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GLASS-SI HETEROJUNCTION SOLAR CELLS

TITLE OF GRANT

GLASS-SI HETEROJUNCTION SOLAR CELLS

GRANT NUMBER

AER74 - 17631

PERIOD OF GRANT

1 AUG. 1974 - 31 JULY 1975

VALUE OF GRANT

$313,900

AUTHOR AND PRINCIPAL INVESTIGATOR

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PRESENTATION

NATIONAL SOLAR PHOTOVOLTAIC PROGRAM REVIEW MEETING
25 JULY 1975
U.C.L.A.

ABSTRACT

The purpose of this project is to investigate glass/Si heterojunctions as solar cells of low cost, suitable for terrestrial applications. The Si is the active material, and the glass serves as a window to solar radiation, an antireflection coating of the Si, and a low resistance contact. Fabrication of the cell is simple and inexpensive. Principal specific goals of the project are (i) the fabrication of solar cells by deposition of various window materials on single and polycrystalline Si, (ii) experimental testing and evaluation of the cells, and (iii) the explanation of the characteristics by the development of suitable models.

During the first six months, the concept of the heterojunction solar cell was shown to be valid in the form of an In_2O_3 window on p-type single crystalline Si. Experimental results showed the principal dark current mechanism in the operating range to be recombination through interface states, and the electron affinity of the In_2O_3 was found to be 0.3 eV greater than that of the Si. This difference limits the open circuit voltage and efficiency of such cells to a maximum of 11%, a probable practical efficiency of the order of 7-8%. It was shown that this limitation could be overcome by a shallow diffusion of donors into the surface of the Si. Heteroface cells of this type showed efficiencies of the order of 9% under simulated AM1 irradiation.

During the second six months, investigations of other crystalline window materials have been initiated. Results of measurements on SnO_2/n-Si, single crystal, indicate an electron affinity difference relative to the Si of approximately 0.85 eV. (The size of this difference makes impractical SnO_2/p-Si cells). Electron emission is the principal dark current mechanism. Although their characteristics are not fully understood, they appear to function somewhat like Schottky barrier cells. Under simulated AM1 irradiation, data for the best of these cells are $V_{oc} = 435$ mV, $J_{sc} = 23.7$ mA/cm^2, and $\eta = 6.3\%$.

Experiments with amorphous glasses such as $0.85V_2O_5{:}0.15P_2O_5$ show these materials to be impractical as solar cell windows. The principal limitation is the intrinsically high resistivity, $\rho \gtrsim 10^5$ Ω-cm. The cells tested show high series resistance and severe suppression of photocurrent in the third and fourth quadrants. A layer of amorphous glass between the Si and a low resistivity crystalline glass could, in principle, increase the open circuit voltage without degrading the curve factor or suppressing photocurrent, but the technical problem of depositing a sound layer no thicker than a few nm is non-trivial. Accordingly, such compound heterojunction cells are also judged to be impractical.

Cells of In_2O_3 on grown ribbon and polycrystalline Si of various grades show characteristics differing between runs, between wafers in the same run, and between locations on the same wafer. With few exceptions, open circuit voltages and conversion efficiencies are low, and suppression of photocurrent is evident on many. Since these poor characteristics are also measured on control units made from single crystal wafers, the source of the degradation appears to be in the processing at some stage where an interfacial layer of SiO_2 is grown. Measurements of these cells suggest that grain boundaries do not act as short circuits and that ribbon substrates are comparable to single crystal, but the facts that an oxide layer is evidently present and that all cells tested are 2.3 x 2.3 mm^2, sawed from material with crystallites of size varying from 0.005-20 mm, make such conclusions tenuous at best.

While the oxide layer problem delayed progress toward the project objectives, it provided data to make possible (i) the development of an explanation of the effects of an interfacial insulating layer based on energy bands and (ii) the development of experimental techniques for the identification of such a layer. The model allows qualitative prediction of changes in photocapacitance with voltage and illumination and changes in I-V characteristics with illumination. In particular, it predicts an increase in photocurrent suppression with increased illumination.

Although the stage of oxide growth in the processing is not known, thermodynamic calculations imply that some reduction by the Si of the In_2O_3 and the SnO_2 oxides is unavoidable. Whether or not a stable equilibrium is reached at some particular oxide thickness is directly related to the question of the stability of cells with these constituents under the conditions of terrestrial application. Data from initial experiments indicate rapid growth of SiO_2 interfacial layers on $S\overset{n}{\cancel{i}}O_2$/Si cells when subjected to a temperature of 200°C and less rapid growth when subjected to xenon illumination (without UV filters) at an intensity of 400 mW/cm^2. The same tests of In_2O_3/Si cells yield no conclusive evidence of degradation.

Continued study of the stability question and the inherently connected oxide layer problem is planned for the remaining period. Since photocurrent suppression is a good indicator of the oxide layer, methods for its detection and quantification will be sought. Publication of experimental results and heterojunction solar cell theory is planned.

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NSF GRANT AER74-17631

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
SYRACUSE UNIVERSITY
SYRACUSE, NEW YORK

INNOTECH CORPORATION
NORWALK, CONN.

PERIOD OF GRANT: 1 AUG. 1974 - 31 JULY, 1975

FUNDING: $313,900

PRINCIPAL INVESTIGATOR:

R.L. ANDERSON
SYRACUSE UNIVERSITY

FIG. 2

OVERALL OBJECTIVES OF PROJECT

THE PURPOSE OF THIS PROJECT IS TO INVESTIGATE GLASS-SILICON HETEROJUNCTIONS AS SOLAR CELLS OF LOW COST, SUITABLE FOR TERRESTRIAL APPLICATIONS. THE PRINCIPAL SPECIFIC GOALS ARE:

A) THE FABRICATION OF GLASS-MONOCRYSTALLINE SI AND GLASS-POLYCRYSTALLINE SI HETEROJUNCTION CELLS.

B) THE EXPERIMENTAL TESTING AND EVALUATION OF THESE CELLS.

C) THE EXPLANATION OF CELL CHARACTERISTICS BY THE DEVELOPMENT OF SUITABLE MODELS.

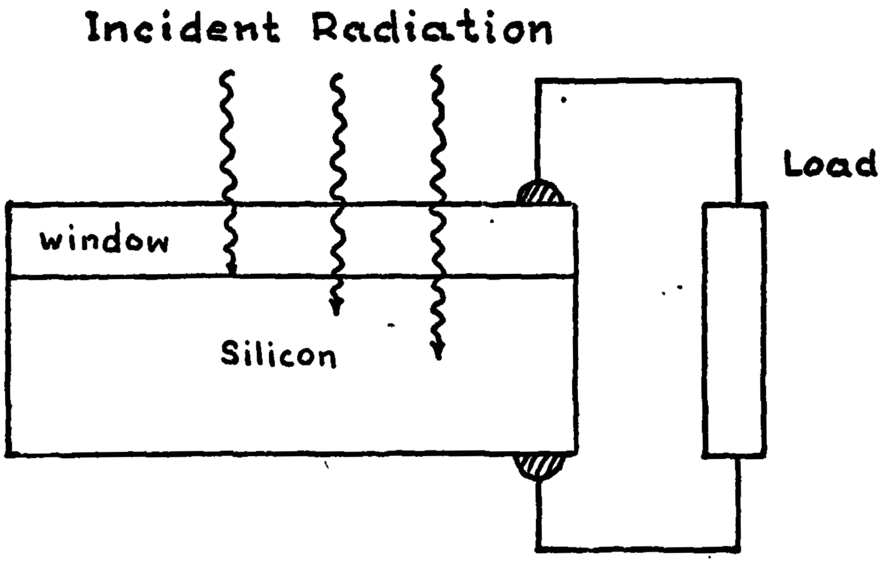


FIG. 3 AER74-17631

ACTIVITY PLANNED FOR 1 JAN - 30 JUNE, 1975

A) INVESTIGATION OF THE FOLLOWING WINDOW MATERIALS ON SINGLE CRYSTAL SUBSTRATES

1) CRYSTALLINE METAL OXIDES: SnO_2, CdO, ZnO . . .
2) AMORPHOUS GLASSES: V_2O_5, TiO_2, V_2O_5:GeO_2 . . .

B) INVESTIGATION OF THE FOLLOWING LOW-COST SUBSTRATES WITH In_2O_3 WINDOWS

1) GROWN RIBBON SI
2) VARIOUS GRADES OF POLYCRYSTALLINE SI

C) DEVELOPMENT OF HIGH EFFICIENCY HETEROFACE SOLAR CELL

D) DEVELOPMENT OF HETEROJUNCTION THEORY

FIG. 4 AER74-17631

OUTLINE OF PROGRESS

I. VALIDATION OF HETEROJUNCTION SOLAR CELL CONCEPT

II. CRYSTALLINE WINDOWS

III. AMORPHOUS WINDOWS

IV. ALTERNATE SUBSTRATES

V. INTERFACE BARRIER LAYER EFFECTS

VI. STABILITY OF CELLS

FIG. 5

In_2O_3/Si CELLS

REASONABLY WELL UNDERSTOOD

$\Delta E_C = 0.30$ eV

DARK CURRENT MECHANISM

RECOMBINATION VIA INTERFACE STATES

MAX $\eta \approx 11\%$
MAX $\eta_{PRACTICAL} \approx 7-8\%$
MAX $\eta_{EXP} \approx 5-6\%$
} FOR SINGLE CRYSTAL Si

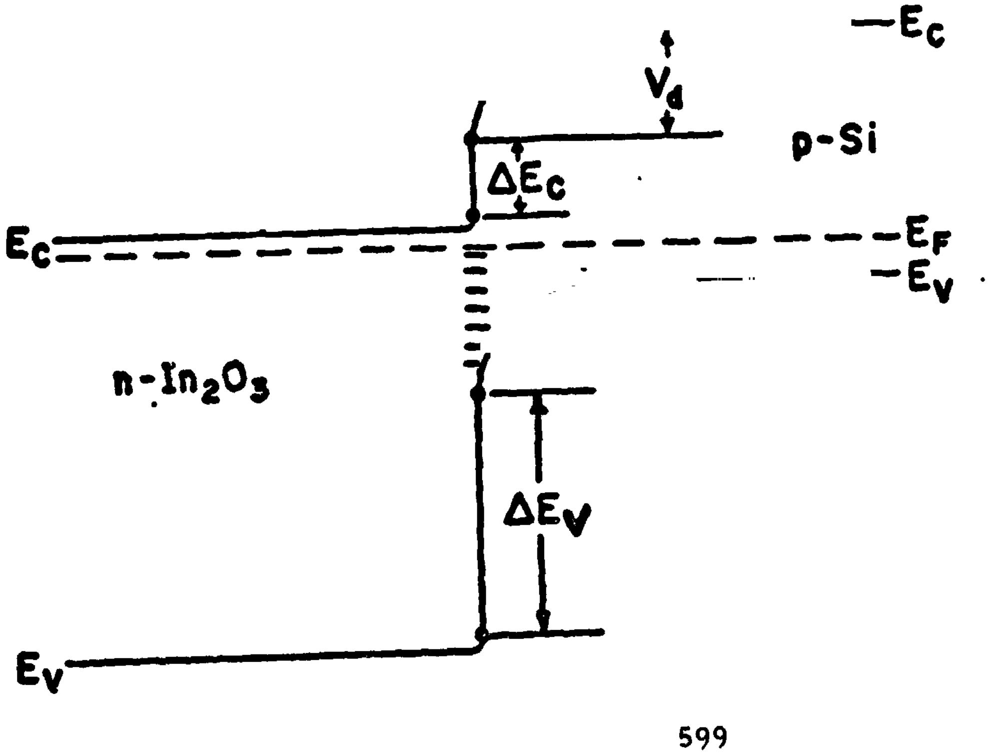


FIG. 6 AER74-17631

HETEROFACE CELLS

1 RUN MADE

EXCESSIVE RESISTANCE BETWEEN In_2O_3 AND SI

($\sim 4\,\Omega/cm^2$)

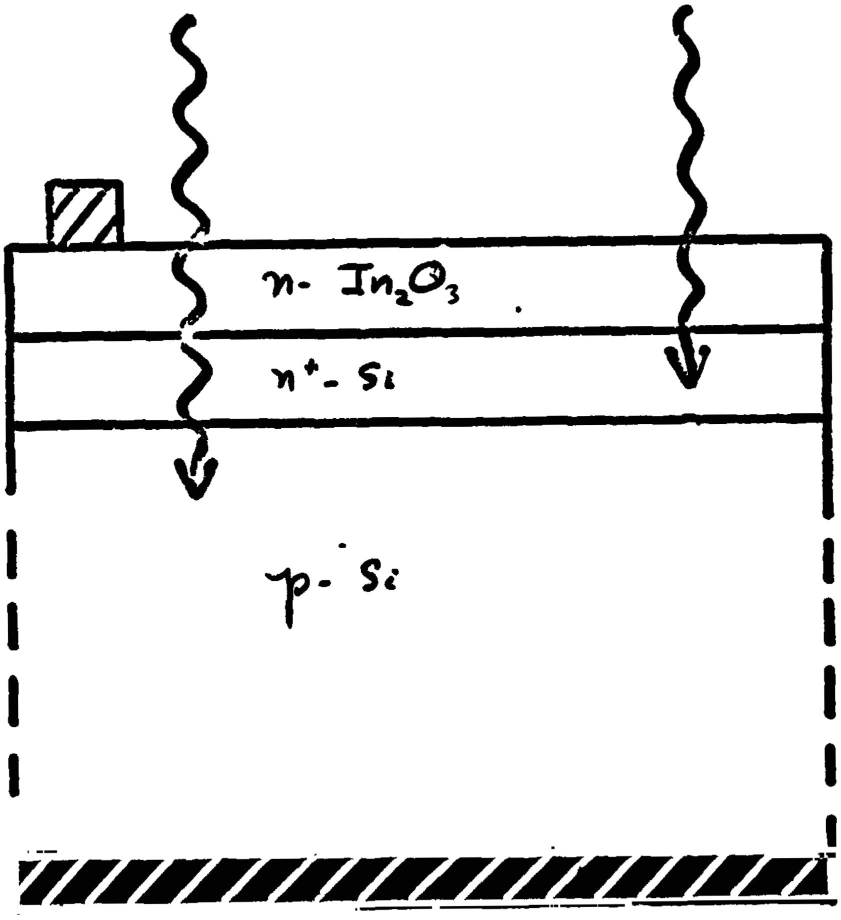


FIG. 7

SnO_2/SI CELLS

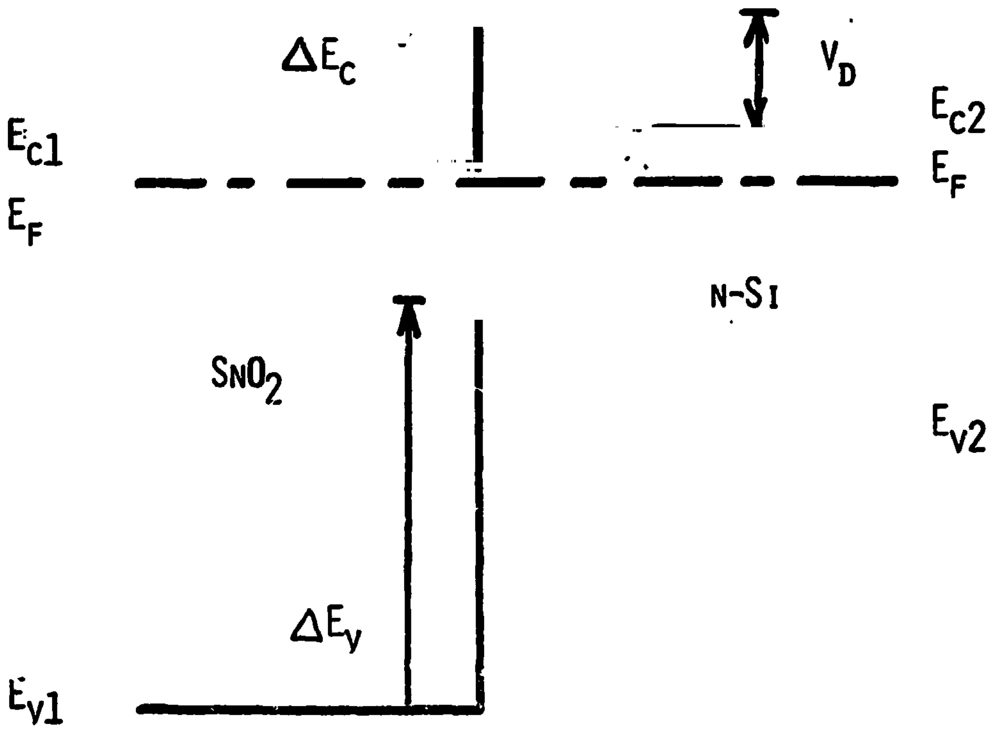
SOMEWHAT UNDERSTOOD

$\Delta E_C \overset{?}{\approx} 0.85$ eV

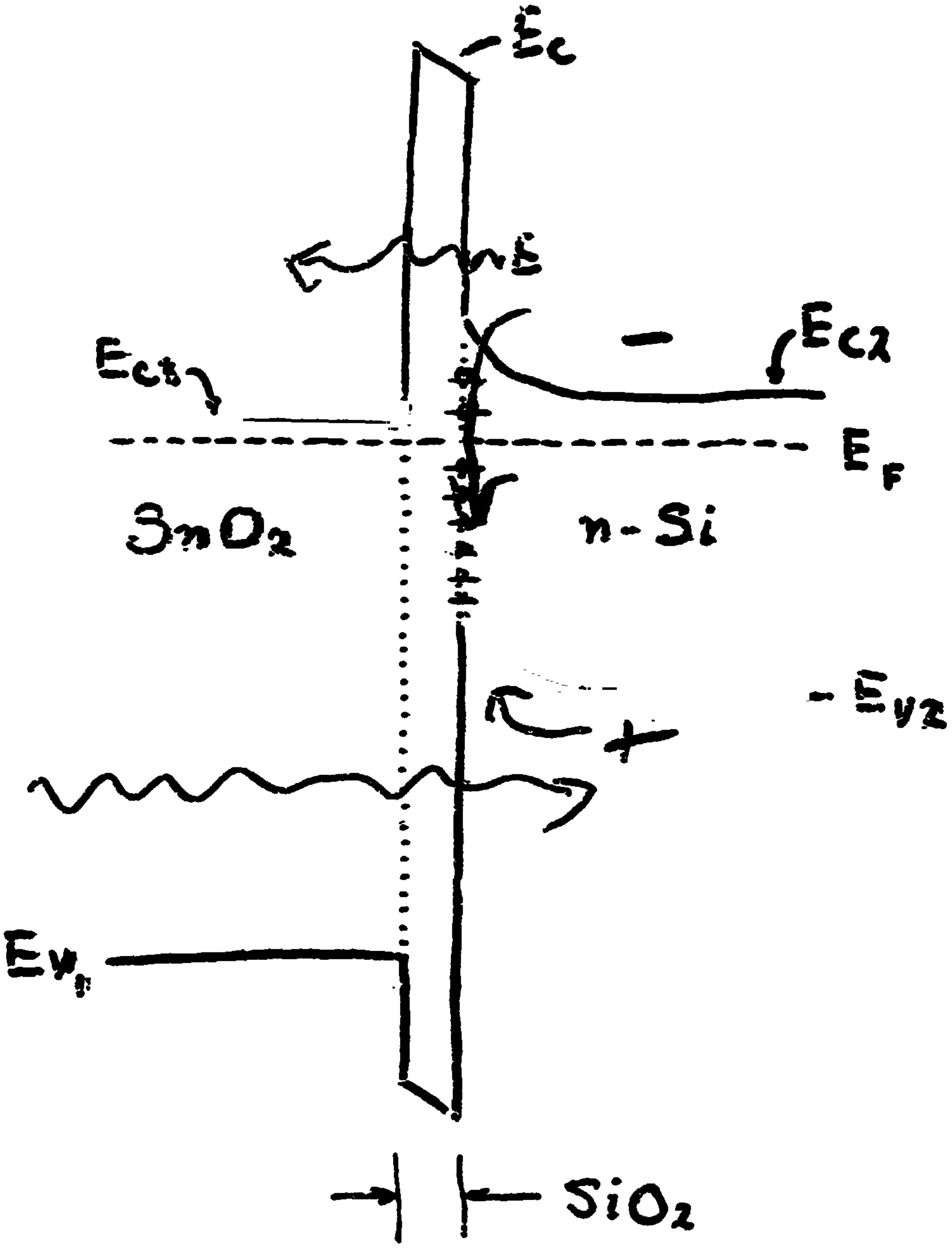
DARK CURRENT MECHANISM: ELECTRON EMISSION

PHOTOCURRENT MECHANISM: RECOMBINATION AT INTERFACE

MAX η NOT DETERMINED



$$T = e^{-\int \sqrt{\frac{2m^*}{\hbar^2}(E_c - E)}\,dx}$$



$$SnO_2 + Si \rightarrow Sn + SiO_2$$

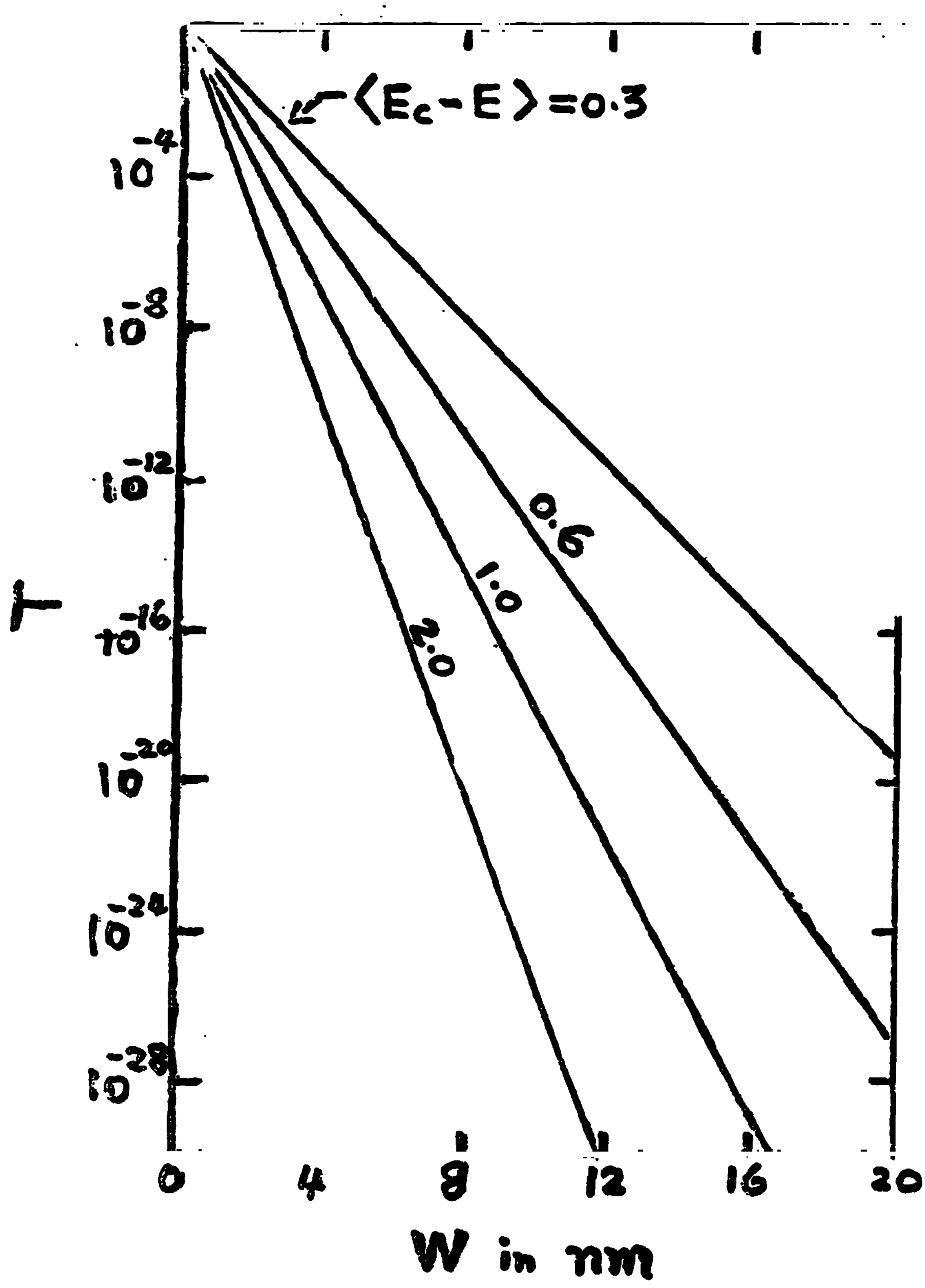

⟨E_c - E⟩=0.3
0.6
1.0
2.0
T
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
0
4
8
12
16
20
W in nm

FIG. 8

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SnO$_2$/n-Si

Best Results

	J_{sc}(mA/cm^2)	V_{oc}(V)	η(%)
Single crystal 0.23 cm x 0.23 cm	24	0.435	6.3

Late Results

	J_{sc}	V_{oc}	η
Single crystal 2 cm x 2 cm	29	0.523	9.4
1 cm x 1 cm	29	0.521	9.9
Poly (grain size?) 2 cm x 2 cm	27	0.469	6.9
1 cm x 1 cm	26	0.470	7.2

FIG. 9

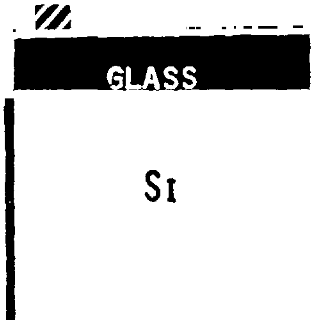
AMORPHOUS GLASS WINDOW

IMPRACTICAL

$\rho_{MIN} > 10^5 \ \Omega\text{-CM}$

R_S TOO LARGE

PHOTOCURRENT SUPPRESSION



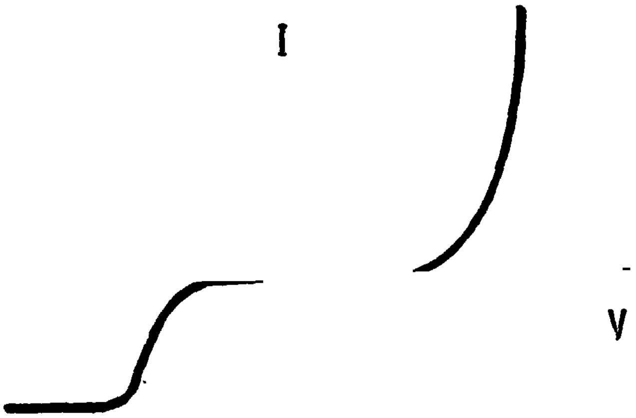
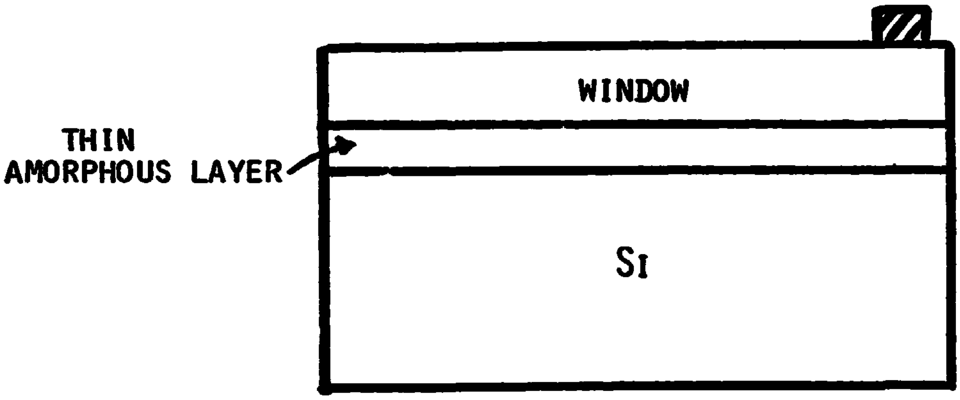
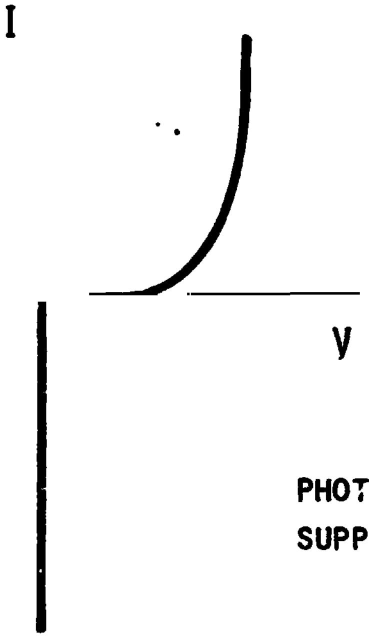


FIG. 10

COMPOUND HETEROJUNCTION

IMPRACTICAL





PHOTOCURRENT SUPPRESSION

FIG. 11 AER74-17631

In_2O_3/P-SI CELLS

SUBSTRATES USED (0.23 CM X 0.23 CM)	BEST η (%)
SINGLE CRYSTAL	4.3
RIBBON	3.4
POLYCRYSTALLINE SI	
LARGE GRAIN	2.9
METAL GRADE	0.5
CVD ON S.C. SUBSTRATE	0.07
CVD EPI ON RECRYSTALIZED MET GRADE (CHU)	1.4
SINGLE CRYSTAL (1 CM X 1 CM)	1.6

MAX V_{OC} 0.323 V

MAX J_{SC} 25 MA/CM^2

LATE RESULTS

	J_{SC} (MA/CM^2)	V_{OC} (V)	η (%)
SINGLE CRYSTAL			
2 CM X 2 CM	24	0.323	4.1
1 CM X 1 CM	25	0.343	4.9
POLY (GRAIN SIZE?)			
2 CM X 2 CM	24	0.357	3.3
1 CM X 1 CM	24	0.359	4.6

FIG. 12

SiO$_2$ INTERFACIAL LAYER

COMPETING MECHANISMS

TUNNELING → PHOTOCURRENT

RECOMBINATION → PHOTOCURRENT SUPPRESSION
VIA INTERFACE
STATES

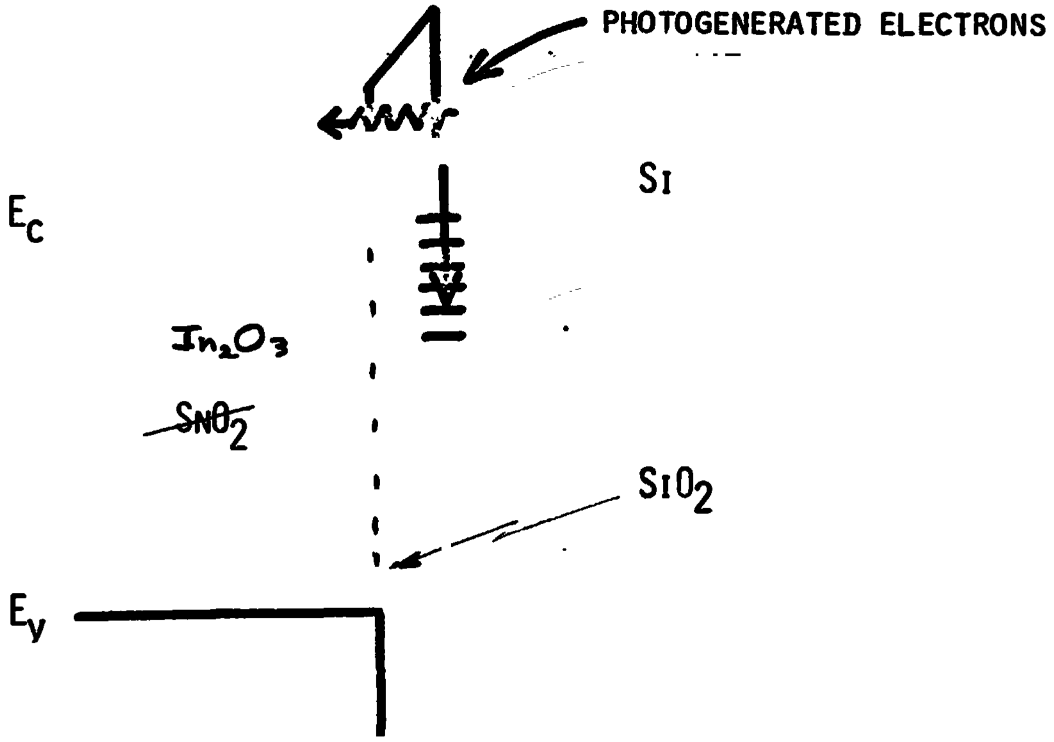


FIG. 13

SiO_2 INTERFACIAL LAYER

EFFECTS

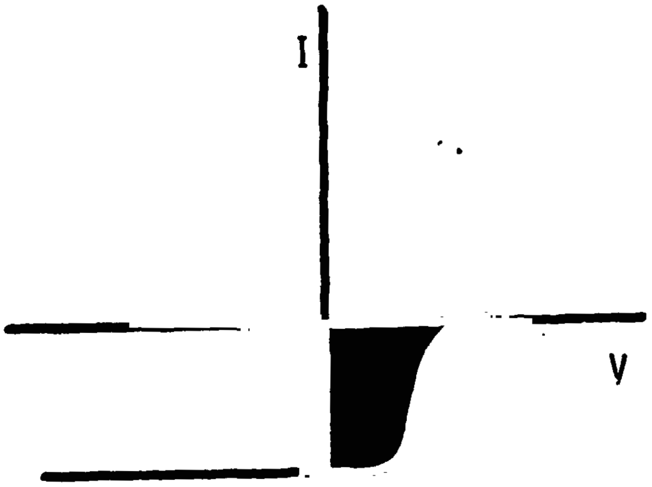
A) DECREASE I_0

<u>IF</u> I_{PH} IS INDEPENDENT OF V

$$V_{OC} = \frac{MKT}{Q} \text{ LN } \left(\frac{I_{PH}}{I_0} + 1\right)$$

AND V_{OC} IS INCREASED

B) SUPPRESSION OF PHOTOCURRENT FOR THICKNESS 2-3 NM



SiO_2 INTERFACE LAYER

ORIGIN OF SiO_2 LAYER UNKNOWN

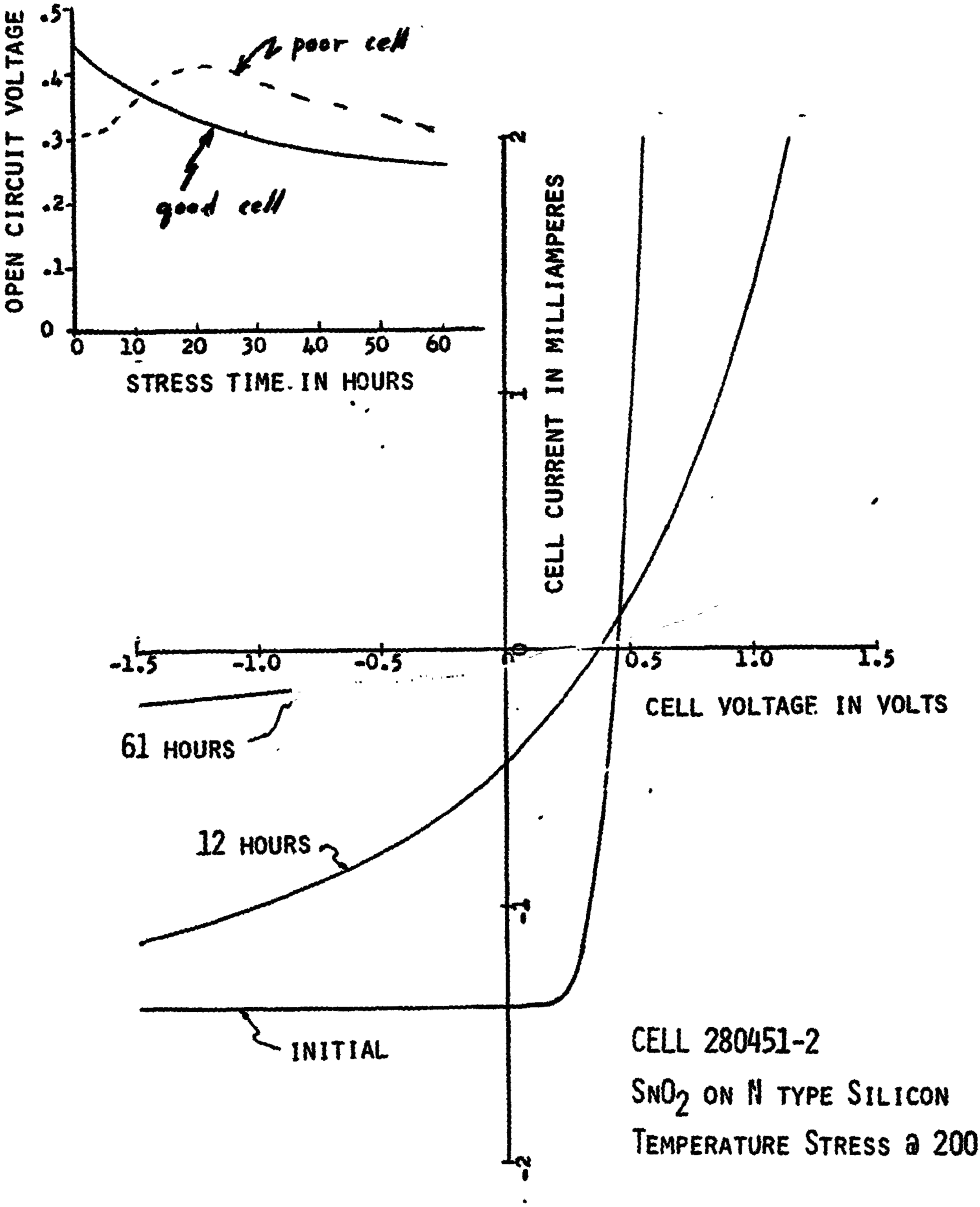
PROCESSING?

$SnO_2 + Si \longrightarrow Sn + SiO_2$

$In_2O_3 + \frac{3}{2} Si \longrightarrow 2In + \frac{3}{2} SiO_2$

AT ROOM TEMP

FIG, 15



CELL 280451-2

SnO_2 ON N TYPE SILICON

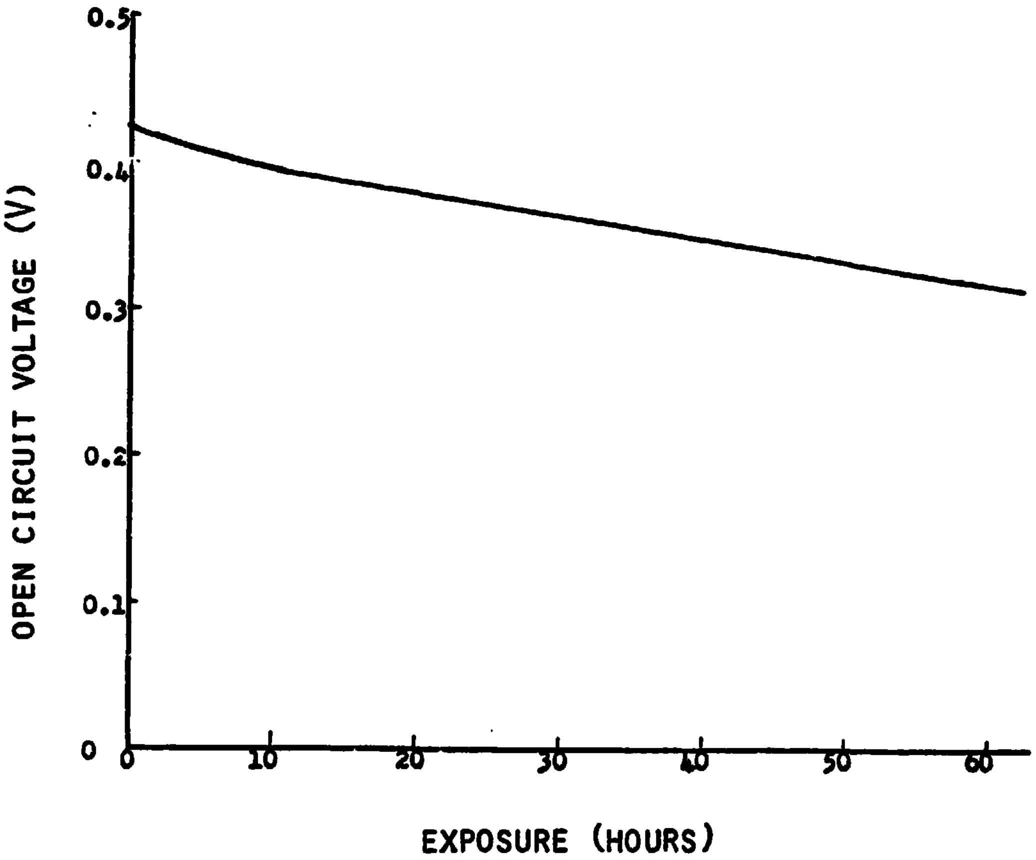
TEMPERATURE STRESS @ 200°C

FIG. 16

AER74-17631

DEGRADATION OF OPEN CIRCUIT VOLTAGE
UNDER 400 mW/cm^2 XENON LAMP ILLUMINATION
CELL 280451-7, SnO_2/n-Si

(At AM1 V_{oc} goes down 12% in 60 hrs.)



DEVICE S280451 UNIT #3

SnO_2 - Si

~~[illegible]~~ CELL

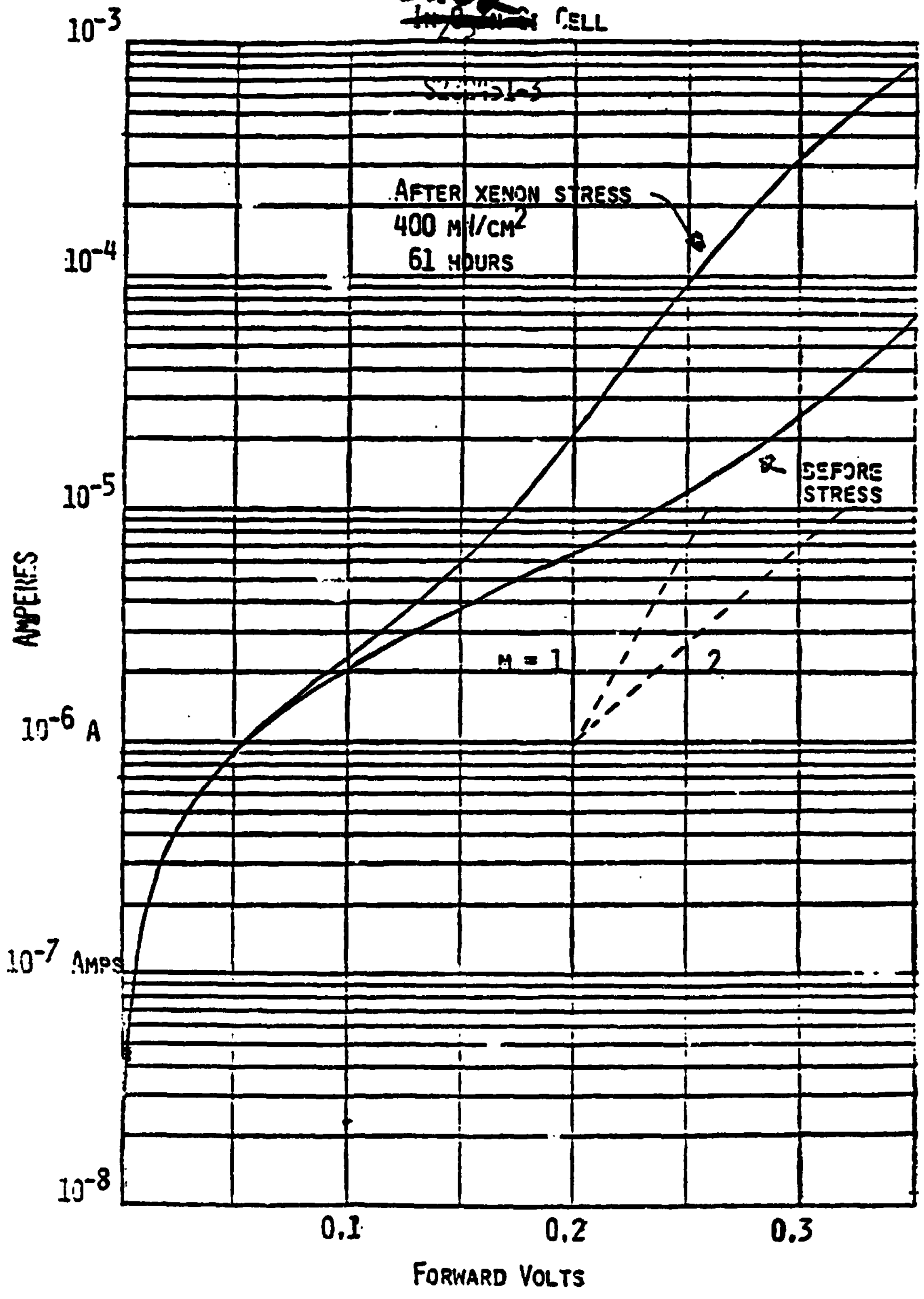


FIG. 17 AER74-17631

SUMMARY OF KEY RESULTS

I. EXPERIMENTAL STUDY AND MODEL OF In_2O_3/Si CELLS ESSENTIALLY COMPLETE. MODEL PREDICTS $\eta_{MAX} \sim 11$-13% AND HIGHER EFFICIENCIES FOR In_2O_3/N^+-P-Si CELLS.

II. EXPERIMENTAL STUDY AND MODEL OF SnO_2/N-Si CELLS NOT COMPLETE, BUT THESE SHOW PROMISE FOR TERRESTRIAL APPLICATION IF STABLE. EFFICIENCY REALIZED 6.3%.

III. AMORPHOUS WINDOWS OR LAYERS SUPPRESS PHOTOCURRENT. NOT PRACTICAL FOR SOLAR CELLS.

IV. INTERFACIAL SiO_2 LAYER SUPPRESSES PHOTOCURRENT AND INCREASES SERIES RESISTANCE. SUPPRESSION INCREASES WITH ILLUMINATION.

FIG. 18 AER74-17631

MAJOR PROBLEMS

I. TECHNICAL
  A. LIMITATION OF V_{OC} BY ΔE_C
  B. PHOTOCURRENT SUPPRESSION
  C. HIGH SERIES RESISTANCE
  D. POOR REPRODUCIBILITY

II. SCHEDULE
  A. START-UP TIME TOO SHORT

FIG. 19. AER74-17631

PLANNED ACTIVITY

I. INVESTIGATE STABILITY OF CELLS

II. INVESTIGATE INTERFACE LAYER EFFECTS

III. DEVELOP METHODS FOR DETECTION OF PHOTOCURRENT SUPPRESSION

IV. PUBLISH EXPERIMENTAL RESULTS AND THEORY OF HJSC's

WHAT SHOULD BE DONE?

I. INVESTIGATE THE THERMODYNAMICS OF VARIOUS WINDOW MATERIALS ON Si, GaAs, ...

II. INVESTIGATE THE CHEMICAL KINETICS OF INTERFACE REACTIONS.

III. DEVELOP EXPERIMENTAL TECHNIQUES FOR ANALYSIS OF INTERFACIAL LAYERS.

IV. DEVELOP METHODS FOR DEGRADATION MEASUREMENT.

V. DEVELOP QUANTITATIVE THEORY OF DEGRADATION.