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SILICON SOLAR CELL PROCESS DEVELOPMENT, FABRICATION, AND ANALYSIS
Seventh Quarterly Report for Period Covering July 1–September 30, 1980

By
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Optical Coating Laboratory, Inc.
Photoelectronics Division
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U.S. Department of Energy

Solar Energy

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SILICON SOLAR CELL PROCESS
DEVELOPMENT, FABRICATION, AND ANALYSIS

SEVENTH QUARTERLY REPORT

FOR PERIOD COVERING
1 JULY 1980 to 30 SEPTEMBER 1980

By

H.I. Yoo, P.A. Iles, and D.C. Leung

JPL CONTRACT NO. 955089

OPTICAL COATING LABORATORY, INC.
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"The JPL Low-Cost Silicon Solar Array Project is sponsored by the U.S. Government of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

ABSTRACT

During this reporting period, work has progressed in fabrication and characterization of solar cells from EFG ribbons and HEM ingots. EFG ribbons grown in carbon-containing gas atmosphere showed improved sheet quality. This new EFG provided an average baseline cell efficiency of 10.3% under AM1 (as opposed to 8.0% for the earlier EFG). The best efficiency achieved by the advanced process was 13.8% AM1.

Evaluation of two ingots from the HEM process indicated that HEM has a problem of inhomogeneity in sheet quality within each of the two ingots studied to date.

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1. INTRODUCTION

The purpose of this program is to evaluate silicon sheet materials in terms of their performance as solar cells. In this contract period, new (grown with CO_2 in the ambient) EFG (RH) ribbon (Mobil Tyco), and two crystals by the heat exchanger method (HEM Crystal System), have been studied. For the EFG ribbon, cells were fabricated using the baseline process, alongside with old EFG ribbon (grown without CO_2 in the ambient) for comparison. Also, high efficiency processes, such as shallow junction, multi AR coating and back surface reflector/back surface field were applied to some of the cells.

For the HEM crystals, one was cut horizontally as usual and the other one was cut vertically so that solar cell performance as a function of position in the crystals could be observed in two different configurations. Besides baseline processing, 600°C annealing and gettering by diffusion glass were also used with two separate groups of samples from the horizontally cut crystal. Furthermore, to selected portions of that crystal, high efficiency processes were applied.

Measured parameters of solar cells included open circuit voltage (V_{oc}), short circuit current (I_{sc}), curve fill factor (CFF), and conversion efficiency (η) under AM1 conditions. Selected measurements under AM0 condition were made for comparison with earlier data. For selected samples, minority carrier diffusion lengths and spectral responses were measured.

For the new EFG material study, dark current were also measured and light spot scanning was performed on selected samples.

In order to further characterize the HEM crystals, light biased minority carrier diffusion length measurements were made on samples from both crystals, to search for recombination centers in certain portions of the crystals. The preliminary results are consistent with the preliminary results from DLTS study of samples from the horizontally cut crystals only. More study is needed in this area.

II. TECHNICAL DISCUSSION

A. New EFG (RH) Solar Cell

1.0 Solar Cell Fabrication

The new EFG ribbons were grown with CO₂ mixed with Ar in the ambient as opposed to pure Ar for the old EFG ribbons. Reference (1) provides technical details of the EFG process. The resistivity is slightly lower, i.e. 0.8 ohm-cm as opposed to 1-2ohm-cm (estimated by zero bias capacitance measurement) of the previous ribbons. The new material was covered by a thin layer of oxidized carbon compound which made an extra etching step necessary. Otherwise, the processes were the same. Baseline cells were fabricated along with old EFG material and CZ control for comparison. In addition, some high efficiency cells were fabricated by applying shallow junction diffusion technique, incorporating back surface reflector (BSR) or back surface field (BSF), narrow grid lines, and multi-layer antireflection coating.

2.0 Solar Cell Performance and Characterization

Characteristics Under Illumination

All solar cells were of 2cm x 2cm size. The products from the baseline process had SiO AR coatings and 90% active area with Ti-Pd-Ag metallization. Solar cell parameters such as I_{sc}, V_{oc}, CFF, and η were measured under both AM1 and AMO conditions at 28°C. Description of the simulator and measurement are given in Reference (2) (3). The results are given in Appendix III and summarized in Table 1 where comparison of the new and old EFG is given.

The new EFG was found to be superior in all parameters, with an average η of 10.3% AM1 as opposed to 8.0% AM1 for the old EFG. The slightly

lower resistivity of the new EFG would account only partly for the higher Voc values. Other factors such as increased minority carrier diffusion length are needed to account for the rest of the performance difference this will be discussed later.

For the high efficiency processes (see section 1.0) the results are listed in Appendix III and summarized in Table 2. The best efficiency achieved was 13.8% AM1.

Dark Current Characteristics

Dark forward currents were measured. The "A" factors, which is defined by $I_{SC} = I_0 \left(e^{\frac{qV}{AKT}} - 1 \right)$, of the baseline samples are listed in Table 3 with their CFF values. Table 3 indicates "A" values equal or more than 2 showing problems of shunting and leading to lower CFF's. All these samples were edge-trimmed so that these values represent leakage in the junction rather than the edge. From the limited number of samples here, it seems that the old EFG material is more likely to form leaky junctions. If the high "A" values (≥ 2) are not counted, the rest of the "A" factors with one exception, are within the 1.6-1.8 range both for the new and old EFG.

Spectral Response

Spectral response was measured by a filter wheel method (see Reference 2 for details). Results for selected baseline and high efficiency cells are presented from Figure 1 to Figure 3. It is clear that the new material is superior. Also, a significant enhancement of long wavelength response was noticed in the high efficiency cells. This indicates that the new EFG

material responds more positively to BSF or BSR treatments than the old EFG . This can be due to longer diffusion lengths (3) as will be seen in the following section.

Minority Carrier Diffusion Length

Minority carrier diffusion length (L_D) was measured by the filter wheel method using the short circuit current method (see Reference 2 for details). Selected samples were measured both in the form of whole samples and at selected areas as shown in the figure attached to Table 4 which gives the results. L_D values of the new EFG range from 30 to 40 μm while the old EFG ranged from 20 to 30 μm . This significant increase in L_D is the most decisive factor that accounts for better I_{sc} , because of better carrier collection. Also, the saturation current decreases with longer L_D and since $V_{oc} = + \frac{kT}{q} \ln \frac{J_{sc}}{I_0}$: the increase of L_D also accounts for part of the increase of V_{oc} . The light bias effect in L_D for the new EFG has not been studied in this report period. Work in this area will be useful to evaluate the true significance of L_D under one sun illumination.

Photoresponse by Small Light Spot Scanning

Localized photoresponse of selected solar cells was made using a small light spot scanning technique (see Reference 5 for the detailed description and procedures of the measurement). Figure 4 and Figure 5 show the relative responses of the typical old and new EFG, respectively, and also CZ control cells. It is obvious from the presented data that the old EFG material has more dips in the response and also has some areas of low response. Chemical etching study in the following section indicates that structural defects are partly responsible for the low response.

TABLE 1

SUMMARY OF BASELINE CELLS FROM EFG RIBBONS

		NEW EFG	OLD EFG	CZ CONTROL
Voc (mV)	AV.	568	524	588
	S.D.	7	5	-
	R	560~580	516~534	588
Jsc (mA/cm ²)	AV.	24.3	21.4	28.0
	S.D.	.7	.8	-
	R	23.0~25.0	20.5~23.0	27.8~28.3
CFF (%)	AV.	75	71	76
	S.D.	3	3	-
	R	69~77	65~75	75~77
η (%)	AV.	10.3	8.0	12.6
	S.D.	0.6	0.4	-
	R	9.6 ~ 11.1	7.4 ~ 8.7	12.3~12.8

- NOTE: 1) 2x2 cm Cells with SiO₂ AR coating measured under AM1 at 28°C test block temperature.
- 2) New EFG: Improved grains, grown in carbon containing gas atmosphere.

TABLE 2

SUMMARY OF HIGH EFFICIENCY CELLS FROM NEW EFG RIBBONS

	Voc (mV)	Jsc (mA/cm ²)	CFF (%)	(%)
AV.	565	28.4	76	12.1
S.D.	9	1.1	2	.7
R	550-574	27.0-30.3	72-78	11.5-13.6

(a)

Voc (mV)	Jsc (mA/cm ²)	CFF (%)	η (%)
578	30.3	79	13.8

(b)

NOTE: 1) 2x2 cm cells with AR coating at 28°C test block temperature under AM1 conditions.

2) Process Used:

(a) SJ,BSR, and MLAR.

(b) SJ, BSF, and MLAR.

TABLE 3

"A" FACTORS FROM DARK I-V MEASUREMENTS

	CELL NOS.	A	CFF
NEW EFG	1	1.71	.77
	2	1.69	.75
	7	1.69	.76
	9	1.62	.75
	11	2.05	.70
	12	1.75	.74
OLD EFG	14	1.79	.73
	16	2.14	.69
	17	1.63	.72
	19	2.0	.70
	21	1.7	.75
	22	1.45	.74
	23	1.73	.74
CZ CONTROL	C-3	1.83	.75
	C-4	1.27	.78

TABLE 4
DIFFUSION LENGTHS OF EFG MATERIAL

Diameter of the Circle = 3mm

	DIFFUSION LENGTH (μ m)					
	WHOLE	1	2	3	4	5
Cz Control C-3	119	119	120	126	126	120
New EFG #7	40	50	48	40	40	34
New EFG #13	28	26	25	18	23	34
Old EFG #16	18	14	24	18	20	17
Old EFG #24	28	34	30	32	34	19

FIGURE 1. SPECTRAL RESPONSE OF BASELINE SOLAR CELLS FROM NEW AND OLD EFG MATERIAL..

(a) Good Cells

FIGURE 1 SPECTRAL RESPONSE OF SOLAR CELLS FROM NEW AND OLD
EFG MATERIAL (Continue)

(b) Bad Cells

FIGURE 2. SPECTRAL RESPONSE OF SOLAR CELLS FROM NEW EFG MATERIAL
WITH SJ, BSR, MLAR, AND NARROW GRIDLINES

FIGURE 3. SPECTRAL RESPONSE OF THE BEST SOLAR CELL ($\eta = 13.8\%$) FROM NEW EFG MATERIAL WITH SJ, NARROW GRIDLINES, BSF, AND MLAR.

FIGURE 4. SMALL LIGHT SPOT SCANNING OF TYPICAL OLD EFG MATERIAL

ESTERLINE ANGUS
INDIANAPOLIS, INDIANA U.S.A.
CHART NO. 15800005 001

FIGURE 5. SMALL LIGHT SPOT SCANNING OF TYPICAL NEW EFG MATERIAL.

(a) A Typical Area

(b) An Area of High Dislocation Density

FIGURE 6. Microscopic Pictures of the Surface of old EFG After Chemical Etching. (200X Magnification)

(a) A Typical Area

(b) An Area of High Dislocation Density

FIGURE 7. Microscopic Pictures of the Surface of New EFG After Chemical Etching (200X Magnification).

Structural Defects

Efforts were made to show structural defects by chemical etching techniques. The etching solution used was diluted Sirtl etch (10 grams of C_2O_3 in 60 ml of deionized distilled water, and an equal volume of concentrated HF). Materials Research Inc. in Utah, reported that 50 seconds by the etching solution distinctly revealed grain boundaries, twin boundaries, and dislocations for EFG (4). Figure 6 and Figure 7 show microscopic pictures of the etched surface of the old and new EFG, respectively; (a) for a typical region and (b) for a area of high dislocation. Dislocation density of the old EFG is considerably higher than the new EFG grown in carbon containing gas atmosphere. The old EFG also showed areas of dislocation clusters, (b) in Figure 6, which is expected to reduce photoresponse significantly. The low localized response in Figure 4 could possibly be due to this dislocation clusters.

B HEM Solar Cells

1.0 Solar Cells Fabrication

Two HEM cast silicon crystals were studied in this contract period (a cube 4"x4"x4" Crystal System #41-07 and a whole ingot Crystal System #41-20). The crystals used semiconductor grade starting materials and the purpose of the study was to test material uniformly by measuring solar cell performance as a function of the position in the crystals. Reference (5) provides technical details of the HEM process. The two crystals, with resistivity of about 2 ohm-cm, were cut differently. The cube #41-07 was cut horizontally with respect to its casting position and wafers were marked relative to the top of the crystal. Ingot #41-24, was cut vertically with respect to casting position, and only central parts of the

crystal were used (Figure 8). 2x2 blanks were cut from both crystals and they were all marked such that their positions were traceable. Baseline process was applied to fabricate cells from both crystals. For the horizontally cut crystal, for some of the cells an extra step of gettering glass was applied before the baseline process was applied. Also, an attempt to anneal the wafers was made on some samples before the baseline process. Because this crystal showed a clear correlation between performance and position, high efficiency processing (including gettering, SJ with narrow grid lines, BSF, MLAR) was applied to the best portion of the crystal. For the vertically cut cells, since no clear correlation was established, only baseline cells were fabricated in this contract period. Some gettered cells will be fabricated in the next period.

2.0 Solar Cell Performance and Characterization

Characteristics Under Illumination

Solar cells by the baseline process had 90% active area and SiO₂ AR coating while high efficiency cells had 94% active and MLAR. Solar cell parameters such as Voc, Isc, CFF, and n were measured at 28°C under AM1 conditions (see Reference 1 for description of simulator). Appendix VI provides the parameters of each individual cell from all processes. In order to illustrate the relations between solar cell performance and position in each of the crystals, Figure 9 gives solar cell efficiency from the baseline process as a function of position of the horizontally cut crystal while Figures 10 to 13 give parameters of the vertically cut. It is obvious that in the horizontally cut crystal a definite pattern can be established. Best solar cell performance is found in the upper middle portion of the crystal, the top portion is slightly inferior, and

performance deteriorates in the lower half with the worst cells close to the seed. After gettering treatment, most improvement was found in the lower middle portion of the crystal. Annealing at 600°C made no significant improvement in cell performance. For the best portion of the crystal, cell performance, whether baseline process or high η processes is comparable to the single crystal CZ controls. The high η result is given in Table 5. Also, no significant deviation was detected between the edge and center portions of any wafer, nor between polycrystalline and single crystalline portions. For this horizontally cut (#41-07) crystal, the only positional variable was the distance from the bottom.

Different conclusions can be drawn for the vertically cut crystal (#41-24). From Figures 10 - 13, it is obvious that a definite pattern cannot easily be established. Judging from Isc (Figure 13) it seems that the edges except on the bottom section deteriorate the most and across the ingot the upper middle portion is the worst section. (Only slight deterioration occurred close to the seed in contrast to the horizontally cut crystal.) All the cells were inferior to the CZ control. The different behavior in the two crystals shows that HEM casting can lead to inconsistent quality.

SPECTRAL RESPONSE

Absolute spectral response (A/W) was obtained using a filter wheel set-up (Reference 2) Figure 14 to Figure 16 show the response of selected samples of baseline, gettered + baseline, and high η processes for samples from the horizontally cut crystal (#41-07). No spectral response was measured for the vertically cut crystal.

Light Bias Minority Carrier Diffusion Length Measurement

The varying performance of solar cells from different portions of HEM crystals indicate the possibility of existence of recombination centers in the low performance positions. Light bias minority carrier diffusion length measurements could easily indicate their existence. Selected samples from both crystals were measured by the SSI 100 diffusion length meter which has a built in light bias source.

The difference between the SSI system and the filter wheel is that the SSI can only measure a relatively small localized area of the solar cell. The bias source was a tungsten-halogen lamp. The bias level varied from approximately 1/3 sun to 6.8 suns. The results are shown in Figure 17 and Figure 18 for the respective crystals. Also observed were photodegradation effect in some of the cells as indicated by cell 2-3 in Figure 17 and cell 5 in Figure 18.

For solar application, the level of excitation usually fall within an intermediate range i.e., the concentration of excess carriers (Δp) is lower than the majority carrier level but higher than the minority carrier level; and this is certainly true in the study here. From Appendix V, Δp values of the cells (#5-22 and #12-2) were estimated to be 3.2×10^{15} for #5-22 and 4×10^{14} for #12-2, indicating the values below the majority carrier density (P_0) of 10^{16} level. Δp of the poor performance cell (#12-2) is negligible compared to P_0 , while this is not true for the good performance cell (#5-22).

After establishing the range of excitation, it would be informative to look at a single model of one recombination center. For the poor performance

cells, equation (9) of Appendix V shows that τ increases with an increasing slope with G; i.e., $\frac{d\tau}{dG}$ should increase. Since G is proportional to the intensity, it is informative to plot τ vs G. Figure 19 and Figure 20 are the results of the plots for the two sets of cells. It is obvious that the slope ($\frac{d\tau}{dG}$) decreases as G increases for all cells. So it seems that the one level model is inadequate for the poor performance cell (#12-2). However, the same cannot be said for the good cell (5-22); As demonstrated in Appendix V, the one level model would have the declining slope behavior for the good cell, especially when excess carrier concentration is approaching the majority carrier concentration (P_0). Thus the one level model cannot be ruled out for the good performance cells.

DLTS Measurements

In order to look at the defect structure from a different direction, some preliminary deep level transient spectroscopy (DLTS) measurements for the horizontally cut crystals were made. The DLTS systems used (reference #6 for the DLTS systems) belongs to JPL under Task 2 of the LSA project. Not enough measurements were made to achieve consistency of the results. However, preliminary indications were that extra distributions of defect levels existed in the lower portion of the crystal (8 and 12-series) while these levels could not be found in the upper portion (5 and 2 series). This is consistent with the light bias results. There is also some indication that a common defect level exists in all cells.

More detailed work is needed to clarify this overall picture, particularly to correlate the varying performance at different portions with probable impurities or other defects.

TABLE 5

SUMMARY OF HIGH EFFICIENCY CELLS FROM A SELECTED PORTION
OF A HEM INGOT

	Voc (mV)	Jsc (mA/cm ²)	CFF (%)	η (%)
AV	597	32.4	78	15.0
S.D.	3	.6	2	.5
R	588-602	30.6-33.3	75-80	13.5-15.7

- NOTE:
- 1) 2x2 cm cells with AR coating measured under AM1 at 28°C test block temperature.
 - 2) Solar cells were fabricated from a portion of the ingot (#41-07), where good baseline performance was obtained.
 - 3) Processes used were Gettering, SJ, BSF, and MLAR.

FIGURE 8

CROSS SECTION OF A VERTICALLY CUT HEM INGOT

A HEM INGOT (ID #41-24)

FIGURE 9. AVERAGE EFFICIENCY vs. POSITION OF THE HORIZONTALLY CUT HEM (BASELINE PROCESS)

FIGURE 10

SHORT CIRCUIT CURRENT DENSITY (AM1, NO AR) MAPPING OF A VERTICALLY CUT
HEM WAFER

SEED

NOTE: UNIT: mA/cm^2
Jsc OF CONTROL CELL = $21.3 \text{ mA}/\text{cm}^2$

FIGURE 11

OPEN CIRCUIT VOLTAGE (AM1, NO AR) MAPPING OF A VERTICALLY CUT HEM WAFER

SEED

NOTE: Unit: mV

Voc of Control Cell = 567 mV

FIGURE 12

EFFICIENCY (AM1, NO AR) MAPPING OF A VERTICALLY CUT HEM WAFER

SEED

NOTE:

UNIT:

%

η OF CONTROL CELL = 9.1

FIGURE 13

EFFICIENCY (NORMALIZED WRT TO THE CONTROL CELLS) MAPPING OF A VERTICALLY
CUT HEM WAFER

SEED

NOTE: UNIT: Percentage
AVERAGE: 78

FIGURE 14 (A). SPECTRAL RESPONSE OF SOLAR CELLS FROM HEM
MATERIAL - BASELINE PROCESS

FIGURE 14 (B), SPECTRAL RESPONSE OF SOLAR CELLS FROM HEM MATERIAL -
BASELINE PROCESS (Continue)

FIGURE 15(A)

SPECTRAL RESPONSE OF SOLAR CELLS FROM HEM
MATERIAL: GETTERING + BASELINE PROCESS

FIGURE 15 (B). SPECTRAL RESPONSE OF SOLAR CELLS FROM HEM MATERIAL;
GETTERING + BASELINE PROCESS (Continue)

FIGURE 16. SPECTRAL RESPONSE OF SOLAR CELL FROM HEM MATERIAL:
GET, SJ, NARROW GRIDLINES, BSF, MLAR PROCESS

FIGURE 17

L_D 's vs. No. of Suns for Horizontally-Cut HEM Cells (Cells' No. in Parenthesis)

FIGURE 18

L_D vs. No. of Suns for Vertically Cut HEM Cells
(Cells' No. in Parenthesis)

FIGURE 19

Lifetimes vs. No. of Suns for Horizontally Cut
(Cells' No. in Parenthesis)

FIGURE 20

Lifetimes vs. No. of Suns for Vertically Cut HEM
Cells (Cells' No. in Parenthesis)

III. CONCLUSIONS & RECOMMENDATIONS

The conclusions and recommendations reached after processing and evaluation of the sheets are as follows.

EFG Ribbons

- o EFG ribbons grown in carbon containing gas atmosphere showed significant improvement in sheet quality. Chemical etching study indicated that new EFG showed better structural perfection; i.e., larger grain size and less dislocation density, and the diffusion length was significantly higher.
- o The new EFG demonstrated an average baseline cell efficiency of 10.3% AM1 as opposed to 8.0% AM1 for the earlier EFG. The best efficiency achieved by the advanced process was 13.8% under AM1 conditions.

HEM

- o Evaluation of two ingots suggested that HEM has problems of ingot reproducibility from run to run and also in uniformity of sheet quality within an ingot. Portions of sheet with quality equivalent to the conventional CZ, could be less than 50 percent.
- o Gettering and low temperature annealing experiment did not improve cell efficiency significantly. Detailed analysis of defects and impurities is necessary to identify the potential areas of degrading silicon sheet quality.

IV. WORK PLAN STATUS

The following silicon sheets are expected for processing and evaluation during the next period.

- o Further evaluation of the HEM ingots by introducing other process variations.
- o Performance comparison of EFG ribbons grown in CO-on and CO-off atmosphere.
- o Fabrication and evaluation of dendritic web solar cells.

V.

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APPENDIX I

TIME SCHEDULE

TIME SCHEDULE

TASK	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL
1. PROCESS SHEET SAMPLES													
a) Baseline Process													
b) Analysis													
c) Back Up Measurements													
d) Test Alternate Process													
2. REPORTS													
a) Monthly		▲	▲		△	△		△	△		△	△	
b) Quarterly				▲			△			△			
c) Final													△
3. INTEGRATION MEETING													

APPENDIX II
ABBREVIATION

ABBREVIATIONS

V_{OC} :	Open Circuit Voltage
I_{SC} :	Short Circuit Current
J_{SC} :	Short Circuit Current Density
I_{SCR} :	Short Circuit Current (Red Response) at Wavelength Above $\sim .6 \mu m$
I_{SCB} :	Short Circuit Current (Blue Response) at Wavelength Below $\sim .6 \mu m$
CFF:	Curve Fill Factor
η :	Solar Cell Conversion Efficiency
L:	Minority Carrier Diffusion Length (D.L.)
I_{MAX} :	Current at Maximum Power Point
V_{MAX} :	Voltage at Maximum Power Point
P_{MAX} :	Maximum Power Point
BSF:	Back Surface Field
BSR:	Back Surface Reflector
V_B :	Bias Voltage
I_O :	Diode Saturation Current
HEM:	Heat Exchanger Method
EFG:	Edge Defined Film-Fed Growth
SOC:	Silicon on Ceramic
RTR:	Ribbon-to-Ribbon
SPV:	Surface Photovoltage
MLAR:	Multi-Layer Anti-Reflective
R_s :	Series Resistance

APPENDIX III

ELECTRICAL DATA SHEETS FOR EFG SOLAR CELLS

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EFG Solar Cells (2x2 cm), Baseline Process
SiO AR Coating

TEST CONDITION: AM1

TEMPERATURE: 28°C Test Block Temperature

DATE: 7/80

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm ²
1	568	98			93	452	42.04	76	10.5	4
2	560	94			87	453	39.41	75	9.9	"
7	578	100			92	480	44.16	76	11.0	"
8	580	100			92	483	44.44	77	11.1	"
9	566	96			90	466	41.94	77	10.5	"
10	566	98			87	453	39.41	71	9.9	"
11	566	98			85	452	38.42	69	9.6	"
12	560	92			85	452	38.42	75	9.6	"
(Above from new EFG (Run # 18-2053) with surface layer removed)										
14	522	86			77	425	32.73	73	8.2	
16	522	82			70	425	29.75	70	7.4	4
17	526	84			76	421	32.00	72	8.0	"
19	524	86			76	421	32.00	71	8.0	"
20	520	85			72	413	29.74	67	7.4	"
21	534	88			81	430	34.83	74	8.7	"
22	516	82			76	416	31.62	75	7.9	"
23	530	84			78	417	32.53	74	8.1	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EFG Solar Cells (2x2 cm), Baseline Process.

SiO₂ AR Coating

AM1

28°C Test Block Temperature

DATE: 7/80

[illegible]

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EFG SOLAR CELLS (2x2cm), Baseline Process

SiO AR Coating

TEST CONDITION:

AMO

TEMPERATURE:

28°C Test Block Temperature

DATE: 7/80

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	η	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm ²
1	571	116	50	65	111	460	51.06	77	9.5	4
2	565	112	48	63	105	450	47.25	75	8.8	"
7	580	120	51	68	113	467	52.77	76	9.8	"
8	581	120	50	69	109	485	52.86	76	9.8	"
9	579	114	50	64	105	470	49.35	75	9.2	"
10	569	115	49	65	102	455	46.41	71	8.6	"
11	568	115	49	66	100	460	46.00	70	8.5	"
12	563	111	48	62	100	462	46.20	74	8.6	"
	(Above from new EFG (Run # 18-205-3) with Surface layer removed,									
27	521	74	22	51	61	315	19.22	49	4.2	3.40
31	537	84	24	60	66	352	23.23	52	4.3	4.00
	(Above from new EFG (Run # 18-205-4) with no surface layer removed)									
14	523	103	47	54	94	417	39.20	73	7.3	4
16	528	99	46	51	85	425	36.13	69	6.7	"
17	531	100	46	51	91	418	38.04	72	7.0	"
18	528	81	37	42	68	432	29.38	69	6.7	3.23
19	528	102	47	54	91	415	37.77	70	7.0	4

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION:

EFG SOLAR CELLS (2x2cm), Baseline Process

TEST CONDITION:

SiO AR Coating

TEMPERATURE:

AMO

28°C Test Block Temperature

DATE: 7/80

NO.	V _{OC} mV	I _{SC} mA	I _{SCB} mA	I _{SCR} mA	I _{Max} mA	V _{Max} mV	P _{Max} mW	CFF %	η %	AREA cm ²
20	519	101	46	53	87	420	36.54	70	6.8	4
21	538	104	46	57	96	435	41.76	75	7.7	"
22	520	98	45	51	90	420	37.80	74	6.7	"
23	525	101	47	53	93	422	39.25	74	7.3	"
24	536	109	48	60	93	422	39.25	67	7.3	"
26	515	59	27	31	52	425	22.10	73	6.4	2.57
(Above from old EFG)										
(Cell # 14~21 from EFG Run # 16-227-3J-2)										
(Cell # 22~26 from EFG Run # 16-227-3H-2)										
C-2	592	134	53	80	124	490	60.76	77	11.3	4.0
C-3	592	133	54	80	122	483	58.93	75	10.9	"
C-4	594	131	52	80	124	488	60.51	78	11.2	"
(Above CR control cells)										

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EFG CELLS, SJ + BSR + MLAR PROCESS

TEST CONDITION:

TEMPERATURE:

AM1

28°C

TEST BLOCK

9/80

[illegible]

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: EFG Cells, SJ + BSF + MLAR Process

TEST CONDITION: AM1

TEMPERATURE: 28°C Test Block 9/80

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APPENDIX IV

ELECTRICAL DATA SHEETS FOR HEM SOLAR CELLS

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM (2 x 2 cm) Cells, Baseline Process, First Page
 SiO AR Coating
 TEST CONDITION: AMI
 TEMPERATURE: 28°C Test Block 8/80

NO.	V _{OC}	J _{SC}	P _{Max}	CFF	n	AREA
	mV	mA/cm ²	mW	%	%	cm ²
2-2	.568	26.1		.77	11.3	4.0
2-3	.562	25.1		.71	10.0	"
2-4	.564	25.6		.75	10.8	"
2-5	.566	26.1		.75	11.1	"
2-20	.566	26.5		.72	10.8	"
2-21	.562	25.4		.71	10.1	"
2-22	.560	26.6		.64	9.5	"
2-23	.566	26.1		.76	11.3	"
5-1	.582	27.5		.78	12.5	"
5-2	.582	28.5		.75	12.4	"
5-4	.582	28.0		.76	12.3	"
5-5	.580	27.5		.76	12.1	"
5-20	.582	28.0		.77	12.6	"
5-21	.580	27.9		.77	12.4	"
5-22	.582	28.0		.74	12.0	"
5-23	.580	27.0		.77	12.1	"
8-1	.534	20.5		.75	8.3	"
8-2	.534	20.7		.74	8.2	"
8-3	.544	22.6		.74	9.1	"
8-4	.556	23.5		.74	9.7	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION:	HEM (2 x 2 cm) Cells, Baseline Process,	Second Page
	SiO ₂ AR Coating	
TEST CONDITION:	AM1	
TEMPERATURE:	28°C Test Block	8/80

NO.	V _{OC}	J _{SC}	P _{Max}	CFF	n	AREA
	mV	mA/cm ²	mW	%	%	cm ²
8-20	.534	21.1		.75	8.4	4.0
8-21	.538	21.1		.77	8.7	"
8-22	.536	20.6		.75	8.3	"
12-1	.510	20.1		.72	7.4	"
12-2	.506	18.7		.73	6.9	"
12-3	.522	22.0		.66	7.5	"
12-4	.514	20.6		.73	7.8	"
12-21	.532	21.5		.72	8.2	"
12-22	.518	19.5		.73	7.4	"
12-25	.510	18.7		.74	7.0	"
12-26	.506	18.1		.75	6.9	"
(Above HEM baseline cells)						
C-1	.592	27.4		.75	12.1	4.0
C-3	.586	28.3		.73	12.2	"
C-4	.588	28.3		.73	12.2	"
(Above CZ control cells)						

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM (2 x 2 cm) Cells, Gettering & Baseline, First Page
 S10 Air Coating
 TEST CONDITION: AMI
 TEMPERATURE: 28°C Test Block 8/80

NO.	V _{OC}	J _{SC}	P _{Max}	CFF	η	AREA
	mV	mA/cm ²	mW	%	%	cm ²
2-7	.572	25.5		.77	11.1	4.0
2-8	.580	27.4		.75	11.9	"
2-9	.576	27.0		.71	11.1	"
2-10	.576	26.6		.73	11.1	"
2-11	.578	27.0		.69	10.8	"
5-5	.582	27.4		.76	12.1	"
5-6	.584	27.5		.77	11.9	"
5-7	.574	27.0		.74	12.1	"
5-8	.582	27.9		.74	12.0	"
5-9	.582	28.3		.73	12.1	"
5-10	.582	27.8		.74	12.0	"
8-5	.560	25.5		.73	10.5	"
8-6	.558	25.0		.71	9.9	"
8-8	.562	25.0		.72	10.4	"
8-9	.582	27.0		.72	11.0	"
8-10	.550	24.0		.74	9.7	"
8-11	.552	25.0		.73	10.0	"
12-5	.520	21.1		.71	7.8	"
12-6	.510	19.7		.68	6.9	"
12-7	.508	20.5		.71	7.4	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM (2 x 2 cm) Cells - Gettering & Baseline,
SiO AR Coating

Second Page

TEST CONDITION: AMI

TEMPERATURE: 28°C Test Block

8/80

[illegible]

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM CELLS, GET + SJ + BSF + MLAR PROCESS

TEST CONDITION:

TEMPERATURE:

AM1

28°C

TEST BLOCK

9/80

NO.	V _{OC}	J _{SC}	P _{Max}	CFF	η	AREA
	mV	mA/cm ²	mW	%	%	cm ²
1	592	32.2		77	14.7	3.96
2	596	31.6		79	14.9	3.91
3	600	33.3		78	15.7	3.83
4	596	32.6		75	14.6	3.89
5	600	33.3		78	15.5	3.87
6	598	32.2		79	15.1	3.88
7	598	32.4		79	15.4	4.06
8	600	32.7		80	15.7	"
9	598	31.9		79	15.0	"
10	594	32.7		75	14.6	"
11	594	32.4		77	14.8	"
12	592	32.2		77	14.6	"
13	588	30.6		75	13.5	"
14	596	32.8		75	14.7	"
15	596	32.9		75	14.8	"
16	596	32.3		78	15.0	"
17	596	32.2		78	15.1	"
18	600	33.2		77	15.4	"
19	602	32.8		80	15.7	"
20	600	32.7		80	15.7	"

(Above HEM cells)

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION:	CZ CELLS, SJ + BSF + MLAR
	FOR COMPARISON WITH HEM CELLS
TEST CONDITION:	AM1
TEMPERATURE:	28°C TEST BLOCK

AM1

28°C TEST BLOCK

9/80

[illegible]

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM Solar Cells (2x2 cm), Anealing + Baseline

from 4" x 4" x 4" ingot

TEST CONDITION: AM1

TEMPERATURE: 28°C Test Block

NO.	V _{OC}	J _{SC}	P _{Max}	CFF	n	AREA
	mV	mA/cm ²	mW	%	%	cm ²
1-4	570	26.6		75	11.3	
1-6	572	27.0		75	11.6	
1-7	562	26.0		71	10.4	
1-10	570	27.0		75	11.6	
1-12	570	27.4		74	11.5	
1-13	562	26.5		72	10.7	
1-11	570	27.0		74	11.4	
4-3	586	29.3		75	12.8	
4-5	588	29.0		76	12.9	
4-6	574	28.0		74	11.8	
4-7	576	28.9		74	12.4	
4-10	584	28.4		74	12.3	
4-11	578	28.3		74	12.1	
4-12	578	28.4		72	11.9	
4-13	582	28.5		74	12.3	
7-2	576	28.0		73	11.8	
7-3	528	20.2		72	7.7	
7-4	580	28.4		75	12.4	
7-5	548	23.0		73	9.2	
7-7	570	26.6		75	11.3	
7-8	574	26.4		76	11.6	
7-9	564	27.4		74	11.5	

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM Solar Cells (2x2 cm), Annealing + Baseline
from 4"x 4"x 4" ingot.
 TEST CONDITION: AM1
 TEMPERATURE: 28°C Test Block

NO.	V_{OC}	J_{SC}	P_{Max}	CFF	n	AREA
	mV	mA/cm ²	mW	%	%	cm ²
7-10	572	28.0		75	12.0	
11-5	502	18.1		76	6.9	
11-20	522	20.2		74	7.8	
11-21	492	18.1		75	6.7	
11-23	492	18.1		75	6.6	
11-24	510	19.2		69	6.7	
11-26	522	20.1		75	7.9	
11-27	494	18.2		72	6.5	
11-28	522	20.2		75	7.9	
		control cells				
C-2	586	29.0		76	13.0	
C-4	582	29.5		72	12.3	

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APPENDIX V

INTERPRETATION OF LIGHT BIAS DIFFUSION LENGTH MEASUREMENTS

APPENDIX V

A. Estimating the Levels of Excitation

Consider cells 5-22 (good) and 12-2 (poor) for the horizontally cut crystal:

$$\Delta p = G \tau \quad (\text{where } G \text{ is the generation rate and } \tau \text{ the lifetime}) \quad (1)$$

$$J_{sc} = q G L_n \quad (\text{assuming diffusion current dominates}) \quad (3)$$

For cell 5-22 at 1 sun and from eq (2):

$$G = \frac{J_{sc}}{q L_n} = 8.79 \times 10^{18}$$

Using eq (1) and $D_n = 9 \text{ cm}^2/\text{sec}$ for $10^{16}/\text{cm}^3$ majority carriers (Ref.7)

$$\Delta p \Big|_{1 \text{ sun}} = G \tau \Big|_{1 \text{ sun}} = G \frac{L_n^2}{D} = 3.87 \times 10^{14}/\text{cm}^3$$

In the same cell at max excitation (6.8 sun), since $G \propto$ no. of suns.

$$\Delta p \Big|_{6.8 \text{ sun}} = 6.8 \times \frac{\tau \Big|_{6.8 \text{ sun}}}{\tau \Big|_{1 \text{ sun}}} \times \Delta p \Big|_{1 \text{ sun}} = 3.24 \times 10^{15} \leq 10^{16}$$

In cell 12-2, similar calculation yields:

$$G \Big|_{1 \text{ sun}} = 7.3 \times 10^{19}$$

$$\Delta p \Big|_{1 \text{ sun}} = 2.07 \times 10^{13}$$

$$\Delta p \Big|_{\text{max}} = 4.02 \times 10^{16}$$

One can see $G \Big|_{1 \text{ sun}}$ is considerably higher than for the good cell, because the assumption of eq. (2) is not as good for the poor cell. So one can say an overestimation of Δp exists for the poor cells. In spite of this, the $\Delta p \Big|_{\text{max}}$ is still orders of magnitude below 10^{16} majority carrier level in the poor performance cells.

B. Minority Lifetime For One Level Model

The lifetime of a material with single recombination level is:

$$\tau = \tau_p = \tau_n = \tau_{p0} \frac{n_0 + n_1 + \Delta p}{p_0 + n_0 + \Delta p} + \tau_{n0} \frac{p_0 + p_1 + \Delta p}{p_0 + n_0 + \Delta p} \quad (3)$$

$$\Delta p = \Delta n \quad (3) \quad \tau_{p0} = \frac{1}{N_t \sigma_p v_t} \quad \text{and} \quad \tau_{n0} = \frac{1}{N_t \sigma_n v_t} \quad \text{are the}$$

lifetimes of both carriers if they are minority carriers in strongly doped samples.

Also $n_1 = N_c \exp(E_t - E_f) / kT$ and $p_1 = N_v \exp(E_f - E_t) / kT$ are the carrier concentrations assuming Fermi level coincided with the recombination level. For p-type material under intermediate excitation ($p_0 > \Delta p > n_0$) and for recombination centers above E_f , $p_0 \gg p_1$.

$$\text{Therefore (3) reduces to: } \tau = \tau_{p0} \frac{\Delta p + n_1}{p_0 + \Delta p} + \tau_{n0} \quad (4)$$

a) For the poor performance cell:

$$\Delta p \ll p_0$$

$$\text{equation(4) becomes } \tau = \tau_{p0} \frac{\Delta p + n_1}{p_0} + \tau_{n0} \quad (5)$$

$$\begin{aligned} \tau &= \frac{\tau_{p0}}{p_0} \Delta p + \frac{\tau_{p0}}{p_0} n_1 + \tau_{n0} \\ &= a \Delta p + b \end{aligned} \quad (6)$$

where a, b are constants.

$$\text{Since } \Delta p = G \tau \quad (7)$$

$$\tau = aG\tau + b$$

$$\frac{d\tau}{dG} = \frac{ab}{(1-aG)^2} \quad (9)$$

$\frac{d\tau}{dG}$ increases with G for $aG < 1$.

b. For good performance cells, eq. (4) should be applied:

$$\tau = \tau_{p0} \frac{\Delta P + n_1}{P_0 + \Delta P} + \tau_{n0} \quad (5)$$

$$\Rightarrow \tau + \delta\tau = \tau_{p0} \frac{\Delta P + \delta\Delta P + n_1}{P_0 + \Delta P} - \tau_{p0} \frac{\Delta P + n_1}{(P_0 + \Delta P)^2} (\delta\Delta P) + \tau_{n0}$$

Since $\Delta P = G\tau$

$$\delta\Delta P = \delta(G\tau) = G\delta\tau + \tau\delta G$$

$$\begin{aligned} \tau + \delta\tau &= \tau_{p0} \frac{G\tau + n_1}{P_0 + G\tau} + \frac{\tau_{p0}}{P_0 G\tau} (G\delta\tau + \tau\delta G) \\ &\quad - \frac{\tau_{p0} (G\tau + n_1)}{(P_0 + G\tau)(P_0 + G\tau)} (G\delta\tau + \tau\delta G) + \tau_{n0} \end{aligned} \quad (6)$$

Subtract (5) from (6):

$$\begin{aligned} \delta\tau &= \frac{\tau_{p0}}{P_0 G\tau} \left(1 - \frac{(G\tau + n_1)}{P_0 + G\tau}\right) (G\delta\tau + \tau\delta G) \\ &= \frac{\tau_{p0}}{P_0 + G\tau} \frac{P_0 - n_1}{P_0 + G\tau} (G\delta\tau + \tau\delta G) \end{aligned}$$

$$\frac{\delta\tau}{\delta G} = \frac{\tau_{p0}}{P_0 + G\tau} \frac{P_0 - n_1}{P_0 + G\tau} \left(G \frac{\delta\tau}{\delta G} + \tau\right)$$

$$\frac{\delta\tau}{\delta G} = \frac{\tau \frac{\tau_{p0} (P_0 - n_1)}{(P_0 + G\tau)^2}}{1 - \frac{G\tau_{p0} (P_0 - n_1)}{(P_0 + G\tau)}}$$

$$= \frac{\tau \tau_{p0} (P_0 - n_1)}{(P_0 + G\tau)^2 - G\tau_{p0} (P_0 - n_1)}$$

$$\frac{\delta\tau}{\delta G} = \frac{\tau \tau_{p0} (P_0 - n_1)}{P_0^2 + 2P_0 G\tau + (G\tau)^2 - G\tau_{p0} (P_0 - n_1)} \quad (7)$$

Assume that τ changes very slowly compared with G and $P_0 > n_1$.

Whether $\frac{\delta \tau}{\delta G}$ increases with G is determined by the terms in the denominator of eq (7) .

$$\text{If } 2 p_0 G \tau - G \tau_{p_0} (p_0 - n_1) > 0 \quad (8)$$

The denominator of eq (7) will increase with G and $\frac{\delta \tau}{\delta G}$ will decrease with G.

Since $\tau_{\max} = \tau_{p_0} + \tau_{n_0}$ and $\tau_{\min} = \tau_{n_0}$ from Figure 19 for the good performance cells, it is conceivable that $\tau_{p_0} < \tau$ for the increase of lifetime $(\tau - \tau_{\min}) < \tau_{\min}$. (There is no proof for we have not reached $\tau_{\max}$). From eq. (8) as long as $2\tau \geq \tau_{p_0}$, (9) $\frac{d\tau}{dG}$ will decrease with G and it is obvious that such condition eq. (9) can be fulfilled with a large range of possible τ_{p_0} and therefore the one level model cannot be ruled out for the good performance cells. For the poor performance cells, it is obvious that $\tau \gg \tau_{\min}$ and $\tau_{p_0} \gg \tau_{n_0}$ and $\tau_{p_0} \approx \tau_{\max} > \tau$. Also, $(G\tau)^2 = \Delta P^2$ is small, therefore the term with -G dominates and $\frac{\delta \tau}{\delta G}$ always increases, a result consistent with the previous conclusion.