.3
0.2
0.1
0
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1


Voc
Isc
Isc, mA
100
50
0
10
20
30
40
50
60
70
80
90
100
INTENSITY
0.6
0.5
0.4
0.3
0.2
0.1
0
Voc, V
497


140
100
50
I, mA
0
100
200
300
400
500
600
V, mV
7/14/75
EXXON
7/26/76

PLANS FOR MIS SILICON CELLS

HETEROSTRUCTURE SINGLE CRYSTAL SILICON
PHOTOVOLTAIC SOLAR CELLS
TYPE B: METAL HETEROJUNCTION SILICON DEVICES

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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Presented at the National Solar Photovoltaic Program Review Meeting
August 3-6, 1976
University of Maine at Orono
Orono, Maine 04473

Abstract

PLANS FOR MIS CELLS

OBJECTIVES

The overall objective for this project is to assess the technical and commercial practicability for power generation of metal heterojunction silicon photovoltaic cells of the metal-insulator-semiconductor (MIS) variety. Three major tasks are planned to achieve this objective: (1) fabrication of standard and experimental cells, (2) evaluation of cell performance and relation of performance to theoretical models, and (3) exploration of optimized cell performance.

PREVIOUS ACTIVITIES

In the simplest models for the MIS cell, the current at the insulator-semiconductor interface which opposes the photogenerated current consists of two components: the thermionic emission current of majority carriers and the (much smaller) minority carrier diffusion current. If the total bucking current is carried by direct tunneling through the insulator, the I-V behavior of the cell is very sensitively affected by small changes and insulator thickness. On the other hand, if the insulator current is primarily supported by hopping, the thermionic contribution should be reduced by introducing fixed charges at the insulator-semiconductor interface and by permitting the trapping of thermionically emitted carriers in insulator centers of appropriate distribution and cross-section. This approach is based on theoretical work at Penn State. Its usefulness is supported by open circuit voltage and efficiency measurements on cells

which are prepared with various insulators. Work at Westinghouse Research on insulator preparation and treatment has established that interface charge and insulator trapping can be controlled over ranges of interest for MIS solar cells.

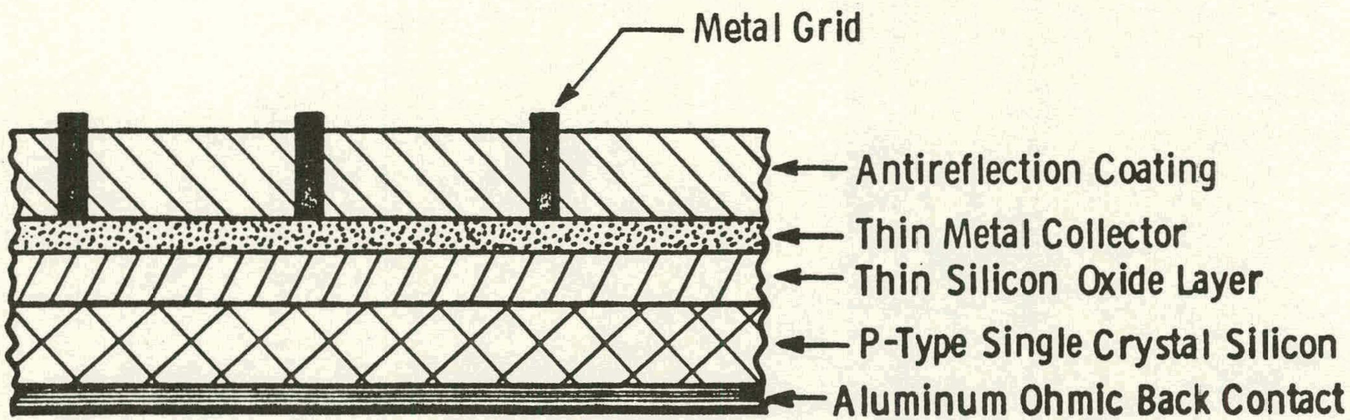
FUTURE PLANS

The program involving Westinghouse Research and Penn State University will explore the behavior and performance of MIS solar cells in which the insulating layer fixed charge and trapping properties will be deliberately varied. The Westinghouse effort will be directed toward preparing thin silicon dioxide films by chemical vapor deposition. Properties of the films will be varied by a number of means including pre-deposition surface treatments in-situ and by post deposition treatments of the insulators or completed cell structures. The Penn State group will prepare "standard" cells for comparison purposes. All performance will be characterized and modelled. In addition, auxiliary experiments will be performed on the cell constituents as required for as complete characterization of the cells as possible. The two groups will interact on measurements, modelling and fabrication details.

OVERALL PROJECT OBJECTIVE

Fabricate, test, evaluate and model metal heterojunction silicon photovoltaic cells of the MIS variety to assess their technical and commercial practicability for power generation.

Dwg. 6379A03



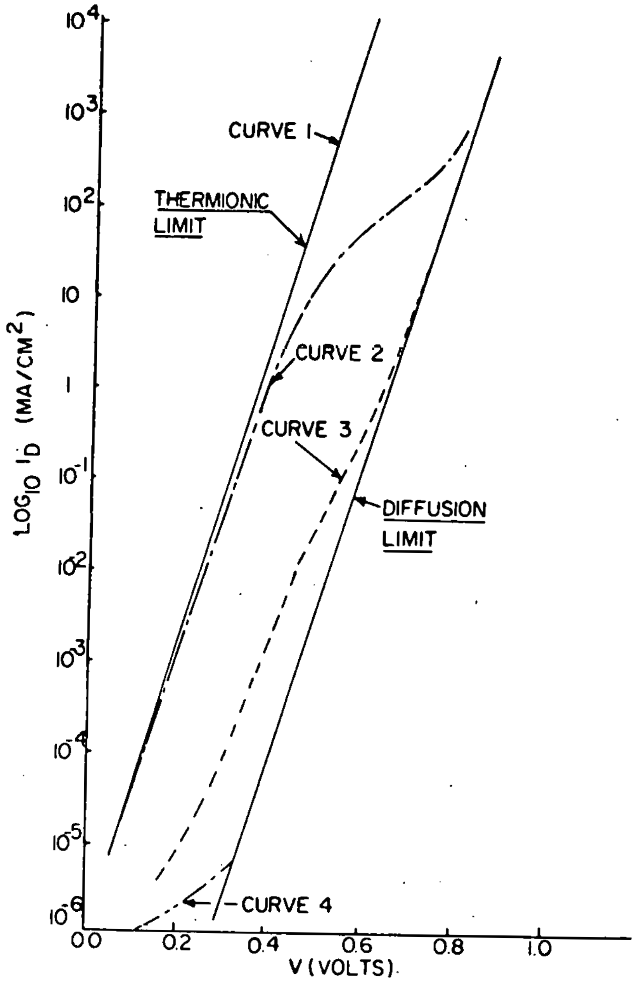
Schematic cross section of portion of proposed MIS cell.

$$V = V_s + V_i$$

$$I_{net} = I_{photo} - I_{thermionic} - I_{diffusion}$$

majority carriers: $$I_{thermionic} = A^* T^2 \exp\left[-\frac{e\phi_B}{kT}\right]\left\{\exp\left(\frac{eV_s}{kT} - 1\right)\right\}$$

minority carriers: $$I_{diffusion} = \frac{en_{po}D_n}{L_n}\left\{\exp\left(\frac{eV_s}{kT} - 1\right)\right\}$$

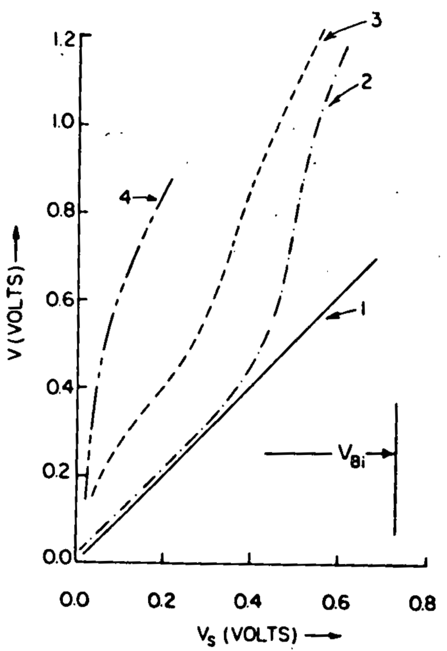


Dark I-V characteristics

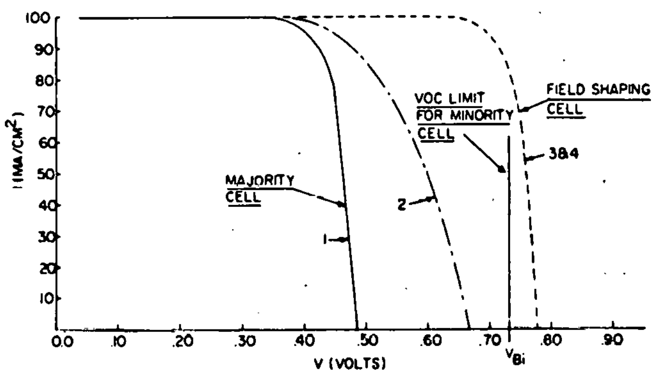
Table: Parameter changes for MIS model

Curve	N_{SS} $(m^{-2}eV^{-1})$	ϕ_o (eV)	E_{FSS}
1	0	--	--
1	1×10^{16}	.715	V
2	5×10^{14}	.715	0.0
3	1×10^{16}	.715	0.0
4	1×10^{16}	.365	0.0

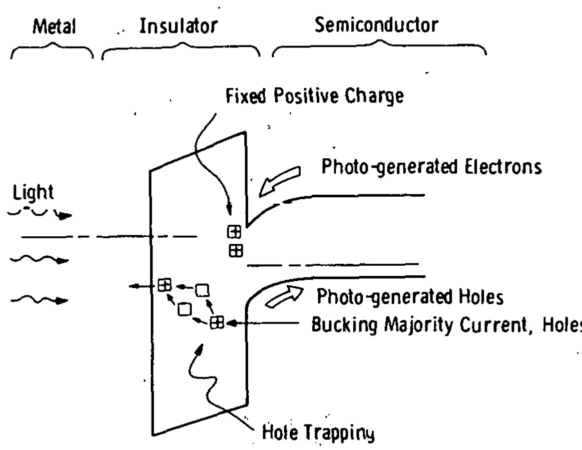
Note: ϕ_m adjusted to maintain ϕ_B constant



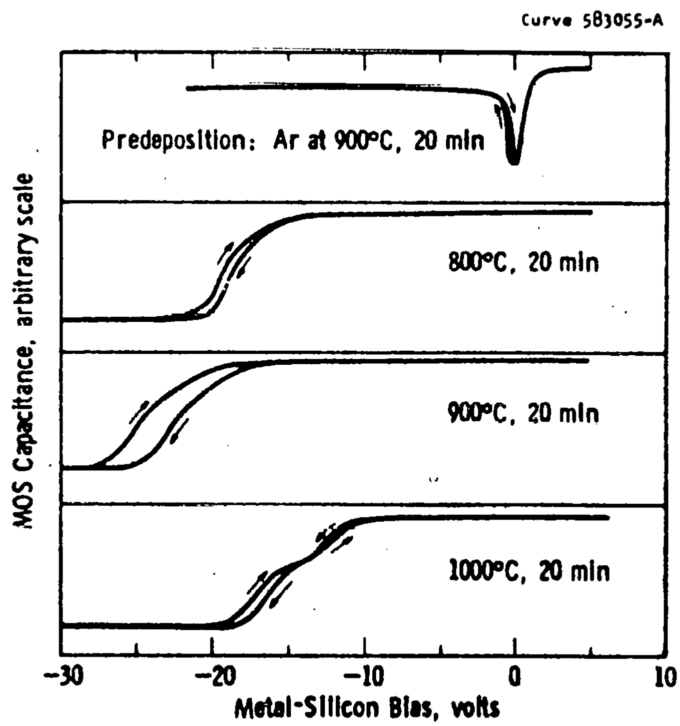
The voltage V developed by the device as a function of the voltage developed in the semiconductor alone, V_s.



I-V characteristics under illumination. The usual limit on V_{oc} (ie, V_{bi}) is shown for the parameters used in the numerical evaluation.



Model of solar cell when developing power



Effect of predeposition treatment on (100) n-type silicon.

PLANNED ACTIVITY FOR THE NEXT SIX MONTHS

- Begin fabrication of standard and practical cells.
- Initiate evaluation and modelling of cell performance.
- Prepare insulators with controlled charge and interface state properties.
- Begin considering yield/cost factors.

CUPROUS OXIDE PHOTOVOLTAIC CELLS

NATIONAL SCIENCE FOUNDATION

NSF GRANT-AER-75-23453

TWO YEARS FROM 1 OCTOBER 1975 TO 30 SEPTEMBER 1977

AMOUNT: $82,300

DAN TRIVICH
PROFESSOR OF CHEMISTRY
WAYNE STATE UNIVERSITY
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PRINCIPAL INVESTIGATORS: DAN TRIVICH, PROFESSOR OF CHEMISTRY
E. Y. WANG, ASSOC. PROF. ELEC. ENG.
(RICHARD J. KOMP, RESEARCH ASSOCIATE)

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING
AUGUST 3-6, 1976
UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE

CUPROUS OXIDE PHOTOVOLTAIC CELLS

D. Trivich, E. Y. Wang and R. J. Komp
Wayne State University

(Abstract)

I. OBJECTIVES: The objective is to prepare low cost cuprous oxide photovoltaic cells of good efficiency. It is expected that these will be front wall cells using single crystal or coarsely polycrystalline Cu_2O with Schottky barriers or heterojunctions.

II. PREVIOUS ACTIVITY: A semi-empirical analysis of the Cu/Cu_2O cell indicated that a maximum value of J_{sc} would be 23 mA/cm^2 (AMO). This, with a V_{oc} of 0.35V and FF of 0.48 would give an efficiency of 2.5%. It was estimated that further improvement could give an efficiency of 6% and an ultimate value of 12%.

In the first quarter of the project, as reported at Lake Buena Vista in January 1976, a method was developed for preparing front wall cells with isolated sheets of Cu_2O. The method consists of: oxidation of Cu sheet at 1000°C, conversion to single crystal by annealing at 1080-1120°C, grinding and polishing, etching in 8M HNO_3, vacuum heat treatment at 100°C, application of top metal contact and grids by vacuum evaporation, application of back contact of silver paint.

The cells prepared by January 1976, had a J_{sc} of ~0.1 mA/cm^2, V_{oc}~0.3V and a cell resistance of ~$10^3 \Omega$.

III. CURRENT EFFORTS: Substantial improvement in the properties of the Cu_2O cells has been attained. The J_{sc} has been improved to 10mA/cm^2, V_{oc}~0.35V, and the cell resistance reduced to 30-50Ω. While several processing steps were improved, the most important factor in the improvement was the introduction of an additional step of a final anneal of the Cu_2O sheet at 500°C followed by quenching. This improved the conductivity, lowered the cell resistance and increased J_{sc}.

The steps in the processing were varied to determine the important variables.

1. Variation in Starting Material: Different samples of Cu gave Cu_2O with resistivities of $2x10^3$ to $2x10^5 \Omega$cm. The lower resistivity samples produced cells with better J_{sc}.
2. Etching Procedures: Etchants tried were $8MHNO_3$, 0.5M NaCN, a conc. mixture of HNO_3 -H_3PO_4 -HAc and combinations of these. A final treatment with HNO_3 gave best results.
3. Vacuum Heat Treatment: Treatment of the sample in vacuum at ~100°C is necessary but the best temperature is not yet established. Too high a temperature gives unstable cells.
4. Metal Contacts: Cu contacts have given the best cells but Al is nearly as good. Sn and Pb give good rectifying junctions but poor photovoltaic response. Au gives an ohmic contact. In gives a moderate photovoltaic effect.
5. Optical Transmission of Coatings: To obtain low enough sheet resistance, R_{sh}~50-100Ω/square, the coatings had to be thick enough that the transmission was 50% for Cu and Al. For Sn and Pb, the transmission was 15% for R_{sh}~ $10^3 \Omega$/square.
6. Heterojunctions: SnO_2 and In_2O_3 were applied on Cu_2O by various methods but only slight photovoltaic effects were obtained.

7. Electron Microsope Studies: The surfaces of Cu_2O after various etching teatments were examined in a scanning electron microscope. The most effective etchant for producing good junctions, 8M HNO_3, produced the roughest surfaces. This may be responsible for the necessity of having relatively thick metal coatings to achieve low sheet resistance.

8. Detailed Electrical Measurements: Measurements were made of I-V, J_{SC}-V_{OC} and C-V characteristics of Cu/Cu_2O and Al/Cu_2O cells. These gave a barrier height of 0.69 to 0.73 eV and a built-in potential of 0.3V. The results can be explained by a thermionic emission model and can be fitted to the equation.

$$I = I_o \left[\exp(\frac{qV}{nkT}) - 1 \right] = AT^2 \exp(-\frac{q\phi_B}{kT}) \left[\exp(\frac{qV}{nkT}) - 1 \right]$$

where $n \sim 2$-3, A is the Richardson constant and ϕ_B is the barrier height. The barrier height is temperature dependent and this is explained as being due to a deep acceptor level

IV. SUMMARY OF KEY RESULTS: The procedures for preparing Schottky barriers on Cu_2O have been substantially improved. The metals tested were Cu, Al, Pb, Sn and In. Heterojunctions with SnO_2 and In_2O_3 were also explored. The best results were obtained with Cu/Cu_2O and Al/Cu_2O cells, which gave $J_{SC} \sim 10$ mA/cm^2, $V_{OC} \sim 0.35$V, FF ~ 0.35 and an efficiency η (AM1) = 1.2%. The etching procedure has been identified as one source of difficulty.

V. FUTURE PLANS: The general aim is to improve further the efficiency of Cu_2O photovoltaic cells. Better etching procedures will be sought in order to reduce the required thickness of the metal coating thus giving higher optical transmission and better J_{SC}. Heterojunctions and other metal contacts will be explored in order to give a better V_{OC}. In order to improve the fill factor by lowering the cell resistance, methods will be sought to improve the bulk conductivity of the Cu_2O by introducing impurities in the Cu or the Cu_2O. The electrodeposition of Cu_2O will be further investigated as a possible low cost method of preparing cells. Detailed studies of cell characteristics will be made in order to develop theoretical models to explain their behavior.

1. CUPROUS OXIDE PHOTOVOLTAIC CELLS

(A) NSF GRANT AER-75-23453

(B) AT DEPARTMENTS OF CHEMISTRY AND ELECTRICAL ENGINEERING, WAYNE STATE UNIVERSITY, DETROIT, MICHIGAN 48202

(C) PERIOD: TWO YEARS FROM 1 OCTOBER 1975

(D) AMOUNT: $82,300

(E) PRINCIPAL INVESTIGATORS: DAN TRIVICH, PROFESSOR OF CHEMISTRY; E. Y. WANG, ASSOCIATE PROFESSOR OF ELECTRICAL ENGINEERING

2. OBJECTIVE: THE OBJECTIVE IS TO DEVELOP METHODS FOR PREPARING LOW-COST CUPROUS OXIDE PHOTOVOLTAIC CELLS OF GOOD EFFICIENCY. IT IS EXPECTED THAT THESE WILL BE FRONT WALL CELLS ON SINGLE CRYSTAL OR COARSELY POLYCRYSTALLINE SHEET Cu_2O, USING SCHOTTKY BARRIERS OR HETEROJUNCTIONS.

3. BASIC METHOD OF PREPARATION OF Cu_2O PHOTOVOLTAIC CELLS

(1) Oxidation of Cu sheet in air at 1000°C

(2) Conversion of Cu_2O sheet to single crystal by annealing in air at 1080-1120°C

*(3) Anneal of Cu_2O sheet in air at 500°C followed by quenching in water.

(4) Surface preparation by grinding and polishing

(5) Etch in 8 M HNO_3 for 1-2 sec., followed by fast water rinse and drying.

(6) Vacuum Treatment

  (a) Heat treatment at 75-100°C for 10 min.

  (b) Application of thin metal coat by evaporation, e.g. Cu

  (c) Application of grids by evaporation through a mask

(7) Application of back contact e.g. silver paint

(8) Measurement of I-V curves in light and in dark

(Results reported in Lake Buena Vista in Jan. 1976:
$J_{SC} \sim 0.1$ mA/cm^2, $V_{OC} \sim 0.3$ V, $R_S \sim 10^3 \Omega$)

(Current Results: $J_{SC} \sim 10$ mA/cm^2, $V_{OC} \sim 0.35$ V, $R_S \cong 50 \Omega$)

4. SURVEY OF RECENT ACTIVITY

(1) Variation in Starting Material

(2) Etching Procedures

(3) Vacuum Heat Treatment

(4) Metal Contacts

(5) Optical Transmission of Coatings

(6) Heterojunctions

(7) Electron Microscope Studies

(8) Detailed Electrical Measurements

4. SURVEY OF RECENT ACTIVITY

(1) Variation in Starting Material
(2) Etching Procedures
(3) Vacuum Heat Treatment
(4) Metal Contacts
(5) Optical Transmission of Coatings
(6) Heterojunctions
(7) Electron Microscope Studies
(8) Detailed Electrical Measurements

(1) VARIATION IN STARTING MATERIAL

(A) PROCEDURE: HH-OFHC 0.032" Cu SHEET, OXIDIZED 1000°, CONVERTED TO SINGLE CRYSTAL, ANNEALED 500°C, QUENCHED; Ag PAINT CONTACTS ON GROUND SURFACES.

(B) RESULTS: ρ VARIED FROM 2×10^3 TO $1.85 \times 10^5 \Omega \cdot cm$ LOW RESISTIVITY MATERIAL GAVE BETTER CELLS WITH $J_{SC} \sim$ 2-3 mA/cm^2 WHILE HIGH RESISTIVITY SAMPLES GAVE $J_{SC} \sim$ 0.2 TO 0.5 mA/cm^2.

(C) CONCLUSION: SOURCE Cu IS PROBABLY VARIABLE IN COMPOSITION DUE TO ACCIDENTAL IMPURITIES OR POSSIBLY IMPURITIES ARE INTRODUCED DURING OXIDATION AND/OR CRYSTAL GROWTH.

(2) ETCHING PROCEDURES

(A) PROCEDURE: CELLS MADE BY NORMAL PROCEDURE EXCEPT FOR DIFFERENT ETCH PROCEDURES

	ETCH	(B) RESULTS
(1)	30 MIN IN 0.5 N NACN	NO PHOTOVOLTAIC EFFECT
(2)	SAME AS (1) FOLLOWED BY 1 SEC 8 M HNO_3	SMALL EFFECT
(3)	15 MIN IN EBISUZAKI ETCH*	MODERATELY GOOD CELLS $J_{sc} \sim 1.2$ MA/CM^2 $V_{oc} \sim 0.26$ V
(4)	SAME AS (3) FOLLOWED BY 1 SEC 8 M HNO_3	VERY GOOD CELLS $J_{sc} \sim 7$ MA/CM^2 $V_{oc} \sim 0.33$ V

*EBISUZAKI ETCH: 17 PTS. BY VOL HNO_3, 41.5 PTS. 85% H_3PO_4 41.5 PTS. ACETIC ACID.

(C) CONCLUSION: ETCHING IS NECESSARY AFTER GRINDING; HNO_3 IS BEST ETCHANT; PRESENT PROCEDURE DIFFICULT TO CONTROL AND NEEDS IMPROVEMENT.

ALL CELLS WERE AL/Cu_2O SCHOTTKY BARRIER CELLS. SIMILAR RESULTS WERE OBTAINED WITH Cu/Cu_2O CELLS.

(3) VACUUM HEAT TREATMENT

(A) PROCEDURE: NORMAL PREPARATION PROCEDURE. HEAT TREATMENT VARIED WITH TEMPERATURE OF STAGE FROM 75° TO 150°C. TIME TO REACH TEMPERATURE WAS 15 MIN. TIME OF TREATMENT WAS 10 MIN.
COOLING TIME WAS 15 MIN.

(B) RESULTS: BEST RESULTS OBTAINED AT INTERMEDIATE TEMPERATURES; TOO HIGH TEMPERATURE GAVE UNSTABLE CELLS WITH DRIFTING CHARACTERISTICS.

(C) CONCLUSION: HEAT TREATMENT IS DESIRABLE BUT OPTIMUM SAMPLE TEMPERATURE IS NOT YET ESTABLISHED SINCE BEST TEMPERATURES MEASURED AT STAGE DIFFERED FROM DOWNWARD TO UPWARD EVAPORATION CONFIGURATION.

(4) METAL CONTACTS

METALS USED: CU, AL, PB, AU, IN

COPPER: MOST USED; BEST RESULTS $J_{SC} \sim 10$ MA/CM^2; $V_{OC} \sim 0.35$ V

ALUMINUM:

STABLE CELLS (S-TYPE) $J_{SC} \sim 4\text{-}5.5$ MA/CM^2

$V_{OC} \sim 0.28\text{-}0.33$ V

FF $\gtrsim 0.25$

DRIFTING TYPE CELLS (D-TYPE): UNSTABLE; CHARACTERIZED BY LARGE (UPWARD) DRIFT IN J_{SC}

MAX $J_{SC} \sim 2$ MA/CM^2

V_{OC} UP TO 0.45 V

D-TYPE CELLS APPEAR TO RESULT FROM HIGHER TEMPERATURES IN THE VACUUM HEAT TREATMENT. (D-TYPE BEHAVIOR CAN BE OBTAINED WITH CU CONTACTS ALSO.)

LEAD: POOR PHOTOVOLTAIC EFFECT $J_{SC} \sim 0.2$ MA/CM^2, $V_{OC} \sim 0.09$ V; GOOD RECTIFIER CHARACTERISTICS

TIN: POOR PHOTOVOLTAIC EFFECT ($J_{SC} \sim 0.04$ MA/CM^2, $V_{OC} \sim 0.08$ V); GOOD RECTIFIER CHARACTERISTICS

METAL CONTACTS (CONTINUED)

GOLD: NO PHOTOVOLTAIC EFFECT OR RECTIFICATION CHARACTERISTICS. VERY GOOD OHMIC CONTACT ON AS-GROUND SURFACE OF Cu_2O.

INDIUM: EXPLORATORY; MAY GIVE HIGHER V_{OC}

CONCLUSION: BEST RESULTS OBTAINED WITH CU WITH $J_{SC} \sim 10$ mA/cm^2 AND $V_{OC} \sim 0.35$ V. AL APPROACHES THIS. PERHAPS THE PREPARATION METHOD NORMALLY PRODUCES A Cu/Cu_2O CONTACT.

(5) Optical Transmission of Coatings

(a) Procedure: For optical transmission experiments, metal coatings were made on glass microscope slides. Measurements were made as a function of wave-length on Cary 14 Spectrophotometer.

For sheet resistance measurements, metal coatings were made on high resistivity Cu_2O sheets, ground, polished and etched in normal procedure for photovoltaic cell preparation.

(b) Results: For Cu and Al, transmission was 50% for coatings thick enough to give R_{SH} of 50-100 Ω/square

For Sn and Pb, transmission was 15% for R_{SH} = 10^3 Ω/square.

(c) Conclusion: Present procedures are not adequate to produce simultaneously high transmission and low sheet resistance.

(6) HETEROJUNCTIONS

(A) PROCEDURE: SnO_2 APPLIED BY ELECTRON BEAM EVAPORATION OR THERMAL DECOMPOSITION OF SPRAY OF $SnCl_4$ ON HEATED SAMPLE.

In_2O_3 APPLIED BY VACUUM EVAPORATION ON HEATED SAMPLE.

(B) RESULTS: WITH SnO_2, NO PHOTOVOLTAIC EFFECT BUT POORLY RECTIFYING JUNCTIONS WERE OBTAINED.

WITH In_2O_3, HIGH RESISTANCE CELLS OBTAINED WITH VERY LITTLE PHOTOVOLTAIC EFFECT, $J_{SC} \sim 0.01$ mA/cm^2, $V_{OC} \sim 0.3$ V.

(C) GOOD PROCEDURES HAVE NOT YET BEEN DEVELOPED TO PREPARE HETEROJUNCTIONS OF OXIDES ON Cu_2O. THERE ARE GOOD REASONS TO CONTINUE INVESTIGATION OF THE FIELD.

(7) ELECTRON MICROSCOPE STUDIES

(A) PROCEDURE: SURFACES OF Cu_2O AFTER VARIOUS ETCHING PROCEDURES WERE EXAMINED IN A SCANNING ELECTRON MICROSCOPE UP TO 10,000X.

(B) RESULTS: HNO_3 GAVE A FAIRLY ROUGH, HIGHLY FACETED STRUCTURE WITH FACETS ~ 1μ WIDE

NACN GAVE SMOOTHER SURFACE

EBISUZAKI ETCH GAVE SMOOTHER STRUCTURE BUT SUBSEQUENT HNO_3 ETCH DEVELOPED FACETS.

(C) CONCLUSION: THE ROUGH SURFACES PRODUCED BY HNO_3 MAY REQUIRE EXCESSIVELY THICK METAL FILMS FOR ELECTRICAL CONTINUITY.

THE SMOOTHER ACTING ETCHANTS DO NOT GIVE EFFECTIVE JUNCTIONS FOR OTHER REASONS.

IMPROVED RESULTS CAN BE EXPECTED FROM IMPROVEMENTS IN ETCHING AND OTHER SURFACE PREPARATION PROCEDURES.

(8) DETAILED ELECTRICAL MEASUREMENTS

(A) PROCEDURE: CORRECTION IS MADE FOR THE EFFECT OF SERIES RESISTANCE IN THE I - V AND J_{SC} - V_{OC} MEASUREMENTS. THE CAPACITANCE-VOLTAGE, C-V, RELATIONSHIP WAS MEASURED WITH A DYNAMIC AC LOCK-IN TECHNIQUE. THE TEMPERATURE DEPENDENCE OF I - V AND I_{SC} - V_{OC} WAS ALSO OBTAINED.

(B) RESULTS: THE I - V RELATIONSHIP CAN BE DESCRIBED BY

$$I = I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] = AT^2\exp\left(-\frac{q\phi_B}{kT}\right)\left[\exp\left(\frac{qV}{nkT}\right) - 1\right]$$

WHERE N VARIES FROM 2 TO 3, THE BARRIER HEIGHT IS 0.69 EV FOR Cu/Cu_2O AND 0.73 EV FOR Al/Cu_2O. THE I_{SC} - V_{OC} CURVES GIVE SIMILAR RESULTS. THE BUILT-IN POTENTIAL FROM C-V MEASUREMENTS IS 0.3 EV. THESE VALUES AGREE WITH OUR PREVIOUS MEASUREMENTS.

(C) CONCLUSION: THE RESULTS CAN BE DESCRIBED BY A THERMIONIC EMISSION MODEL INSTEAD OF A PROPOSED MIS MODEL.

THE TEMPERATURE DEPENDENCE OF I_0 AND ϕ_B IS UNUSUAL AND IS PROBABLY DUE TO A DEEP ACCEPTOR LEVEL.

SUMMARY OF KEY RESULTS

SUBSTANTIAL IMPROVEMENT HAS BEEN MADE IN THE PREPARATION OF CUPROUS OXIDE PHOTOVOLTAIC CELLS, ESPECIALLY WITH CU AND AL SCHOTTKY BARRIERS. THE J_{SC} HAS BEEN IMPROVED FROM 0.1 mA/cm^2 TO 10 mA/cm^2, WITH V_{OC} OF 0.35V AND FF OF 0.35, AND AN EFFICIENCY η(AM1) = 1.2%.

MAJOR PROBLEMS

TECHNICAL:

1. TRANSMISSION OF COATINGS: METAL TOP LAYER IS CURRENTLY LIMITED TO 50% TRANSMISSION IN ORDER TO ACHIEVE ELECTRICAL CONTINUITY, I.E. LOW SHEET RESISTANCE.
2. ETCHING PROCEDURE: THE HNO_3 ETCH REQUIRES VERY SHORT PROCESSING TIME WHICH IS DIFFICULT TO CONTROL.
3. HETEROJUNCTIONS: GOOD PROCEDURES NEED TO BE DEVELOPED TO APPLY OXIDE COATINGS TO FORM GOOD HETEROJUNCTIONS.
4. CELL RESISTANCE: RESISTIVITY OF BULK Cu_2O NEEDS TO BE FURTHER DECREASED.

SCHEDULE AND COST:

PROJECT IS ON SCHEDULE AND WITHIN BUDGET. IT WOULD BE DESIRABLE TO INCREASE THE TECHNICAL EFFORT IN ORDER TO MAKE MORE RAPID PROGRESS.

PLANNED ACTIVITY FOR NEXT 6 MONTHS

1. DEVELOPMENT OF BETTER ETCHING PROCEDURES.

2. IMPROVEMENT IN TRANSMISSION OF TOP CONTACT.

3. IMPROVEMENT OF V_{OC} BY USE OF HETEROJUNCTIONS AND OTHER CONTACTS.

4. IMPROVEMENT OF FILL FACTOR BY IMPROVING BULK CONDUCTIVITY THROUGH DOPING OF Cu_2O.

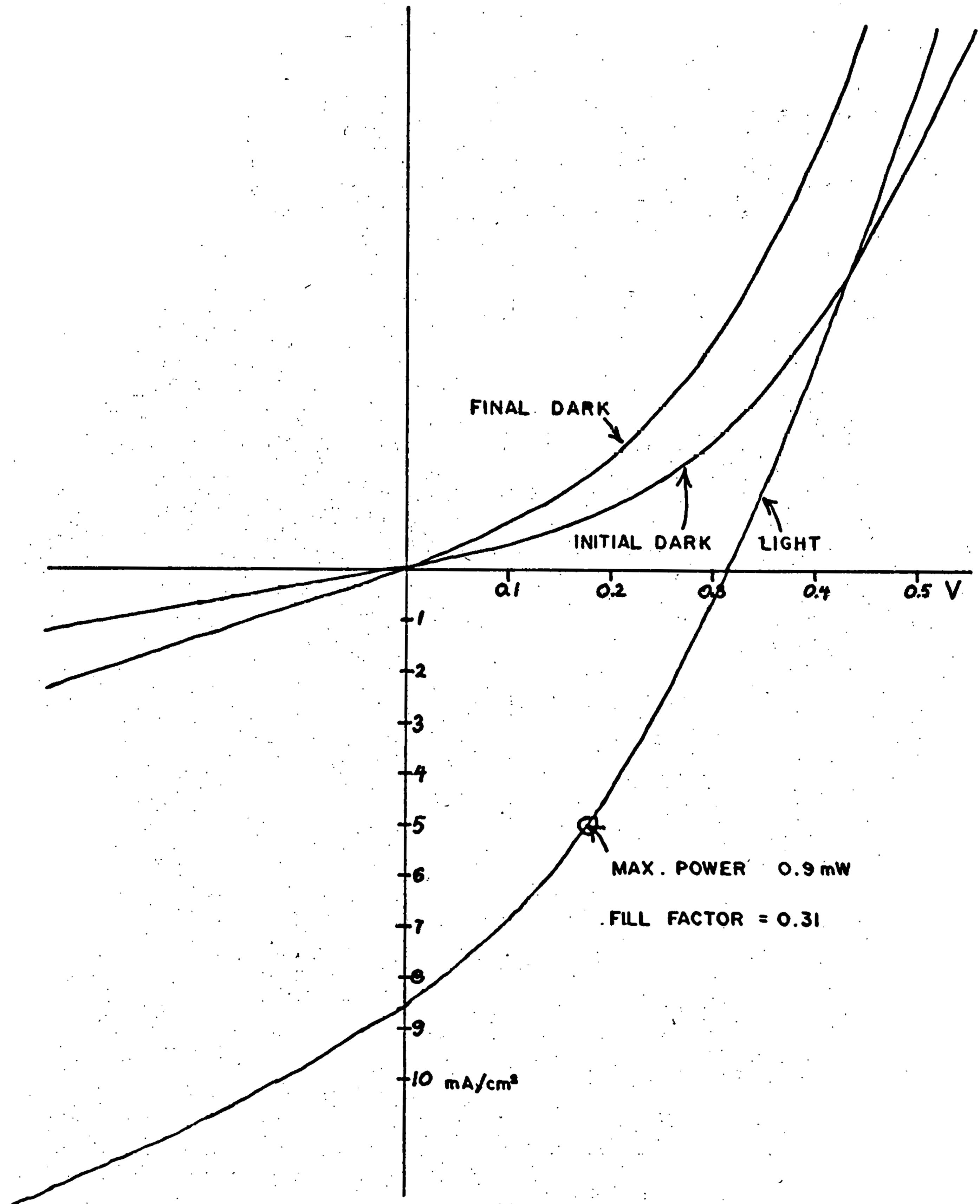
5. INVESTIGATION OF THE ELECTRODEPOSITION OF Cu_2O AS A LOW COST METHOD OF PREPARATION OF CELLS.

6. DETAILED MEASUREMENT OF PROPERTIES TO DEVELOP A THEORETICAL MODEL.

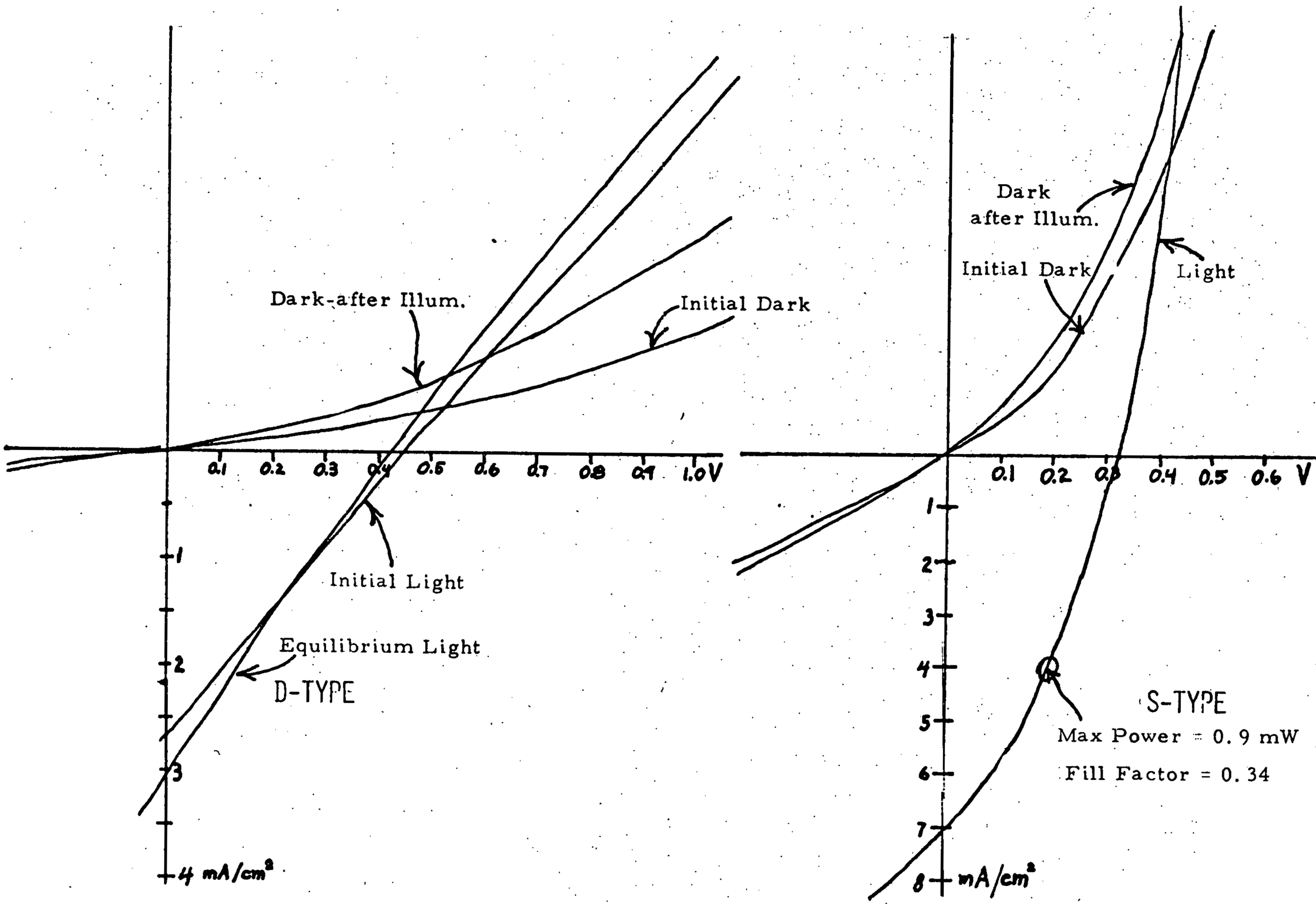
PLANNED RENEWAL REQUESTS

EXPIRATION OF GRANT IS SEPTEMBER 30, 1977

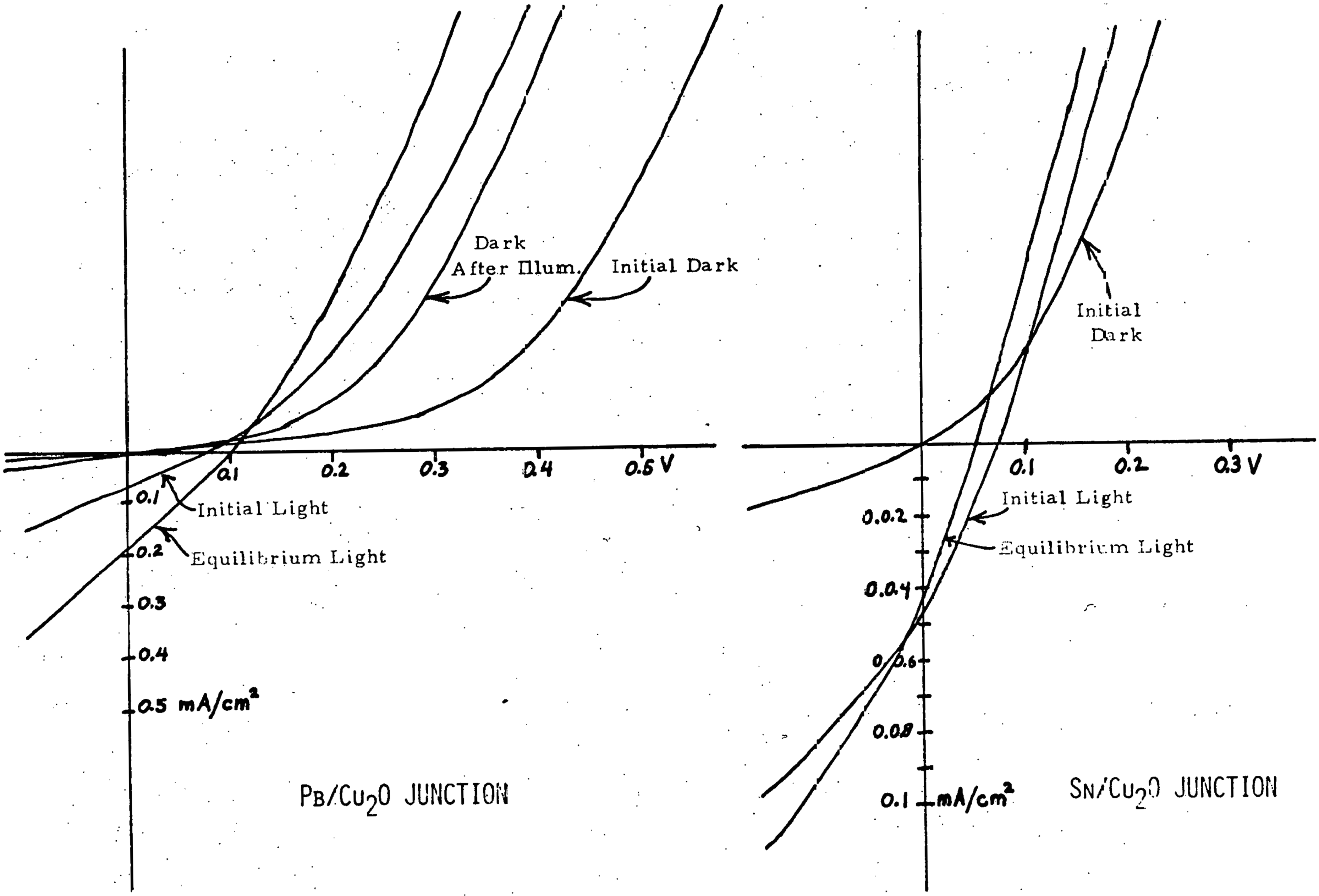
RENEWAL REQUEST WILL BE MADE AT APPROPRIATE TIME. IT WOULD BE DESIRABLE TO EXPAND THE PROJECT BEFORE THE RENEWAL.



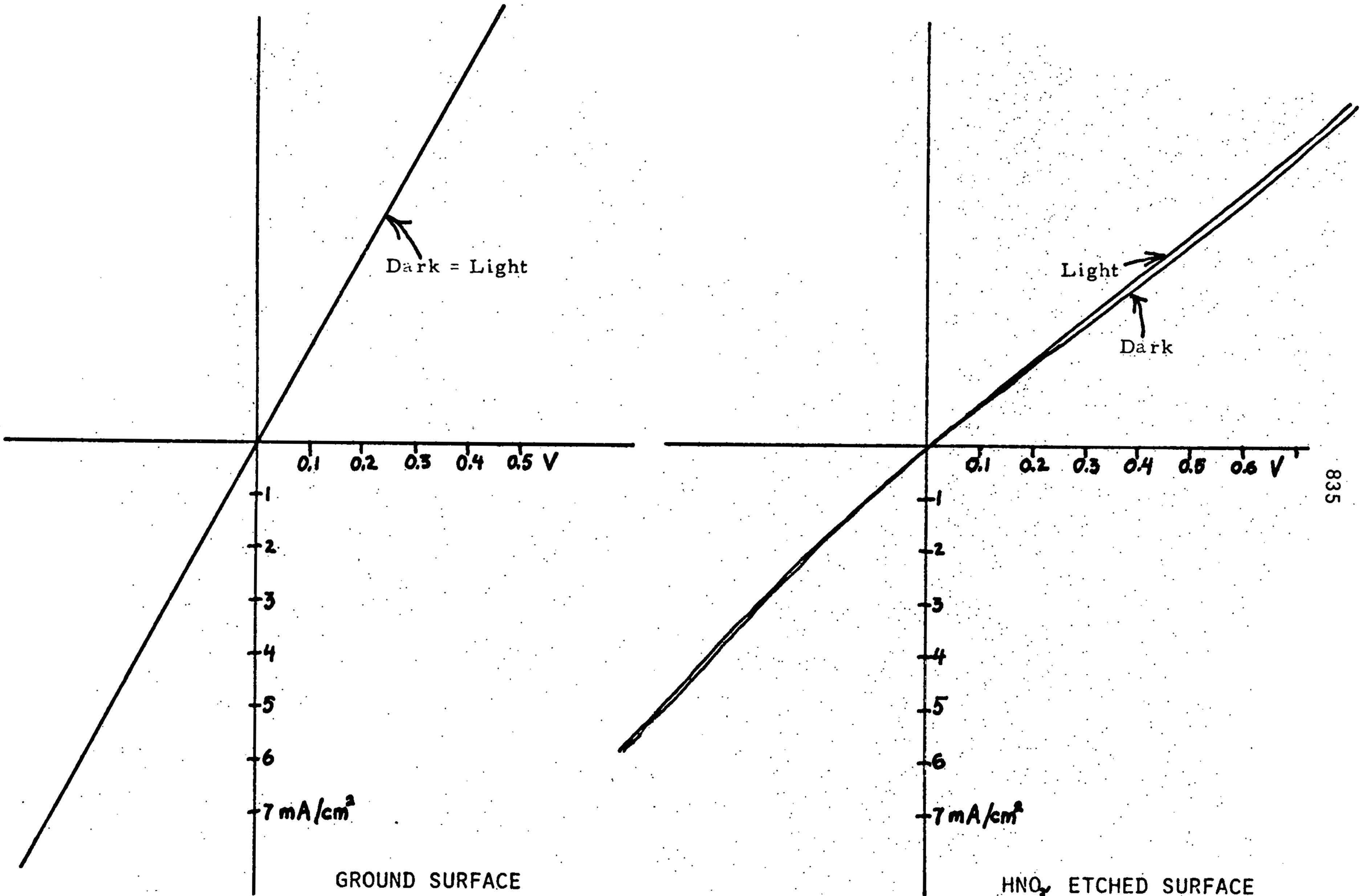
TYPICAL J-V CURVE-COPPER/Cu_2O JUNCTION



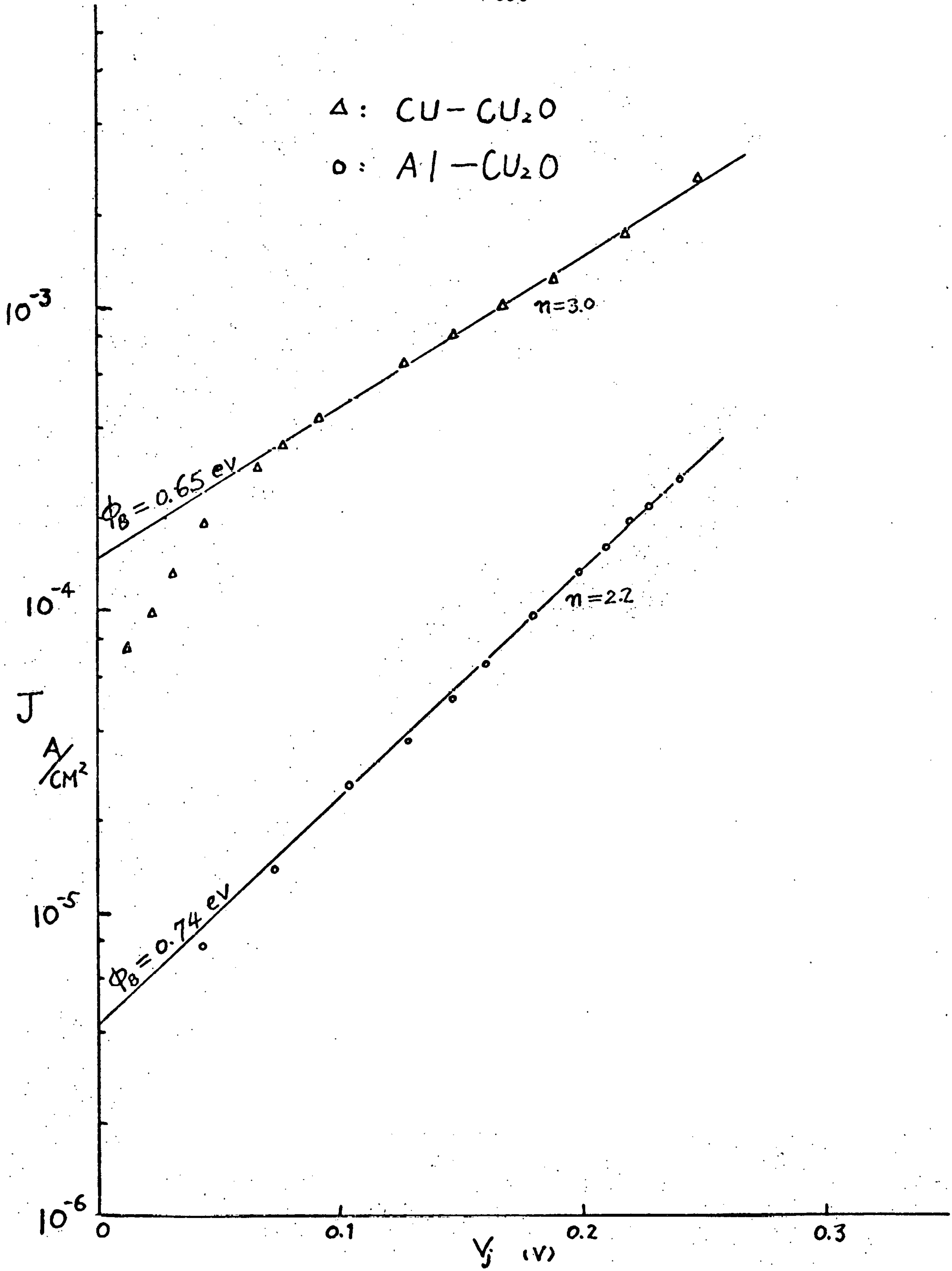
J-V CURVES-ALUMINUM/Cu_2O JUNCTIONS



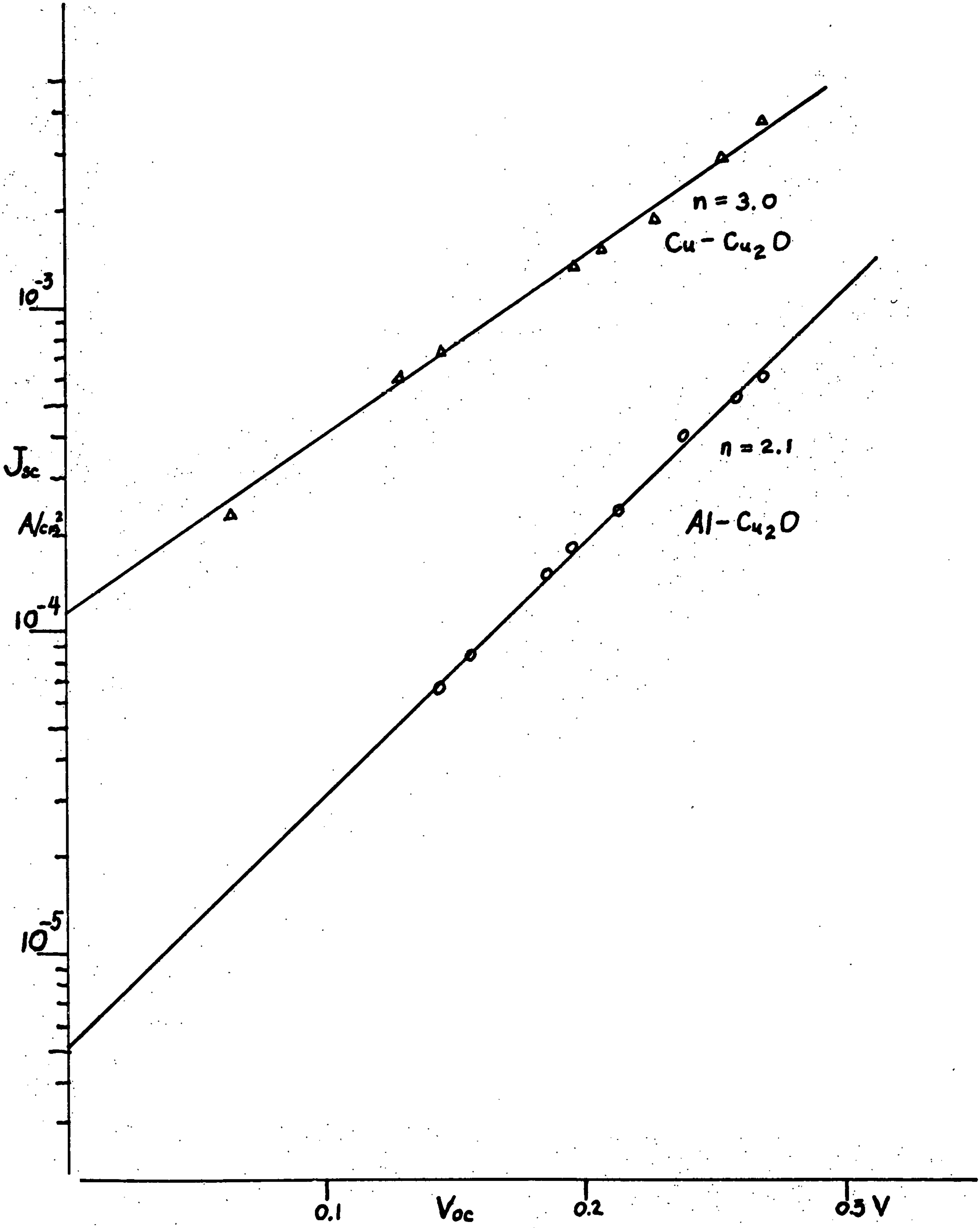
J-V CURVES-TIN & LEAD ON Cu_2O



J-V CURVES-GOLD/Cu_2O JUNCTIONS

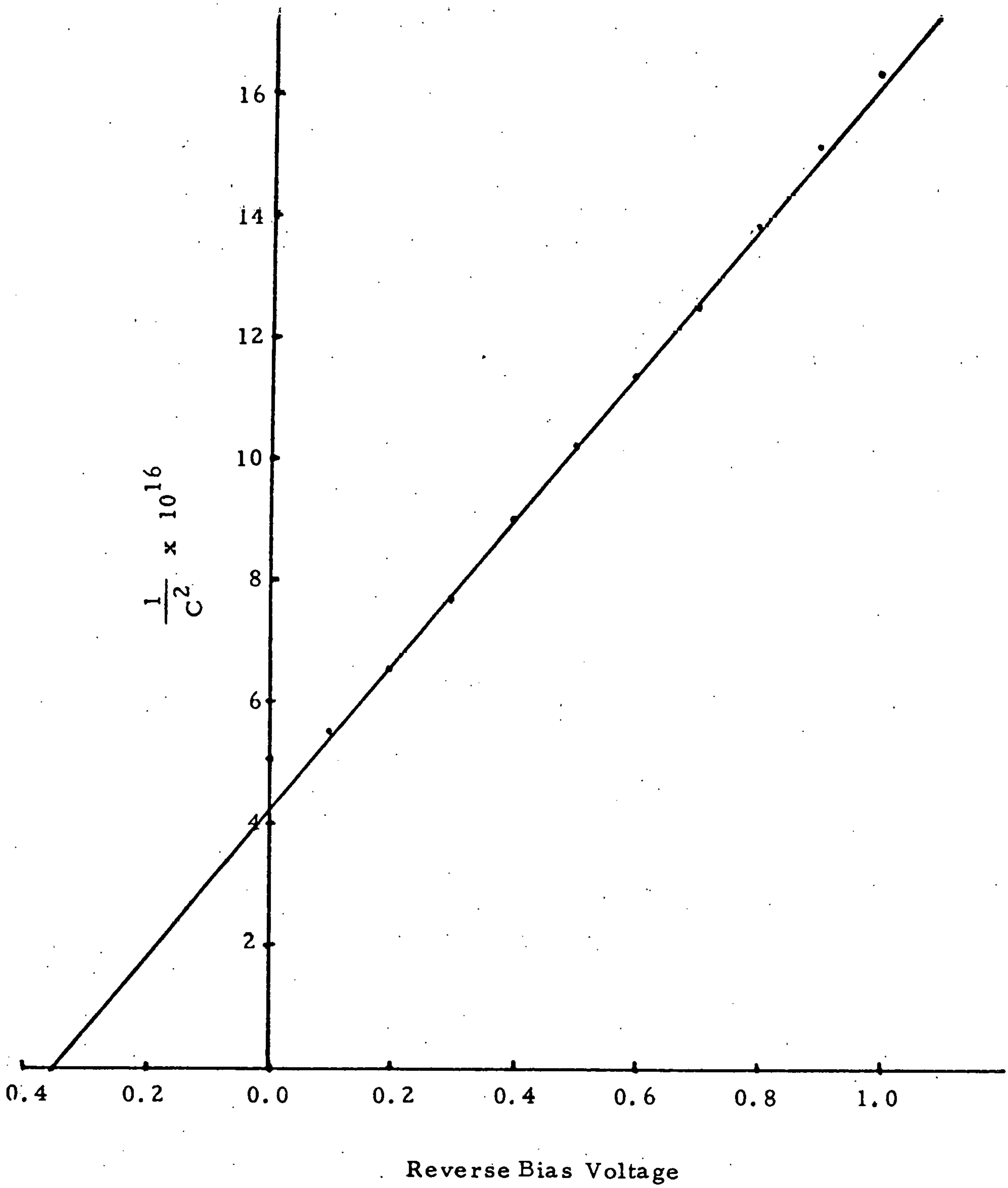


Δ: CU − CU₂O
o: Al − CU₂O
n=3.0
n=2.2
φB = 0.65 eV
φB = 0.74 eV
10^-3
10^-4
10^-5
10^-6
J
A/CM²
0
0.1
0.2
0.3
Vj (V)



J_{SC} - V_{OC} Relationship of Cu_2O Cells

Capacitance-Voltage Measurements on an Al/Cu_2O cell (KW-2)



INVESTIGATION OF LOW COST SOLAR CELLS BASED ON Cu_2O

NATIONAL SCIENCE FOUNDATION
AER75-20501

PERIOD OF CONTRACT: 9/1/75 - 8/31/76
(RENEWED FOR 9/1/76 - 8/31/78)

VALUE: $33,400
($83,200 FOR 9/1/76 - 8/31/78)

BY

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PRINCIPAL INVESTIGATOR: LARRY C. OLSEN

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING
AUGUST 3 - 6, 1976
UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE 04473

1. OBJECTIVES

The overall objective and specific near-term objectives are given in Figure 1. Near-term efforts will primarily involve thin-film backwall cell development and initiation of efforts on frontwall cells.

2. PREVIOUS ACTIVITIES AND BACKGROUND MATERIAL

A. Motivation for Cu_2O

Figure 2 indicates some of the key points which provide impetus to investigate Cu_2O solar cells. Large grain Cu_2O films can be obtained simply by oxidizing copper. The band gap is in the appropriate range for photovoltaic energy conversion. A partially oxidized copper substrate results in a Cu/Cu_2O interface which is a Schottky barrier (acutally MIS structure) with an effective barrier height of ~0.7 eV. Finally, estimated fabrication costs indicate that backwall cells can be produced at possibly 10¢ per peak watt under AM1 conditions. This cost assumes that a copper coated substrate can be obtained in large quantities for ~$\$5/m^2$.

It is particularly important to examine photon absorption in Cu_2O and the impact on solar cell efficiency. Figure 3 gives the relative AM1 intensity versus photon energy, and the absorption coefficient versus photon energy for Cu_2O (from Ref. 1) and Si. If we assume that Cu_2O can exhibit diffusion lengths on the order of a micron, then we must require $\alpha \sim 5 \times 10^3$ cm^{-1} to achieve a reasonable quantum efficiency. Thus, the effective band gap of Cu_2O is ~2.1 eV. The maximum possible current is ~13 mA/cm^2. It is interesting to note that in order for thin-film Si cells to have larger possible short-circuit currents, diffusion lengths significantly greater than 1 μm must be obtained and film thicknesses greater than 1 μm must be possible.

Figure 4 gives the usual results for ideal n/p cells. Note that Cu_2O is as attractive as $CuInSe_2$ and Si. This is a valid conclusion even if we assume an effective E_g of 2.1 eV ($\eta \sim 16\%$). Although no donor impurity is known for Cu_2O, heterojunctions are possible. Figure 4 is also appropriate for n/p heterojunctions assuming built-in voltages near E_g can be achieved.

Figure 5 describes the Cu/Cu_2O backwall structure. It seems clear that this device structure has low cost potential. It is also possible that we can learn to partially oxidize copper such that the junction conductance is quite high in the forward direction, thus providing an attractive substrate for frontwall structures.

B. Previous Work

Figure 2 summarizes main elements of previous work. It is important to note that substantial quantities of large area backwall rectifiers were made in production during the 1930's. It is also important to note that work preceeding this effort at JCGS determined that the Cu/Cu_2O interface has an appreciable interfacial layer.[2]

C. Progress for Previous 6 Months

Figure 6 lists the highlights of the work carried out in the previous 6 months. Figure 7 describes the system used for controlled oxidation of Cu. Figure 8 indicates typical results for Cu_2O grain size films grown at 800°C, 900°C and 1050°C using a slow cooling process referred to as the N_2- cooled process. Films of Cu_2O cooled by water-quenching have smaller grain size.

3. CURRENT EFFORTS

Efforts during the past six months have concentrated on the tasks shown in Figure 9.

A. Collection Efficiency Measurement

Figures 10 and 11 describe our approach to determining absolute spectral collection efficiency. Figure 10 depicts a nulling technique which can be used to measure the true short-circuit current, even if a cell has a significant R_s and low R_{sh}. Figure 11 illustrates the technique utilized for measurement of reflection coefficient. A prism type beam splitter allows approximate normal incidence beam measurements. A value of short-cirucit current (I_{sc}) is measured for Detector #1 with the slide in the position shown, and then for Detector #1 with the beam incident on that cell. Knowledge of these currents and transmisssion characteristics of the prism allows one to determine R_λ of the sample. Reflectivity measurements for a evaporated Ag film from 400 nm to 1000 nm agree with values in the AIP handbook to within 2%.

B. Thin-Film Backwall Cells

Techniques have been developed for fabricating backwall cells with Cu_2O film thicknesses from 2 to 10 μm. Devices made thus far have current-voltage characteristics of these cells that are inferior to thick film cells due to decreased shunt resistance. Figure 12 provides an overview of I-V characteristics for several kinds of cells. These will be discussed in more detail at a later date. However, note that n-values are typically >3, which is consistent with a MIS model. Note also that R_s values are large. Improved contacts must be developed. Finally, cell #6 is typical of thin-film cells at this point.

Figure 13 gives results for Q_λ of thin-film cells. These results have just been obtained and represent a ten-fold improvement over results of last period. More detailed analysis is required before we can determine the depletion layer collection and that due to diffusion from the bulk. It is interesting to note that the AM1 current density possible with cell 76 P 2 is ~1.2 mA/cm^2. If this value of I_{sc} is combined with I-V parameters for cell #1 in Figure 12 (assuming $R_s < 1\ \Omega$), we calculate an AM1 power conversion efficiency of 0.3%.

C. MIS Solar Cell Theory

Figure 14 shows a p-MIS cell under short-circuit conditions. MIS current-voltage characteristics are calculated for tunneling due to electrons (J_{TE}) and holes (J_{TH}). Figure 15 summarizes the theoretical aspects. The theory will be discussed in detail in the 1976 photovoltaic conference. The main advantage of MIS cells is that as a voltage V is developed across a load, the built-in voltage associated with the depletion region is reduced only by V/n instead of V, thereby reducing the normal leakage current.

Figure 16 gives calculated results for power conversion efficiency versus the interfacial film thickness (δ) for Cu/Cu_2O MIS cells, assuming various values of Q. These calculations represent a more sophisticated analysis than previously reported. The Q values refer to a maximum value for I_{sc} of 13.1 mA/cm^2 (the AM1 value for E_g = 1.95 eV). Note that if Q = 0.6, a value of $\eta \approx 9.5\%$ is possible.

Figure 17 gives results for other semiconductors. The solid curve is appropriate for an electron affinity of 4.1 eV. The solid circles refer to calculations based on actual values of χ. These calculations are ideal in that Q = 1.0. Otherwise, the values chosen for χ_c, χ_v and D_s/K_i seem reasonable. It is assumed that copper is used as the metal.

D. Other Studies

Figure 18 indicates some other studies which have been carried out. We have found that addition of Cd reduces ρ from 3 x 10^3 to 30 Ω-cm. An evaporate layer of In_2O_3 which was subsequently heat treated gave a contact of negligible resistance on a slab of Cu_2O. Assuming the In_2O_3 is n-type, the carrier density must be so high and/or the Fermi levels are nearly the same distance below the vacuum level before contact, so that very good tunneling is achieved. The Cd-regrown cell refers to a backwall cell in which Cd is diffused along grain boundaries to short the junction, and then the cell is heated at 1050°C in air to produce further oxidation. It is possible that CdO is formed along the grains, giving rise to a high R_{sh}.

4. SUMMARY OF KEY RESULTS

Key results are listed in Figure 20. It should be noted that measurements of Q_λ are considered the first of an involved study.

5. FUTURE PLANS

Efforts in the coming year will consist of three main tasks aimed at developing two device concepts, namely, backwall and frontwall cells based on Cu_2O. The three tasks are indicated in Figure 21.

Thin-film backwall cell studies will include investigation of possible contacts, further collection efficiency analysis, and characterization of the Cu/Cu_2O interface. Thick-film devices will also be studies in detail to provide a reference for the thin-film cells and to possibly suggest a way to oxidize copper without a barrier existing at the Cu/Cu_2O interface. Finally, frontwall studies will be initiated using completely oxidized wafers of copper. These wafers will be polished to eliminate the disordered region which exists at the middle of such samples. Frontwall cells will include heterojunctions and MIS structures. Inlcuded in the heterojunction category will be easily deposited semiconductors which have $E_g < 2$ eV.

REFERENCES

1. I. Pastrynak, "Temperature Dependence of the Light Absorption Coefficient in Cuprious Oxide Crystals in the Visable Region of the Spectrum," Soviet Physics -- Solid State 1, 888 (1959).

2. L. C. Olsen and R. C. Bohara, "Experimental and Theoretical Studies of Cu_2O Schottky Barrier Solar Cells," Proc. 11th Photovoltaic Specialists Conference, 381 (1975).

1. OBJECTIVES

OVERALL OBJECTIVE

TO INVESTIGATE LOW COST SOLAR CELLS BASED ON Cu_2O

NEAR TERM OBJECTIVES

- IMPROVE THIN FILM Cu/Cu_2O BACKWALL CELL I-V CHARACTERISTICS
- CARRY OUT COLLECTION EFFICIENCY ANALYSIS OF BACKWALL CELLS
- CHARACTERIZE Cu/Cu_2O BARRIER IN BACKWALL CELLS IN MORE DETAIL
- INITIATE FRONTWALL CELL STUDY INVOLVING SCHOTTKY BARRIERS AND HETEROJUNCTIONS ON POLYCRYSTALLINE Cu_2C

Figure 1.

2. PREVIOUS ACTIVITIES AND BACKGROUND MATERIAL

A. MOTIVATION FOR Cu_2O

- OXIDIZED COPPER GIVES P-TYPE LAYER WITH LARGE GRAINS
- Eg IN APPROPRIATE RANGE - MAXIMUM n/p AMI EFFICIENCY ~ 18%
- Cu/Cu_2O JUNCTION IN PARTIALLY OXIDIZED COPPER IS SCHOTTKY BARRIER WITH $\Phi_B \sim 0.7\,eV$
- ESTIMATED COST FOR 10% BACKWALL CELLS IS ~ $10¢/W_{PK}$

B. PREVIOUS WORK

- BACKWALL RECTIFIERS MADE IN PRODUCTION AND IN LARGE SIZES IN 1930's
- PHOTORESPONSE STUDIES BY TRIVICH INDICATED BARRIER HEIGHT OF 0.6 - 0.8 FOR Cu/Cu_2O INTERFACE
- WORK PRECEDING THIS GRANT JCGS INDICATED Cu/Cu_2O BACKWALL CELL HAS MIS STRUCTURE

Figure 2.

SOLAR SPECTRUM AND PHOTON ABSORPTION CONSIDERATIONS

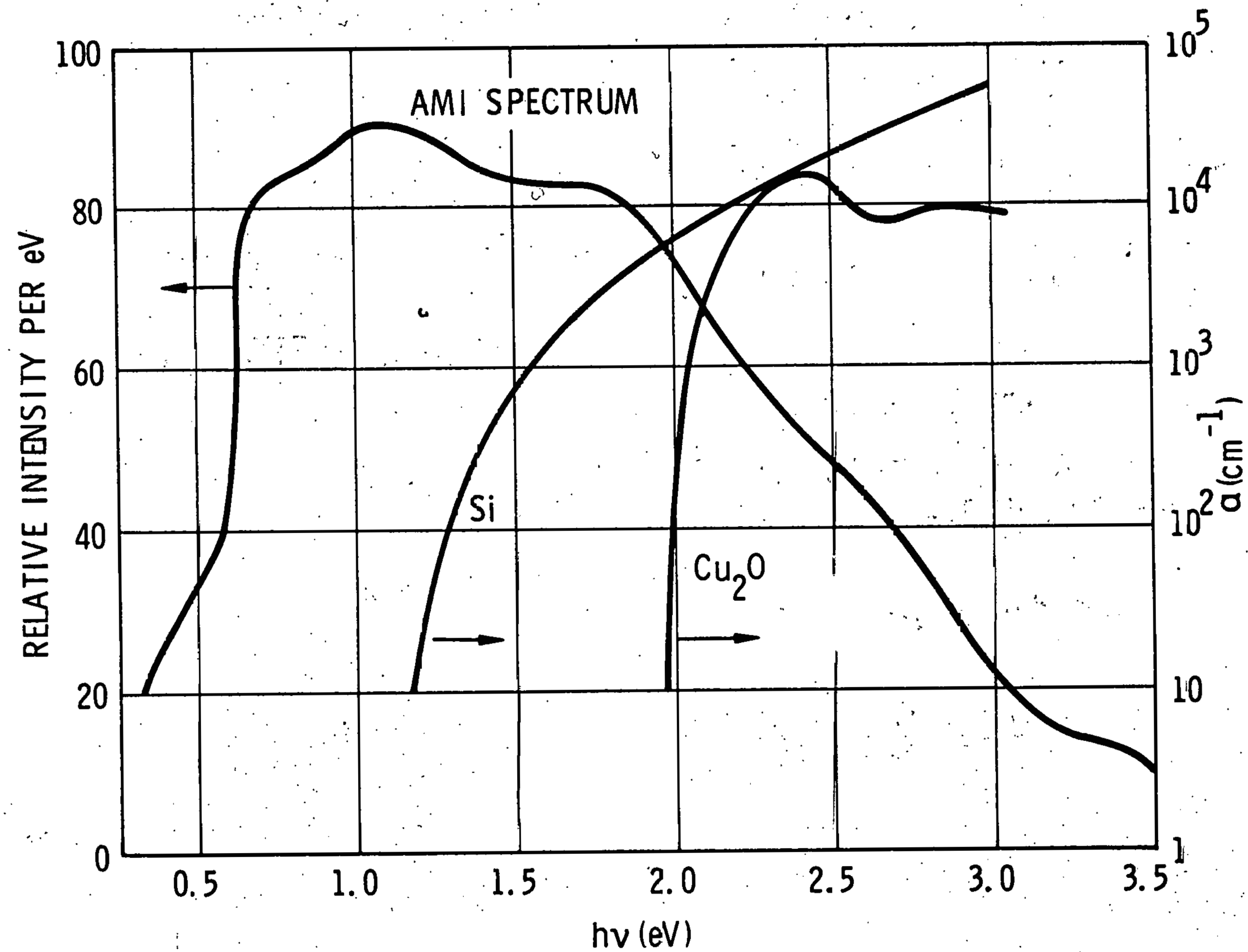


Figure 3.

MAXIMUM POWER CONVERSION
EFFICIENCY VS BAND GAP

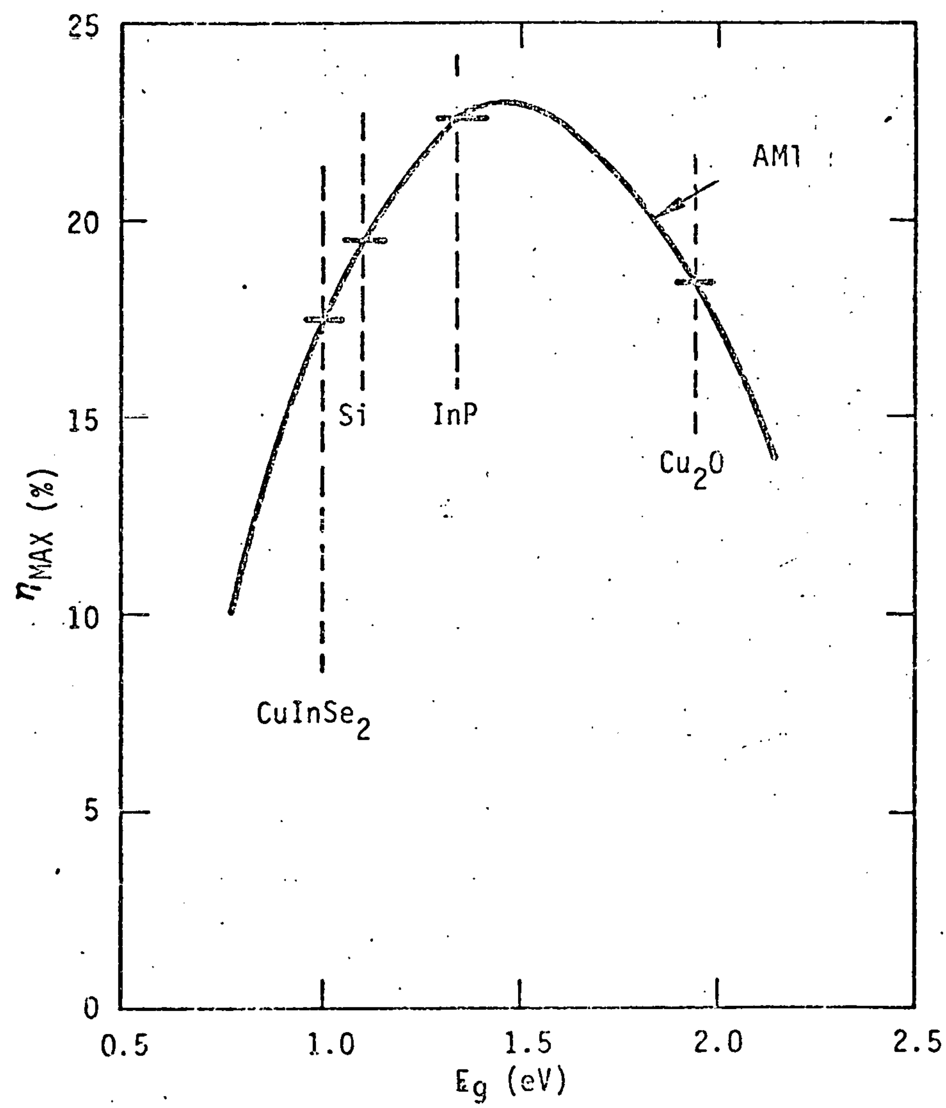


Figure 4.

Cu/Cu_2O BACKWALL CELL STRUCTURE

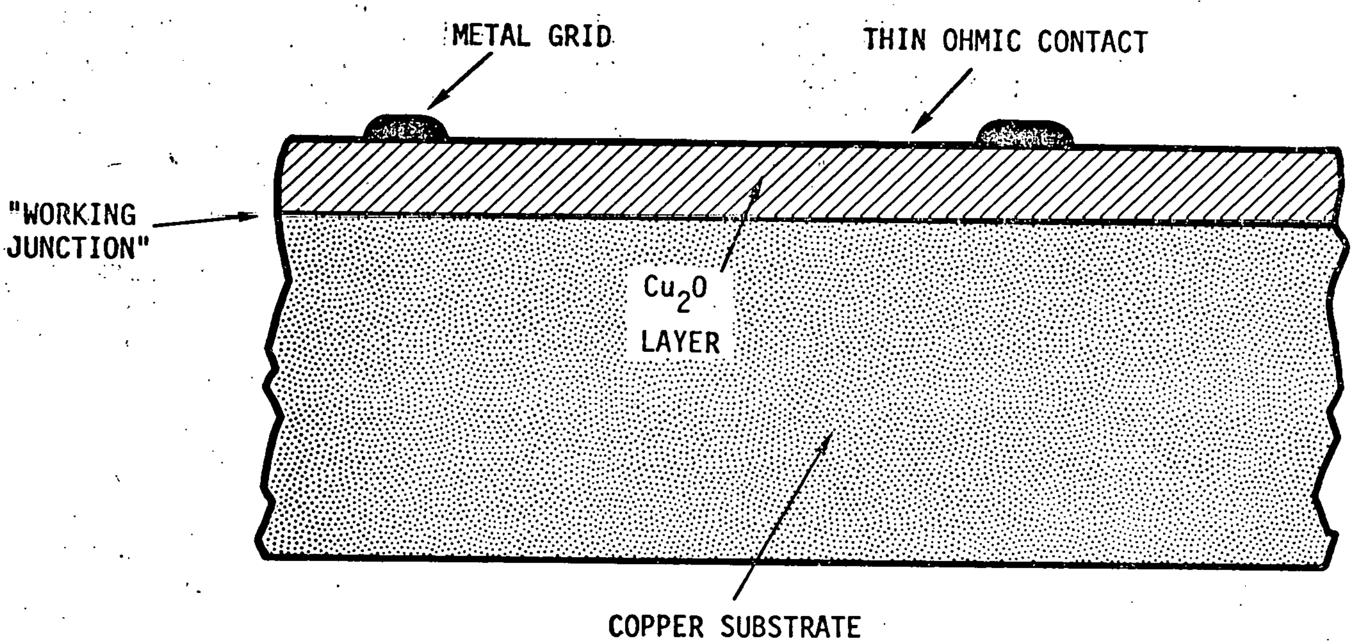


Figure 5.

2. PREVIOUS ACTIVITIES (CONT.)

C. PROGRESS FOR PREVIOUS 6 MONTHS

- ESTABLISHED SYSTEM FOR OXIDATION OF COPPER
- ESTABLISHED CAPABILITY FOR COLLECTION EFFICIENCY MEASUREMENT
- COMPUTER CODES FOR DEVICE ANALYSIS:
    - I-V AND C-V
    - COLLECTION EFFICIENCY
    - MIS SOLAR CELL CALCULATIONS
- CHARACTERIZED MICROSTRUCTURE AND GROWTH RATES FOR Cu_2O FILMS-WATER QUENCHED AND N_2-COOLED

Figure 6.

OXIDATION SYSTEM

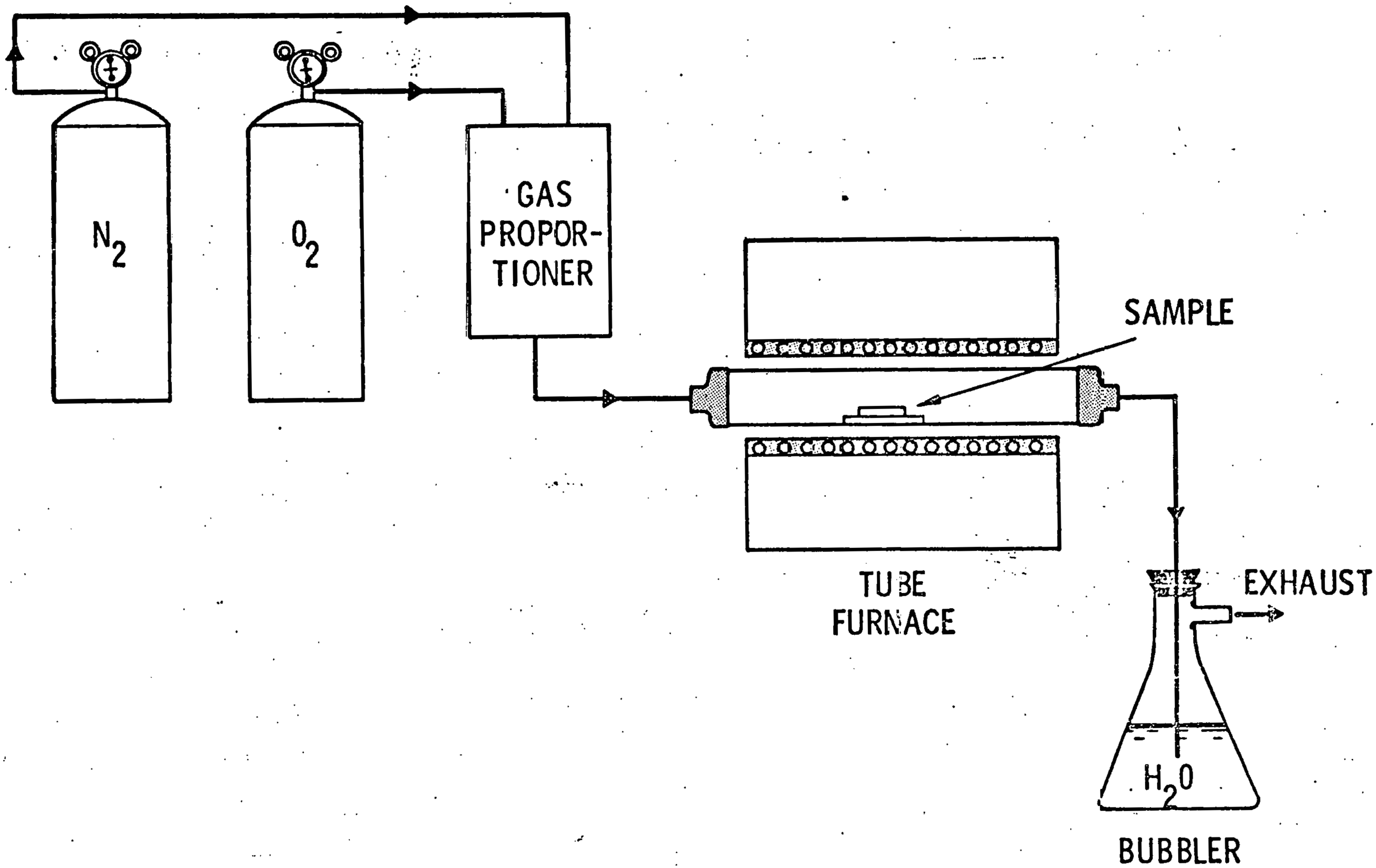
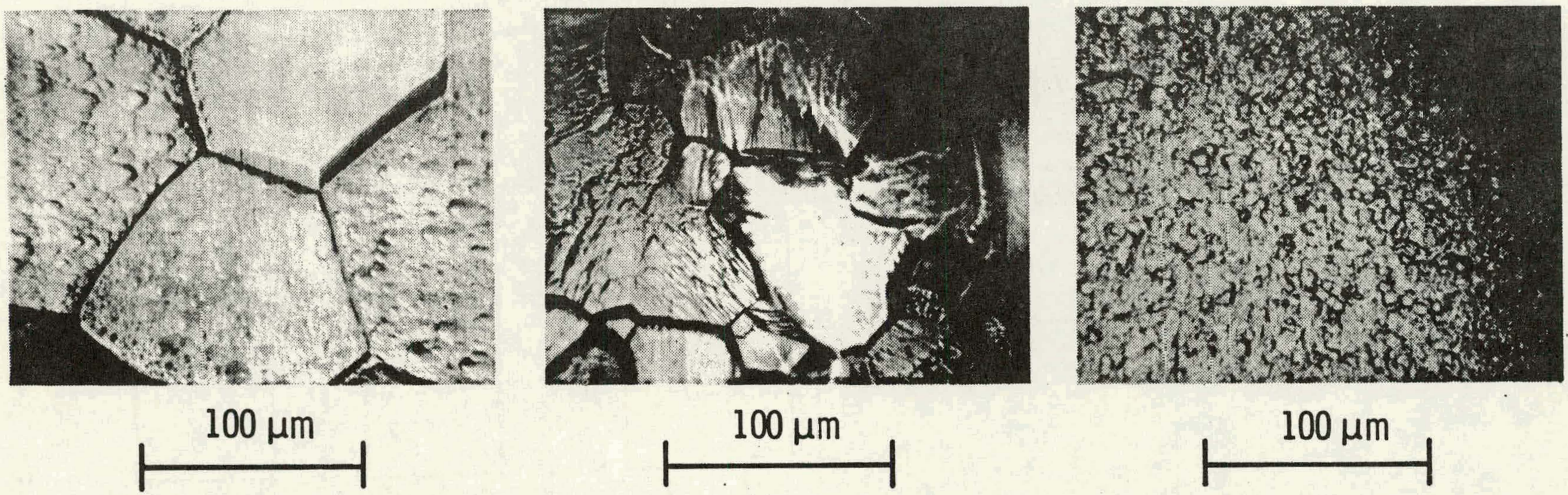


Figure 7. System for controlled oxidation of copper.

Cu_2O FILMS ON SINGLE CRYSTAL Cu
AND N_2 COOLED



(a) 75-S7. GROWN AT 1050°C (b) 75-S9. GROWN AT 900°C (c) 75-S12. GROWN AT 800°C

Figure 8.

3. CURRENT EFFORTS

A. COLLECTION EFFICIENCY MEASUREMENTS

B. THIN-FILM BACKWALL CELLS

C. MIS SOLAR CELL THEORY

D. OTHER STUDIES

Figure 9.

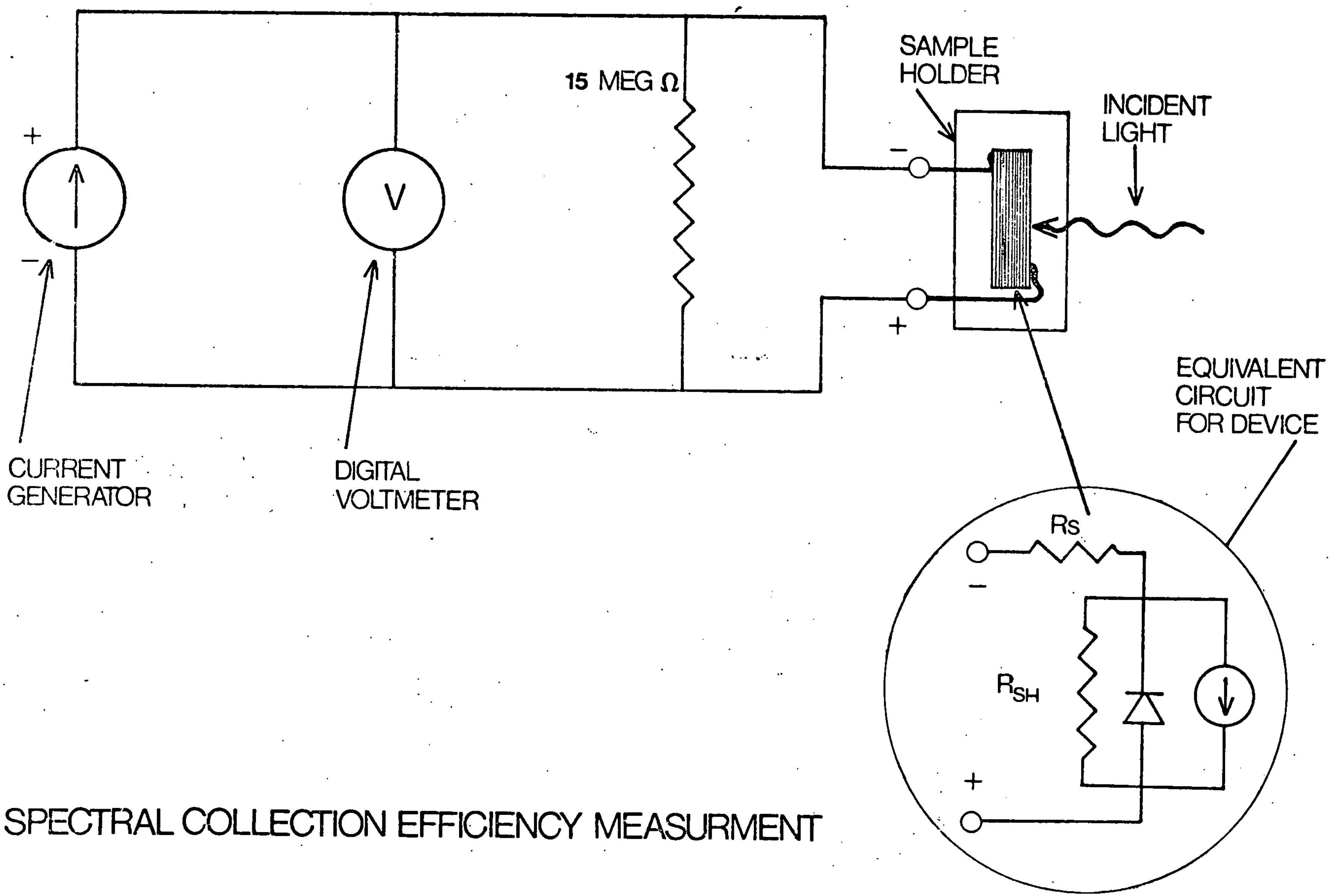

15 MEG Ω
SAMPLE HOLDER
INCIDENT LIGHT
CURRENT GENERATOR
DIGITAL VOLTMETER
EQUIVALENT CIRCUIT FOR DEVICE
Rs
RSH
SPECTRAL COLLECTION EFFICIENCY MEASURMENT

Figure 10.

REFLECTIVITY MEASURMENT

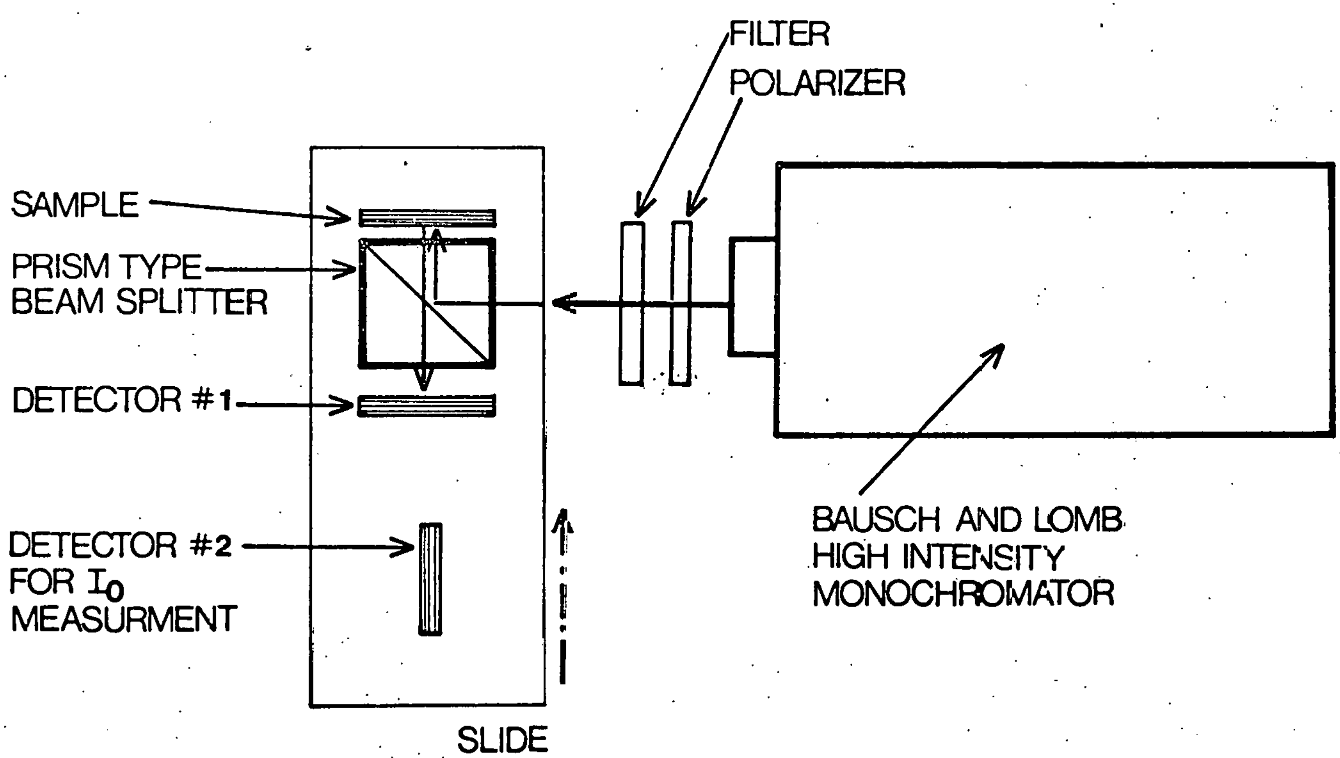
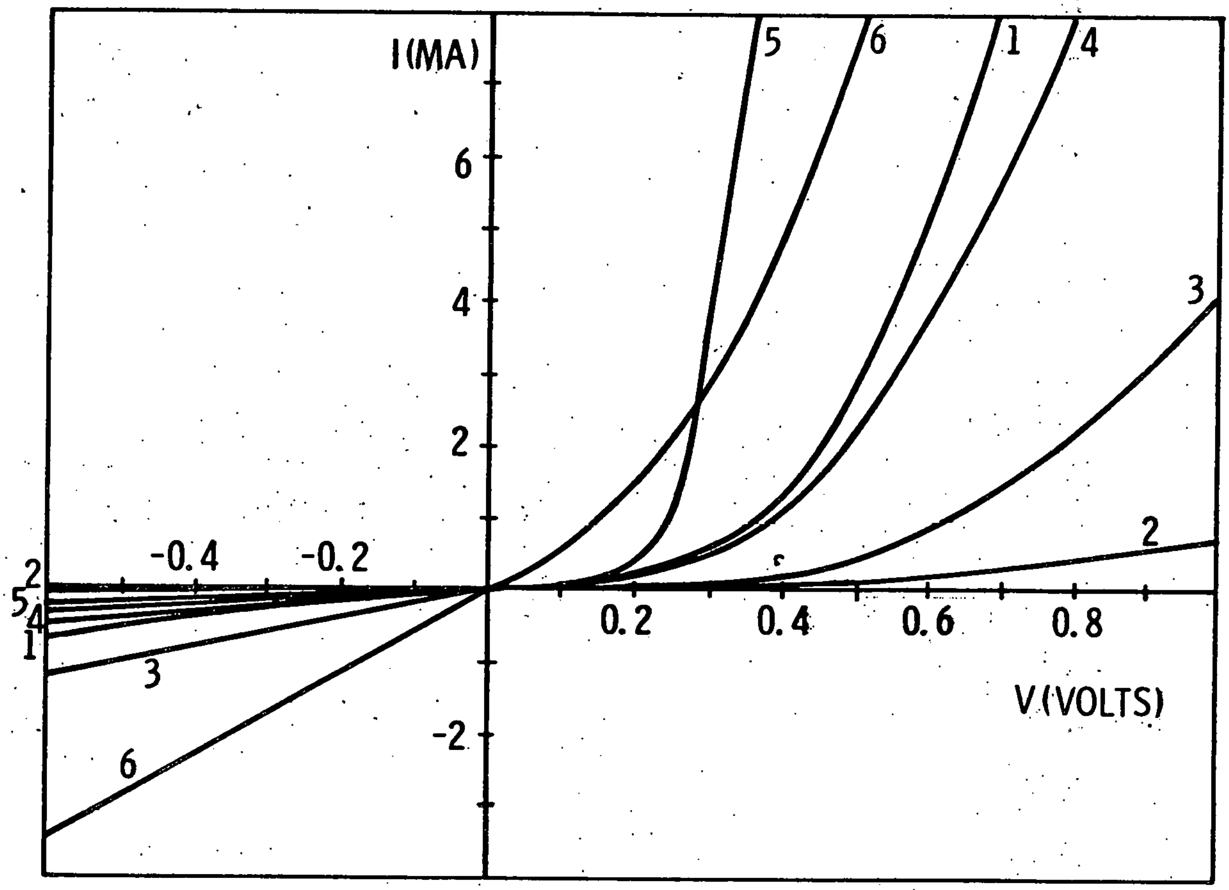


Fig 11.

854



DEVICE	GROWTH	CONTACT	R_S (Ω)	R_{SH} (Ω)	n	J_o $10^{-6}\frac{A}{cm^2}$
1	WQ	Cu	33	1370	3.66	6.50
2	NC	Cu	600	5430	~5.40	5.90
3	NC	Na_2S DIP	50	5000	4.30	3.93
4	NC	$ZnCl_2$ / Na_2S	50	2000	2.04	0.70
5	Cd REGROWN	Na_2S DIP	12	4000	1.35	0.54
6	NC	$ZnCl_2$ / Na_2S	16	155	3.52	18.4

NOTES:

a. CELL AREAS ARE 2.85 cm^2

b. Cu_2O THICKNESS OF CELL #6 IS ~8μm. ALL OTHER CELLS HAVE 30-40 μm OF Cu_2O

Figure 12.

SPECTRAL COLLECTION EFFICIENCY FOR BACKWALL Cu / Cu_2O CELLS

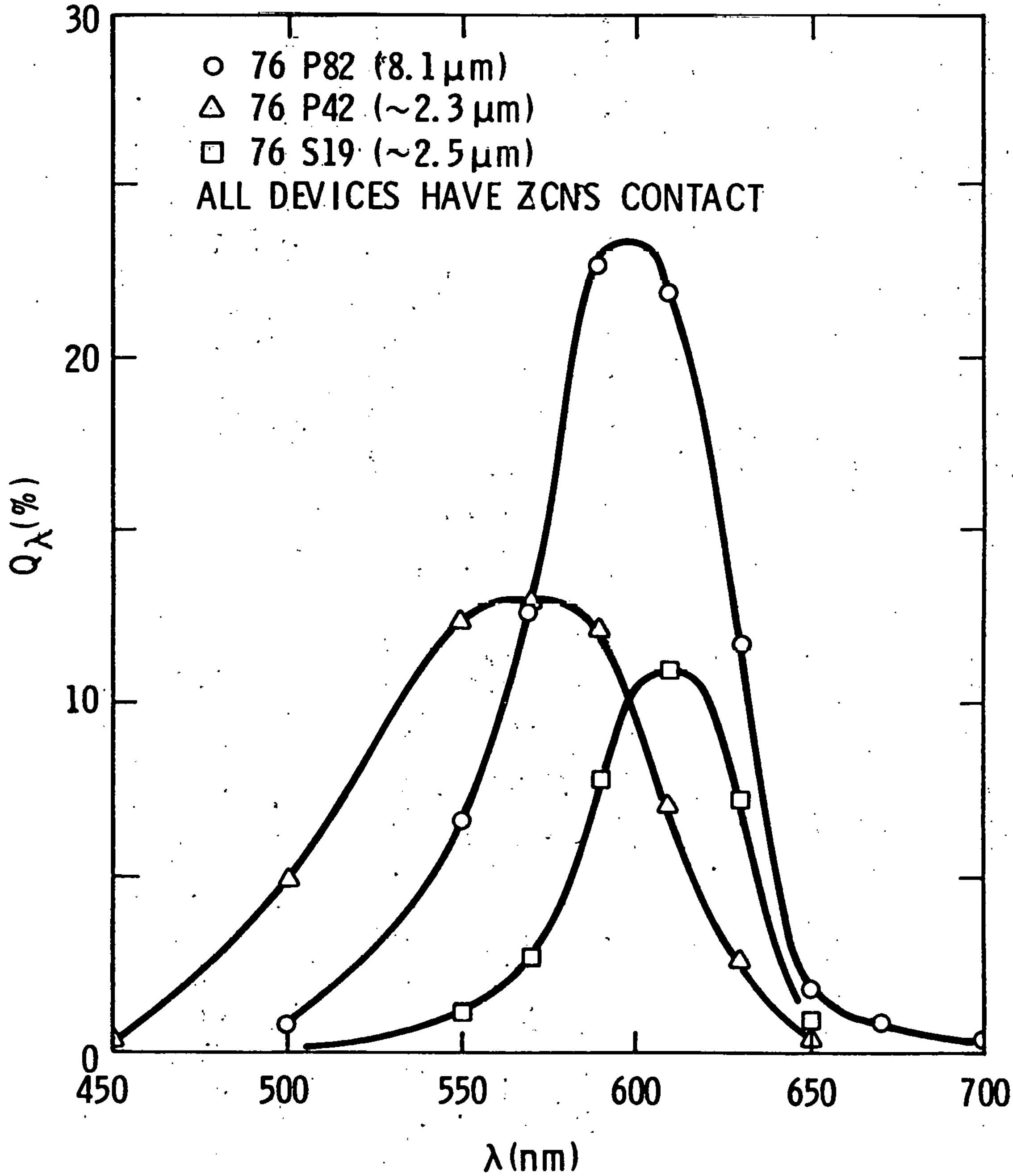


Figure 13.

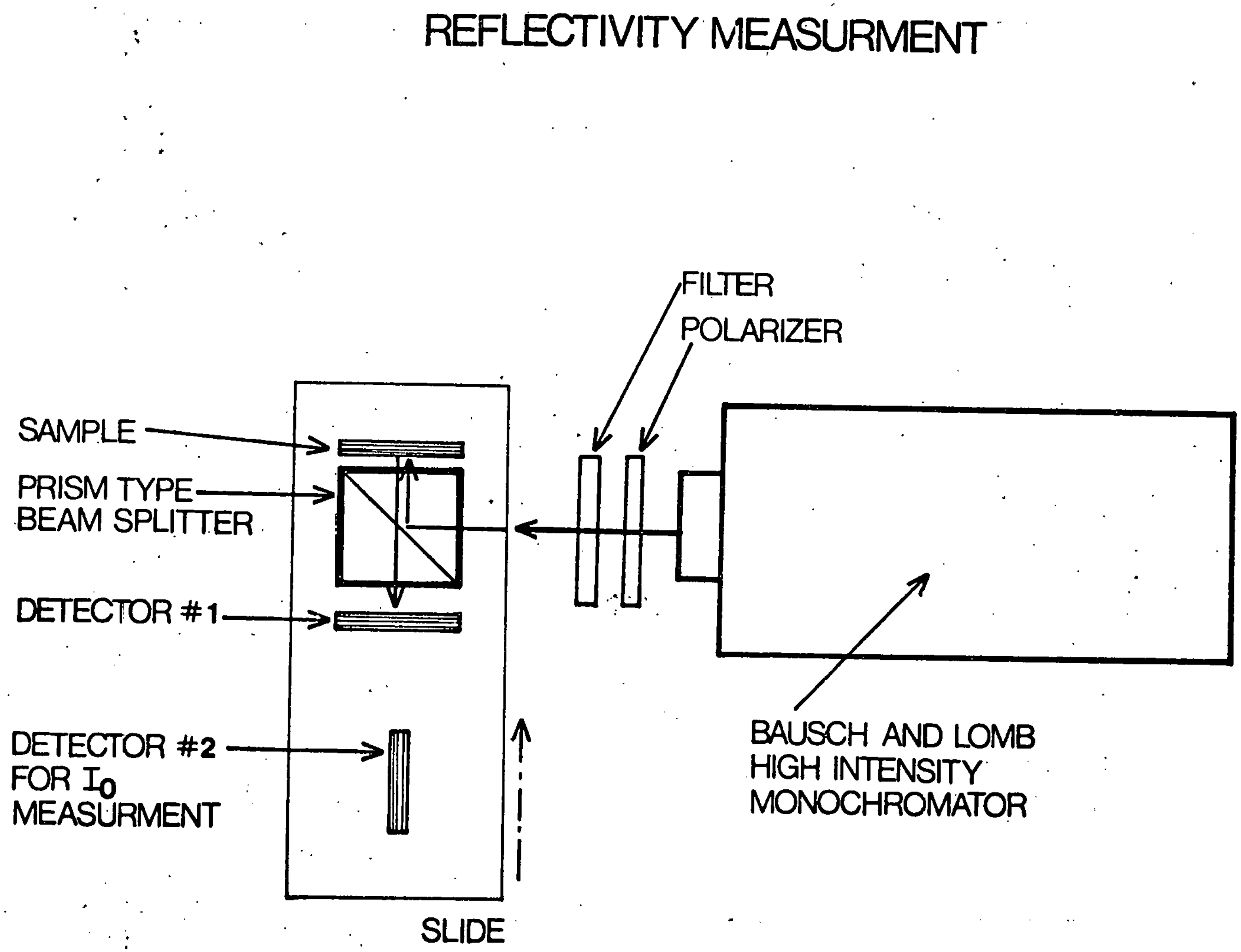

REFLECTIVITY MEASURMENT
FILTER
POLARIZER
SAMPLE
PRISM TYPE
BEAM SPLITTER
DETECTOR #1
DETECTOR #2
FOR I0
MEASURMENT
SLIDE
BAUSCH AND LOMB
HIGH INTENSITY
MONOCHROMATOR

Figure 14.

P-MIS ELECTRON BAND DIAGRAM FOR SHORT-CIRCUIT CONDITIONS

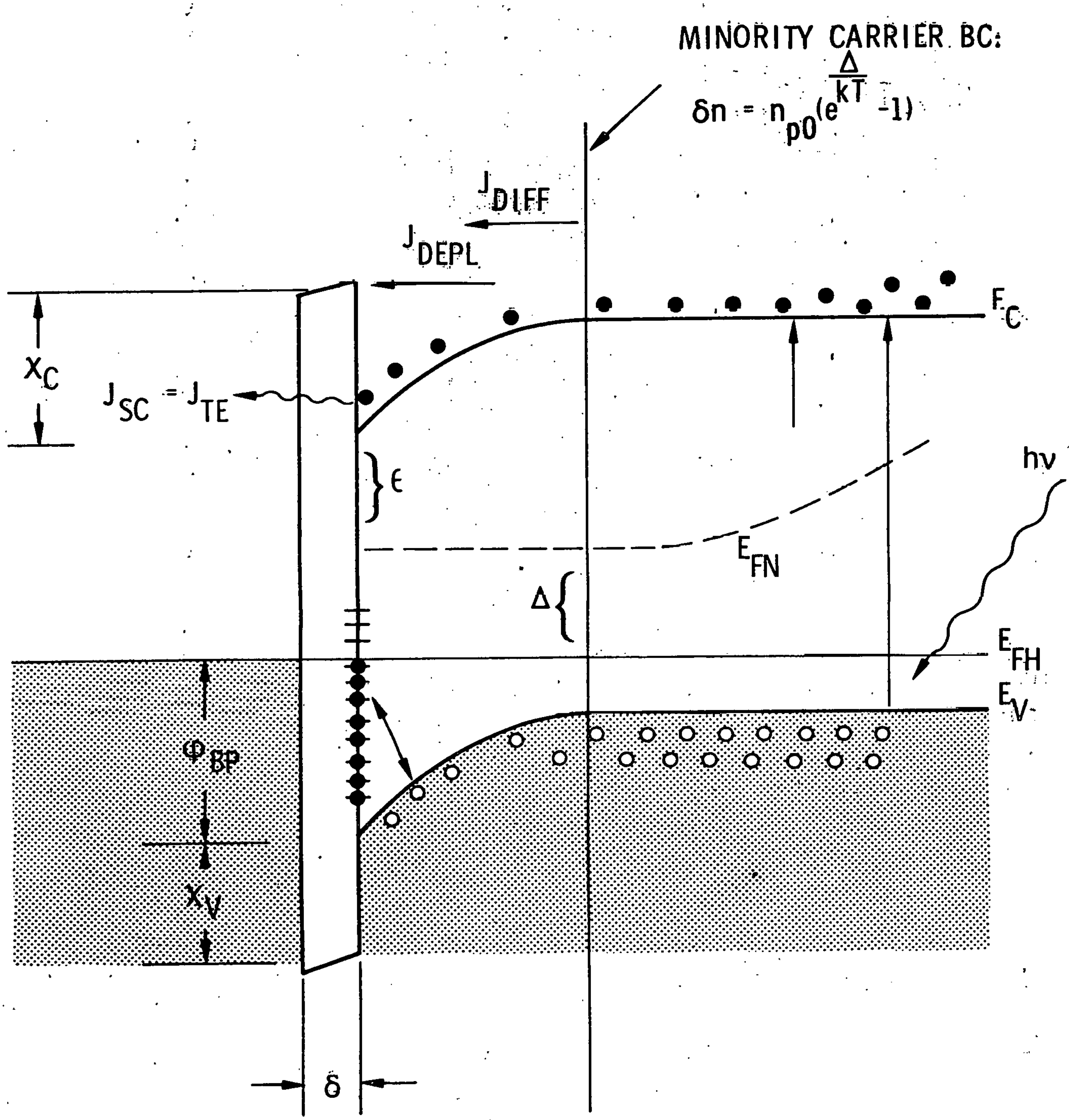
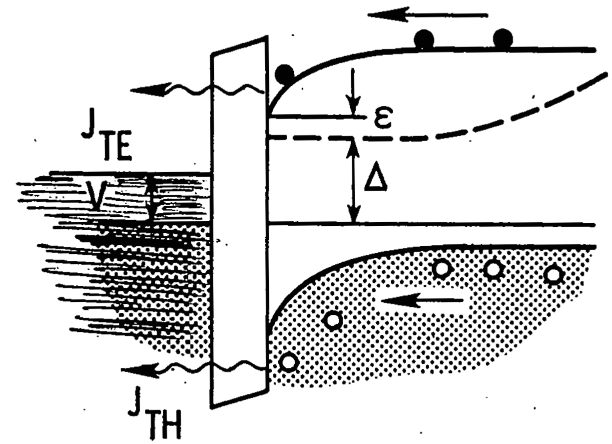


Figure 15.

MIS SOLAR CELL THEORY
CURRENT VOLTAGE CHARACTERISTICS



(1) $J = J_{TE} - J_{TH}$

(2) $J_{TH} = J_S \left[\exp\left(\frac{V}{nkT}\right) - 1\right]$

$$J_S = A^*_{tH}\, T^2\, e^{-X_c^{1/2}\delta}\quad e^{-\Phi_{BP}/kT}$$

$$\Phi_{BP} = \frac{1}{n}\,(E_g + X - \Phi_m) + \left(1 - \frac{1}{n}\right)\Phi_0$$

$$n \approx 1 + \frac{e\delta D_s}{\varepsilon_i} \quad \Phi_0 = E_g/3$$

(3) $J_{TE} = A^*_{TE} T^2\, e^{-X_v^{1/2}\delta}\quad F(\varepsilon)$

$$F(\varepsilon) \simeq e^{-\varepsilon/kT}$$

FOR $\varepsilon \gtrsim 0.1\,\text{eV}$

ALSO

(4) $J_{TE} = J_{DEPL} + J_{DIFF}$

$$= QJ_{MAX} - J_{on}\left(e^{\frac{\Delta}{kT}}\, e^{\frac{V}{nkT}} - 1\right) \qquad J_o = en_{p0}\frac{L_n}{\tau_n} \approx 1.5 \times 10^{11}\ e^{\frac{-E_g}{kT}}\ \frac{MA}{cm^2}$$

Q = SOLAR CELL COLLECTION EFFICIENCY FOR RELATED SCHOTTKY BARRIER ($\delta = 0$)

COMPUTATIONAL PROCEDURE

(3) AND (4) $\Longrightarrow \varepsilon$

SOLVE (1) FOR MAX POWER

Figure 16.

CALCULATED EFFICIENCY OF Cu / Cu_2O MIS CELLS

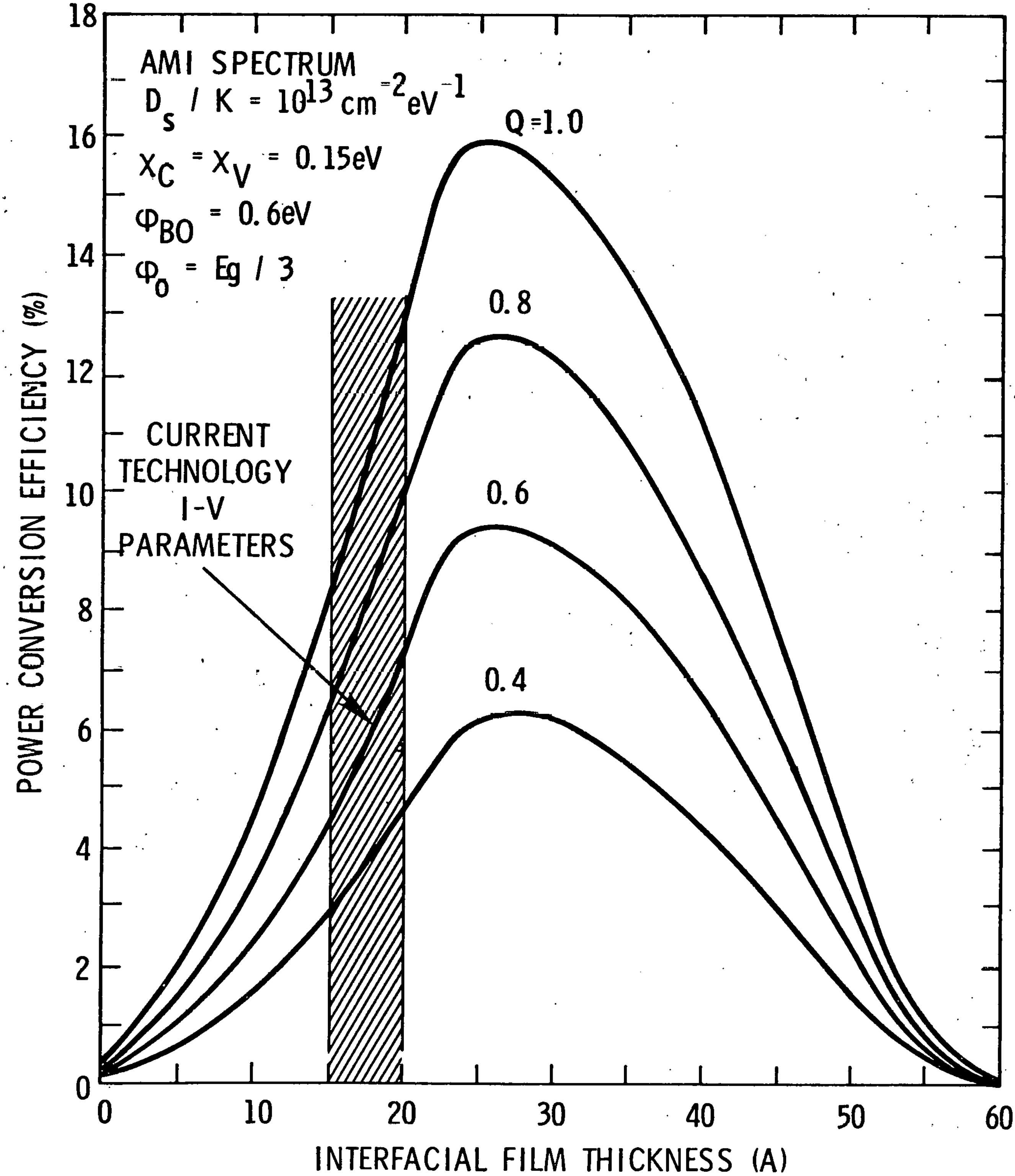


Figure 17.

CALCULATED AMI POWER CONVERSION EFFICIENCY

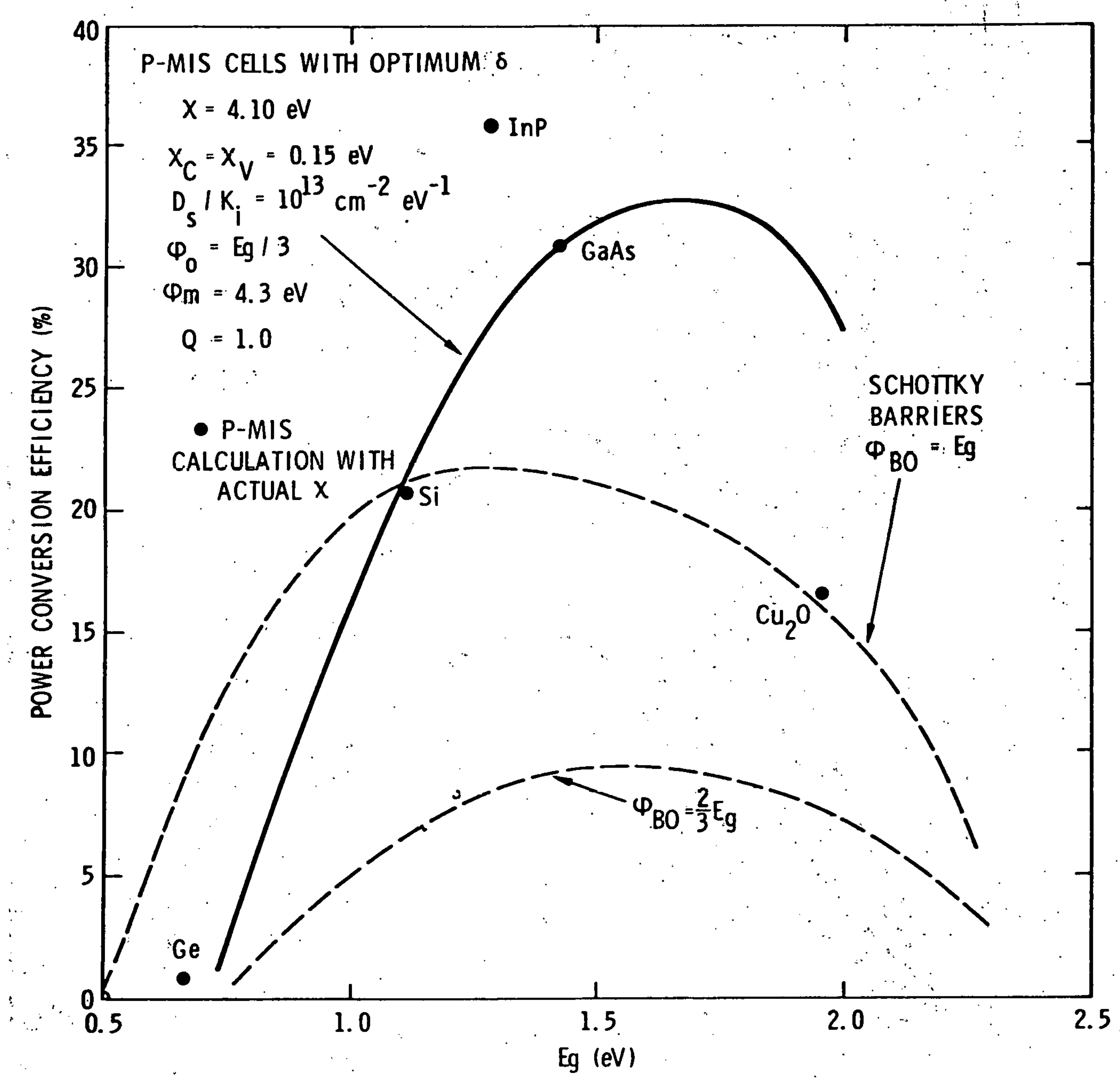


Figure 18.

OTHER STUDIES

DOPING OF Cu_2O

- SINGLE CRYSTAL Cu_2O (P-TYPE) DOPED WITH Cd:
  $\rho \sim 3000\ \Omega\text{-cm} \longrightarrow 30\ \Omega\text{-cm}$

OHMIC CONTACTS TO Cu_2O

- EVAPORATED Cu AND Ni (NOT ON N_2-COOLED MATERIAL)
- Na_2S DIP $\longrightarrow$ Cu_2S LAYER (UNSTABLE)
- $ZnCl_2/Na_2S$ DIP (STABLE)
- EVAPORATED In_2O_3

Cd-REGROWN CELLS

- DIFFUSED Cd INTO Cu_2O AND RE-OXIDIZED YIELDS
  $R_{sh} \approx 30,000\ \Omega\text{-cm}^2$

Figu 9.

4. SUMMARY OF KEY RESULTS

- COLLECTION EFFICIENCY MEASUREMENT WELL DEVELOPED
- THIN FILM BACKWALL CELLS FABRICATED WITH Cu_2O THICKNESS IN RANGE OF 2 TO 10 μm
- SPECTRAL COLLECTION EFFICIENCY FOR BACKWALL CELLS MEASURED
- MIS SOLAR CELL THEORY REFINED
- PROGRESS MADE REGARDING DOPING Cu_2O MORE P-TYPE AND OHMIC CONTACTS

Figure 20.

5. FUTURE PLANS

A. THIN FILM Cu/Cu_2O BACKWALL CELLS

- CONTACT INVESTIGATION
- COLLECTION EFFICIENCY ANALYSIS
- CHARACTERIZATION OF Cu/Cu_2O INTERFACE

B. MIS ANALYSIS OF THICK FILM BACKWALL CELLS

DEPENDENCE OF BARRIER PARAMETERS ON:

- COPPER SUBSTRATE
- OXIDATION TEMPERATURES
- Cd DOPING

C. FRONTWALL CELL STUDIES

- HETEROJUNCTIONS ON POLYCRYSTALLINE Cu_2O
- SCHOTTKY BARRIERS AND MIS STRUCTURES ON POLYCRYSTALLINE Cu_2O

Fig 21.

Zn_3P_2 FOR SOLAR CELLS

IMPROVED SEMICONDUCTORS FOR PHOTOVOLTAIC CELLS

ERDA

E(49-18)-2460

PERIOD OF GRANT: JUNE 18, 1976 - JULY 18, 1977

VALUE: $231,543

GEORGE WARFIELD
PRINCIPAL INVESTIGATOR
EXECUTIVE DIRECTOR
INSTITUTE OF ENERGY CONVERSION
UNIVERSITY OF DELAWARE
NEWARK, DE 19711

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING
AUGUST 3 - 6, 1976
UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE 04473

ABSTRACT

I. OBJECTIVES:

The overall objective of this project is to evaluate Zn_3P_2 "as a promising inorganic semiconductor having potential for mass-produced, low-cost high efficiency photovoltaic solar cells" (1)

II. PREVIOUS ACTIVITIES:

Prior to responding to the RFP from which this project has evolved, The Institute of Energy Conversion conducted an extensive literature search to identify one or more materials which would be responsive to the RFP. This search isolated Zn_3P_2 as the most promising compound for more detailed study. The analysis leading to this choice is presented as the main part of this report.

III. CURRENT ACTIVITIES:

The project has been underway for only one month. In this time we have identified at least three commercial sources for Zn_3P_2 powder and have ordered material from each. We have also started to synthesize our own material by reacting pure zinc and phosphorous in sealed quartz tubes under the appropriate temperature conditions. We have prepared a system to produce single crystals by growth from solution, and have an evaporator ready to produce these films. Both can be put in operation as soon as powder is available.

IV. SUMMARY OF KEY RESULTS:

Premature to report results.

V. FUTURE PLANS:

These are best summarized by the Program Plan below.

(1) ERDA RFP Improved Semiconductors for Photovoltaic Cells.

PROGRAM PLAN

TASK			MONTH 1	2	3	4	5	6	7	8	9	10	11	12	13
CONSTITUENT MATERIALS	SINGLE CRYSTAL	Develop Growth Techniques	—	—	—										
		Provide Experimental Material			—	—	—	—	—	—	—	—	—	—	
		Structural Characterization			—	—									
		Optical Characterization			—	—	—								
		Develop Ohmic Contacts				—	—	—							
		Electrical Characterization				—	—	—	—						
	THIN FILMS	Preliminary Growth			—	—	—								
		Experimental Material					—	—	—	—	—	—	—	—	
		Structural Characterization				—	—	—	—	—					
		Optical					—	—	—						
		Ohmic Contacts						—	—						
		Electrical Properties					—	—	—	—					
DEVICES		Diode Formation						—	—	—	—	—			
		I-V Analysis, Light-Dark							—	—	—	—	—	—	
		Photocapacitance							—	—	—	—	—	—	
		Chemical Stability							—	—	—	—	—	—	
		Diffusion Lengths										—	—	—	
MILESTONES		Usable Single Crystals		▲											
		Usable Thin Films				▲									
		Preliminary Optical Data				▲									
		Thin Film Optical Data						▲							
		First Order Mobility Measurements							▲						
		Refined Optical Data										▲			
		Refined Transport Data												▲	
		Prototype Photovoltaic Device									▲				
REPORTS		Monthly	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	▲	
		Quarterly			▲			▲			▲				
		Draft Final													▲

OBJECTIVE OF PROJECT

TO EVALUATE Zn_3P_2 "AS A PROMISING INORGANIC SEMICONDUCTOR HAVING POTENTIAL FOR MASS-PRODUCED, LOW-COST, HIGH EFFICIENCY PHOTOVOLTAIC SOLAR CELLS."[1]

(1) ERDA RFP FOR IMPROVED SEMICONDUCTORS FOR PHOTOVOLTAIC CELLS

CLASS I

PHYSICAL CHARACTERISTICS NECESSARY FOR GOOD ABSORBERS IN ANY TYPE OF THIN FILM PHOTOVOLTAIC DEVICE FOR TERRESTRIAL USE

1. BAND GAP 0.9 - 2.2 eV
2. BAND GAP DIRECT WITH OPTICAL ABSORBTION COEFFICIENT, $\alpha > 10^4$ cm^{-1} FOR PHOTON ENERGIES > 1.5 eV
3. HIGH MOBILITY AND/OR LONG MINORITY CARRIER DIFFUSION LENGTH, L.

CLASS II

ECONOMIC CHARACTERISTICS

1. CHEMICAL STABILITY FOR LONG LIFE
2. ABUNDANT SUPPLY OF MATERIALS
3. LOW EXTRACTION AND REFINEMENT COSTS
4. ADAPTABILITY TO LOW COST THIN FILM FABRICATION PROCESSES

CLASS III

CONDITIONS FOR DEVICE FABRICATION

1. AVAILABILITY OF BOTH CONDUCTIVITY TYPES FOR HOMOJUNCTION CELLS
2. CRYSTALLOGRAPHIC, CHEMICAL AND ELECTRICAL COMPATIBILITY WITH OTHER COMPONENTS FOR HETEROJUNCTION CELLS

CLASS IV

BOUNDARY CONDITIONS SET BY RFP

1. EXCLUSION OF Si, GaAs, InP, CdS, Cu_2S
2. EXCLUSION OF ORGANICS
3. EXCLUSION OF SOLID SOLUTIONS

CLASS V

BOUNDARY CONDITIONS SET BY IEC

1. EXCLUSION OF TERNARY COMPOUNDS

COMPOUNDS SATISFYING CONDITIONS 1 AND 2 OF CLASS I

Ge-Si ALLOYS

Al Sb

Cu_2O

Zn_3P_2

$Zn P_2$

Cd Se

Cd Te

Ge-Si

NOT RESPONSIVE TO RFP AS A CONTINUOUS SOLID SOLUTION IS FORMED

MOST AVAILABLE ABSORBTION DATA SUGGESTS LITTLE BENEFIT GAIN OVER PURE Si

AlSb

MATERIAL WELL DOCUMENTED TO BE VERY UNSTABLE IN AIR

NO THIN FILM TECHNOLOGY EXISTS

Sb IS OF LIMITED ABUNDANCE - LESS THAN 1 PPM IN EARTH'S CRUST

Sb TOXIC TO MARKED DEGREE

Cu_2O

WITH BAND GAP OF 2.0 EV, MAXIMUM SHORT CIRCUIT CURRENT UNDER AM1 WOULD BE 14 MA/CM^2, ASSUMING NO GRID OR REFLECTION LOSSES. (CDS / Cu_2S CELL WOULD HAVE 35 MA/CM^2 UNDER SAME BASIS)

EFFICIENCY OF 10% PROBABLY NOT ACHIEVABLE PRACTICALLY

PHOTOCHEMICAL INSTABILITIES REPORTED

CdSe CdTe

INADEQUATE SUPPLIES OF MATERIALS

LISTED WORLD RESOURCES

Se ~ 10^5 METRIC TONS

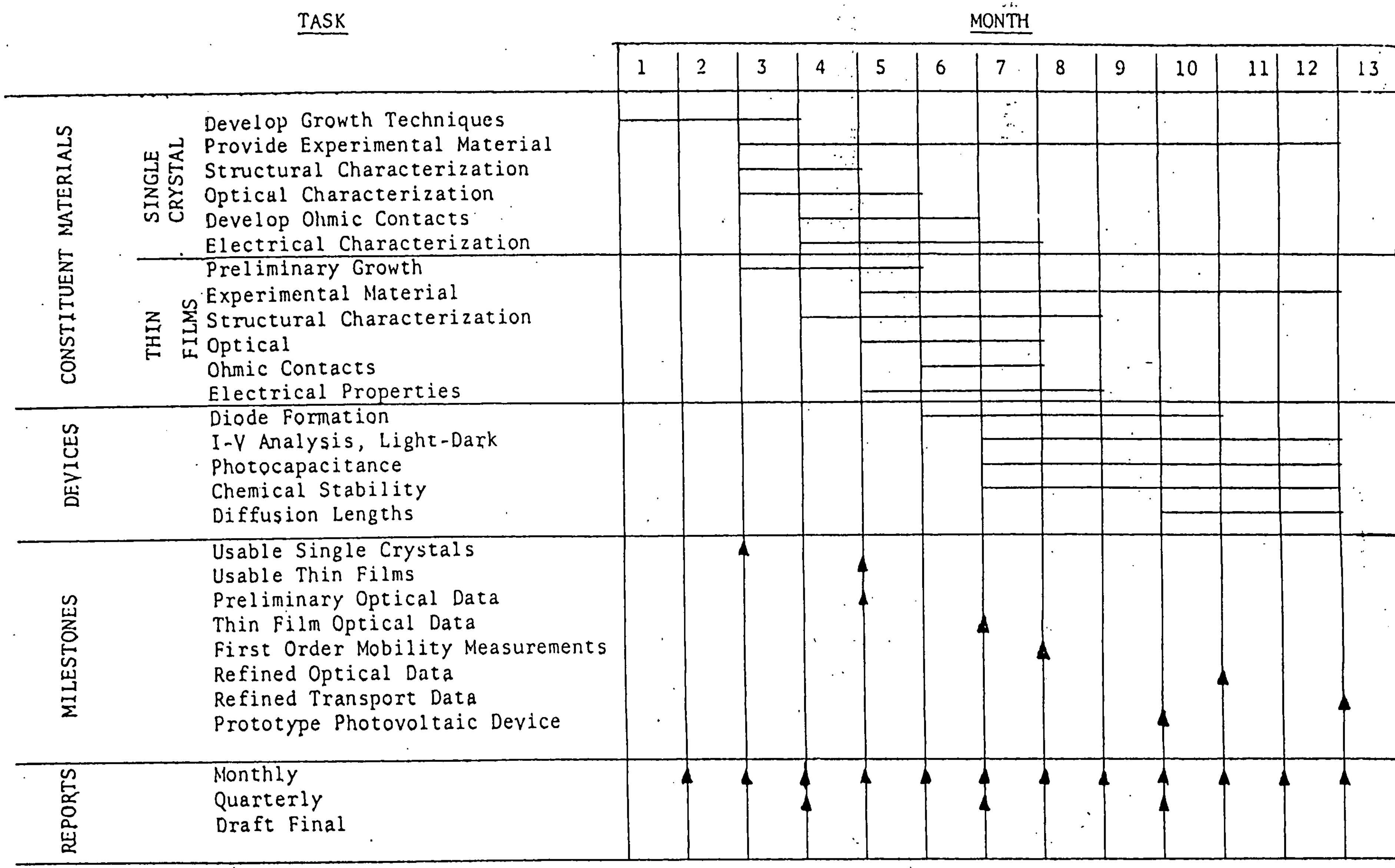
Te ~ 3×10^4 METRIC TONS

FAVORABLE PROPERTIES OF Zn_3P_2

BAND GAP	1.1 - 1.3 eV	PROBABLY DIRECT
OPTICAL ABSORPTION		INDICATIONS OF LARGE α
CHEMICALLY STABLE		SUBLIMES WITHOUT DECOMPOSITION AT 1000°C.

MATERIALS VERY ABUNDANT AND LOW COST

PROGRAM PLAN



IMPROVED SEMICONDUCTORS FOR PHOTOVOLTAIC SOLAR CELLS - $CuInSe_2$

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

E(49-18)-2459

Period of Contract: June 1976 - July 1977

Contract Value: $77,500

Reid A. Mickelsen - Principal Investigator

Boeing Aerospace Company

P.O. Box 3999 M/S 88-43

Seattle, Washington 98124

Presented at the National Solar Photovoltaic Program Review Meeting

August 3-6, 1976

University of Maine at Orono

Orono, Maine 04473

"IMPROVED SEMICONDUCTORS FOR PHOTOVOLTAIC SOLAR CELLS - $CuInSe_2$"

I. OBJECTIVE

The objective of this 13-month research program is the investigation of $CuInSe_2$ thin films as an inorganic semiconductor material having considerable potential for mass produced, low cost, high efficiency photovoltaic solar cells. $CuInSe_2$ was selected for study because it is one of only four material systems which have demonstrated conversion efficiencies greater than 10% and its properties are consistent with a thin film solar cell array costing less than $300/KW. This particular program is viewed as the first phase of the necessary technical effort leading to the development of these low cost thin film arrays.

II. PREVIOUS ACTIVITIES

Since the present study is a newly awarded program which has been in progress for only about one month, there is little to report in the way of previous results.

III. CURRENT EFFORTS

The current program activity is concentrating on the development of a vacuum deposition process for the $CuInSe_2$ thin films. The technique under investigation is based upon three separate, individually controlled vapor sources for the Cu, In, and Se materials. Initially, the Cu and In sources were controlled using quartz crystal microbalances to set source power levels prior to shutter opening and using a thermocouple to establish the Se source temperature/vapor pressure. Since this approach was not found to be sufficiently reproducible, the deposition system is being modified to include three quartz crystal deposition monitors with each shielded such that they monitor only one material at all times, i.e., shutter opened or closed.

The semiconductor films are being deposited onto 0211 glass substrates for electrical and optical measurements and SiO or C coated electron microscope grids for structural studies. Based upon the University of Maine work on $CuInSe_2$ films, the substrate temperature is being maintained in the vicinity of 200°C and a rather slow deposition rate of 1 - 4 Å/S is being utilized.

While an in-depth film characterization is not planned, some electrical, optical and structural studies are in progress. These measurements will be utilized more for correlation to the Maine results than to acquire basic property data on $CuInSe_2$ thin films. The actual measurements being made include sheet resistance, cal absorption, sensitivity to light, and electron diffraction/microscopy. .ll effect apparatus has been constructed for carrier concentration and mobility measurements.

IV. SUMMARY OF KEY RESULTS

Electron diffraction data has shown that the desired chalcopyrite $CuInSe_2$ compound is being formed with an 0.1 - 0.5 micron grain size using the three-source technique. However, free In was also indicated which will necessitate modifying the relative elemental deposition rates. Furthermore, measurements on film properties have shown the desirability of independent quartz crystal microbalance control over all three vapor sources during the entire film deposition cycle.

Hot probe measurements have shown all of the films deposited to date to exhibit P type conduction. This result can be explained by the fact that the Se deposition rate has always been excess of that necessary for the stoichometric compound.

V. FUTURE PLANS

The reproducibility and controllability of the deposited $CuInSe_2$ film properties using the modified deposition technique will be investigated. The electrical, optical and structural properties of the resulting films will be determined and correlated to the more detailed University of Maine and other laboratory studies. Measurements will be conducted to assess the relative stability of these films under various atmospheric conditions. A study of factors relating to the production of large area thin-film arrays incorporating the $CuInSe_2$/CdS cell will also be initiated.

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

E(49-18)-2459

PERIOD OF CONTRACT: JUNE 1976 - JULY 1977

CONTRACT VALUE: $77,500

REID A. MICKELSEN - PRINCIPAL INVESTIGATOR

BOEING AEROSPACE COMPANY

P.O. BOX 3999 M/S 88-43

SEATTLE, WASHINGTON 98124

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

AUGUST 3-6, 1976

UNIVERSITY OF MAINE

ORONO, MAINE 04473

CONTRACT OBJECTIVE:

INVESTIGATION OF $CuInSe_2$ THIN FILMS AS AN INORGANIC SEMICONDUCTOR MATERIAL HAVING POTENTIAL FOR MASS PRODUCED, LOW COST, HIGH EFFICIENCY PHOTOVOLTAIC SOLAR CELL FOR TERRESTRIAL APPLICATIONS.

MAJOR TASK DESCRIPTION:

- DEVELOP AND CHARACTERIZE A $CuInSe_2$ FILM FORMATION TECHNIQUE
- CONDUCT MEASUREMENTS ON PHYSICAL PROPERTIES AND STABILITY OF DEPOSITED FILMS
- ANALYZE HIGH VOLUME PRODUCTION CONCEPTS FOR $CuInSe_2$ CELL

FIRST PHASE OF MULTI-PHASE/YEAR PROGRAM:

PHASE I: FILM FORMATION/CHARACTERIZATION
PHASE II: SMALL AREA PV DEVICE DEVELOPMENT
PHASE III: DEVICE IMPROVEMENT
PHASE IV: LARGE AREA 10% DEVICE DEVELOPMENT
PHASE V: THIN FILM ARRAY DEVELOPMENT

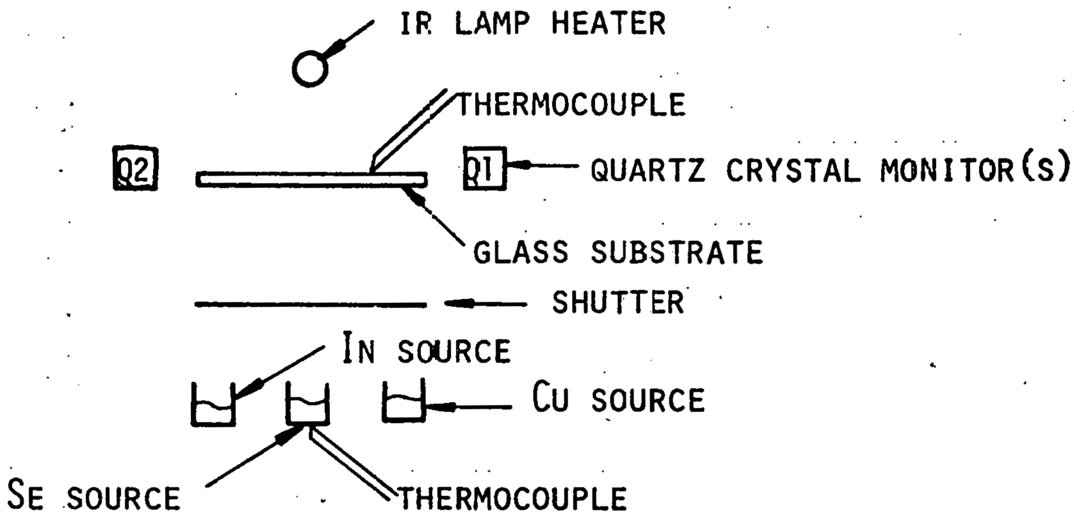
CURRENT PLANNED ACTIVITY:

- NEW PROGRAM - JUNE 18, 1976 TO DATE
- ACQUIRE A VACUUM DEPOSITION TECHNIQUE FOR THE CONTROLLED FORMATION OF $CuInSe_2$ THIN FILMS
- PERFORM PRELIMINARY FILM CHARACTERIZATION STUDIES
- ESTABLISH CLOSE COORDINATION WITH UNIVERSITY OF MAINE AND OTHER LABORATORIES' ACTIVITIES ON $CuInSe_2$

PROGRAM PROGRESS

-FILM FORMATION-

INITIATED $CuInSe_2$ FILM FORMATION STUDIES USING THREE-SOURCE VACUUM DEPOSITION TECHNIQUE.



TYPICAL DEPOSITION PARAMETERS:

PRESSURE:	5×10^{-6} TORR
SUBSTRATE TEMPERATURE:	200°C
SE SOURCE TEMPERATURE:	275°C
FILM THICKNESS:	1 - 3000 Å
DEPOSITION RATE:	1 - 4 Å/S

PROGRAM PROGRESS

- FILM ANALYSIS -

- ELECTRON DIFFRACTION HAS SHOWN $CuInSe_2$ COMPOUND WITH CHALCOPYRITE STRUCTURE. In DIFFRACTION LINE WAS ALSO PRESENT.
- ELECTRON MICROSCOPY HAS INDICATED FILM GRAIN SIZE TO BE IN RANGE OF 0.5 MICRON.
- "HOT PROBE" HAS SHOWN FILMS TO BE P TYPE.
- VARIABILITY IN SHEET RESISTANCE AND OPTICAL ABSORPTION MEASUREMENTS HAS LED TO A MODIFICATION OF DEPOSITION CONTROL TECHNIQUE.
- HALL EFFECT MEASUREMENT APPARATUS HAS BEEN ASSEMBLED AND SPECIMEN DEPOSITION MASKS PREPARED.

SUMMARY OF KEY RESULTS

- o CHALCOPYRITE $CuInSe_2$ FILMS CAN BE FORMED BY THREE-VAPOR SOURCE VACUUM DEPOSITION TECHNIQUE.

- o FILM GRAIN SIZE IS IN RANGE OF 0.1 - 0.5 MICRONS FOR A 200°C SUBSTRATE TEMPERATURE.

- o TO ACHIEVE DEPOSITION REPRODUCIBILITY/CONTROLLABILITY, MICROBALANCE CONTROLLERS ON ALL THREE SOURCES APPEARS NECESSARY.

- o ALL FILMS HAVE SHOWN P TYPE CONDUCTIVITY.

PLANNED ACTIVITY - NEXT SIX MONTHS

- o FURTHER EXPLORE AND REFINE FILM DEPOSITION PROCESS

- o CONDUCT LIMITED HALL EFFECT, OPTICAL ABSORPTION, CRYSTALLINITY, AND PHOTO-CONDUCTIVITY MEASUREMENTS WITH RESPECT TO DEPOSITION PARAMETERS

- o PERFORM FILM STABILITY MEASUREMENTS

- o INITIATE STUDY OF ARRAY PRODUCTION FACTORS BASED UPON THE $CuInSe_2$/CdS THIN FILM CELL

STUDY OF II-IV-V_2 CHALCOPYRITE SEMICONDUCTORS FOR SOLAR CELL APPLICATIONS

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT NO. E(49-18)-2458
PERIOD OF CONTRACT: SEPT. 1, 1976 - OCT. 1, 1977
VALUE: $147,750

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NORTH CAROLINA STATE UNIVERSITY
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5) R.W. HARRISON - RESEARCH TRIANGLE INST.

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

AUGUST 3-6, 1976

UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE 04473

I. OBJECTIVES

The major objective of this program is to investigate the growth and characterization of the II-IV-V_2 ternary semiconductors as a class of materials having promising potential applications for photovoltaic solar cells.

The intent behind this program is a search for semiconductors other than Si, CdS, CdS/CuS, GaAs, and InP as alternative materials for mass-produced, low cost, high efficiency solar cells. The rationale for the choice of the ternary chalcopyrite II-IV-V_2 materials for this purpose can be seen by examining Table I. (See ref. 1, p.218) In this table, the identifiable resources of Ga and In are seen to be very low when compared to the other elements of importance for III-V semiconductors useful in photovoltaic solar cell applications. This is one major negative factor in considering GaAs, InP, and ternary and quaternary III-V Ga and In compounds for this purpose. At the same time, the identifiable resources of Zn, Cd, Si, and As are large. This makes the III-IV-V_2 chalcopyrite compounds $ZnSiAs_2$ and $CdSiAs_2$ potentially attractive from the viewpoint of both supply and economics. Furthermore, since the chalcopyrites are structural analogues to the binary III-V semiconductors, they are expected to have suitable band structure and electrical and optical properties for photovoltaic solar cell applications. This is born out to a large extent by the tabulation of experimental results on these materials presented by Shay and Wernick [2]. However, it must be pointed out that the state of development of chalcopyrites is probably ten years behind the development of binary III-V compounds, although not quite as far behind the ternary and quaternary III-V materials.

II. RESEARCH PLANS

This program begins on Sept. 1, 1976. The plans for this work during the next year can be summarized by the following five tasks, of which the first three will be emphasized during the next six months.

Task 1. Growth of Chalcopyrites for Solar Cells.

A vapor phase epitaxial reactor system will be fabricated and used to deposit layers of $ZnSiAs_2$ and $CdSiAs_2$ on Si substrates.

Task 2. Optimization of Growth Conditions.

The epitaxial reactor conditions will be optimized to produce $ZnSiAs_2$ and $CdSiAs_2$ layers of good crystal quality. Material samples of at least 1% of the month's output and of representative form and quality will be supplied to ERDA designated sources commencing during the third month of the contract effort.

Task 3. Material Characterization.

Experiments will be performed to determine:

a. Material physical and chemical properties

b. Material electrical properties

c. Material optical properties

d. Material mechanical properties

e. Environmental effects on the material

Task 4. Engineering and Economic Factors.

Analysis will be performed to define and project the technology required to fabricate and utilize the material in photovoltaic solar cell devices and arrays. These analyses will include technical and economic considerations.

Task 5. Further Material Development.

At the conclusion of the contract period, a recommendation will be made to ERDA for a suitable development program to employ chalcopyrite materials in mass-produced photovoltaic devices if the analysis of Task 4 indicates sufficient promise relative to existing materials.

LIST OF REFERENCES

1) H.J. Hovel, "Solar Cells," in Semiconductors and Semimetals, vol. 11, ed. R.K. Willardson and A.C. Beer, Academic Press, New York, 1975.

2) J.L. Shay and J.H. Wernick, Ternary Chalcopyrite Semiconductors: Growth, Electronic Properties, and Applications, Pergamon Press, Oxford, 1975.

TABLE 1. IDENTIFIABLE MINERAL RESOURCES[A]

	U.S. Resources		World Resources	
Mineral	Ref. C	Ref. D	Ref. C	Ref. D
Al[B]	---	$2x10^{11}$	---	$3.5x10^{12}$
As	$1.4x10^{6}$	$1.1x10^{6}$	$1.9x10^{7}$	$1.8x10^{7}$
Cd	$2x10^{5}$	$3x10^{5}$	$8.5x10^{5}$	$1.2x10^{6}$
Cu	$9.1x10^{7}$	$6.5x10^{7}$	$4x10^{8}$	$2.9x10^{8}$
Fe	---	$1.2x10^{11}$	---	$2x10^{12}$
Ga	$2.7x10^{3}$	$8.4x10^{3}$	$1.1x10^{5}$	$1.1x10^{5}$
In	$5x10^{2}$	$5.8x10^{3}$	$3.2x10^{3}$	$9x10^{3}$
P	---	$2.9x10^{9}$	---	$5.1x10^{10}$
S	---	$2.9x10^{10}$	---	---
Se	$2x10^{4}$	$1.4x10^{5}$	1.10^{5}	$2.5x10^{6}$
Si	Unlimited		Unlimited	
W	---	$2.9x10^{6}$	---	$5.1x10^{7}$
Zn	---	$1.2x10^{8}$	---	$1.5x10^{9}$

[A]Potentially economically and technologically recoverable at today's market (in metric tons).

[B]Includes all Al ores

[C]"United States Mineral Resources" (D.A.Brobst and W.P. Pratt, eds.) U.S. Dept. of the Interior, Geological Survey Professional Paper 820, U.S.G.P.O., Washington, DC, 1973.

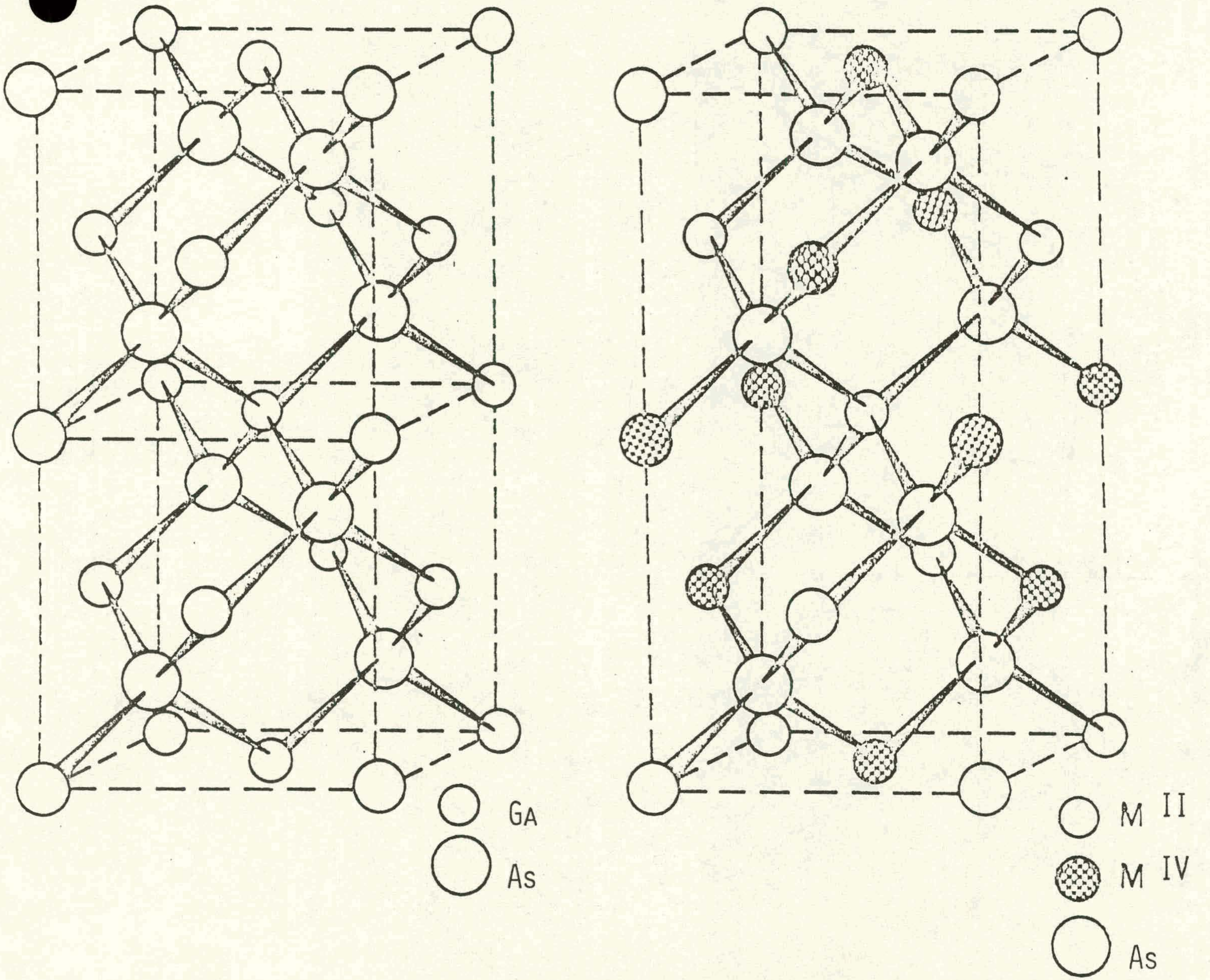
[D]"Assessment of the Tech. Required to Dev. Photovolt. Power Systems for Large Scale National Energy Appl.", JPL Special Publication 43-11, Oct. 15, 1974 (NSF-RA-N-74-072).

TABLE 2. II-IV-V_2 CHALCOPYRITE COMPOUNDS FOR SOLAR CELL APPLICATIONS

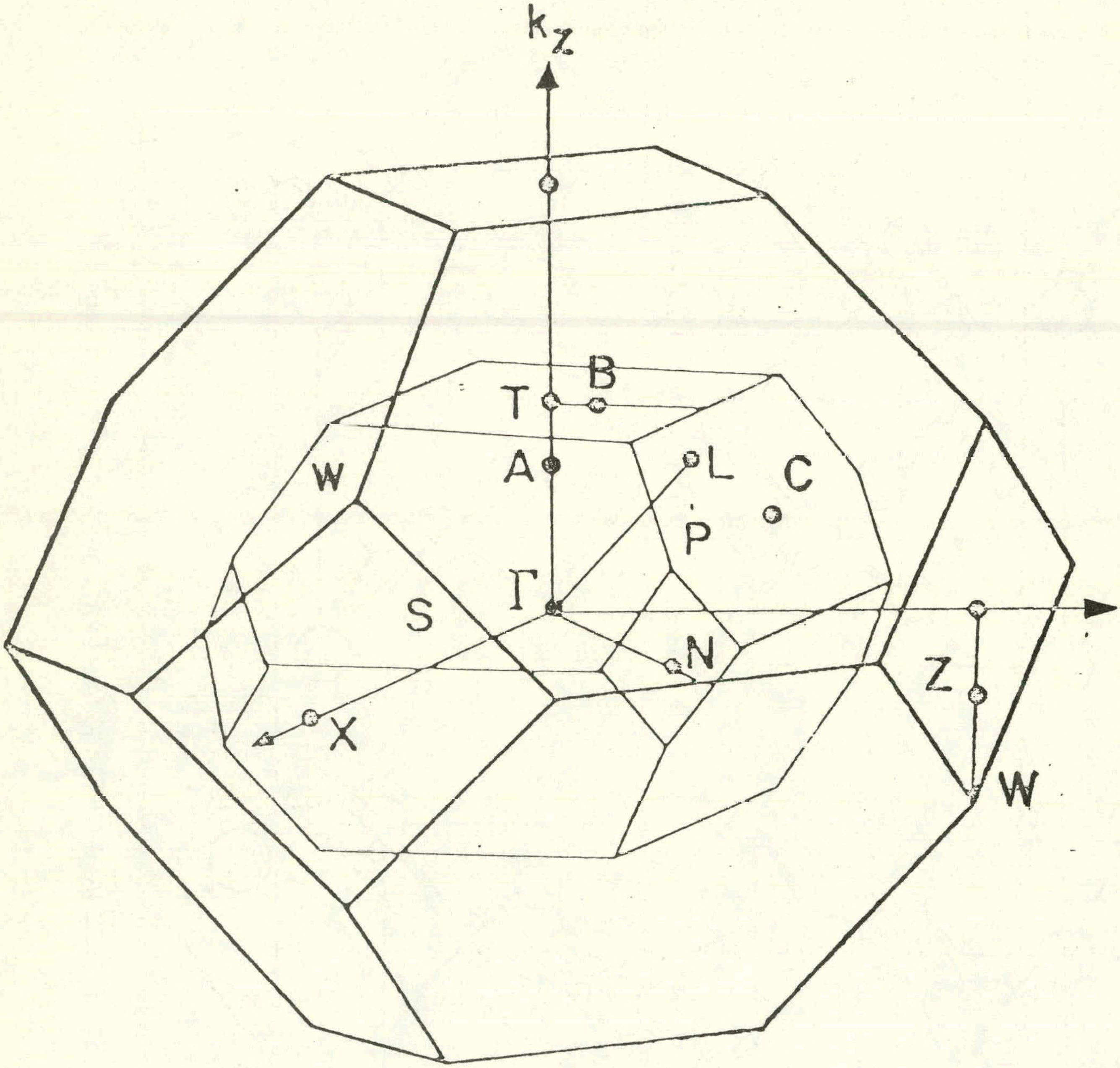
Crystal	Lattice Constant, a (Å)	Band Gap (eV)
$ZnGeAs_2$	5.672	1.15
$CdSnP_2$	5.900	1.17
$CdSiAs_2$	5.884	1.55
$ZnSnP_2$	5.651	1.66
$CdGeP_2$	5.741	1.72
$ZnSiAs_2$	5.608	1.74

TABLE 3. ROOM TEMPERATURE ELECTRICAL PROPERTIES OF II-IV-V_2 CHALCOPYRITE SEMICONDUCTORS

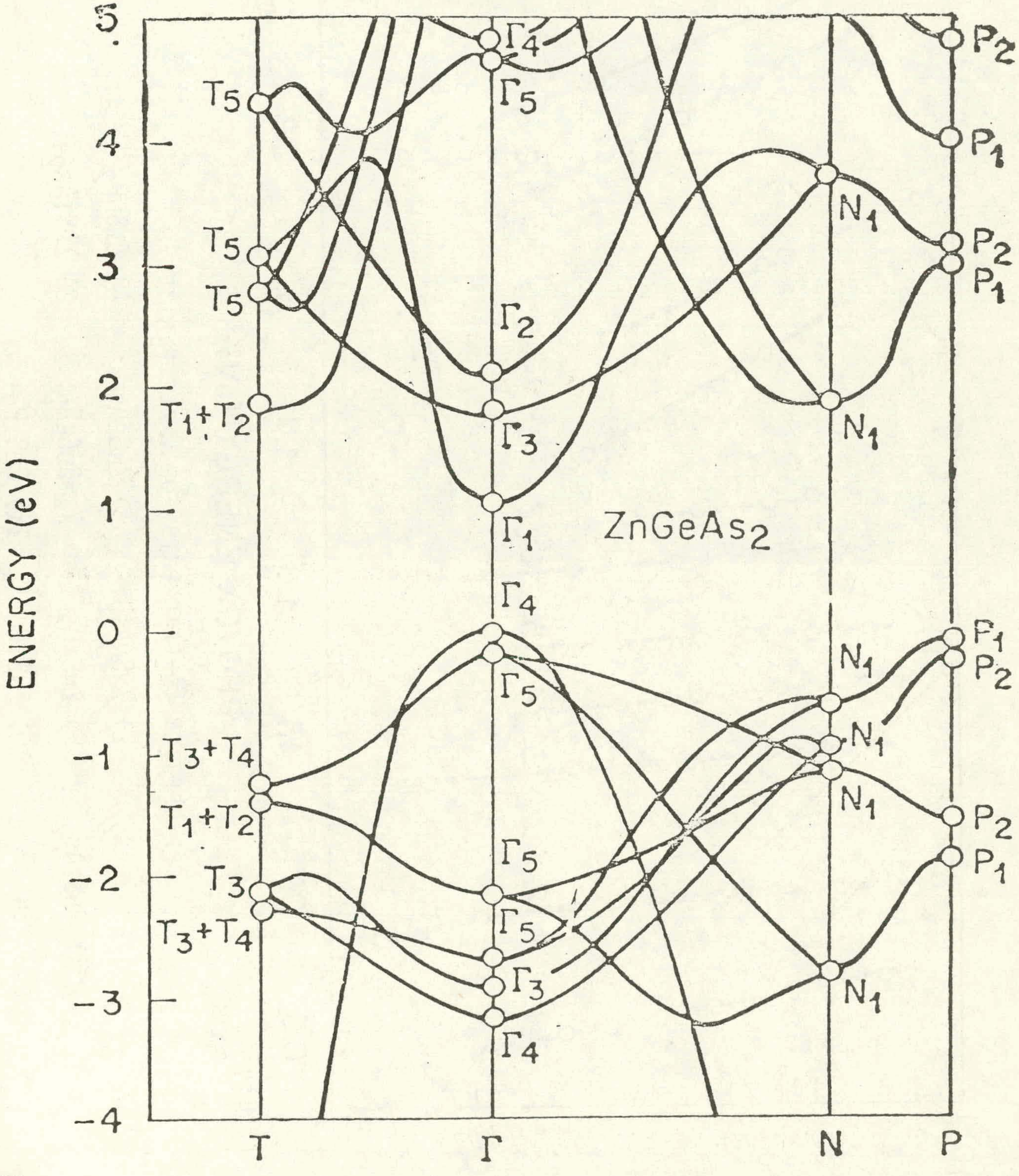
Crystal	Energy Gap (eV)	Growth Method	Carrier Concentration (cm^{-3})	Mobility (cm^2/volt sec)
$ZnGeAs_2$	1.15	Melt	$p = 4\times10^{18}$	23
$CdSnP_2$	1.17	Sn Solution	$n \sim 10^{15} - 10^{18}$	2000
$CdSiAs_2$	1.55	Melt	$p \sim 6\times10^{15} - 4\times10^{16}$	300 - 500
$ZnSnP_2$	1.66	Sn Solution	$p \sim 5\times10^{16}$	55
$CdGeP_2$	1.72	Melt	$n, p \sim 10^{15}$	100
$ZnSiAs_2$	1.74	Melt	$p \sim 10^{15}$	140
$CdSnAs_2$	0.26	Melt	$n \sim 10^{18}$	11,000



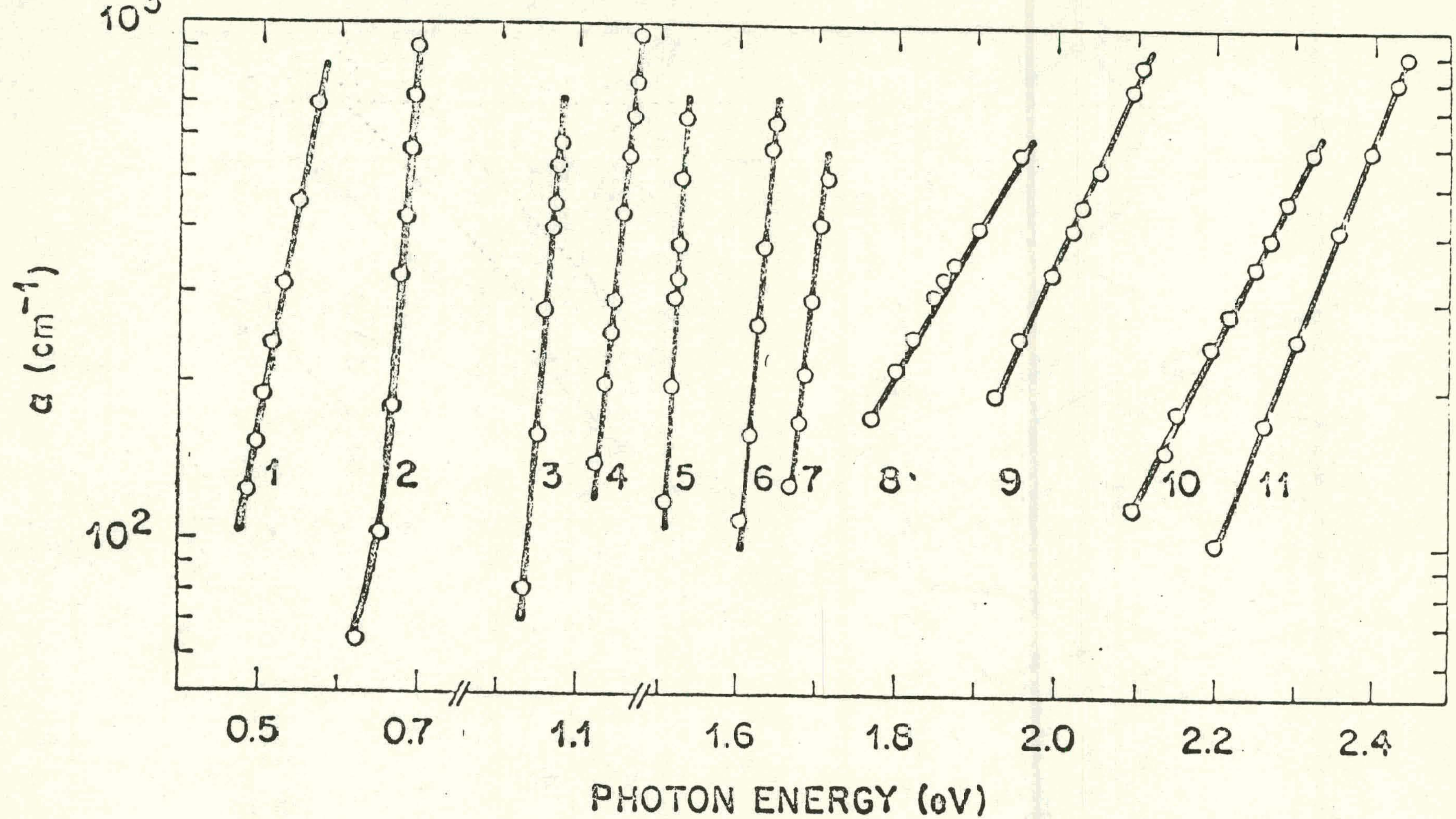
ZINCBLENDE STRUCTURE AND TETRAGONAL CHALCOPYRITE STRUCTURE



COMPARISON OF BRILLOUIN ZONES OF ZINCBLENDE AND CHALCOPYRITE LATTICES

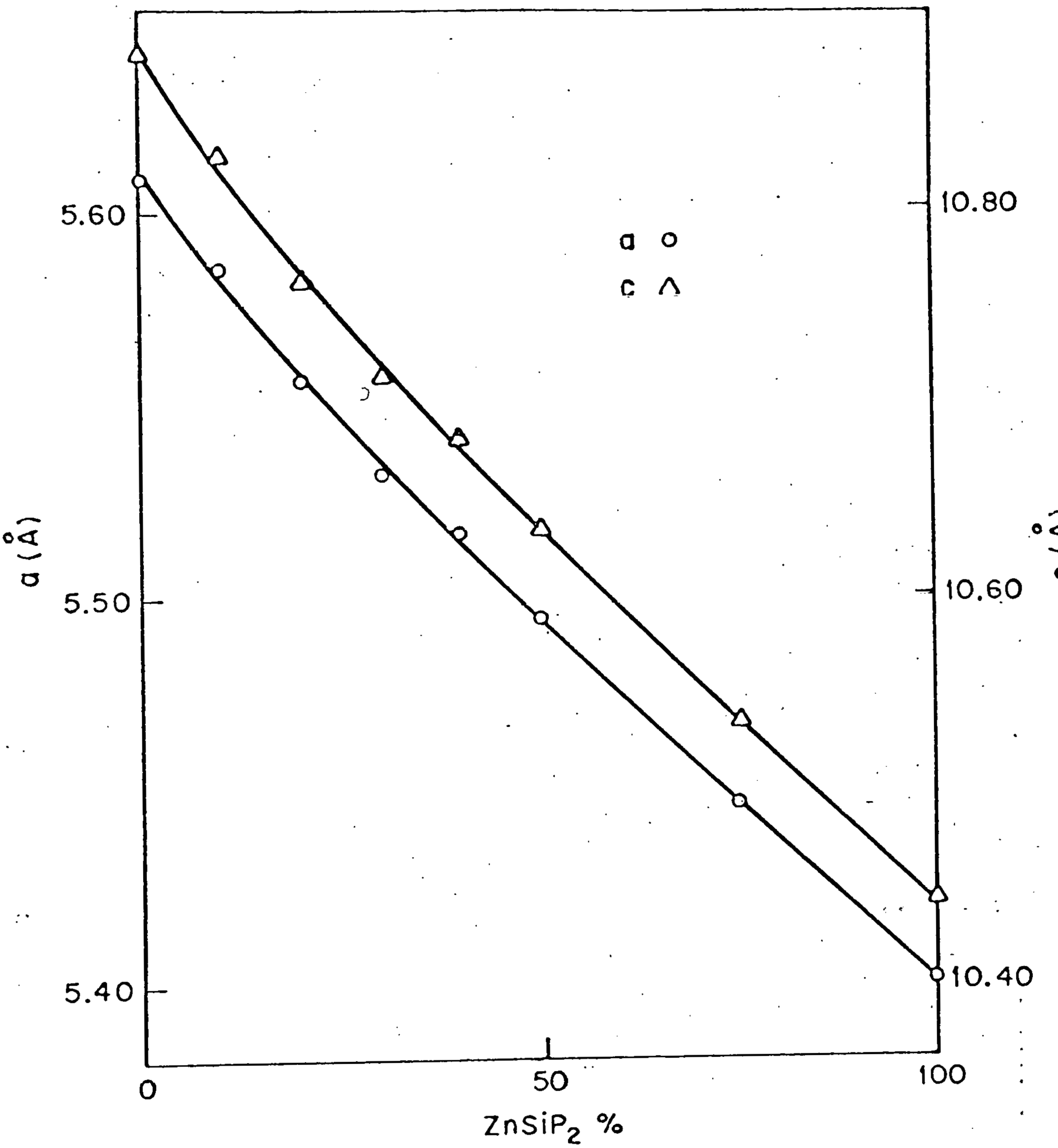


TYPICAL BAND STRUCTURE FOR CHALCOPYRITES



ABSORPTION COEFFICIENTS FOR CHALCOPYRITES

1) $CdGeAs_2$, 2) $ZnSnAs_2$, 3) $ZnGeAs_2$, 4) $CdSnP_2$
5) $CdSiAs_2$, 6) $ZnSnP_2$, 7) $CdGeP_2$, 8) $ZnSiAs_2$
9) $ZnGeP_2$, 10) $ZnSiP_2$, 11) $CdSiP_2$



LATTICE CONSTANTS IN THE $ZnSiAs_xP_{2-x}$ SYSTEM

PROPOSED RESEARCH - WORK STATEMENT

TASK 1. GROWTH OF CHALCOPYRITES FOR SOLAR CELLS.

A VAPOR PHASE EPITAXIAL REACTOR SYSTEM WILL BE FABRICATED AND USED TO DEPOSIT LAYERS OF $ZnSiAs_2$ AND $CdSiAs_2$ ON SI SUBSTRATES.

TASK 2. OPTIMIZATION OF GROWTH CONDITIONS.

THE EPITAXIAL REACTOR CONDITIONS WILL BE OPTIMIZED TO PRODUCE $ZnSiAs_2$ AND $CdSiAs_2$ LAYERS OF GOOD CRYSTAL QUALITY. MATERIAL SAMPLES OF AT LEAST 1% OF THE MONTH'S OUTPUT AND OF REPRESENTATIVE FORM AND QUALITY WILL BE SUPPLIED TO ERDA DESIGNATED SOURCES COMMENCING DURING THE THIRD MONTH OF THE CONTRACT EFFORT.

TASK 3. MATERIAL CHARACTERIZATION.

EXPERIMENTS WILL BE PERFORMED TO DETERMINE:

A. MATERIAL PHYSICAL AND CHEMICAL PROPERTIES

B. MATERIAL ELECTRICAL PROPERTIES

C. MATERIAL OPTICAL PROPERTIES

D. MATERIAL MECHANICAL PROPERTIES

E. ENVIRONMENTAL EFFECTS ON THE MATERIAL

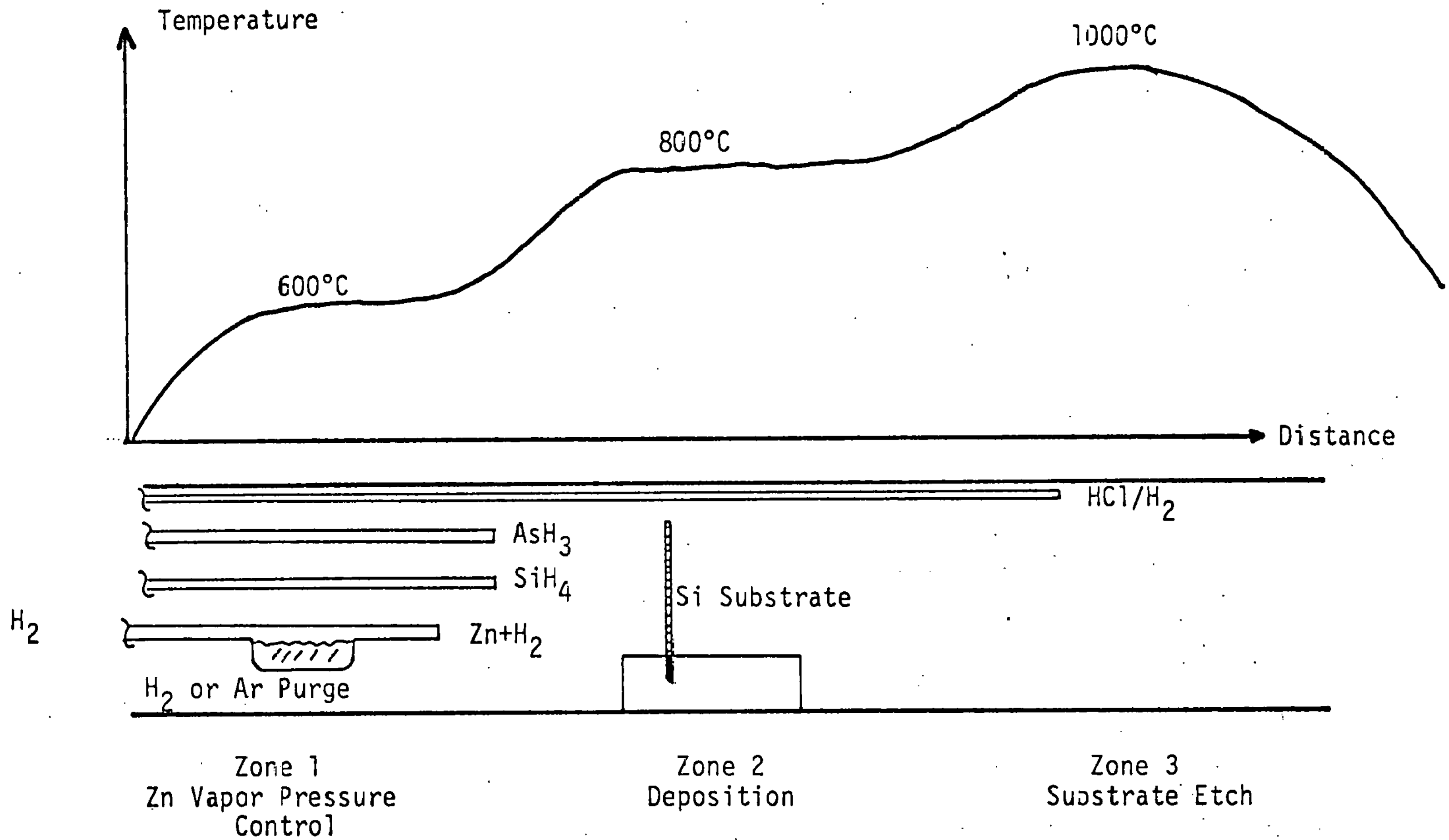
TASK 4. ENGINEERING AND ECONOMIC FACTORS.

ANALYSIS WILL BE PERFORMED TO DEFINE AND PROJECT THE TECHNOLOGY REQUIRED TO FABRICATE AND UTILIZE THE MATERIAL IN PHOTOVOLTAIC SOLAR CELL DEVICES AND ARRAYS. THESE ANALYSES WILL INCLUDE TECHNICAL AND ECONOMIC CONSIDERATIONS.

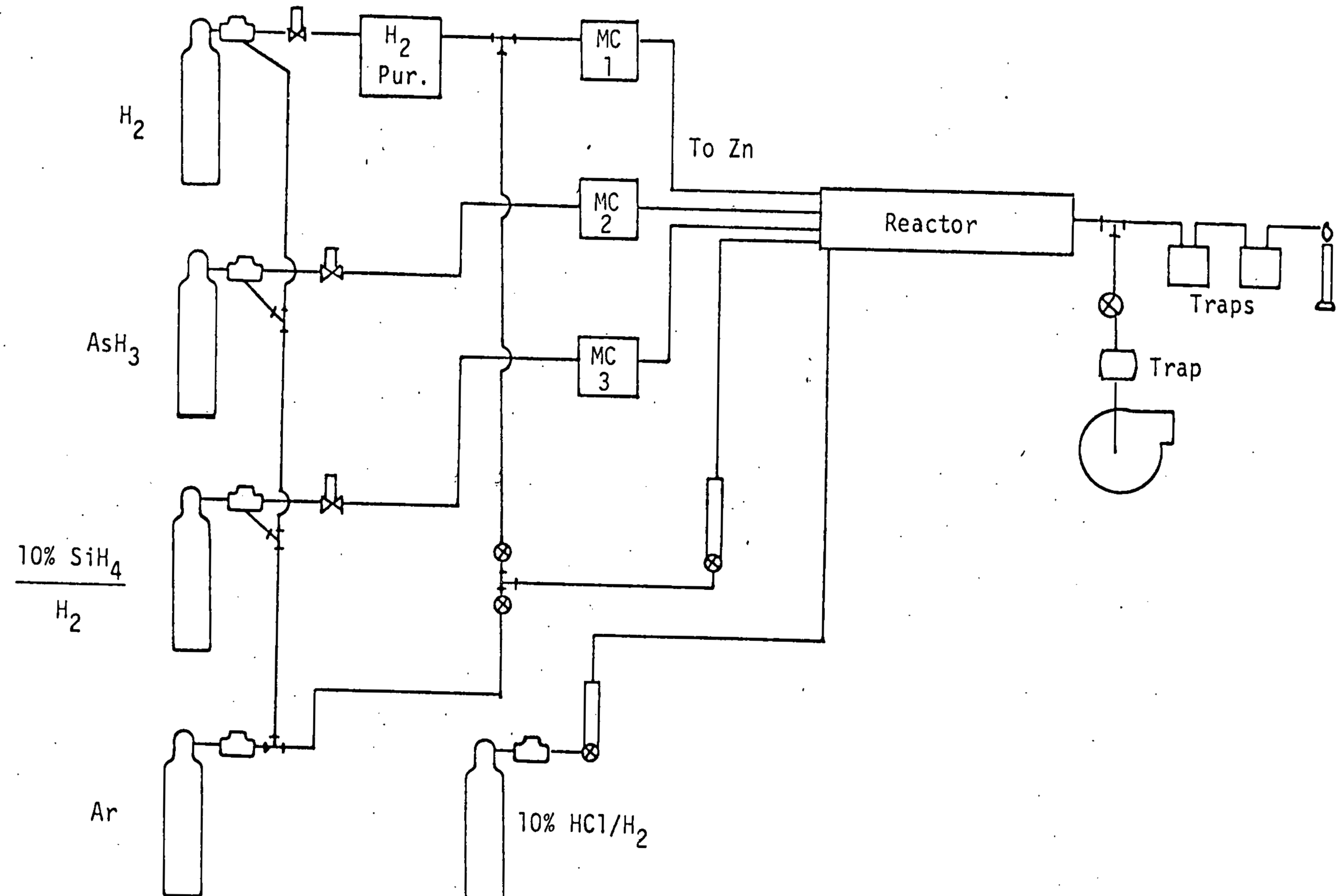
PROPOSED RESEARCH - WORK STATEMENT (CONT.)

TASK 5. FURTHER MATERIAL DEVELOPMENT.

AT THE CONCLUSION OF THE CONTRACT PERIOD, A RECOMMENDATION WILL BE MADE TO ERDA FOR A SUITABLE DEVELOPMENT PROGRAM TO EMPLOY CHALCOPYRITE MATERIALS IN MASS-PRODUCED PHOTOVOLTAIC DEVICES IF THE ANALYSIS OF TASK 4 INDICATES SUFFICIENT PROMISE RELATIVE TO EXISTING MATERIALS.



GROWTH SYSTEM AND TEMPERATURE PROFILE



GROWTH SYSTEM SCHEMATIC

TABLE 4. MATERIAL PROPERTY MEASUREMENTS AND CHARACTERIZATION

Property	Method of Measurement
Composition	Electron microprobe with MAGIC computer analysis of data. Wet chemical quantitative analysis.
Stiochiometry and purity	Electron microprobe and spark source mass spectroscopy used with electrical resistivity versus temp. data. X-ray diffraction and Auger analysis.
Crystallinity, structure & thermal expansion	X-ray diffraction, transmission electron microscopy, scanning electron microscopy.
Energy band gap, optical absorption, refractive index & dichroism	Optical transmission or reflection with polarized radiation relative to crystal axes. Ellipsometry.
Mobility; resistivity, carrier concentration	Van der Pauw technique for Hall effect and resistivity measurement.
Carrier lifetime and diffusion length	γ-ray and/or electron excitation of Schottky barrier diodes-short circuit current measurements.
Hardness, brittleness and plasticity	Standard scratch hardness test with Moh's scale. Elastic analysis calculations based on radius of curvature measurements. Broadening of X-ray diffraction peaks.
Deliquescence and hygroscopicity	Visual inspection and weight gain following exposure in controlled humidity environment.

TABLE 4. (CONT.)

PROPERTY	METHOD OF MEASUREMENT
DISPROPORTIONATION, THERMAL DECOMPOSITION AND CHEMICAL ACTIVITY	EXPOSURE TO ATMOSPHERIC GASES AT ELEVATED TEMPERATURE FOLLOWED BY VISUAL INSPECTION, OPTICAL AND SCANNING ELECTRON MICROSCOPY, ELECTRON BEAM MICROPROBE ANALYSIS.
TOXICITY	EFFECT OF CHRONIC EXPOSURE ON LABORATORY ANIMALS.

PROPOSED PROJECT: Thin-film Photovoltaics

ORGANIZATION: Lincoln Laboratory, M. I. T.

PERIOD OF PROPOSED GRANT: Oct. 1976 - Sept. 1978

PRINCIPAL INVESTIGATOR: J. C. C. Fan

Presented at the National Solar Photovoltaic Program Review Meeting
August 3 - 6, 1976
University of Maine at Orono
Orono, Maine 04473

OBJECTIVE OF PROJECT: Development of methods for the preparation of low-cost, efficient, thin-film solar cells.

To achieve this objective we will prepare large-grained films by laser crystallization, chemical vapor deposition, and vacuum deposition. We will also develop techniques for fabricating solar cells from these films.

ACTIVITY TO DATE

1. Constructed Nd:YAG laser system for irradiation of semiconductor films.
2. Prepared amorphous films of Si and GaAs by RF sputtering.
3. Irradiated amorphous films with scanned, focused laser beam.
4. Initiated theoretical calculation of temperature profile produced in thin films by scanned slit image of laser.
5. Prepared films of Sn-doped In_2O_3 by RF sputtering.

ABSTRACT

The ultimate objective of our thin-film photovoltaic program is the development of low-cost, efficient, thin-film solar cells. To prepare large-grain films for prototype solar cells, we will use laser crystallization, chemical vapor deposition (CVD), and vacuum deposition. We will then develop methods for fabricating solar cells from the films we prepare, placing particular emphasis on alternative techniques for junction formation, including indiffusion of dopants, ion implantation, multi-layer growth, and preparation of Schottky barriers. The application of transparent conductors such as Sn-doped In_2O_3 will also be investigated.

Although we already have some preliminary work underway on CVD and vacuum deposition methods, our major emphasis so far has been on the crystallization of thin films of Si and GaAs by irradiation with a Nd:YAG laser. The laser wavelength is $1.06\mu m$ (1.17 eV), close to the absorption edge of crystalline Si. At this wavelength the absorption coefficient α of crystalline Si is only about $20\,cm^{-1}$, and hence only a few percent of the laser power will be absorbed by a 10-μm-thick film.

For the same thickness of amorphous Si, however, the measured transmission is less than 0.1%, because amorphous Si has a much broader absorption edge than crystalline Si, with band-tailing states that narrow the effective band gap. Thus, amorphous Si films strongly absorb the Nd:YAG laser energy, and such films can easily be heated to a temperature where crystallization occurs ($\sim 700^oC$).

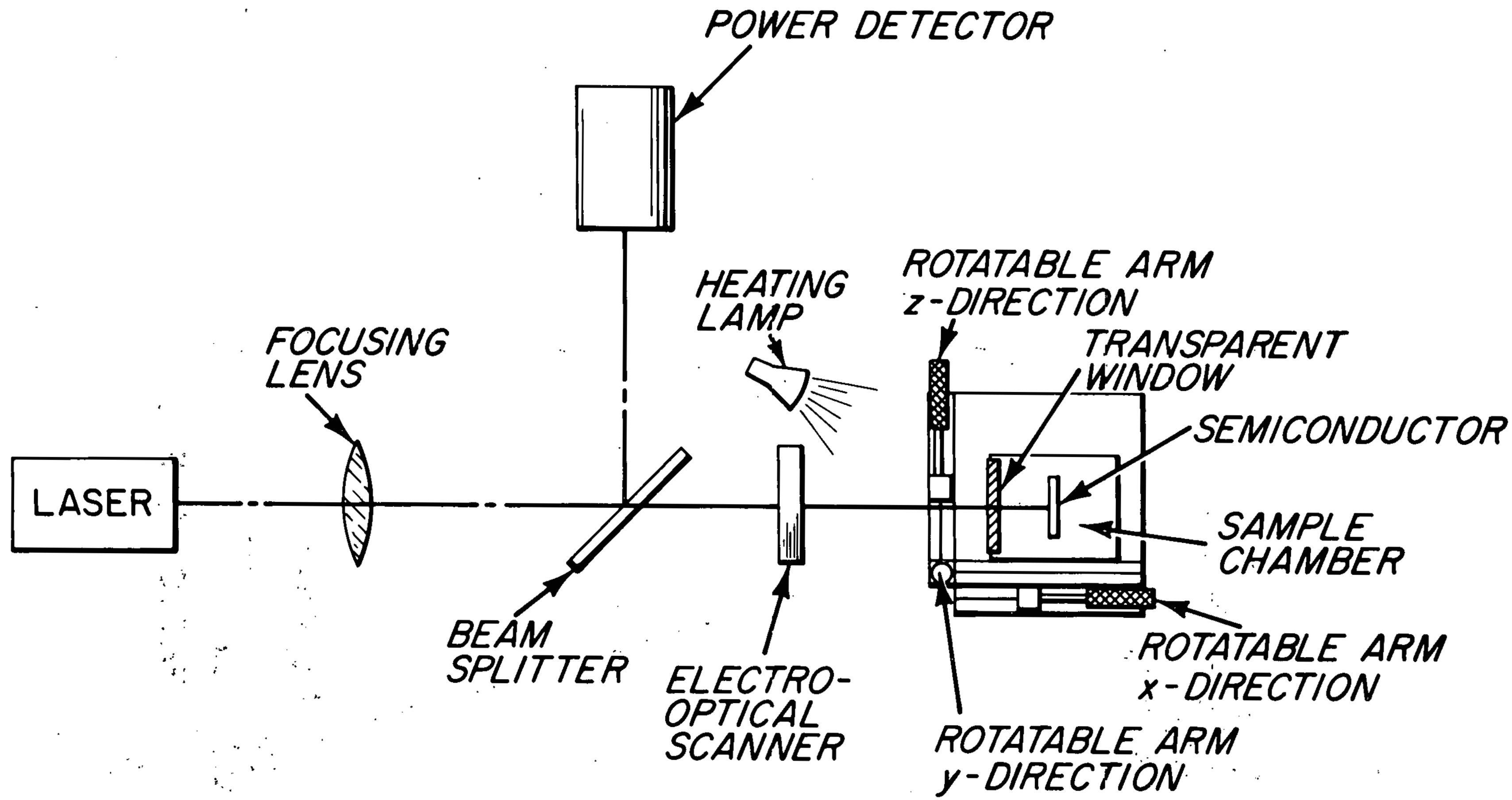
In initial experiments several amorphous Si films ranging from 6 to $11\mu m$ in thickness were deposited on single-crystal Al_2O_3 or fused silica substrates by RF sputtering. The substrate temperature during deposition was estimated to be 200^oC. The films were then irradiated with a 7-watt laser beam that was focused to form a spot typically about $50\mu m$ wide and $100\mu m$ long. The films were scanned laterally at the rate of ~1.2 cm/min with successive overlapping scan lines centered $25\mu m$ apart. The scan rate was limited by the mechanical drive system available and not by sample-heating requirements. Areas of about 0.5 x 0.25 cm were readily scanned.

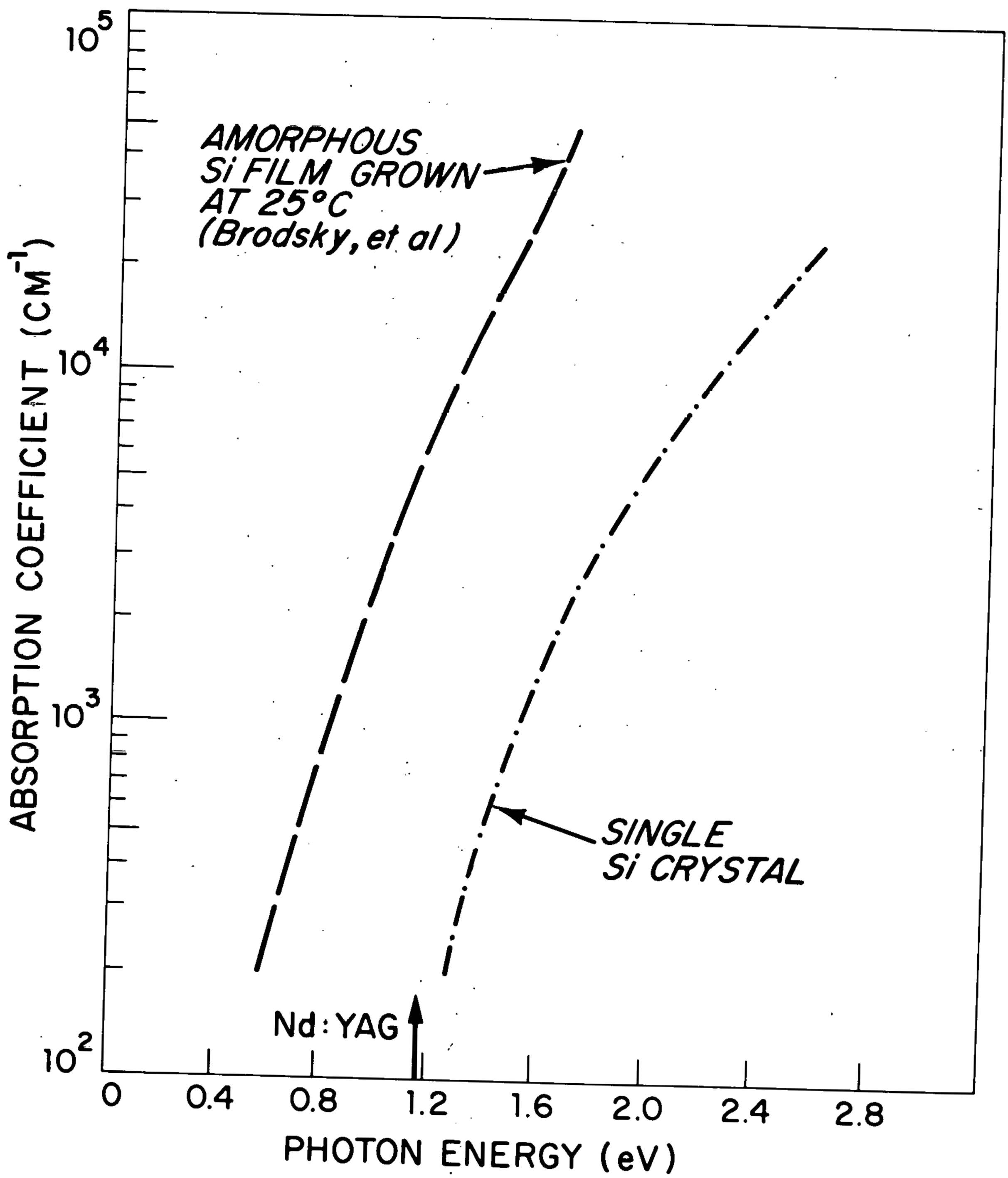
X-ray diffraction patterns for films that had been treated contained sharp Si lines, showing that the films had been crystallized. For some of the films, the lines were so sharp that their width could be attributed to instrumental broadening alone. However, since he x-rays sampled a large area (estimated to be about 1 x 5 mm), several Si lines were always present. Reflection electron diffraction pictures of the films taken in an electron

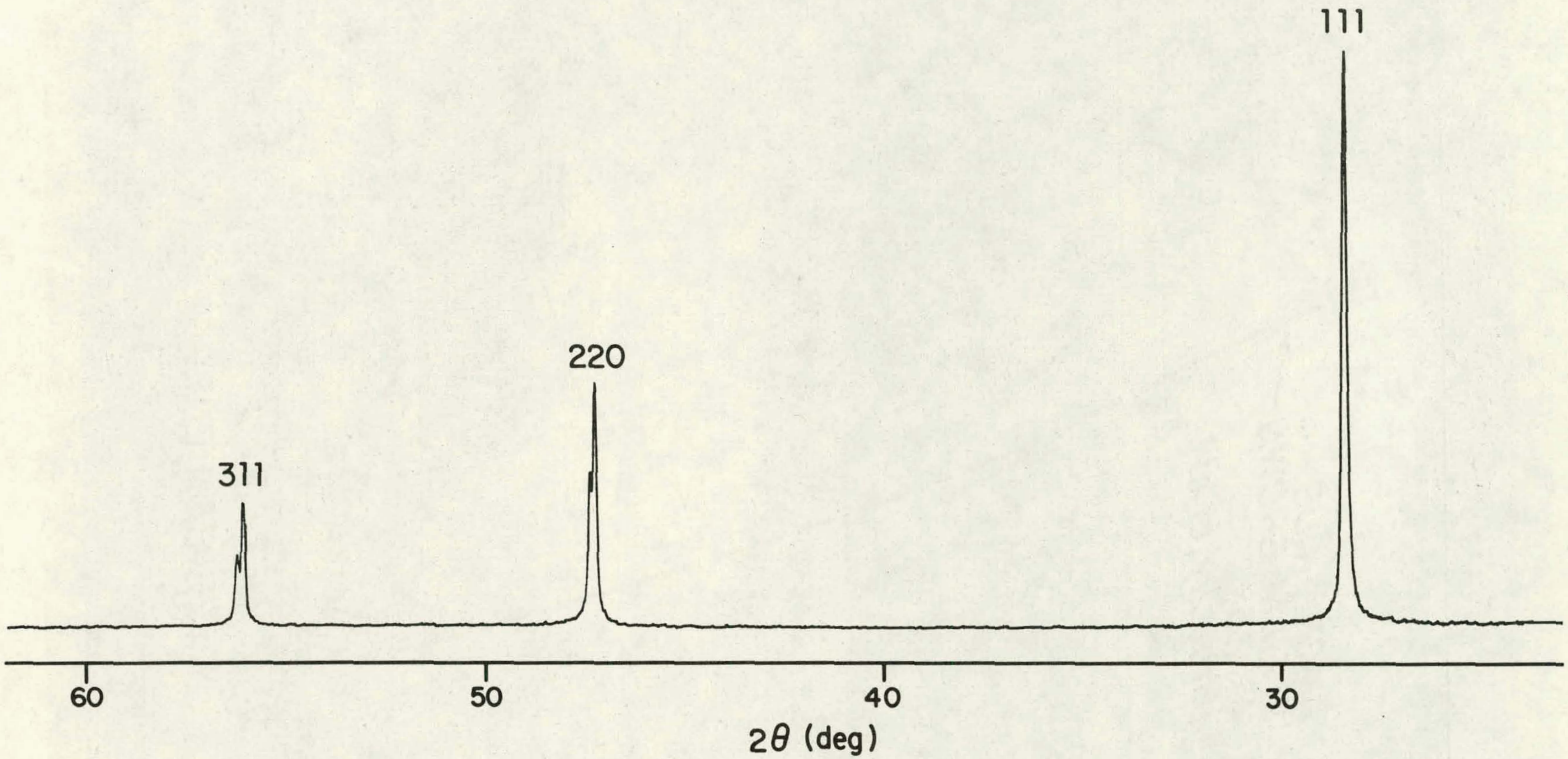
microscope contained diffraction spots indicating the presence of well-ordered crystallites. Linear motion of the microscope stage by 25μm did not significantly alter the spot patterns, indicating some crystallite sizes of at least 25μm.

Some preliminary results have also been obtained on laser crystallization of amorphous GaAs films prepared by RF sputtering. As in the case of Si, crystalline GaAs does not absorb significantly at 1.06μm, but amorphous GaAs does. Films of GaAs 2μm thick were crystallized at a laser power density about a factor of 10 lower than that required for Si. X-ray diffraction patterns showed sharp GaAs peaks, with the ⟨110⟩ peak the strongest, indicating that the crystallites have a preferred ⟨110⟩ orientation. There was no evidence of Ga peaks, indicating no large loss of As during crystallization. Optical microscopy showed features that vary from 20 up to several hundred micrometers, but the films have not been examined by reflection electron microscopy.

The above results indicate that laser crystallization is a promising method for the preparation of large-grained films of Si and GaAs. We next plan to establish optimum processing parameters - including beam shape, scan rate, laser power level, ambient temperature, and ambient atmosphere - for crystallization of amorphous Si and GaAs films. As a first step we have constructed an optical system for focusing the laser beam to a slit image about 3 mm high with a large aspect ratio. The films crystallized with this system will be characterized by a variety of techniques and used for the fabrication of solar cells.


POWER DETECTOR
HEATING LAMP
ROTATABLE ARM z-DIRECTION
TRANSPARENT WINDOW
FOCUSING LENS
SEMICONDUCTOR
LASER
SAMPLE CHAMBER
BEAM SPLITTER
ELECTRO-OPTICAL SCANNER
ROTATABLE ARM x-DIRECTION
ROTATABLE ARM y-DIRECTION


AMORPHOUS Si FILM GROWN AT 25°C (Brodsky, et al)
SINGLE Si CRYSTAL
Nd:YAG
ABSORPTION COEFFICIENT (CM^{-1})
10^5
10^4
10^3
10^2
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
PHOTON ENERGY (eV)


111
220
311
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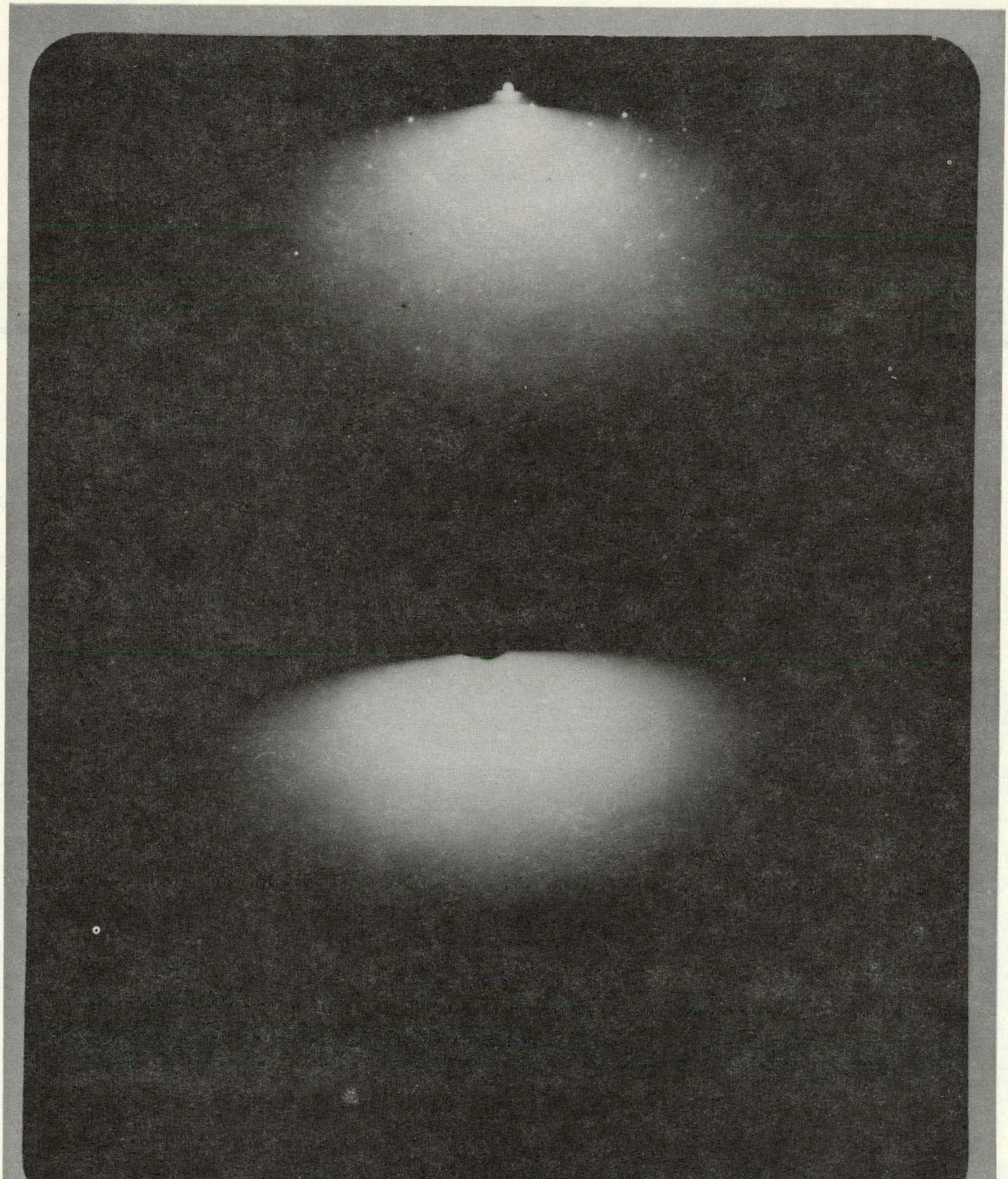
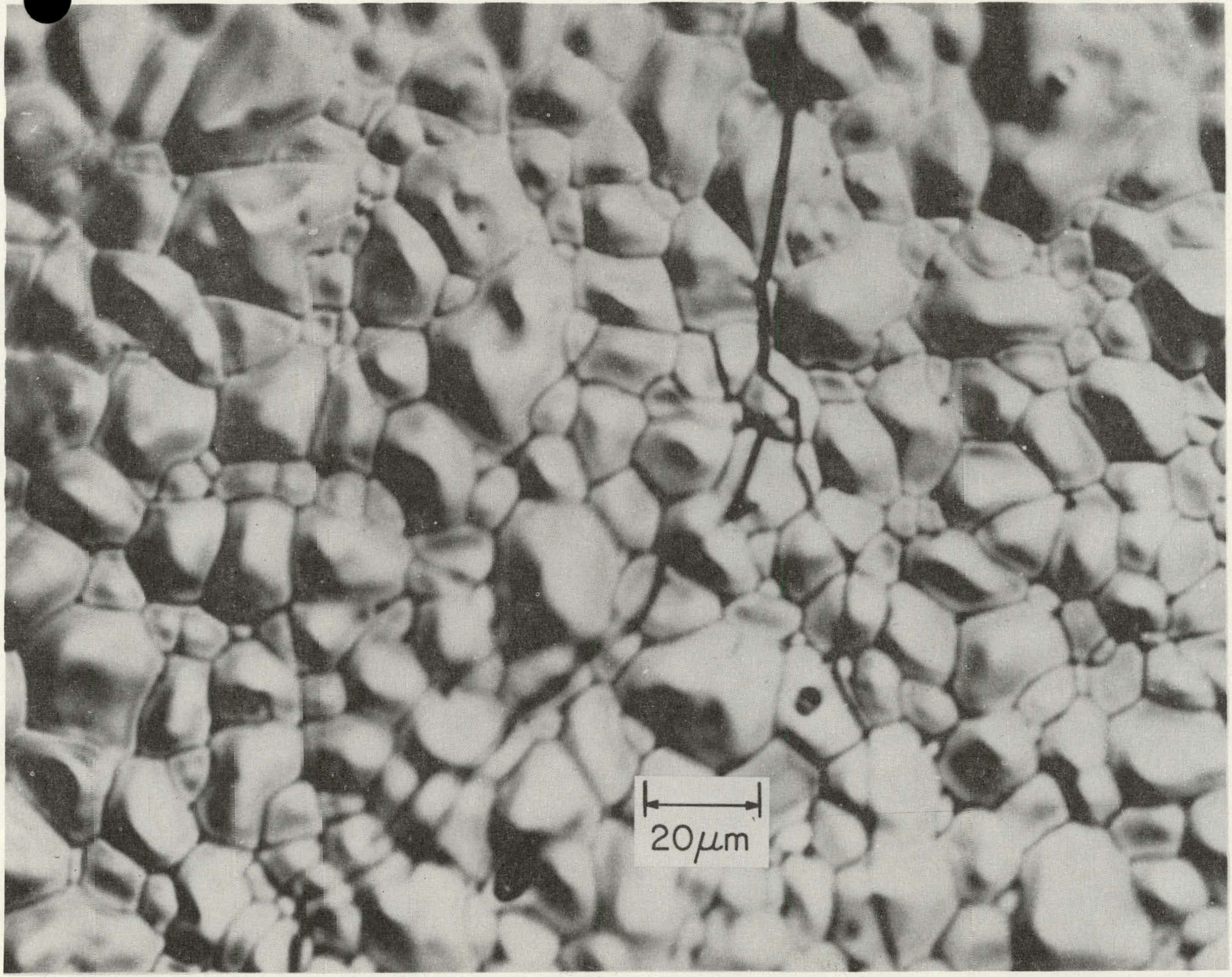
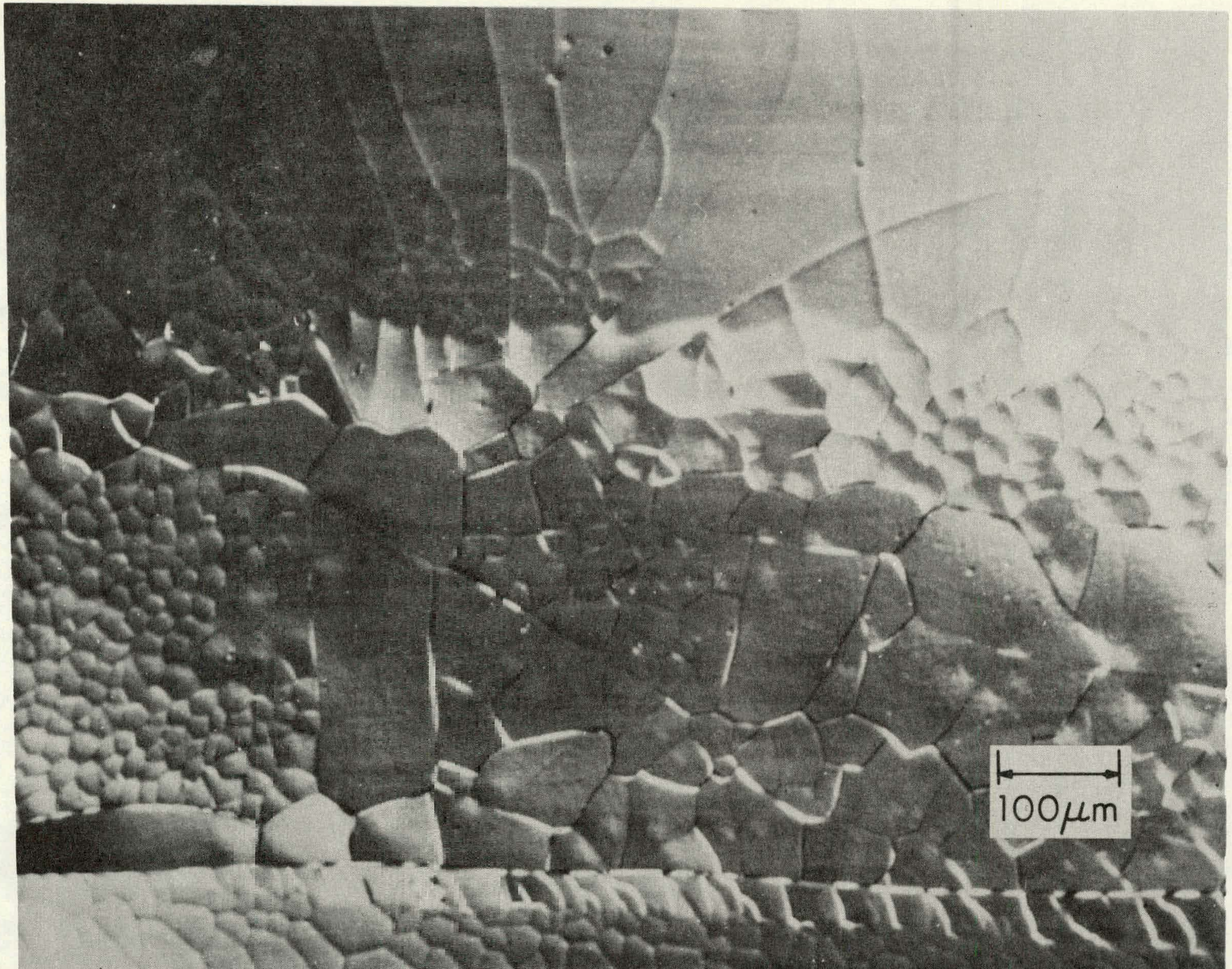
50
40
30
2θ (deg)




20μm


100μm

SUMMARY OF KEY RESULTS

1. Large-grained (> 25 μm), partially oriented Si and GaAs films have been prepared by irradiating amorphous films with a scanned Nd:YAG laser beam focused to a nearly circular spot.

2. An optical system has been constructed for focusing the laser beam to a slit image about 3 mm high with a large aspect ratio.

3. Transparent films of Sn-doped In_2O_3 with high conductivity have been prepared by deposition on heated substrates.

PLANNED ACTIVITY FOR NEXT 6 MONTHS

1. Establish optimum processing parameters - including laser scan rate, laser power level, ambient temperature, and ambient atmosphere - for crystallization of amorphous Si and GaAs films by laser irradiation.

2. Initiate preparation of GaAs films on low-cost substrates by CVD and vacuum deposition.

3. Begin fabrication of solar cells from Si and GaAs films.

InP/CdS THIN FILM GROWTH BY PLANAR REACTIVE DEPOSITION FOR TERRESTRIAL SOLAR CELLS

HUGHES

HUGHES AIRCRAFT COMPANY
RESEARCH LABORATORIES

KEN ZANIO AND LEW FRAAS
PRINCIPAL INVESTIGATORS
HUGHES RESEARCH LABORATORIES
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Malibu, California

PRESENTED AT
THE NATIONAL SOLAR PHOTOVOLTAIC
PROGRAM REVIEW MEETING

AUGUST 3 – 6, 1976

UNIVERSITY OF MAINE AT ORNO
ORNO, MAINE 04473

ABSTRACT

InP/CdS Thin Film Solar Cell by Planar Reactive Deposition

Ken Zanio and Lew Fraas
Hughes Research Laboratories

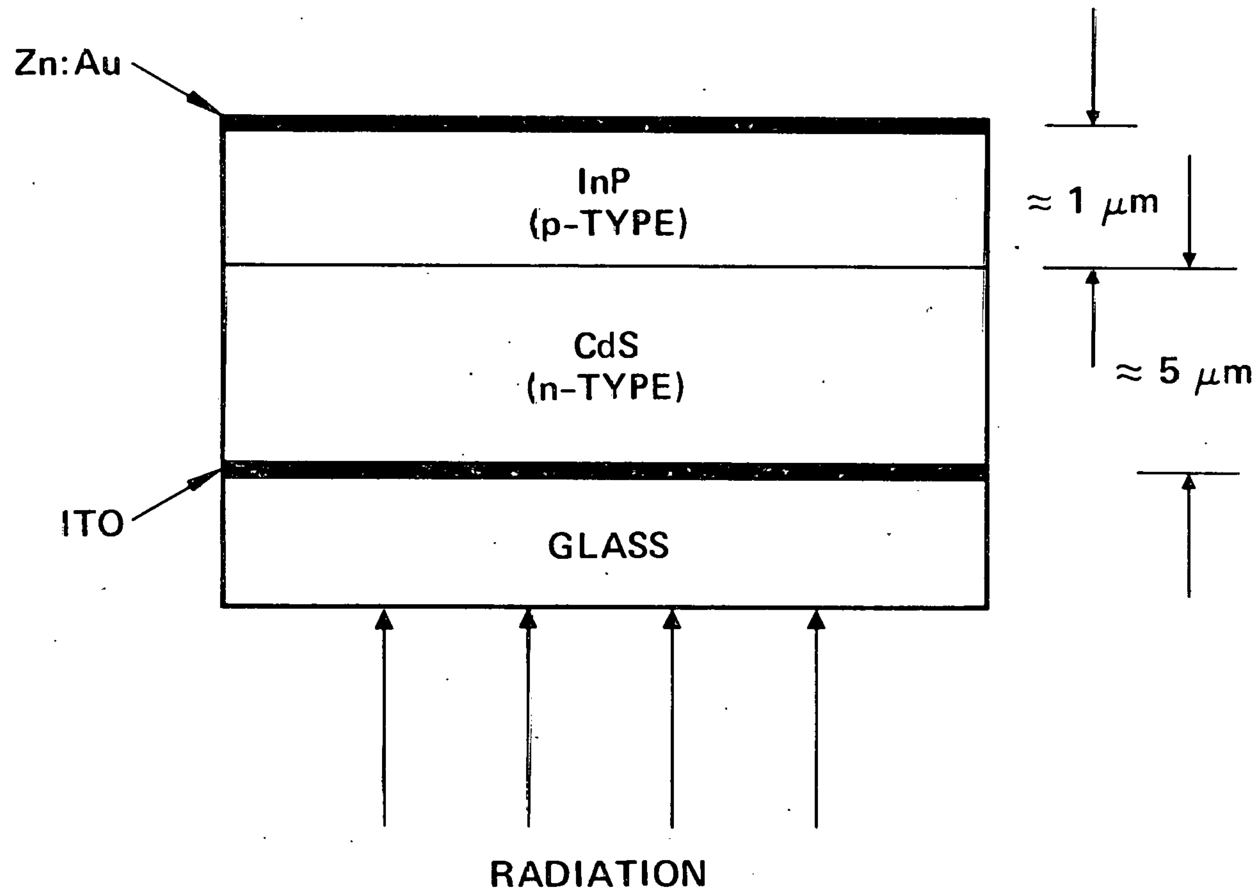
An all thin film InP/CdS terrestrial solar cell is proposed. A thin film configuration is now possible as a result of the successful epitaxial deposition of thin films of InP on single crystals of (0001) CdS at temperature below 390°C by the planar reactive deposition (PRD) technique and the formation of large (20 to 40 μm) single crystals of CdS through recrystallization. The PRD technique is a new thin film technique which offers the advantages of the chemical vapor deposition and molecular beam techniques but is not restricted by their limitations. In this technique indium metal is evaporated from a planar source in the presence of P_2 to form InP. The P_2 is available from the decomposition of phosphine introduced into the indium source chamber. Besides being a low temperature technique this process is scalable and is inherently clean because of the presence of H_2. The CdS films are thermally evaporated and undergo recrystallization in a post-evaporative H_2S heat treatment at about 450°C. They have been formed on soda-lime glass overcoated with indium-tin-oxide. This InP on CdS approach offers a quasi-single crystal all thin film solar cell with an active InP material crystallite width to thickness ratio of better than ten to one. Assuming 10% cell efficiency and 500 MW/year production capacity it is projected that cell costs based upon this thin film approach will be on the order of $250 per peak kW, which is attractive for large scale utility applications.

SOLAR CELL PARAMETERS

Pair	InP/CdS	$GaAs/Ga_{0.2}Al_{0.8}As$
Semiconductor Theoretical Efficiency (%)	28.0	28.5
Theoretical Efficiency with Window (%)	23.2	24.8
Observed Efficiency (%)	12.5	20
Lattice Mismatch (%)	0.3	0.15
Minority Carrier Mobility (cm^2/V-sec)	4500	6000
Semiconductor Bandgap (eV)	1.27 (Direct)	1.43 (Direct)
Window Bandgap (eV)	2.42	2.6
Spike	No	No
Processing Temperature (°C)	350	700

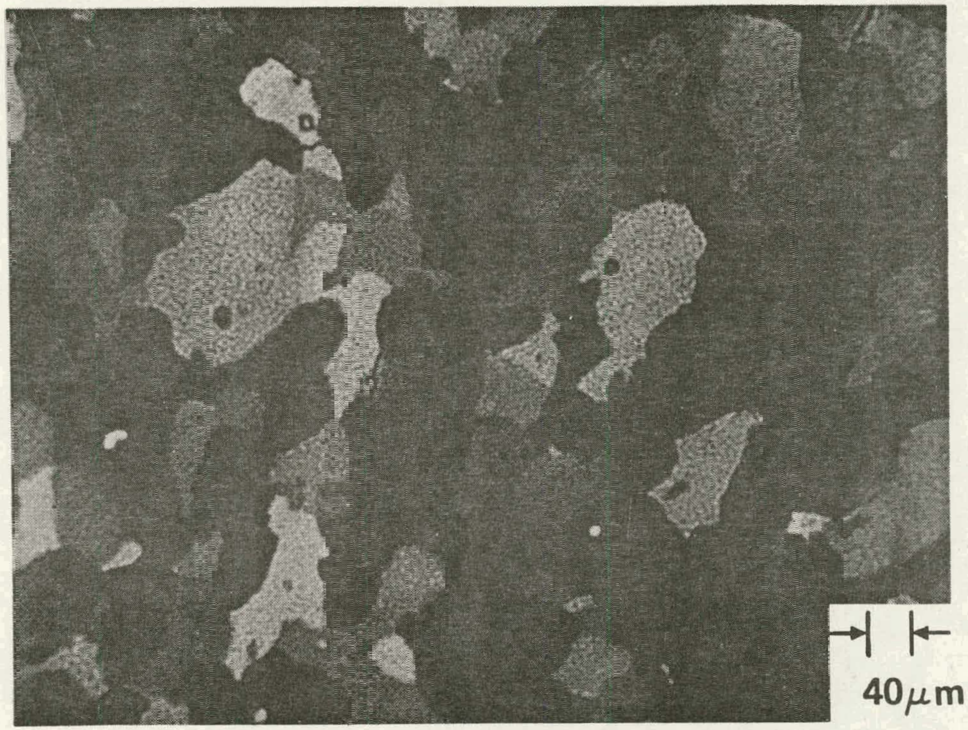
InP/CdS CELL STRUCTURE

4410–5

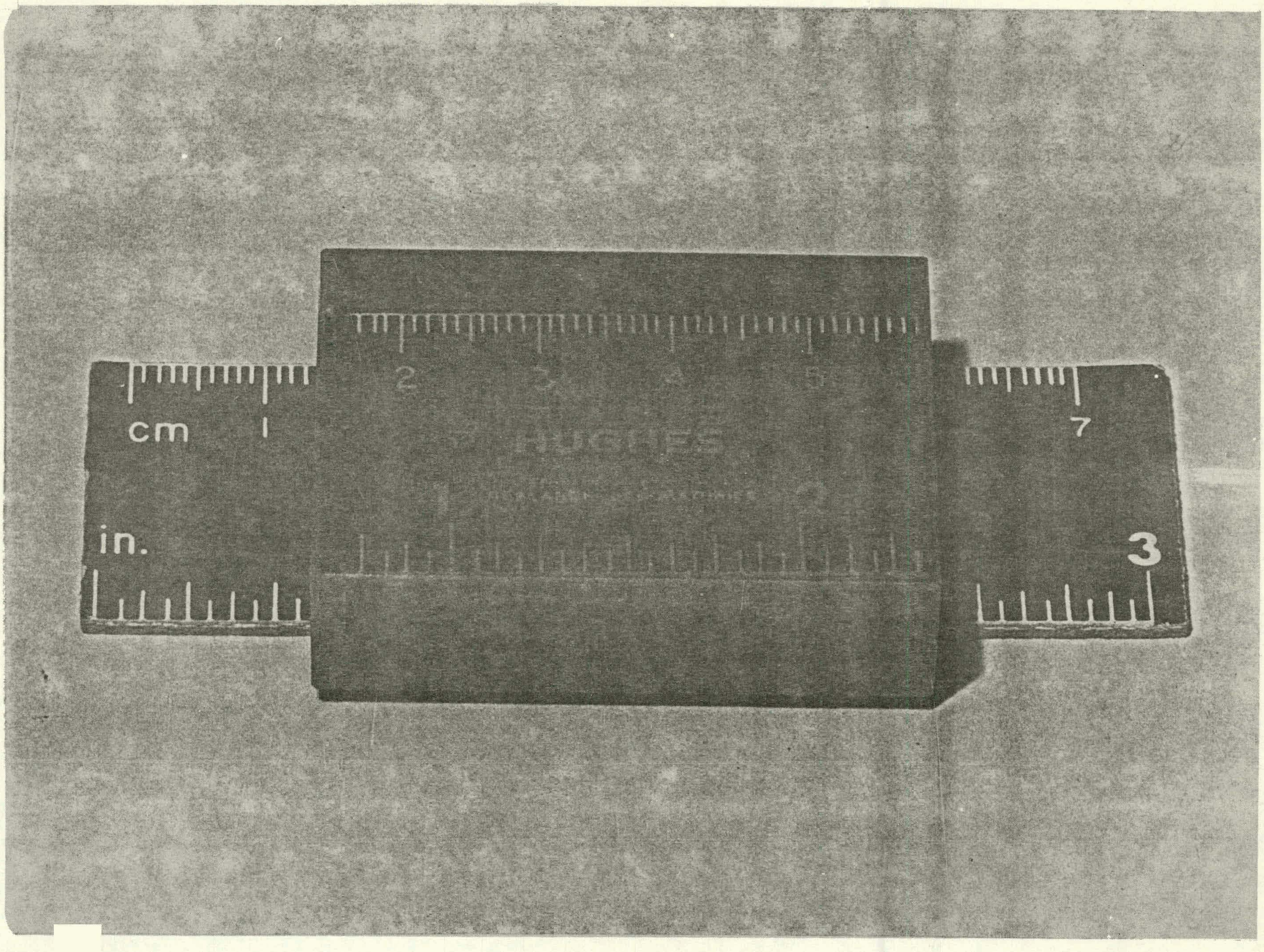


RECRYSTALLIZED CdS

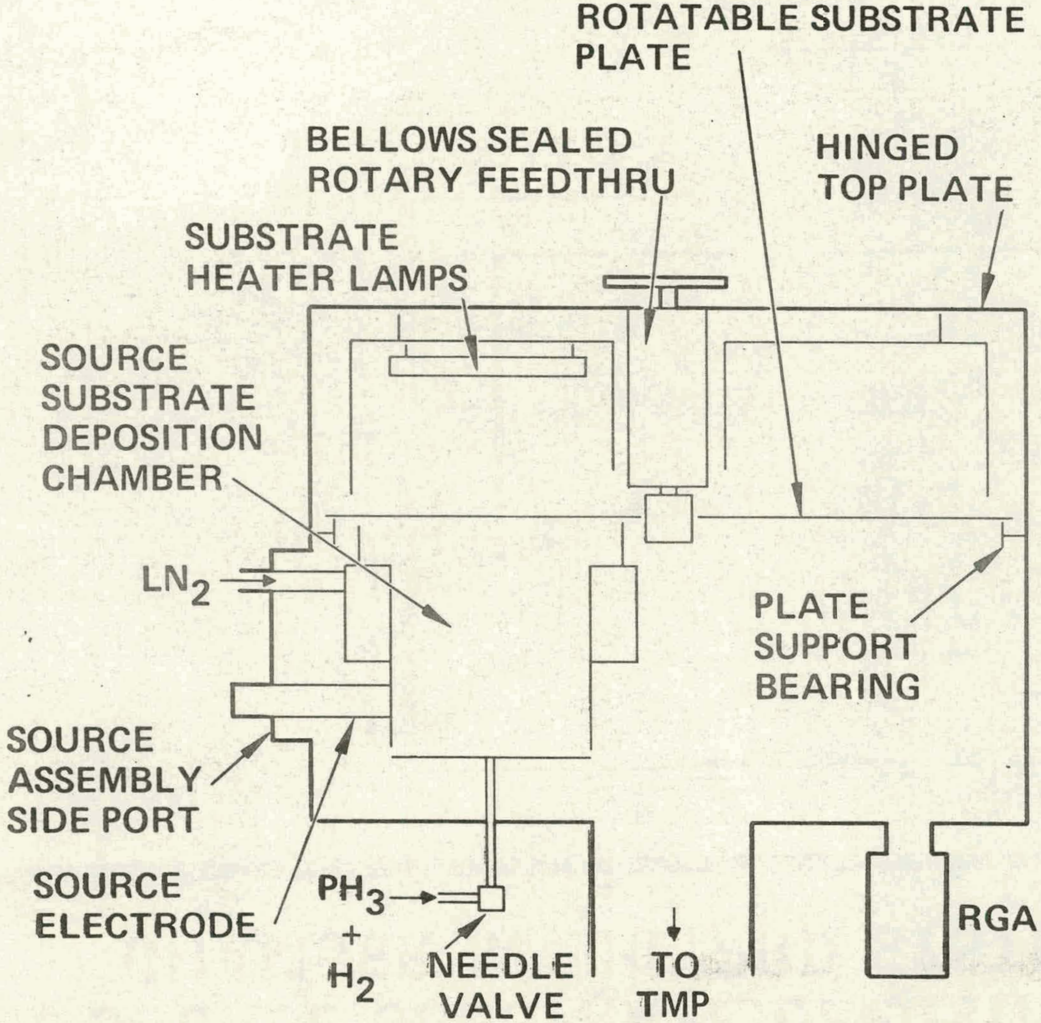
4410–2



CdS/ITO/GLASS


cm
1
7
HUGHES
in.
3

PLANAR REACTIVE DEPOSITION CHAMBER



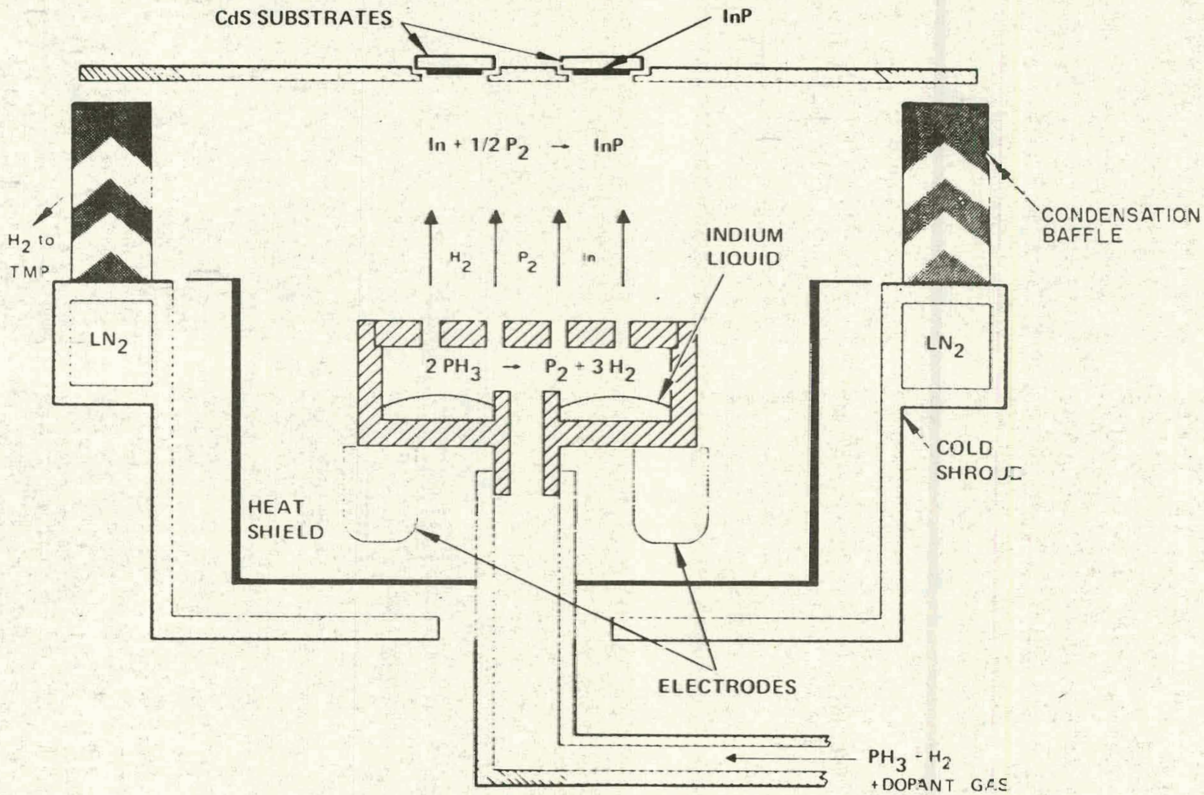
ADVANTAGES

1 NO BELL JAR BAKE OUT REQUIRED

2 BAKE OUT OF LN_2 SHROUD ENCLOSED DEPOSITION CHAMBER AUTOMATIC

3 VITON A O-RINGS FACILITATE LOADING

SOURCE SUBSTRATE DEPOSITION CHAMBER IN THE PRD SYSTEM

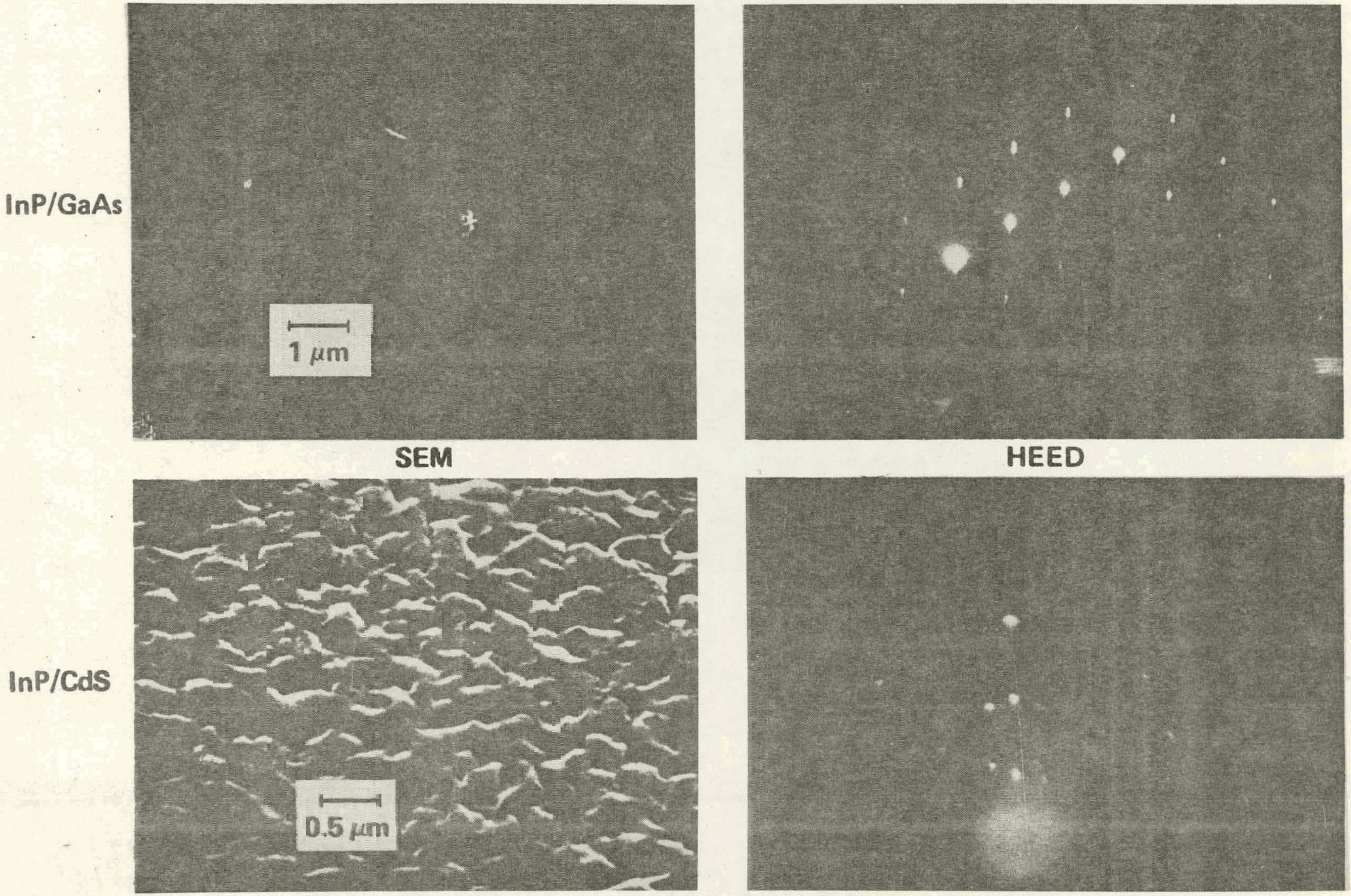


FEATURES

1. PRESENCE OF H_2 REDUCES OXYGEN CONTAMINATION
2. USE OF PH_3 ALLOWS PLANAR GEOMETRY – HUGHES PATENT
3. PLANAR GEOMETRY ALLOWS INCREASED PRODUCTION RATES
4. NEGLIGIBLE WASTE OF INDIUM

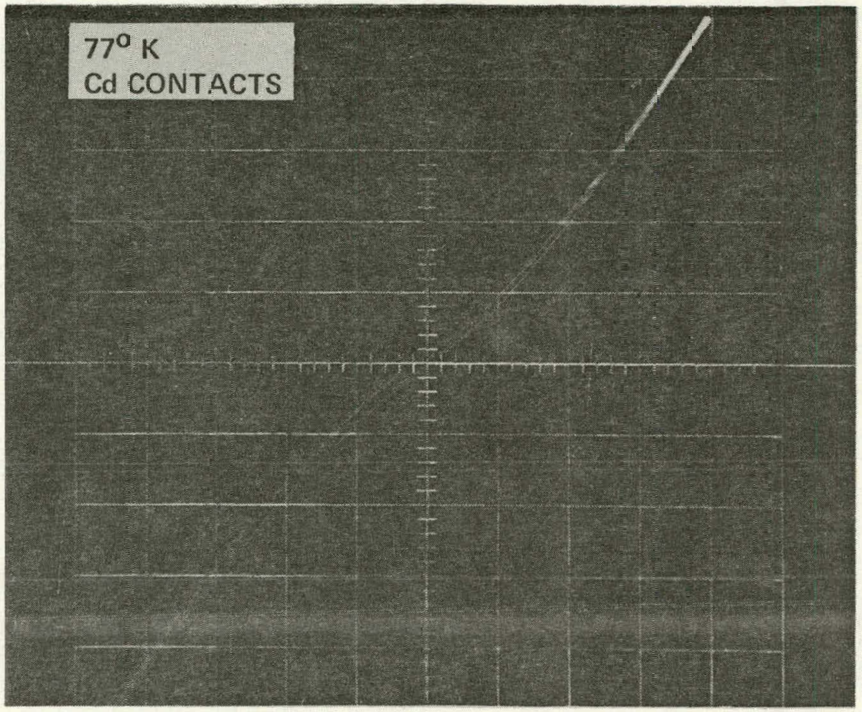
FILMS DEPOSITED BY PRD (1 μm THICK)

5191-5



InP:Cd I-V CHARACTERISTICS

4410–1



SUMMARY OF InP/CdS PROGRESS

- THE CdS/InP SYSTEM IS THEORETICALLY MORE FAVORABLE THAN ANY OTHER THIN FILM SYSTEM
- THE SINGLE CRYSTAL RESULTS ARE PROMISING
- RECRYSTALLIZED CdS IS A SUITABLE AND ALREADY-DEVELOPED SUBSTRATE FOR InP
- InP FILMS HAVE BEEN EPITAXIALLY DEPOSITED ON CdS
- THE ELECTRICAL PROPERTIES OF InP ARE FAVORABLE. MORE SPECIFICALLY; THE SHEET RESISTANCE IS LOW AND THE CONTACTS ARE OHMIC FOR P-TYPE InP.

PROPOSED ALL THIN FILM InP/CdS SOLAR CELL PROGRAM

- OPTIMIZE PRD InP EPILAYERS ON C-AXIS ORIENTED CdS SINGLE CRYSTALS
- ESTABLISH IMPURITY CONCENTRATION LEVELS AND DOPING CONTROLS FOR PRD InP FILMS ON SINGLE CRYSTAL CdS
- CONSTRUCT AND EVALUATE AN InP(THIN FILM)/CdS(SINGLE CRYSTAL) SOLAR CELL
- DETERMINE THAT GOOD EPITAXY CAN BE OBTAINED FOR DIFFERENT CdS CRYSTAL ORIENTATIONS
- DEPOSIT AND EVALUATE InP FILMS ON NONRECRYSTALLIZED AND RECRYSTALLIZED THIN FILM CdS SUBSTRATES
- ESTABLISH ALL THIN FILM CELL EFFICIENCIES AND PRINCIPLE PROBLEM AREAS
- DEVELOP A MODEL CHARACTERIZING THE ALL THIN FILM InP/CdS SOLAR CELL

THIN POLYCRYSTALLINE FILMS OF INDIUM PHOSPHIDE ON LOW-COST SUBSTRATES

U.S. Energy Research and Development Administration
Division of Solar Energy
Photovoltaic Branch

Contract in negotiation with
ERDA Albuquerque Operations Office

Period of Contract: 12 months

Value: To be determined in negotiations

Ralph P. Ruth
Program Manager

Rockwell International
Electronics Research Division
3370 Miraloma Avenue
Anaheim, CA 92803

Co-principal Investigators: P. D. Dapkus and W. I. Simpson

Planned Subcontract:

Department of Materials Science and Engineering
Stanford University
Stanford, CA 94305

Principal Investigator: R. H. Bube

Presented at the

NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

August 3-6, 1976

University of Maine at Orono
Orono, Maine 04473

THIN POLYCRYSTALLINE FILMS OF INDIUM PHOSPHIDE ON LOW-COST SUBSTRATES

Rockwell International
Electronics Research Division
3370 Miraloma Avenue
Anaheim, CA 92803

August 1976

A program has been proposed for the development of methods for making thin-film polycrystalline indium phosphide (InP) photovoltaic cells on inexpensive substrates. A cooperative effort is involved. The Rockwell Electronics Research Division will apply the metal-organic-hydride chemical vapor deposition (MO-CVD) method to the formation of InP films first on single-crystal and subsequently on low-cost polycrystalline or amorphous substrates, and the Stanford University Department of Materials Science and Engineering, as subcontractor, will deposit cadmium sulfide (CdS) and/or similar semiconductor compounds and alloys on the InP films to form hetero-junction device structures. These will then be evaluated for their photovoltaic properties.

The objectives of the work are itemized in Figure 1. The overall objective is to conduct fundamental studies which may lead to a low-cost, high-efficiency, long-life photovoltaic solar cell using a polycrystalline film of InP.

A 12-month program, that will involve 27 manmonths of scientific and engineering effort at Rockwell and another 22 manmonths of faculty and technical staff effort at Stanford, has been planned to pursue the following specific technical objectives: 1) development of the MO-CVD process for growth of good-quality single-crystal or polycrystalline films of InP on carefully-selected low-cost substrate materials; 2) evaluation of the structural, electrical, and optical properties of the resulting InP films; 3) formation of heterojunction device structures by deposition of films of other semiconductors on the InP films, and evaluation of the photovoltaic properties of these composites; and 4) analysis and projection of future costs of large-scale quantities of photovoltaic solar cells made by the process.

In addition, a goal established by ERDA requires that any proposed device configuration should lead, within a period of five years at most, to the ability to produce solar photovoltaic cells having 10 percent AM1 efficiency. This technical goal may not be achieved during the performance period of a twelve-month contract, but it will provide a continuous guideline for conduct of the program. Whereas conversion efficiencies well in excess of 10 percent have been demonstrated in solar cells fabricated in single-crystal forms of several semiconductors, there are only a limited number of semiconductors that offer reasonable likelihood of achieving such efficiencies in thin polycrystalline films deposited on low-cost substrate materials. InP has shown considerable promise as a single-crystal solar cell material, and technical considerations indicate that it is an excellent candidate for successful attainment of the required technical and cost goals in a thin-film configuration.

To meet the above objectives a program consisting of seven specific tasks is planned (Figure 2). These are 1) development of the MO-CVD process for InP film growth; 2) identification, evaluation, and development of inexpensive substrate materials; 3) growth of InP films by MO-CVD on inexpensive substrate materials; 4) evaluation of the properties of the InP films; 5) formation and evaluation of heterojunction photovoltaic device structures on the InP films (Stanford subcontract); 6) analysis and projection of cell performance and costs; and 7) preparation of reports and data and participation in ERDA program review meetings.

The principal technical problems (Figure 3) to be solved in the program are 1) establishing preferred CVD process parameters (temperature, reactant concentrations, carrier gas composition, doping impurities, growth rate) for acceptable properties for the films grown on various substrate materials; 2) identifying suitable substrate materials that will survive the environment of the MO-CVD process and be potentially inexpensive and available in large areas, yet be as favorable as possible to InP grain growth; 3) achieving adequate grain size in the films on inexpensive substrates to provide satisfactory solar cell properties; and 4) achieving hetero-junction structures of InP and CdS (or other semiconductor) having the required photovoltaic properties.

In the proposed approach Rockwell will apply the MO-CVD technique to the formation of films of InP on both single-crystal and low-cost polycrystalline or amorphous substrates, employing a reactor system such as that shown schematically in Figure 4. The principal reaction to be used involves direct combination of triethylindium and phosphine in the reactor chamber at elevated temperature, although the possibility of forming the addition compound of these two reactants outside the reactor chamber at low temperatures will also be investigated (Figure 5).

During the time that the MO-CVD method is being developed specifically for the InP system--initially on suitable single-crystal substrates--concentrated attention will be given to the problem of identifying, preparing, and evaluating potentially inexpensive substrate materials that are (or can be) available in large areas and will tolerate the experimental environment of the MO-CVD process. Some of the materials considered for use as substrates are listed in Figure 6, and include certain high-temperature glasses, polycrystalline ceramics (such as fired aluminas), glass-ceramics, and selected metals--especially molybdenum, tungsten, and Kovar. Thermal expansion coefficients of some of these materials are shown as a function of temperature in Figure 7.

When adequate substrate materials become available--and after the main CVD parameters required for satisfactory deposition of InP are established with reasonable certainty--they will be used for growth of films of InP that will probably be polycrystalline. Special techniques of substrate surface preparation and CVD film nucleation and growth will be invoked in order to achieve sufficient crystal grain size in the films to permit good heterojunction properties and acceptably high photovoltaic power conversion efficiencies. Appropriate doping methods will be applied to achieve the required properties in the InP base material.

When InP films first become available, irrespective of the nature of the substrate, they will be characterized for their various material properties at Rockwell and - to some extent - at Stanford. These initial films and others prepared throughout the program will be used at Stanford for the formation of heterojunction structures by deposition of films of CdS (primarily), ZnCdS, ZnSe, and possible ZnSSe, using vacuum deposition or chemical spraying techniques. The photovoltaic properties of the resulting heterojunctions will be evaluated at Stanford, using electrical contact methods developed earlier in the program both at Stanford and at Rockwell.

Finally, attention will be given to cost analyses of the cell structures as prepared in the program, and projections of the possible costs of large quantities of the cells in future years will be periodically adjusted to make use of technical developments in the on-going work.

The tentative program plan is indicated in the diagram of Figure 8. Details remain to be developed in the contract negotiations with ERDA and in subsequently arranging the subcontract with Stanford.

THIN POLYCRYSTALLINE FILMS OF INDIUM PHOSPHIDE ON LOW-COST SUBSTRATES

OVERALL OBJECTIVE

- TO CONDUCT FUNDAMENTAL STUDIES WHICH MAY LEAD TO A LOW-COST HIGH-EFFICIENCY LONG-LIFE PHOTOVOLTAIC SOLAR CELL USING A POLYCRYSTALLINE FILM OF InP

SPECIFIC TECHNICAL OBJECTIVES

- TO DEVELOP THE METALORGANIC CHEMICAL VAPOR DEPOSITION PROCESS FOR GROWTH OF GOOD-QUALITY SINGLE-CRYSTAL OR POLYCRYSTALLINE FILMS OF InP ON CAREFULLY-SELECTED LOW-COST SUBSTRATE MATERIALS

- TO EVALUATE THE STRUCTURAL, ELECTRICAL, AND OPTICAL PROPERTIES OF THE RESULTING InP FILMS

- TO FORM HETEROJUNCTION DEVICE STRUCTURES BY DEPOSITION OF FILMS OF OTHER SEMICONDUCTORS ON THE InP FILMS, AND TO EVALUATE THE PHOTOVOLTAIC PROPERTIES OF THESE COMPOSITES

- TO ANALYZE PRESENT COSTS AND PROJECT FUTURE COSTS OF LARGE-SCALE QUANTITIES OF PHOTOVOLTAIC SOLAR CELLS MADE BY THE PROCESS UNDER DEVELOPMENT

THIN POLYCRYSTALLINE FILMS OF INDIUM PHOSPHIDE ON LOW-COST SUBSTRATES

SPECIFIC PROGRAM TASKS

1. DEVELOPMENT OF MO-CVD PROCESS FOR InP FILM GROWTH
2. IDENTIFICATION, EVALUATION, AND DEVELOPMENT OF INEXPENSIVE SUBSTRATE MATERIALS
3. GROWTH OF InP FILMS BY MO-CVD ON INEXPENSIVE SUBSTRATE MATERIALS
4. EVALUATION OF InP FILM PROPERTIES
5. FORMATION AND EVALUATION OF HETEROJUNCTION PHOTOVOLTAIC DEVICE STRUCTURES ON InP FILMS (STANFORD SUBCONTRACT)
6. ANALYSIS AND PROJECTION OF CELL PERFORMANCE AND COSTS
7. PREPARATION OF REPORTS AND DATA AND PARTICIPATION IN PROGRAM REVIEW MEETINGS

THIN POLYCRYSTALLINE FILMS OF INDIUM PHOSPHIDE ON LOW-COST SUBSTRATES

PRINCIPAL TECHNICAL PROBLEM AREAS

- ESTABLISHING PREFERRED MO-CVD PROCESS PARAMETERS (TEMPERATURE, REACTANT CONCENTRATIONS, CARRIER GAS COMPOSITION, DOPING IMPURITIES, GROWTH RATE) FOR BEST PROPERTIES OF InP FILMS DEPOSITED ON VARIOUS SUBSTRATES USED

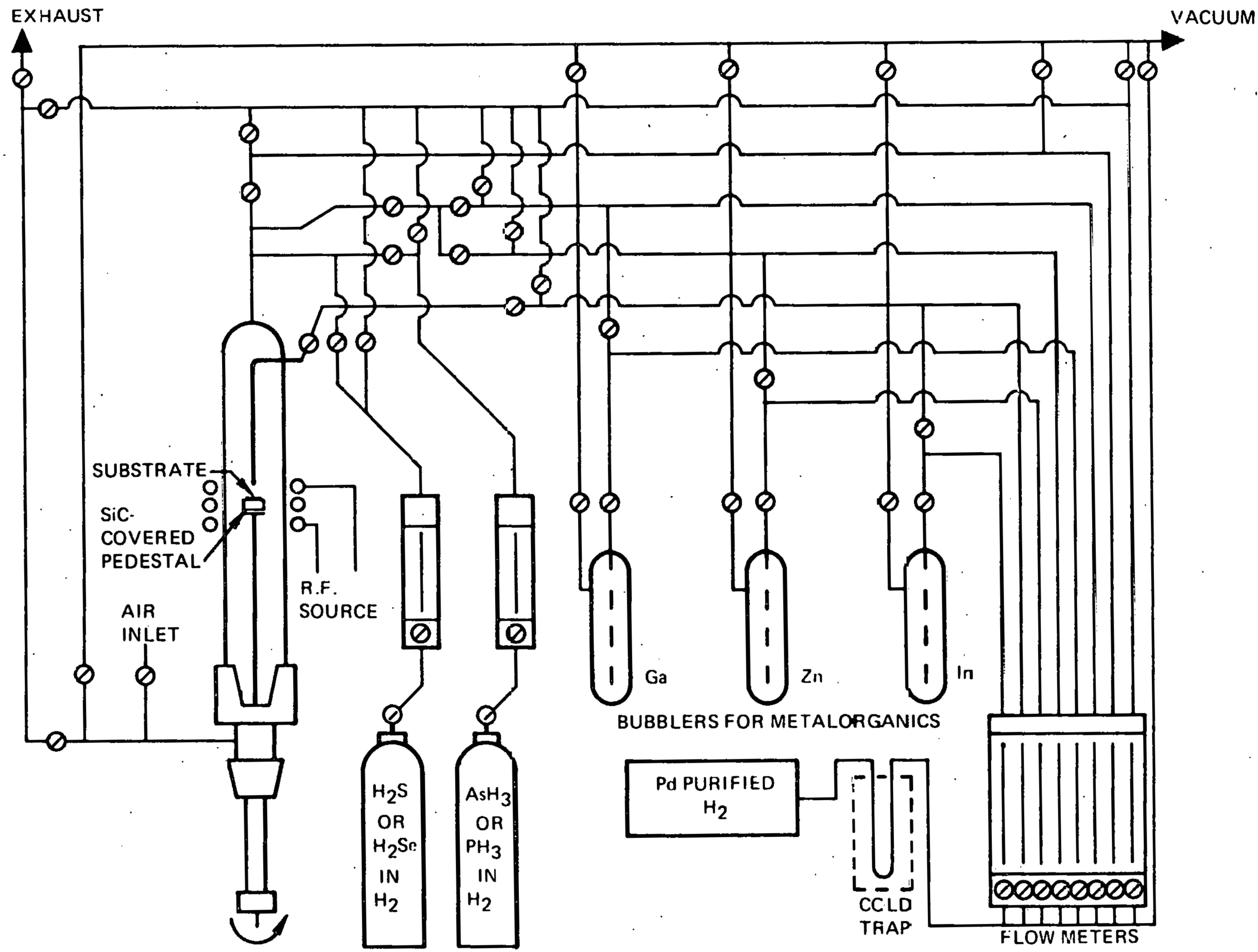
- IDENTIFYING SUITABLE SUBSTRATE MATERIALS THAT WILL SURVIVE ENVIRONMENT OF MO-CVD PROCESS, BE POTENTIALLY INEXPENSIVE AND AVAILABLE IN LARGE AREAS, YET BE AS FAVORABLE AS POSSIBLE TO InP GRAIN GROWTH

- ACHIEVING ADEQUATE GRAIN SIZE IN InP FILMS ON INEXPENSIVE SUBSTRATES TO PROVIDE SATISFACTORY SOLAR CELL PROPERTIES

- ACHIEVING HETEROJUNCTION STRUCTURES OF InP AND CdS (OR OTHER SEMICONDUCTOR) HAVING THE REQUIRED PHOTOVOLTAIC PROPERTIES.

THIN POLYCRYSTALLINE FILMS OF INDIUM PHOSPHIDE ON LOW-COST SUBSTRATES

Schematic Diagram of Reactor System for Deposition of InP and Other Films by MO-CVD Process



THIN POLYCRYSTALLINE FILMS OF INDIUM PHOSPHIDE ON LOW-COST SUBSTRATES

PRINCIPAL CHEMICAL REACTIONS IN InP CVD

DIRECT METALORGANIC-HYDRIDE REACTION IN CVD REACTOR

$$(C_2H_5)_3In + PH_3 \longrightarrow InP + 3C_2H_6$$

(AT ELEVATED TEMPERATURES: 600-700°C)

FORMATION OF ADDITION COMPOUND OUTSIDE REACTOR CHAMBER

$$(C_2H_5)_3In + PH_3 \xrightarrow[\text{room temp}]{} (C_2H_5)_3In{:}PH_3$$

$$(C_2H_5)_3In{:}PH_3 \xrightarrow[\text{heat}]{-C_2H_6} \left[(C_2H_5)_2InPH_2\right]$$

$$\left[(C_2H_5)_2InPH_2\right] \xrightarrow[\text{heat}]{-C_2H_6} \left[C_2H_5InPH\right]_x$$

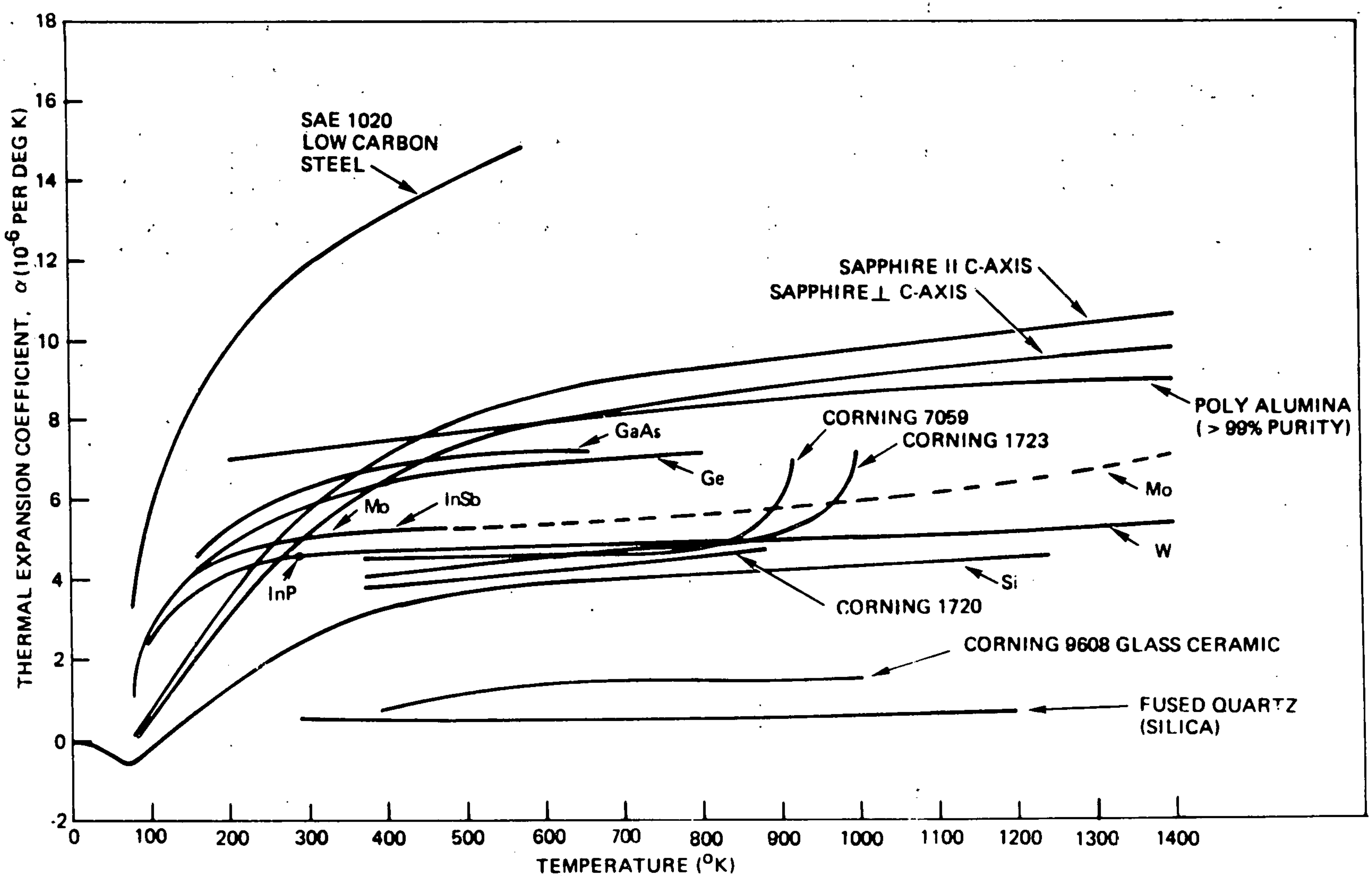
$$\left[(C_2H_5InPH\right]_x \xrightarrow[\text{heat}]{-C_2H_6} InP$$

THIN POLYCRYSTALLINE FILMS OF INDIUM PHOSPHIDE ON LOW-COST SUBSTRATES

Examples of Substrate Materials Considered for InP MO-CVD Growth

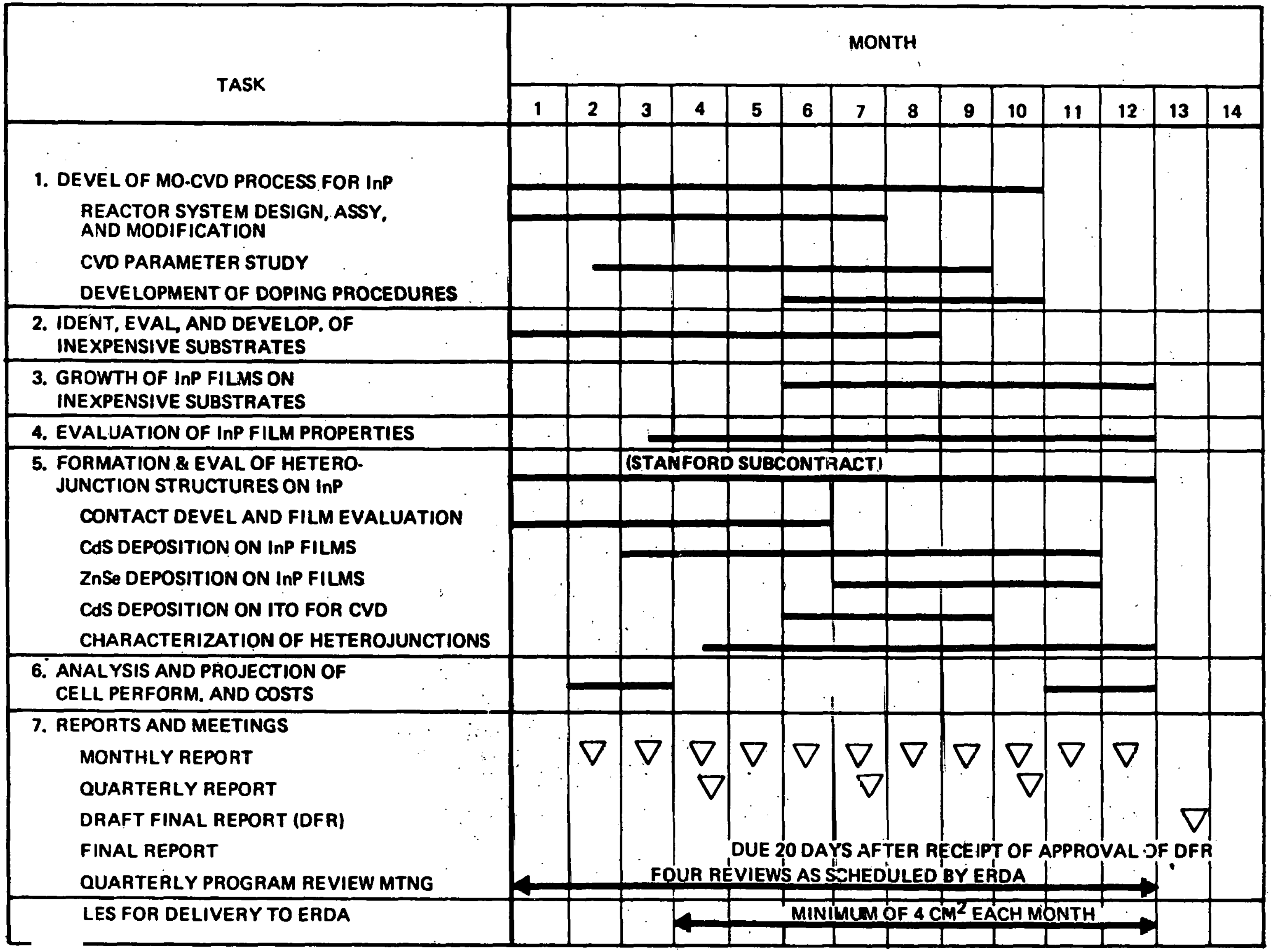
SUBSTRATE IDENTIFICATION	MATERIAL/TYPE	THERMAL EXPANSION COEFF (TEMP RANGE) (10^{-6} PER DEG C)	SURFACE ROUGHNESS	NOMINAL PURITY (%)	REPRESENTATIVE APPROXIMATE COST FOR RELATIVELY LARGE QUANTITIES
Corning 0221	Lime Borosilicate	7.4(0-300 C)	<1 Microinch	–	\$0.031/in.^{2} (12 x 14 in. sheet) as drawn
1723	Aluminosilicate	5.4(25-670 C)	<0.5 Microinch	–	
7059	Barium Alumino-Borosilicate	4.6(0-300 C)	<0.5 Microinch	(Alkali-free)	\$0.11/in.^{2} (144 in.)^2 polished \$0.04/in.^{2} (168 in.)^2 as drawn
Coors ADS96F	Alumina	8.1(25-1000 C)		96	
ADS995	Alumina	7.7(25-1000 C)	8–10	99.5	
Vistal	Alumina	8.3(25-1200 C)		99.9	
MRC Superstrate	Alumina	7.3(25-800 C)	4–5 Max	99.6	\$0.30/in.^{2} (10 x 10^3 in.^{2})
3M ASM614	Alumina	7.9(25-900 C)		96	\$0.06/in.^{2} (40 x 10^3 in.^{2})
ASM772	Alumina	7.7(25-900 C)		99.5	\$0.08/in.^{2} (40 x 10^3 in.^{2})
ASM624 W/743 Glaze	Lead Borosilicate on Alumina	~6.5(40-540 C)	<1 Microinch		\$0.13/in.^{2} (40 x 10^3 in.^{2})
ASM805	Alumina	7.7(25-900 C)	<1–2 Microinch	99.9	\$0.50/in.^{2} (40 x 10^3 in.^{2})
Tungsten	W Sheet or Foil	5.0(25-700 C)			\$~40/lb
Molybdenum	Mo Sheet or Foil	6.0(25-700 C)			\$~35/lb
Kovar	Ni-Co-Fe Alloy Foil or Sheet	8.1(25-700 C)			\$0.06-0.09/in.^{2} (\$5.50-\$8/lb)
InP	Single Crystal Slice	4.5(–)			
GaAs	Single Crystal Slice	6.9 (-62-200 C)			\$5-8/in.^{2}
Sapphire	Single Crystal Ribbon	8.4 (25-800 C)			\$1/in.^{2} (1/2 in. wide ribbon) \$2.39/in.^{2} (10,000 in.^{2} with Grains)

Linear Thermal Expansion Coefficients as Function of Temperature
for InP and Several Other Materials of Interest



THIN POLYCRYSTALLINE FILMS OF INDIUM PHOSPHIDE ON LOW-COST SUBSTRATES

Tentative Program Plan



CADMIUM STANNATE SELECTIVE OPTICAL FILMS FOR SOLAR ENERGY APPLICATIONS

NSF GRANT AER 73-07957

APRIL 1, 1975 — MARCH 31, 1976

$ 160,000

G. HAACKE (PRINCIPAL INVESTIGATOR)
AMERICAN CYANAMID COMPANY
STAMFORD, CONN. 06904

L. C. BURTON
UNIVERSITY OF DELAWARE
NEWARK, DELAWARE 19711

PRESENTED AT THE NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

AUGUST 3-6, 1976
UNIVERSITY OF MAINE AT ORONO
ORONO, MAINE 04473

ABSTRACT

The objective of the project is the development of low sheet resistance (~ 1 ohm/square), transparent cadmium stannate coatings and the incorporation and testing of these electrodes in CdS (backwall) and silicon solar cells. The tasks also include the development of an economical spray deposition technique.

During the past six months work was directed toward improving the economics of the spray deposition process and achieving a better optical quality of low-sheet resistance (< 10 ohm/square), spray coated cadmium stannate films. In addition, conditions were optimized for the sputter deposition of cadmium stannate electrodes onto single crystal silicon substrates and work continued on the CdS backwall solar cell.

Until recently, the conditions used for spray coating cadmium stannate caused concern for the economic viability of this technique. Deposition times of 20 minutes were needed for 10 ohm/square films and a large excess of cadmium in the spray solution was required to achieve compound formation. We have now succeeded in correcting these deficiencies. Coatings with ~ 10 ohm/square sheet resistance can be prepared in three minutes and it is likely that this time can be reduced further. The Cd/Sn ratio in the spray solution has been lowered from 20:1 to 5:1. The optical transmission of films in the 5-10 ohm/square range has been increased significantly from less than 20% to at least 60%. Here, additional work is needed to achieve transmissions higher than 80%.

In preparation for the coating of silicon solar cells with transparent cadmium stannate electrodes by sputtering the deposition conditions onto Si wafers were optimized and the optical properties

investigated. It was established that cadmium stannate imparts solar selectivity to the silicon substrate; typical values are 0.1 emissivity and 85% total absorption (without antireflective coating). Seven silicon solar cells were received from NASA and coated with cadmium stannate electrodes. The cells have been returned to NASA for testing and evaluation.

$Zn_xCd_{1-x}S$ films have been deposited onto Cd_2SnO_4. An initial adherence problem was alleviated by depositing the Cd_2SnO_4 onto Corning 7059 glass. Optical bandgap, lattice parameter and electrical resistivity measurements were made. V_{oc} values up to .63 volts were measured for $Cd_2SnO_4/Zn_xCd_{1-x}S/Cu_yS$ solar cells, with $x \cong .2$.

CADMIUM STANNATE
SELECTIVE OPTICAL FILMS FOR SOLAR ENERGY APPLICATIONS

NSF GRANT AER 73-07957

AMERICAN CYANAMID COMPANY
UNIVERSITY OF DELAWARE

GRANT PERIOD: APRIL 1, 1975 – MARCH 31, 1976

AWARD: $ 160,000

PRINCIPAL INVESTIGATOR: G. HAACKE

6

PROJECT OBJECTIVES

- PREPARE HIGHLY TRANSPARENT, ELECTRICALLY CONDUCTING THIN COATINGS OF CADMIUM STANNATE
- DEVELOP SPRAY TECHNOLOGY FOR FABRICATION OF CADMIUM STANNATE FILMS ON TRANSPARENT SUBSTRATES
- EVALUATE PERFORMANCE OF CADMIUM STANNATE BACKWALL ELECTRODES IN CdS SOLAR CELLS
- DEPOSIT CADMIUM STANNATE FILMS ONTO SILICON SUBSTRATES AND ASSES POTENTIAL FOR FRONT ELECTRODES IN SILICON SOLAR CELLS

PLANNED ACTIVITY

- IMPROVE OPTICAL PROPERTIES AND REPRODUCIBILITY OF LOW-SHEET RESISTANCE (<10 OHM/SQUARE) SPRAY COATED CADMIUM STANNATE FILMS.

- INCREASE BACKWALL EFFICIENCY OF CdS CELLS BY OPTIMIZING FABRICATION PROCEDURE.

- COAT SILICON SOLAR CELLS WITH CADMIUM STANNATE FRONT ELECTRODES AND EVALUATE PERFORMANCE.

SPRAY DEPOSITION OF CADMIUM STANNATE

- ECONOMICS OF DEPOSITION PROCESS IMPROVED BY:
  1. REDUCTION OF SPRAY TIME FROM 20 MIN. TO 3 MIN. FOR ~ 10 OHM/SQUARE FILMS
  2. DECREASE OF Cd/Sn RATIO IN SPRAY SOLUTION FROM 20:1 TO 5:1

- OPTICAL TRANSMISSION OF FILMS IN 5 - 10 OHM/SQUARE RANGE INCREASED FROM $<$ 20% TO 60%

- REPRODUCIBILITY OF ACHIEVING SHEET RESISTANCES $<$ 20 OHM/SQUARE SIGNIFICANTLY IMPROVED

- LOWEST SHEET RESISTANCE TO DATE: 3 OHM/SQUARE

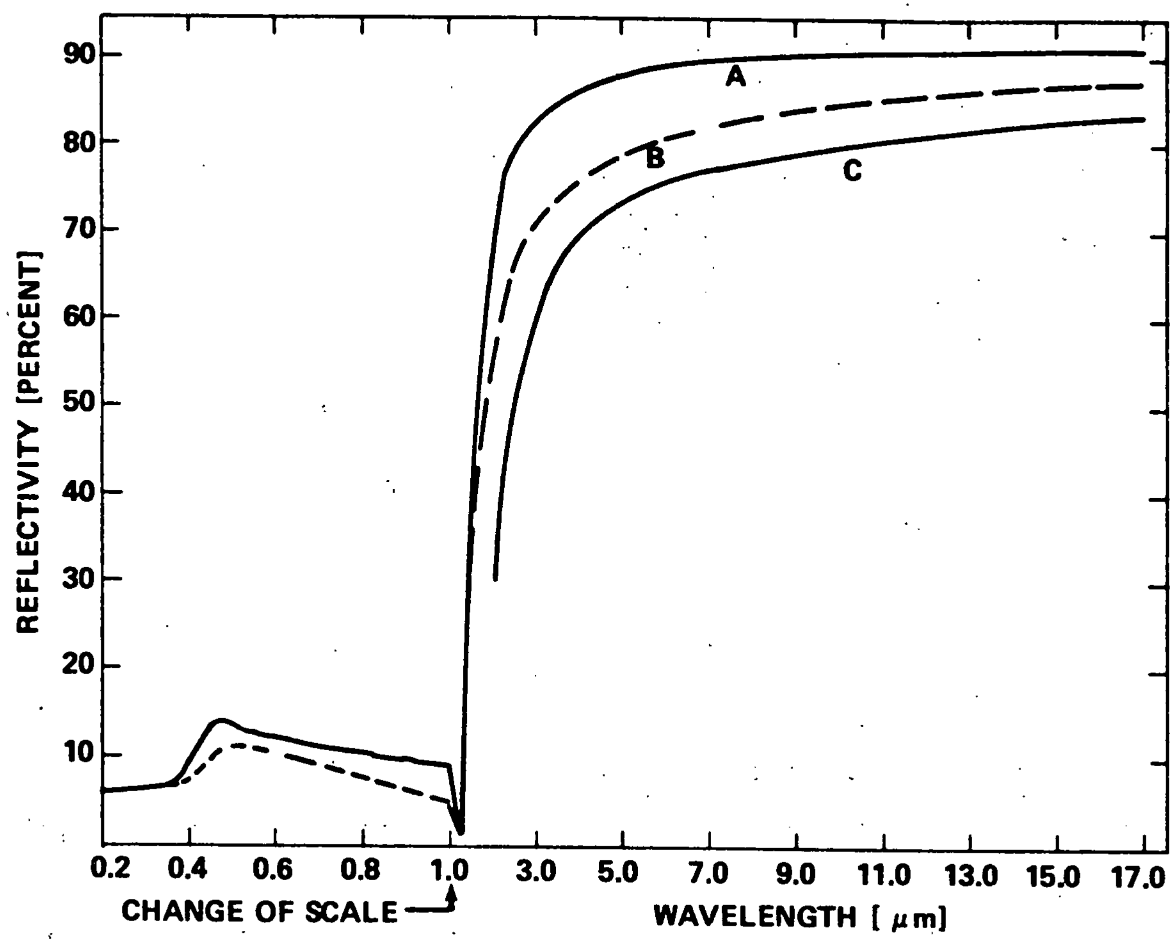
CADMIUM STANNATE DEPOSITION ONTO SILICON SUBSTRATES

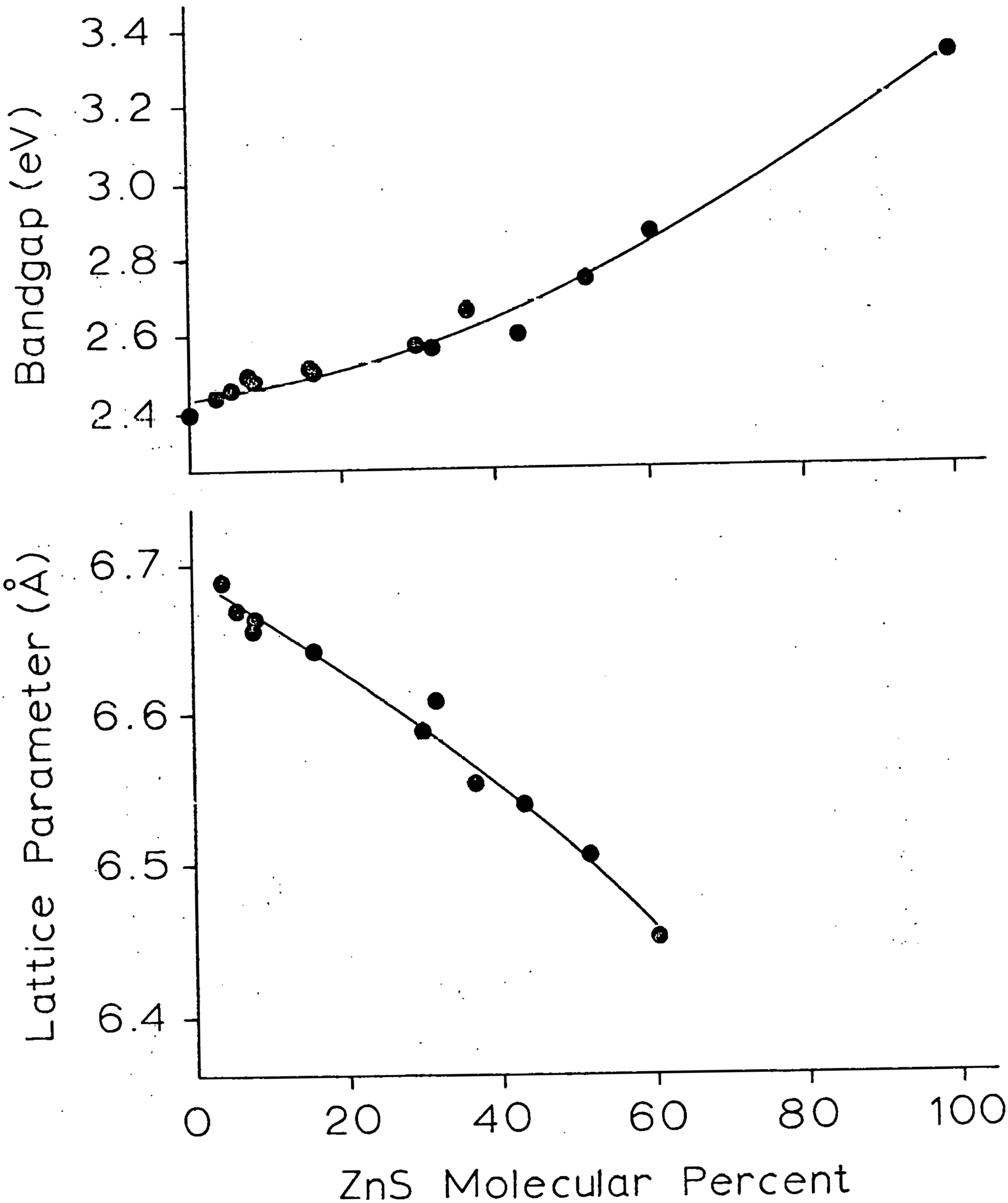
- OPTICAL (REFLECTIVITY) AND ELECTRICAL PROPERTIES OF SPUTTER-COATED FILMS ON SILICON DEPEND ON SUBSTRATE SURFACE PREPARATION

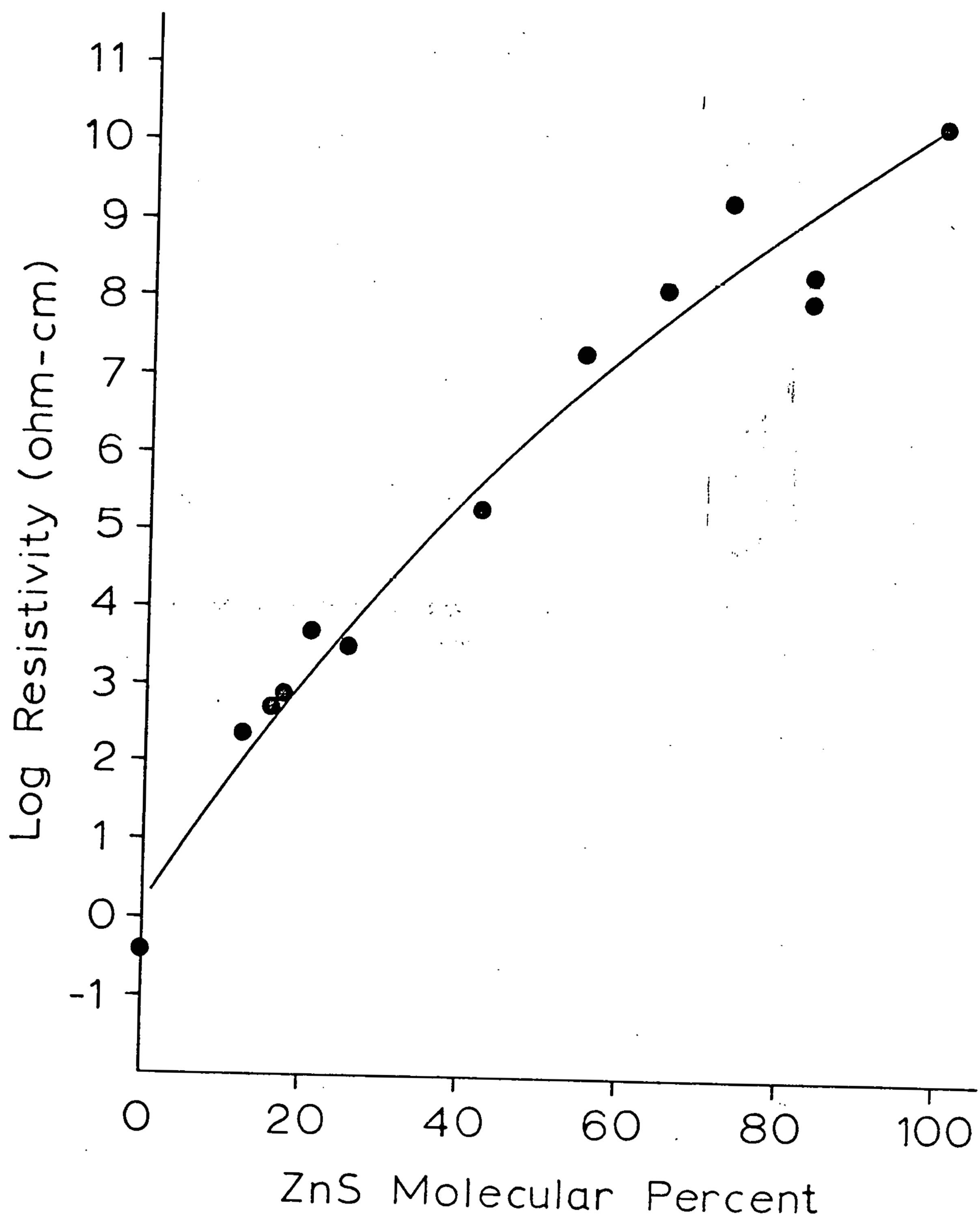
- CADMIUM STANNATE COATED SILICON FORMS HIGHLY SELECTIVE SOLAR ABSORBER

- SEVEN SILICON SOLAR CELLS RECEIVED FROM NASA, COATED WITH CADMIUM STANNATE ELECTRODES AND RETURNED FOR EVALUATION

Reflectivity of Cd_2SnO_4 Films on Silicon




3.4
3.2
3.0
2.8
2.6
2.4
Bandgap (eV)
6.7
6.6
6.5
6.4
Lattice Parameter (Å)
0
20
40
60
80
100
ZnS Molecular Percent


11
10
9
8
7
6
5
4
3
2
1
0
-1
Log Resistivity (ohm-cm)
0
20
40
60
80
100
ZnS Molecular Percent

SUMMARY OF KEY RESULTS

- IMPROVED TRANSPARENCY OF SPRAY COATED CADMIUM STANNATE FILMS IN 5-10 OHM/SQUARE RANGE

- IMPROVED ECONOMICS OF SPRAY DEPOSITION TECHNOLOGY

- Cd_2SnO_4 SUITABLE SUBSTRATE FOR $Zn_xCd_{1-x}S$ FILM. $Cd_2SnO_4/Zn_xCd_{1-x}S/Cu_yS$ BACKWALL CELLS WITH V_{oc} UP TO .63V FABRICATED

- SILICON SOLAR CELLS COATED WITH TRANSPARENT CADMIUM STANNATE ELECTRODES AND SUBMITTED FOR EVALUATION

SEMI ANNUAL NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING

August 3 - 5, 1976
University of Maine, Orono, Maine

DATE	TIME	EVENT	SPEAKER
Mon. Aug. 2		Arrival of Most Attendees	
Tues. Aug 3	8:30 AM	Registration	
	9:00	Welcome Announcements	Kazmerski/U of Maine
		SESSION I - Status of Photovoltaic Conversion Program - Chairman - M. Prince	
	9:10	Opening Comments	Blieden/ERDA
	9:20	National Photovoltaic Plan - Update	Prince/ERDA
	9:30	Preview of Meeting	Magid/ERDA
	9:40	R&D Monitoring and Management	Warschauer/ERDA
	9:50	Discussion	
	10:00	Coffee Break	
		SESSION II - Photovoltaic Systems I - Chairman - L. Magid	
	10:15 AM	Mission Analysis	Leonard/Aerospace
	10:45	Solar Electricity - An Utility Viewpoint	Braun/So. Cal. Edison
	11:05	Systems Definition Project	Schueler et al./ Sandia
	11:35	Discussion	
	11:50	Lunch Break	
		SESSION III - Polycrystalline Silicon Materials and Devices - Chairman D. M. Warschauer	
	1:00 PM	Low-Cost Thin-Film Silicon Cells	Chu /SMU
	1:20	Epitaxial Silicon Technology	D'Aiello/RCA
	1:40	CVD Silicon	Manasevit/Rockwell
	2:00	Ultravacuum Vapor Deposition of Silicon	Frost/G.E.
	2:20	Recrystallization of Thin-Film Silicon	Kirpatrick/Simulation Physics
	2:40	Amorphous Silicon Cells	Carlson/RCA
	3:00	Transient Capacitance Measurements	Lindholm/U. Fla. Sah/ U. Ill.
	3:20	Energy Beam Deposition of Silicon	Baghdadi/Motorola
	3:40	Discussion	
	3:55	Coffee Break	

SESSION IV - Photovoltaic Systems II -
Chairman - L.M. Magid

4:10	Conceptual Design and Systems Analysis	Kirpich/G.E.
4:40	Conceptual Design and Systems Analysis	Pittman/Westinghouse
5:20	" " " "	Bartels/Spectrolab
5:50	Discussion	
6:00	Adjournment	

Wed.Aug.4

SESSION V-II-VI Semiconductor Materials
and Devices - Chairman D.M. Warschuaer

8:30 AM	CdS Spray Technology	Jordan/Baldwin
8:45	" " "	Samara/Sandia
9:00	CdS Thin-Film Cells	Barnett/U. Dela.
9:20	" " " "	Shirland/Westinghouse
9:40	II-VI Heterojunctions	Bube & Fahrenbruck/ Stanford U.
10:00	Coffee Break	
10:15	Cu_2S and Ternary Compound Cells	Loferski/Brown U.
10:35	Thin-Film Ternary Cells	Kazmerski/U of Maine
10:55	CdTe on Glass Cells	Rod/ Monogram
11:15	Discussion	
11:30	Lunch Break	

SESSION VI - Low-Cost Silicon Solar Arrays
Chairman - L.M. Magid

1:00 PM	Low-Cost Silicon Solar Array Project	Forney/JPL
1:05	Si Material Task	Lutwack/JPL
1:25	Si Sheet Task	Zountendyk/JPL
1:45	Encapsulation Task	Carroll/JPL
2:05	Automated Array Task	Hasback/JPL
2:25	Large Scale Production Task	Sequeria/JPL
2:45	Engineering & Design	Ross/JPL
3:00	Discussion	
3:15	Coffee Break	

SESSION VII - Tests and Demonstrations
Chairman - D.M. Warschauer

3:30 PM	Test & Applications Project	Deyo et al/NASA-Lewis
4:30	Applications Activities	Pope/Lincoln Lab
4:50	Military Applications Project	Faehn/MERADCOM
5:10	Discussion	
5:45	Adjournment	
6:00	Social Gathering	

Thurs. Aug. 5

SESSION VIII - Concentration Systems
Chairman - L.M. Magid

8:15 AM	Concentration Systems Project	Schueler et al./Sandia
9:00	High Energy Density P/V Convertors	Navon/U. Mass.
9:20	Discussion	
9:35	Coffee Break	

SESSION IX - GaAs Materials & Devices
Chairman - D. M. Warschauer

9:50 AM	AMOS GaAs Solar Cells	Stirn/JPL
10:10	Thin-Film GaAs Cells	Mattes/Stanford Univ.
10:30	Polycrystalline GaAs Cells	Ghandhi/Reasselear Poly
10:50	CVD GaAs	Dapkus/Rockwell
11:10	Thin-Film GaAs Cells	Chu/SMU
11:30	Discussion	
11:45	Lunch Break	

SESSION X - Other Materials & Devices
Chairman - D.M. Warschauer

1:00 PM	Silicon Schottky Photovoltaic Devices	Anderson/Rutgers Univ.
1:20	Heterojunction Solar Cells	Anderson/Syracuse Univ.
1:40	Efficient Oxide Semiconductor Solar Cells	DuBow/Colorado St. U.
2:00	Silicon Heterojunction Investigation	Shaw/EXXON
2:20	Plans for MIS Silicon Cells	Szedon/Westinghouse & Penn St. Univ.
2:40	Coffee Break	
2:55	Cuprous Oxide PV Cells	Trivich/Wayne St. Univ.
3:15	Cuprous Oxide Solar Cells	Olsen/U. of Wash.
3:35	Zn_3P_2 for Solar Cells	Warfield/U. of Delaware
3:55	$CuInSe_2$ for Solar Cells	Mickelsen/Boeing
4:15	Ternary Materials for Solar Cells	Littlejohn/N.C. State U.
4:35	Thin-Film Photovoltaics	Zieger/Lincoln Lab
4:55	InP Film Growth by Vapor Deposition	Zanio/Hughes
5:15	" " " " "	Ruth/Rockwell & Stanford Univ.
5:35	Discussion	
5:50	Meeting Adjournment	

Fri. Aug. 6	9:00 AM	Closed Meeting of Ad Hoc Photovoltaic Review Group
	1:30 PM	Adjournment

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