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MASTER SILICON SOLAR CELL PROCESS DEVELOPMENT, FABRICATION
AND ANALYSIS

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ABSTRACT

Solar cells were fabricated from HEM (Crystal Systems), SOC (Honeywell) and semi-continuous CZ wafers (HAMCO), and their performance was characterized. Shallow junction, BSF and gettering steps were applied on HEM wafers, resulting in significant enhancement in carrier collection (J_{sc}) by the gettering process. Improvement in efficiency was achieved on SOC solar cells by increasing active area of the cells (Photoresist techniques were used instead of metal shadow mask).

Standard HAMCO solar cells were fabricated on wafers from one of HAMCO's 100kg continuous runs. Performance of the solar cells, as a function of ingot growth sequence and position within the ingots, indicated; 1) single crystalline HAMCO cells showed efficiency the same as conventional CZ control cells (usually even higher efficiencies were observed), 2) no significant performance degradation was observed on the cells from the last grown ingot, and 3) cells made from poly crystalline sections indicated lower conversion efficiency.

The BSF study showed that the higher the resistivity of the starting substrates, the greater the relative improvement in cell performance, probably because of greater shift in Fermi levels at the back L/H junction (pp^+) and the higher values of initial minority carrier diffusion length. This study also suggested that proper control of the BSF process could minimize the junction shunting problems.

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I. INTRODUCTION

This program investigates, develops, and utilizes technologies appropriate and necessary for improving the efficiency of solar cells made from various unconventional silicon sheet materials. During this reporting period, work has progressed in fabrication and characterization of solar cells from HEM (Crystal Systems), SOC (Honeywell), and Semi-Continuous CZ wafers (HAMCO). Solar cells were fabricated using various process modifications, such as formation of shallow junction and BSF, fabrication of large area cells (1"x1") and gettering by diffusion glasses, etc. Shunting characteristics and the effectiveness of the BSF process used were investigated as a function of the starting substrate properties, such as method of crystal growth (i.e., CZ versus FZ), crystal orientation and doping level.

The solar cell parameters measured included open circuit voltage (Voc), short circuit current (Isc), curve fill factor (CFF), and conversion efficiency (all taken under AMO illumination). Additional measurements under AM1 simulation conditions have been included for the standard solar cells, for direct evaluation and to collect information on the AM1/AMO conversion factors for the various sheet materials. Also, measurement for typical cells included spectral response and minority carrier diffusion length. No data on dark I-V characteristics and photoresponse by fine light spot scanning were included since the results were similar to those reported in an earlier technical report (1). The results obtained were compared to the properties of cells made from conventional single crystalline CZ silicon with an emphasis on statistical evaluation. Increased emphasis was given toward modifying the process to yield increased performance.

II. TECHNICAL DISCUSSION

A. HEM SOLAR CELLS

1.0 SOLAR CELL FABRICATION

Metal shadow masks for 1"x1" solar cells were delivered to ASEC from a vendor and large area solar cells (1"x1") were fabricated on HEM slices using the standard process. The mask was expected to provide an active area of about 90-92% (with sixteen (16) grid lines per inch). An effort was made to form a shallow junction by using reduced diffusion time (ten minutes of diffusion instead of twenty minutes of diffusion time in standard process). The same 1"x1" metal mask was used for metallization for both diffusion conditions.

Gettering by diffusion glasses was added to the standard process since the possibility of impurity contaminations from the HEM process (crucible and growing atmosphere) was anticipated. The gettering step was carried out on the cleaned saw-cut HEM wafers by forming diffusion glasses at 875°C for about an hour (oxygen bubbling through POCl₃ source). After this step, chemical polishing removed the diffused layers (and if successful, removed some gettered impurities) and the saw damage layer simultaneously; standard processing followed thereafter to fabricate 2x2cm solar cells.

2.0 SOLAR CELL PERFORMANCE AND CHARACTERIZATION

Characteristics Under Illumination

Finished solar cells had evaporated SiO₂ AR coatings with Ti-Pd-Ag

metallization. Solar cell parameters, such as I_{sc} , V_{oc} , CFF and , were measured under an AMO simulator at 25°C test block temperature. (Description of the simulator and the light intensity calibration methods used are discussed in Appendix IV of reference (1)).

Solar cell parameters of the large area (1"x1") HEM solar cells from both standard and shallow junction processes are given in Appendix III. Table 1 and Table 2 summarize the results for the standard cells and for the shallow junction cells. The standard solar cells showed an average AMO efficiency of 10% for single crystalline HEM and 9.7% for poly crystalline HEM. The shallow junction solar cells indicated a slight improvement in efficiency for both single crystalline and poly crystalline HEM. CZ control cells showed an average efficiency of 11.4%. In both cases, there were no remarkable differences in cell performance between single crystalline and poly crystalline HEM. This indicates that use of HEM silicon with large crystallites (mm size) does not significantly reduce solar cell performance.

Parameters for solar cells using the gettering process (see section 1.0 for the details), are summarized in Table 3. The solar cells from this process showed an average AMO efficiency of 10.3% for the single crystalline HEM cells and 9.8% for the poly crystalline HEM cells. This is a significant improvement over the previously reported standard cell performance (the result reported in reference (2)), using the same silicon and process conditions.

A BSF process was applied to HEM. However, the majority of the solar cells showed severe junction shunting problems. No electrical data is presented for these cells.

Spectral Response

Absolute spectral response (A/W) was measured using a filter wheel set-up (refer to Appendix V of reference (1) for the details). Responses are plotted in Figure 1 for the large area (1"x1") HEM solar cells with shallow junction. A good cell and a bad cell were shown in the figures and significant difference in long wavelength response is noticed: long wavelength response of the CZ control cell is considerably higher than the HEM solar cells. Figure 2 shows response plots of the gettered HEM solar cells (2x2cm). Long wavelength responses of the gettered cells are not as high as for the control cell. However, some improvement in long wavelength region was noticed compared with the response of the standard cells reported in reference (2), indicating improvement in bulk minority carrier lifetime by the gettering step used.

Minority Carrier Diffusion Length

Minority carrier diffusion length (L) was measured using a short circuit current method for the finished solar cells. (See Appendix V-B of reference (1) for the detailed description on measurement procedure.)

Solar cells utilizing the gettering step showed an average diffusion length of about 70 μ m which is an improvement over the cells without the gettering treatment. Typical L -values of the HEM cells without the treatment (Gettering) and for the CZ control cells were about 50 μ m and 150 μ m, respectively.

Conclusion

Attempts to increase output of cells made from HEM silicon sheets showed that the use of a shallow junction gave only slight improvement, that gettering produced significant improvement and that the BSF process caused excessive shunting, preventing accurate evaluation of the effects of this process. There was little difference for cells made from single or poly crystal HEM Si using the same process. However, the grain sizes for the poly crystals were large (mm) and other tests (reported later) show that for such large grains, performance close to that for single crystals is obtained.

FIGURE 1: Spectral Response of Solar Cells (1"x1")
from HEM.

FIGURE 2: Spectral Response of Solar Cells from HEM: Gettering Process

TABLE 1

SUMMARY OF PARAMETERS OF SOLAR
CELLS (1"x1") FROM HEM: STD PROCESS

		SINGLE	POLY	CONTROL
V_{OC} (mV)	Average	596	591	596
	Standard Deviation	4	4	1
	Range	592-603	585-596	595-598
J_{SC} (mA/cm ²)	Average	29.7	30.8	32.8
	Standard Deviation	1.3	3.0	0.5
	Range	28.1-31.5	27.8-31.0	32.2-33.2
CFF(%)	Average	76	75	78
	Standard Deviation	2	3	1
	Range	72-79	70-79	77-79
η (%)	Average	10.0	9.7	11.4
	Standard Deviation	0.6	0.6	0.2
	Range	8.9-10.9	8.4-10.5	11.1-11.5

NOTES:

- Cells (1"x1") with SiO AR coating measured under AMO condition at 25°C test block temperature.
- Sample size: HEM single - 10 cells
Poly - 10 cells
Control - 4 cell

TABLE 2

SUMMARY OF PARAMETERS OF SOLAR
CELLS (1"x1") FROM HEM: SHALLOW JUNCTION PROCESS

		SINGLE	POLY	CONTROL
$V_{OC}(mV)$	Average	591	589	596
	Standard Deviation	3	3	
	Range	586-596	584-592	
$J_{SC}(mA/cm^2)$	Average	30.4	31.1	34.9
	Standard Deviation	1.3	1.3	
	Range	28.4-32.6	29.2-31.6	
CFF(%)	Average	76	75	80
	Standard Deviation	2	2	
	Range	73-78	73-78	
$\eta(\%)$	Average	10.1	10.2	12.3
	Standard Deviation	0.5	0.5	
	Range	9.4-11.0	9.3-10.6	

NOTES:

- Cells (1"x1") with SiO AR coating measured under AMO condition at 25°C test block temperature.
- Sample size: HEM single - 7 cells
Poly - 8 cells
Control - 1 cell

TABLE 3

SUMMARY OF PARAMETERS OF SOLAR CELLS
FROM HEM: GETTERING & STD PROCESS

		SINGLE	POLY	CONTROL
$V_{OC}(mV)$	Average	596	588	591
	Standard Deviation	11	17	5
	Range	582-610	553-600	585-595
$J_{SC}(mA/cm^2)$	Average	33.0	31.3	35.3
	Standard Deviation	1.1	3.2	0.2
	Range	31.3-34.5	25.0-33.5	35.0-35.5
CFF(%)	Average	71	72	72
	Standard Deviation	4	4	5
	Range	64-76	64-76	64-75
$\eta(\%)$	Average	10.3	9.8	11.1
	Standard Deviation	0.9	1.5	0.9
	Range	8.9-11.8	6.5-11.2	9.8-11.6

NOTES:

- Cells (2x2 cm) with SiO₂ AR coating measured under AM0 conditions at 25°C test block temperature
- Sample size: Single - 11 cells
Poly - 9 cells
Control - 4 cells

B. SOC SOLAR CELLS

1.0 SOLAR CELL FABRICATION

Standard SOC solar cells were fabricated using the same process sequences, described in the annual report (1) (a p^+ layer in the back was formed by alloying of thin aluminum layers during the diffusion step).

Shallow junction solar cells were fabricated using a shorter diffusion time than the standard diffusion step, (10 minutes of diffusion instead of 20 minutes) resulting in a sheet resistance of about 40-50 ohms/square.

Since metal shadow masks resulted in excessive smearing of the front grid line metallization in the past, photoresist techniques were used to form the front contact lines. This method provided a better metallization scheme. Mesa solar cells, with cell sizes ranging between 7cm^2 and 19cm^2 , were fabricated using waxing techniques. Evaporated SiO or multi-layers were used as AR coatings and indium solder was pressed into the back opening for electrical tests.

2.0 SOLAR CELL PERFORMANCE AND CHARACTERIZATION.

Characteristics under illumination

Solar cell parameters, such as I_{sc} , V_{oc} , CFF, and η , were measured under AMO and AM1 solar simulation at an estimated cell temperature of around 28 30°C . Note. Difficulties in controlling cell temperature were experienced due to the warpage of the substrates.

Electrical data of the individual SOC solar cells, for both standard and shallow junction processes, is given in Appendix IV. Table 4 summarizes the results of the standard process SOC cells, indicating an average AMO efficiency of about 6.5% (7.6% AM1). This is a slight improvement over the previous results presented in the annual report (1), which is mainly due to increase in I_{sc} by increasing the active area of the solar cells. Most of the solar cells indicated problems of low CFF, (the average CFF was about 66%), and the problems were from both high series resistance and low shunt resistance. At present, shunting characteristics are speculated to be related to material properties, such as inclusions or precipitates, and high series resistance could be due to the problems of forming proper ohmic contacts through the back opening in the ceramic substrates.

Table 5 summarizes the parameters of solar cells from the shallow junction process. Cells with both SiO AR coating (SOC A) and MLAR coating (SOC B) are given in the table, indicating an average AMO efficiency of 6.7% (7.8% AM1) and 6.9% (8.4% AM1) respectively. These solar cells showed an improvement in efficiency (an average AMO efficiency of 6.7% versus 6.5% for the standard cells), mainly due to an increase in I_{sc} , specifically an increase in the blue response of the cells (I_{scb}).

Conclusion

With more careful processing, SOC cells were similar to those fabricated earlier. The addition of a shallow junction, greater active area and more effective AR coatings provided a slight increase in performance, but not sufficient to indicate that this more costly processing should be included.

TABLE 4

SUMMARY OF PARAMETERS OF SOLAR CELLS
FABRICATED FROM SOC; STD PROCESS

		SOC		CZ CONTROL
		AM1	AM0	AM0
$V_{OC}(mV)$	Average	524	529	589
	Standard Deviation	4	4	3
	Range	515-528	521-533	583-592
$J_{SC}(mA/cm^2)$	Average	22.6	25.5	34.7
	Standard Deviation	0.5	0.6	0.6
	Range	22.0-23.5	24.8-26.5	34-35.5
CFF(%)	Average	65	66	73
	Standard Deviation	2	3	3
	Range	61-68	59-69	68-74
$n(\%)$	Average	7.6	6.5	11.0
	Standard Deviation	0.4	0.4	0.5
	Range	7.1-8.3	6.0-7.1	10.3-12.1

NOTES:

1. Cells with SiO AR coating measured at 25°C test block temperature.
2. Cell sizes: SOC : ranges 7-19 cm²
Control: 4 cm²
3. Sample size: SOC : 8 cells
Control: 8 cells

TABLE 5

SUMMARY OF PARAMETERS OF SOLAR CELLS
FABRICATED FROM SOC; SHALLOW JUNCTION PROCESS

		SOC A		SOC B	
		AM0	AM1	AM0	AM1
$V_{OC}(mV)$	Average	528	523	529	529
	Standard Deviation	6	4	-	-
	Range	522-536	518-528	524-534	526-531
$J_{SC}(mA/cm^2)$	Average	26.9	23.5	26.0	23.7
	Standard Deviation	0.6	0.5	-	-
	Range	26.2-27.4	23.0-24.0	24.9-27.5	22.6-25.0
CFF(%)	Average	64	64	68	67
	Standard Deviation	2	2	-	-
	Range	62-66	61-66	68	66-68
$\eta(\%)$	Average	6.7	7.8	6.9	8.4
	Standard Deviation	0.4	0.5	-	-
	Range	6.3-7.1	7.3-8.2	6.7-7.3	8-8.9

NOTES:

- Cells with SiO AR coating (SOC A) and MLAR coating (SOC B) measured at 25°C test block temperature.
- Cell size: SOC A ranges 12-18cm²
SOC B ranges 14-19cm²
- Sample size; Sample size:
SOC A: 5 cells
SOC B: 3 cells

C. SOLAR CELLS FROM SEMI-CONTINUOUS CZ PROCESS (HAMCO)

SOLAR CELL FABRICATION

Nine ingots were grown at HAMCO using a semi-continuous CZ technique (HAMCO Run #62). The silicon ingots are identified in numerals 1-9 in order of growth sequence and silicon slab sections are identified with letters (T,M, and B), referring to the relative position in each ingot from which the slabs were taken; top, middle, and bottom, respectively. Ingot diameters varied from about 4" to 5.5" and they were sliced into wafer forms using an ID saw. Wafers were cut to 2x2 cm blanks and the blanks were thinned down to about 13 mils using planar etching solution. Standard and BSF solar cells were fabricated. Refer to Appendix III of reference (1) for the process details.

Large area blanks (1"x1") were prepared and solar cells were fabricated by formation of a shallow junction (sheet resistance of about 40 ohm/square). Fine grid line metallization was applied using a metal shadow mask.

The resistivity measured by a four point probe ranged between 1.5 3.5 ohm-cm with p-type conductivity. The Minority carrier diffusion length (L) of the single crystal section of the ingots ranged between 70 170 m. L of the CZ control was about 140 m.

2.0 SOLAR CELL PERFORMANCE AND CHARACTERIZATION

Characteristics Under Illumination

Solar cell parameters, such as I_{sc} , V_{oc} , CFF, and η , were measured under AMO solar simulation at 25°C test block temperature. Some of the selected cells were tested under AM1 conditions. Detailed information on individual cells from standard, BSF and large area processes is given in Appendix V.

Figure 3, 4, and 5 summarize the cell parameters of the STD solar cells under AMO conditions, short circuit current density, open circuit voltage and efficiency, respectively. The figures indicate average values and ranges of the parameters as a function of the ingot growth sequence. The average short circuit current density showed a tendency to decrease as the number of ingots grown increased; i.e. a J_{sc} drop of about $2\text{mA}/\text{cm}^2$ is noticed in the last ingot (9M). This indicates a possibility of accumulation of impurities in the repeated charging and pulling steps. The open circuit voltage and efficiency appear to be about the same from the first ingot to the last.

Note: Since J_{sc} showed a tendency to decrease as the ingot number increased, the efficiency should show the same trend if CFF stays about the same. In this case, CFF showed a tendency to increase and no clear explanation for this can be given at present. Solar cells from poly crystalline sections (3B, 7B, and 9B) showed average efficiencies considerably lower than those of the single crystalline cells, being about 9.5% for the poly cells and above 11% for the single crystal cells. Most of the single crystal HAMCO cells indicated efficiencies higher than the conventional CZ control cells processed alongside.

The large area cells (1"x1") showed results similar to the standard 2x2 cm cells in terms of efficiency values and trends, etc. Solar cells from the BSF process also did not show improvement in cell performance mainly due to the low CFF caused by junction shunting problems (See section D below).

Table 6 gives the AMO - AM1 conversion ratio of J_{sc} and for the HAMCO solar cells for both the standard cells and the 1"x1" cells. The table indicates that AM1 efficiency is approximately 12- 15% higher than AMO efficiency. The reasons for some higher conversion values for the 1"x1" cells are not understood at present.

Spectral Response

Absolute spectral response (A/W) was obtained using a filter wheel set-up (refer to Appendix V of reference (1) for the details). Responses of the standard solar cells are plotted in Figure 6. Responses of a cell from the first ingot (1T) and a cell from the last ingot (9M) are shown in the figure along with a conventional CZ control cell

Note: Both 1T and 9M cells are single crystalline. Response of the 1T cell shows slightly higher response than the control cell in keeping with the slightly higher efficiency. However, a cell from the last ingot (9M) showed lower response in long wavelength, suggesting reduction in minority carrier diffusion length.

Minority carrier diffusion length

Minority carrier diffusion length (L) was measured using a short circuit current method for the solar cells used for the spectral response measurement. L of the cells from the first ingot (1T) and the last ingot (9M) (both single crystal) were about 170 μ m and 70 μ m, respectively. This is a significant difference in L between ingots grown first and last. However, the efficiency difference between the cells made from the ingots is expected to be less than 2%. (Refer to Figure 52 of reference(1), efficiency vs minority carrier diffusion length). The L-values correlate with the spectral responses.

Conclusion

Continuous Czochralski silicon shows an output equivalent to or better than the conventional CZ crystal for most of the growth sequence (if not polycrystals). Only the last ingot showed decrease, probably from impurity accumulation.

FIGURE 3 SHORT CIRCUIT CURRENT DENSITY (AM0) VERSUS INGOT GROWTH SEQUENCE

FIGURE 4

OPEN CIRCUIT VOLTAGE (AMO) VERSUS INGOT GROWTH SEQUENCE

OPEN CIRCUIT VOLTAGE, VOLTS

.60
.58
.56
.54

○: TOP SECTION
△: MIDDLE SECTION
×: BOTTOM SECTION
□: CZ CONTROL

AVERAGE VALUES

1

2

3

4

5

7

8

9

CONTROL

INGOT NUMBER IN GROWTH SEQUENCE

FIGURE 5 - AMO EFFICIENCY (STANDARD PROCESS) VERSUS INGOT GROWTH SEQUENCE

FIGURE 6: SPECTRAL RESPONSE OF STANDARD SOLAR CELLS FROM HAMCO WAFERS.

TABLE 6

AN AMO-AM1 CONVERSION OF SHORT CIRCUIT
CURRENT DENSITY (J_{SC}) AND EFFICIENCY (η) OF HAMCO SOLAR CELLS

	$J_{SC}, \frac{AMO}{AM1}$		$\eta, \frac{AM1}{AMO}$	
	A	B	A	B
AVERAGE	1.19	1.16	1.12	1.15
STANDARD DEVIATION	0.01	0.02	0.01	0.03
RANGE	1.17-1.20	1.12-1.18	1.10-1.14	1.08-1.21

NOTES:

- Cells with SiO AR coating with cell size:
A: 2x2 cm
B: 1"x1"
- Sample size:
A: 18 cells
B: 18 cells
- See Appendix IV of reference (1) for an AMO simulator and Appendix II of reference (2) for AM1 simulator and intensity calibration.

D. BSF PROCESS DEVELOPMENT

The BSF process is a well-known and widely used technique to improve silicon solar cell performance by increasing V_{oc} and I_{sc} . The solar cell structure under investigation was n^+pp^+ , in which a BSF (p^+ layer) was formed by screen printing aluminum paste, followed by an alloy formation step. This process can provide advantages in solar cell performance, but in practice can also give possible yield problems, mainly due to junction shunting or leakage. The main source of the shunting problems was identified in a previous report (2) as aluminum contamination of the front junction area. The major mechanism of aluminum contamination was thought to be due to the transport of the aluminum at the alloying step in the form of flying particles or possibly by the transport of aluminum atoms along the silicon edges. Past experience indicated that junction shunting by the BSF process depended on the starting silicon properties. Thus, during this reporting period, work has progressed to observe possible junction shunting characteristics and the effectiveness of the BSF process as a function of: (1) starting silicon resistivities; 0.3 15 ohm-cm, (2) crystal orientation; (100) vs (111), (3) crystal growing method; CZ vs FZ, and (4) quality of silicon, i.e., minority carrier diffusion length (L).

1.0 EXPERIMENTAL

The BSF was formed by screen printing aluminum paste and alloying at 800°C (refer to Appendix III of reference (1) for the process details). The BSF was applied on single crystalline 3" wafers and Table 7 gives information on the starting substrates. Each group of the substrate consists of nine (9) wafers; six (6) for the BSF cells and three (3) for the control cells (cells without BSF). Each wafer provided six identical 2x2 cm solar cells.

NOTE: An exception was for the 0.3 ohm-cm FZ wafers; a single 3" cell was fabricated from each wafer.

Experiments were carried out carefully to minimize the aluminum contamination on the front junction area at alloying step, i.e., loading only a small number of wafers in the alloying furnace, extra care in cleanliness, etc. The solar cells were tested under AMO simulation conditions without AR coating.

2.0 RESULTS AND DISCUSSION

Shunting Characteristics

Most of the solar cells (above 90%) did not show any shunting problems, which could be due to the careful control of the BSF used. The results of this experiment also suggested that there is no strong correlation between junction shunting problems and crystal orientation, doping level and crystal growing method of the starting substrates. This result does not agree with the past experiences and the result reported in the Fourth Quarterly Report (3), especially the dependence of shunting problems on the starting substrate doping level.

NOTE: More junction shunting problems were experienced in the past on the substrates of low resistivity, i.e., 0.3 1 ohm-cm. The present experimental result indicated that junction shunting problems can possibly be minimized by proper control of the process.

Effectiveness of the BSF Process

Improvement of solar cell parameters by the BSF process was obtained for the various types of the starting substrates. (Refer to Table 7 for the

details.) The results are summarized in Table 8, in which enhancements in V_{oc} , J_{sc} , and η are noticed for cells with the BSF compared to the STD cells without the BSF. Efficiencies of the STD cells quoted here are based on an assumption that the same average CFF can be obtained for cells with and without the BSF, i.e., minimum effects of processing on CFF are assumed.

Using the resistivity information (or doping level) in Table 7, improvements of cell parameters as a function of the starting substrate resistivity were obtained; Figure 7 for the open circuit voltage (V_{oc}), Figure 8 for the short circuit current density (J_{sc}), and Figure 9 for the conversion efficiencies (η), respectively.

Open circuit voltage improvements depended strongly on the substrate resistivity; about 10 mv improvement for 0.3 ohm-cm versus 50 mv improvement for 15 ohm-cm. The short circuit current density also depended on the substrate resistivity, mainly due to the dependence of the minority carrier diffusion length (L) on the substrate resistivities. Figure 10 plots J_{sc} vs L , indicating a J_{sc} improvement of about 1 mA/cm^2 for $L=100 \text{ }\mu\text{m}$ and 2 mA/cm^2 for $L=250 \text{ }\mu\text{m}$. The efficiency enhancement strongly depended on the starting substrate resistivity since both the J_{sc} and the V_{oc} improvement depended on the resistivity. Figure 9 indicates that the conversion efficiency improved by about 0.3% for the 0.3 ohm-cm substrates and by 1.2% for the 15 ohm-cm substrates.

Table 8 suggests that the improvement of J_{sc} and V_{oc} does not appear to be a strong function of either the crystal orientation or the crystal growing methods.

Conclusions

These tests show that the extra care in processing reduced the shunting effects observed earlier. With this care, the shunting does not show the dependence on the starting silicon properties. Also, the real effect of BSF could be determined. In general, the BSF produced greater relative increases for higher resistivity (probably because of the greater shift in Fermi levels, and the higher values of the initial diffusion length; these increases were seen in both V_{oc} and J_{sc} , with a resulting increase in efficiency). It should be noted that in spite of the large relative increase for the highest resistivities tested, the final efficiencies were similar for the range 1-15 ohm-cm, with a slight increase at the high end.

FIGURE 7

EFFECT OF A BSF PROCESS ON OPEN CIRCUIT VOLTAGE OF SOLAR
CELL AS A FUNCTION OF THE STARTING SILICON SUBSTRATE RESISTIVITY

FIGURE 8

EFFECT OF A BSF PROCESS ON SHORT CIRCUIT CURRENT DENSITY OF
SOLAR CELL AS A FUNCTION OF THE STARTING SILICON SUBSTRATE RESISTIVITY

FIGURE 9

EFFECT OF A BSF PROCESS ON SOLAR CELL EFFICIENCY
AS A FUNCTION OF THE STARTING SILICON SUBSTRATE RESISTIVITY

FIGURE 10

EFFECT OF A BSF PROCESS ON SHORT CIRCUIT CURRENT DENSITY
OF SOLAR CELLS AS A FUNCTION OF MINORITY CARRIER DIFFUSION LENGTH

TABLE 7

INFORMATION ON SILICON
SUBSTRATES USED FOR THE BSF TEST

SUBSTRATE I.D. #	GROWTH METHOD	ORIENTATION	RESISTIVITY (OHM-CM)	L (mm)
0	FZ	(100)	0.3	130
1	CZ	(100)	1.6	260
2	CZ	(111)	1.8	180
3	FZ	(100)	2.0	240
4	FZ	(111)	2.1	260
5	CZ	(100)	14	250
6	CZ	(111)	13	250
7	FZ	(100)	11	340
8	FZ	(111)	15	290

NOTE: 1) L; Minority carrier diffusion length

2) Substrate thickness: $\approx$ 13 mils
Diameter : 3 inches

TABLE 8
SOLAR CELL PARAMETERS WITH AND WITHOUT THE BSF

I.D.#		V_{OC} (mv)		J_{SC} (ma/cm ²)		CFF (%)		n(%)	
		AVERAGE	RANGE	AVERAGE	RANGE	AVERAGE	RANGE	AVERAGE	RANGE
0	BSF	605		26.0		77		9.0	
	STD	598		25.0		77		8.5	
1	BSF	594	588-596	27.7	27.3-28.1	77	73-78	9.3	8.9-9.6
	STD	580		26.3		77		8.7	
2	BSF	595	592-598	27.4	27.0-27.7	78	75-79	9.4	9.1-9.6
	STD	577		25.5		78		8.5	
3	BSF	592	586-596	28.0	27.6-28.3	77	75-79	9.4	9.0-9.8
	STD	579		26.2		77		8.7	
4	BSF	593	590-596	27.8	27.5-28.0	76	74-77	9.3	9.0-9.5
	STD	573		25.8		76		8.3	
5	BSF	581	572-586	28.6	28.4-28.8	77	75-77	9.4	9.2-9.6
	STD	539		26.6		77		8.2	
6	BSF	590	586-596	28.5	28.3-28.7	77	76-77	9.6	9.4-9.7
	STD	535		26.0		77		7.9	
7	BSF	577	568-584	28.7	28.4-29.1	76	75-78	9.4	9.2-9.6
	STD	546		26.8		76		8.2	
8	BSF	588	584-592	28.5	28.3-28.8	76	76-77	9.5	9.4-9.6
	STD	531		26.3		76		7.9	

NOTES:

1. STD cells (2x2 cm) without AR coating measured under AMO conditions at 25°C test block temperature.
2. STD: Standard cells without the BSF
BSF: Standard cells with the BSF
3. Efficiencies of the STD cells quoted here are based on an assumption that same average CFF can be obtained between cells with and without the BSF.

III. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A. HEM CELLS

The standard process cell results were consistent with earlier work. Using "improved processes", showed that the use of shallow junctions gave marginal increases and the use of BSF was inconclusive because of junction shunting; the work described in D shows that reassessment of BSF processing on HEM silicon should be done, although the lower L-values may not show full benefit from the BSF process.

The use of gettering gave significant improvements, and this confirms the suspicion that impurities were introduced during the HEM process. This is an important fact for the HEM sheet manufacturers to consider (also see conclusions under D).

The large grain poly crystal samples evaluated in this period performed almost as well as single crystal samples. This result is confirmed by later work (to be reported next month) showing that for grain sizes mm size this convergence is obtained.

B. SOC CELLS

Even with improved processing, SOC cells were similar to those made earlier. The small increase, noted when a combination of shallow junctions, greater active area and better MLAR coating was used, did not appear to justify the additional costs involved. There are continuing problems with series resistance, mainly from difficulty in contacting the back surface. The

warpage makes the cell temperature determination uncertain.

The low diffusion length suggests that even if a BSF process can be applied to 30% of the back surface area, it may not be effective.

C. HAMCO (CONTINUOUS CZOCHRALSKI) CELLS

The successive ingots grown from one crucible with replenishment of Si showed consistent behavior (at or above normal 6-8 kg crystals) for most of the ingots; near the end of the last ingot cell performance decreased, possibly because of the accumulation of impurities in the melt, and also the effect of the repeated "starts". Any poly crystalline regions decreased output particularly when the grain size was small.

D. BSF PROCESS DEVELOPMENT

The work in this quarter used the results obtained previously (where the shunting problems were attributed to aluminum penetration of the PN junction) and showed that with extra care, this shunting could be reduced or prevented. It was then possible to evaluate the effects of this BSF processing on various resistivities. Generally the high resistivities gave greater proportional improvements in all performance. However, a fairly broad resistivity range (1-15 ohm-cm) gave comparable results, and it appears for good cells to be obtained from sheet silicon, the sheets should have resistivities in this range, and should also have reasonably high diffusion length to allow the full effects of the BSF to be included.

RECOMMENDATIONS

The back-up measurements (spectral response, diffusion length and diode characteristics) continue to support the photovoltaic behavior. However, they

should be continued because they add insight toward guiding the choice of the optimum processing, or for feedback on failure modes to help manufacturers improve the sheet performance.

Also the work begun on AM1/AMO ratios should be continued; later, mostly AM1 information will be presented.

The "customized" process improvements (chosen after analysis of the standard process results), should be continued to indicate the upper efficiency boundaries for the sheets.

Some lower cost processes will be included in the improvement program, to obtain an early warning of possible conflicts in the process variables.

IV. WORK PLAN STATUS

The following areas of work are planned during the next period.

Semi-Continuous CZ (HAMCO)

- o Fabrication of BSF solar cells.
- o Large area high efficiency cells.

EFG (RH) Ribbon

- o STD cell fabrication from the characterized EFG ribbons (MRI).
- o Reproducibility tests on the previous results of heat treatment and grain boundary passivation runs.

Implementation Of Other Processes

- o Two step gettering in an effort to improve bulk properties of sheet silicon.
- o Application of potential low cost contacts to see the effect of the contact system on cell performance.

Effect Of Grain Size On Solar Cell Parameters

- o To determine effects of grain size on cell parameters from a relatively pure poly silicon, i.e., poly Cz wafers, etc.
- o Grain sizes under investigation will be between 0.5 10mm which is a range of practical interest at present, in consideration of low cost substrate development, such as casting and ribbon growth techniques, etc.

V. REFERENCES

- (1) H.I. Yoo, et.al., "Silicon Solar Cell Process Development, Fabrication and Analysis", JPL Contract No. 955089, Annual Report, June, 1979.
- (2) H.I. Yoo, et.al., "Silicon Solar Cell Process Development, Fabrication and Analysis", JPL Contract No. 955089, Fifth Quarterly Report, December, 1979
- (3) H.I. Yoo, et.al., "Silicon Solar Cell Process Development, Fabrication and Analysis", JPL Contract No. 955089, Fourth Quarterly Report, September, 1979.

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APPENDIX I
TIME SCHEDULE

APPLIED SOLAR ENERGY CORPORATION

formerly Optical Coating Laboratory Photoelectronics Division

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TIME SCHEDULE (PHASE II)

TASK	MONTH												
	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL
PROCESS SHEET SAMPLES													
(A) STANDARD CELLS													
(B) ANALYSIS													
(C) BACK UP MEASUREMENTS													
(D) TEST ALTERNATE PROCESS													
(E) BSF PROCESS DEVELOPMENT													
REPORTS													
(A) MONTHLY		▲	▲		▲	▲		▲	▲		Δ	Δ	
(B) QUARTERLY				▲			▲			Δ			
(C) FINAL													Δ

APPENDIX II
ABBREVIATIONS

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 SOLAR CELLS FROM HEM

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM Solar Cells (1"x1"), STD Process, 1st Sheet

SiO AR Coating

TEST CONDITION: AMO

TEMPERATURE: 25°C Test Block

DATE: _____

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
1	603	200	83	117	185	515	95.3	79	10.9	6.45
2	593	197	83	114	177	506	89.6	77	10.3	"
3	596	189	79	111	172	505	86.9	77	10.0	"
4	601	195	80	116	176	515	90.6	77	10.2	"
5	593	183	75	107	166	500	83.0	76	9.5	"
6	592	181	77	103	152	510	77.5	72	8.9	"
7	594	182	79	102	160	507	81.1	75	9.4	6.40
8	598	198	83	116	179	505	90.4	76	10.4	6.45
10	596	203	85	118	186	502	93.4	77	10.7	"
11	597	183	76	107	162	506	82.0	75	9.4	"
			Above	single crystal	Solar cell					
13	596	194	81	110	180	510	91.8	79	10.5	6.45
15	593	195	83	113	178	508	90.4	78	10.4	"
16	595	183	76	105	163	512	83.5	77	9.6	"
17	593	185	78	107	164	512	84.0	77	9.6	"
19	585	179	75	104	148	495	73.3	70	8.4	"
20	590	195	79	115	163	510	83.1	72	9.4	"
21	588	200	84	117	176	490	82.2	73	9.6	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM Solar Cells (1"x1"), STD Process, 2nd Sheet

SiO AR Coating

TEST CONDITION:

AMQ

TEMPERATURE:

25 C Test Block

DATE:

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF	n	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm ²
22	589	195	82	113	168	498	83.7	73	9.6	6.45
23	593	198	83	115	178	500	89.0	76	10.2	"
			Above cells with same degree of polycrystallinity							
			Control cells							
C-1	598	214	86	129	198	507	100.4	78	11.5	6.45
C-3	596	213	84	130	198	507	100.4	79	11.5	"
C-4	595	211	84	127	194	502	97.4	78	11.5	"
C-5	596	208	82	127	194	501	97.2	78	11.1	"
X	HEM Identification									
	Cell # 1 through 12				from	HEM JPL ID #1-1216				
	Cell # 13 " 23				"	"	"	"	"	#1-1217

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM Solar Cells (1"xl"), SJ + STD Process

SiO AR Coating

TEST CONDITION: AMO

TEMPERATURE: 25°C Test Block

DATE: _____

NO.	V _{OC} mV	I _{SC} mA/cm ²	I _{SCB} mA	I _{SCR} mA	I _{Max} mA	V _{Max} mV	P _{Max} mW	CFF %	η %	AREA cm ²
1	592	30.2	} single crystal From JPL I.D. 1-1216				85	74	9.8	6.45
2	590	31.2					89	75	10.2	"
3	590	29.8					88	78	10.1	"
4	590	30.4					85	73	9.7	"
5	586	28.4					82	76	9.4	"
6	592	30.4					91	78	10.4	"
7	596	32.6	} poly From JPL I.D. 1-1217				96	76	11.0	"
9	588	29.2					81	73	9.3	"
10	592	30.9					89	76	10.2	"
11	592	32.7					92	74	10.6	"
12	590	32.7					91	73	10.4	"
13	590	31.6					92	76	10.5	"
14	590	31.3					93	78	10.7	"
15	588	30.8					90	77	10.3	"
16	584	29.4					81	74	9.4	"
			control	cell						
C1	596	34.9					107	80	12.3	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM Solar Cells (2x2 cm), Gettering + STD Process, First Sheet

SiO₂ AR Coating

TEST CONDITION: AMO

TEMPERATURE: 25°C Test Block

DATE: _____

NO.	V _{OC}	I _{SC}	I _{SCB}	I _{SCR}	I _{Max}	V _{Max}	P _{Max}	CFF		AREA
	mV	mA	mA	mA	mA	mV	mW	%		cm ²
1	602	134	57	78	121	475	57.5	71	10.6	4.0
3	606	137	58	79	126	490	61.7	74	11.4	"
4	583	128	55	74	96	492	40.1	64	8.9	3.95
5	587	131	56	75	112	450	50.4	66	9.3	4
6	592	129	56	73	113	470	53.1	70	9.8	"
7	584	125	55	70	114	475	54.2	74	10.0	"
8	582	126	56	70	113	470	53.1	72	9.8	"
9	598	129	56	73	113	470	53.1	69	9.8	"
10	607	134	56	79	118	505	59.6	73	11.0	"
11	609	137	57	80	130	490	63.7	76	11.8	"
12	610	138	57	81	126	482	60.7	72	11.2	"
			Abuse	single	crystal					
13	553	100	50	49	76	465	35.3	64	6.5	4
14	566	108	51	56	96	450	43.8	72	8.1	"
15	595	123	54	69	114	480	54.7	75	10.1	"
17	600	133	56	78	126	470	59.2	74	10.9	"
18	599	133	56	77	121	482	53.3	73	9.9	"
20	599	134	57	77	125	485	60.6	76	11.2	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HEM Solar Cells (2x2 cm), Gettering + STD process, 2nd Sheet

SiO₂ AR Coating

TEST CONDITION:

AMO

TEMPERATURE:

25°C Test Block

DATE:

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APPENDIX IV

ELECTRICAL DATA SHEETS FOR SOLAR CELLS FROM SOC

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: SOC Solar Cells, STD Process

SiO AR Coating

TEST CONDITION: AMO

TEMPERATURE: 28~30°C Cell Temp.

DATE:

NO.	V _{OC} mV	I _{SC} mA	I _{SCB} mA	I _{SCR} mA	I _{Max} mA	V _{Max} mV	P _{Max} mW	CFF %	n %	AREA cm ²
209-11	533	286	130	155	232	390	90.5	59	6.0	11.12
209-12	531	246	105	141	212	422	89.5	69	6.9	9.55
209-15	530	494	224	269	405	412	166.9	64	6.5	18.90
211-10	531	281	121	158	238	418	99.5	67	6.5	11.35
211-11	528	354	158	194	306	415	127.0	68	6.6	14.21
212-6	532	320	137	182	278	418	116.2	68	7.1	12.09
212-8	527	447	195	248	385	404	155.5	66	6.5	17.81
214-10	521	177	81	96	144	406	58.5	63	6.1	7.08
			control	cells						
C-1-2	592	140	58	82	126	475	59.9	72	11.1	4
C-1-4	590	136	55	81	124	465	57.7	72	10.7	"
C-2-1	583	142	57	84	114	465	65.6	79	12.1	"
C-2-3	587	140	55	84	122	480	58.6	71	10.8	"
C-3-1	586	141	57	84	123	455	56.0	68	10.3	"
C-3-3	592	138	54	84	126	475	59.9	73	11.1	"
C-4-3	592	136	53	83	124	480	59.5	74	11.0	"
C-4-4	590	138	55	84	124	480	59.5	73	11.0	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: SOC Solar Cells, STD Process

SiO AR Coating

TEST CONDITION: AM1

AM1

TEMPERATURE:

28~30°C Cell Temp.

DATE:

[illegible]

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: SOC Solar Cells, Shallow Junction

SiO₂ AR Coating

TEST CONDITION: AMO, Parenthesis numbers for AM1

TEMPERATURE: 25°C Test Block

DATE:

[illegible]

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: SOC Solar Cells, Shallow Junction

MLAR Coating

TEST CONDITION: AMO, Parenthesis numbers for AM1

TEMPERATURE: 25°C, Test Block

DATE:

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APPENDIX V

**ELECTRICAL DATA SHEETS FOR SOLAR CELLS
FROM SEMI-CONTINUOUS CZ (HAMCO)**

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HAMCO Solar Cells (2x2 cm), STD Process, 1st Sheet
 SiO AR Coating
 TEST CONDITION: AMO
 TEMPERATURE: 25°C Test Block

NO.	V _{OC}	J _{SC}	P _{Max}	CFF	η	AREA
	mV	mA/cm ²	mW	%	%	cm ²
1T-1	582	35.3	56	68	10.4	4
1T-2	593	34.9	63	76	11.6	4
1T-3	590	35.8	58	69	10.8	4
1T-4	592	36.6	63	73	11.6	4
1B-1	588	33.6	56	71	10.4	4
1B-2	590	34.2	58	72	10.7	4
1B-3	594	35.3	61	72	11.3	4
1B-4	590	34.6	58	71	10.7	4
2T-1	594	35.0	62	74	11.4	4
2T-2	598	35.3	62	73	11.5	4
2T-4	590	35.6	58	69	10.8	4
2B-1	586	34.2	53	66	9.8	4
2B-2	592	35.4	59	70	10.9	4
2B-3	592	35.5	58	69	10.8	4
2B-4	596	34.1	61	75	11.3	4
3T-1	598	35.3	63	75	11.7	4
3T-2	596	36.5	64	73	11.8	4
3T-3	598	35.7	65	76	12.1	4
3B-1	566	30.8	52	74	9.6	4
3B-2	578	32.1	55	74	10.2	4
3B-3	562	29.4	49	74	9.0	4
3B-4	574	30.6	53	75	9.8	4

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HAMCO Solar Cells (2x2 cm), STD Process, 2nd Sheet

TEST CONDITION: SiO₂ AR Coating

TEST CONDITION: AMO

TEMPERATURE: 25°C Test Block

NO.	V _{OC}	J _{SC}	P _{Max}	CFF	η	AREA
	mV	mA/cm ²	mW	%	%	cm ²
4T-1	588	33.3	54	69	10.1	4
4T-2	590	36.0	59	69	10.8	4
4T-3	594	35.2	62	74	11.4	4
4T-4	592	34.8	59	72	11.0	4
4B-1	594	34.4	62	76	11.5	4
4B-2	588	33.6	61	77	11.2	4
4B-3	594	33.5	61	77	11.3	4
4B-4	592	34.5	61	75	11.3	4
5T-1	596	35.5	61	72	11.3	4
5T-3	592	34.2	55	68	10.3	4
5T-4	596	35.7	62	73	11.4	4
5B-1	594	34.4	61	74	11.2	4
5B-2	596	35.0	62	75	11.6	4
5B-3	590	33.9	60	75	11.0	4
5B-4	586	32.9	55	71	10.2	4
7T-1	590	32.9	56	73	10.4	4
7T-2	596	34.9	62	75	11.6	4
7T-3	594	34.7	61	74	11.3	4
7B-1	574	31.9	53	72	9.7	4
7B-2	556	29.7	42	64	7.9	4
7B-3	576	31.9	54	73	10.0	4
7B-4	554	29.8	46	70	8.6	4

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HAMCO Solar Cells (2x2 cm), STD Process, 3rd Sheet
SiO AR Coating
 TEST CONDITION: AMO
 TEMPERATURE: 25°C Test Block

NO.	V _{OC}	J _{SC}	P _{Max}	CFF	η	AREA
	mV	mA/cm ²	mW	%	%	cm ²
8T-1	590	33.6	57	72	10.5	4
8T-2	596	35.2	64	76	11.8	4
8T-4	586	32.5	52	68	9.6	4
8m-1	594	35.0	63	76	11.7	4
8m-2	596	35.0	63	76	11.7	4
8m-3	596	34.8	63	75	11.6	4
8m-4	596	34.5	62	76	11.6	4
8B-1	586	33.0	58	75	10.7	4
8B-2	530	25.8	38	73	7.1	4
8B-3	568	31.4	52	73	9.7	4
8B-4	586	33.0	54	69	9.9	4
9T-1	594	34.9	62	75	11.5	4
9T-2	598	35.7	63	74	11.8	4
9T-3	598	34.9	62	74	11.5	4
9T-4	596	35.7	62	73	11.5	4
9m-1	596	34.6	62	75	11.5	4
9m-2	596	33.7	62	77	11.5	4
9m-3	592	33.9	59	74	10.9	4
9m-4	590	31.6	55	74	10.2	4
9B-1	568	30.0	51	75	9.5	4
9B-2	574	31.0	53	75	9.9	4
9B-3	570	30.4	52	75	9.6	4
9B-4	568	30.1	50	73	9.3	4

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Cells (2x2' cm) for HAMCO STD Process

SiO₂ AR Coating

TEST CONDITION:

TEMPERATURE: 25°C Test Block

[illegible]

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HAMCO Solar Cells (2x2 cm), STD Process
 SiO AR Coating, Selected samples for AM1 measurement.
 TEST CONDITION: AM1
 TEMPERATURE: 25°C Test Block

NO.	V _{OC}	J _{SC}	P _{Max}	CFF	η	AREA
	mV	mA/cm ²	mW	%	%	cm ²
1T-2	584	29.2	51	75	12.8	4
1B-3	584	29.5	50	72	12.4	4
2T-1	586	29.2	51	74	12.6	4
2B-4	586	28.8	51	76	12.8	4
3T-3	590	29.9	54	76	13.4	4
3B-2	568	27.4	46	74	11.5	4
4T-3	586	29.4	51	74	12.8	4
4B-1	584	29.1	52	76	12.9	4
5T-4	588	30.2	52	73	13.0	4
5B-2	586	29.6	51	74	12.8	4
7T-2	588	29.5	52	76	13.1	4
7B-3	568	27.1	45	73	11.2	4
8T-2	586	29.3	53	76	13.1	4
8M-2	588	29.6	52	75	13.1	4
8B-1	578	28.0	48	74	11.9	4
9T-2	588	29.7	53	76	13.2	4
9M-1	588	29.1	51	74	12.7	4
9B-2	564	26.2	44	75	11.0	4
		Control	cells			
C3	584	29.1	50	73	12.5	4
C4	586	28.4	49	74	12.3	4

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HAMCO Solar Cells (2x2 cm), BSF Process, 1st Sheet
SiO AR Coating

TEST CONDITION: AMO

TEMPERATURE: 25°C Test Block

NO.	V _{OC}	J _{SC}	P _{Max}	CFF	η	AREA
	mV	mA/cm ²	mW	%	%	cm ²
1T-1	590	35.6		.70	10.8	4.0
1T-2	586	35.0		.74	11.2	"
1T-3	588	35.3		.69	10.6	"
3T-1	592	31.8		.75	10.5	"
3T-2	592	34.6		.74	11.2	"
3T-3	592	33.2		.70	10.1	"
5T-1	590	35.2		.73	11.3	"
5T-2	590	33.0		.70	10.1	"
7T-1	592	33.0		.75	10.9	"
7T-2	592	34.5		.74	11.2	"
8T-1	592	33.7		.77	11.4	"
8T-2	588	34.9		.74	11.2	"
8T-3	588	34.2		.73	10.9	"
8B-1	518	24.4		.74	6.9	"
8B-2	572	32.4		.68	9.3	"
8B-3	542	28.5		.74	8.4	"
8B-4	522	29.9		.69	6.4	"
9B-1	562	29.1		.73	8.9	"
9B-2	560	30.1		.67	8.4	"
9B-3	560	28.4		.74	8.7	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HAMCO Solar Cells (2x2 cm), BSF Process, 2nd Sheet

SiO AR Coating

TEST CONDITION:

AMO

TEMPERATURE:

25°C Test Block

[illegible]

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HAMCO Solar Cells (1"x1"), SJ + STD Process, 1st Sheet

SiO AR Coating

TEST CONDITION: AMO

TEMPERATURE: 25°C Test Block

DATE: _____

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
1T-1	590	34.3					100	77	11.5	6.45
1T-2	590	32.4					96	78	11.0	"
1T-3	590	34.0					101	78	11.6	"
1B-1	568	24.7	Front Contact Smearing Problem				64	71	9.3	"
1B-2	572	30.6					85	75	9.7	"
1B-3	578	31.8					89	75	10.2	"
2T-1	588	31.6					91	76	10.4	"
2T-2	588	33.3					97	77	11.2	"
2T-3	590	32.6					96	78	11.1	"
2B-1	588	32.9					96	77	11.0	"
2B-2	584	32.7					91	74	10.5	"
3T-1	588	31.9					94	77	10.7	"
3T-2	588	32.5					96	78	11.0	"
3T-3	590	32.7					96	77	11.0	"
3B-1	560	29.2					79	75	9.0	"
3B-2	564	29.8					60	74	9.2	"
3B-3	566	30.0					84	76	9.6	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HAMCO Solar Cells (1"x1"), SJ + STD Process,

2nd Sheet

TEST CONDITION:

SiO AR Coating

TEMPERATURE:

AMO

25°C Test Block

DATE: _____

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
4T-1	588	29.7	Front Contact Smearing problem				88	78	10.1	6.45
4T-2	592	33.4					99	78	11.3	"
4T-3	590	33.2					97	77	11.1	"
4B-1	590	32.6					95	77	11.0	"
4B-2	586	32.8					91	75	10.5	"
5T-1	594	33.8					99	76	11.3	"
5T-2	592	33.1					96	76	11.0	"
5T-3	592	33.6					100	78	11.5	"
5B-1	584	32.9					95	77	10.9	"
5B-2	576	31.3					88	76	10.2	"
5B-3	586	32.9					96	77	11.1	"
7T-1	590	33.4					99	78	11.4	"
7T-2	590	33.1					98	78	11.3	"
7T-3	588	33.2					96	77	11.1	"
7B-1	566	30.7					80	71	9.2	"
7B-2	574	29.3					85	78	9.7	"
7B-3	572	29.6					83	76	9.5	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HAMCO Solar Cells (1"x1"), SJ + STD Process,

3rd Sheet

TEST CONDITION: SiO₂ AR Coating

TEMPERATURE: AMO

25°C Test Block

DATE:

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
8T-1	586	32.3					95	78	10.9	6.45
8T-2	588	33.3					97	77	11.2	"
8T-3	586	32.5					96	78	11.0	"
8M-1	590	33.7					100	78	11.5	"
8M-2	592	32.9					98	78	11.3	"
8M-3	590	33.4					98	77	11.3	"
8B-1	540	26.7					68	74	7.9	"
8B-2	564	29.3					75	70	8.6	"
8B-3	572	30.6					86	76	9.9	"
9T-1	592	33.3					99	78	11.4	"
9T-2	592	33.4					99	77	11.3	"
9T-3	592	34.1					100	77	11.5	"
9M-1	590	32.7					96	77	11.0	"
9M-2	588	32.4					90	73	10.3	"
9M-3	590	31.2					92	78	10.6	"
9B-1	562	28.1					75	74	8.7	"
9B-2	564	28.7					78	75	9.0	"
9B-3	558	27.0					73	75	8.3	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Cells (2x2 cm) for HAMCO , SJ + STD Process,

4th Sheet

SiO AR Coating

TEST CONDITION: AMO

TEMPERATURE: 25°C Test Block

DATE:

[illegible]

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: HAMCO Solar Cells (1"x1"), SJ + STD Process 1st Sheet

SiO AR Coating, Selected samples for AM1 measurements.

TEST CONDITION: AM1

TEMPERATURE: 25°C Test Block

DATE:

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
1T-3	584	29.0					85	78	18.2	6.45
1B-2	566	27.1					76	76	11.7	"
2T-2	582	28.5					81	76	12.5	"
2B-1	582	29.3					85	77	13.2	"
3T-3	582	27.8					77	74	11.9	"
3B-3	560	25.5					72	79	11.1	"
4T-2	586	29.0					84	77	13.0	"
4B-1	584	28.0					81	77	12.6	"
5T-3	586	29.0					84	77	13.1	"
5B-3	582	28.0					82	78	12.8	"
7T-2	586	28.8					82	76	12.8	"
7B-2	568	25.4					72	78	11.2	"
8T-2	584	28.7					84	78	13.0	"
8M-1	586	29.1					86	78	13.3	"
8B-3	566	26.9					73	75	11.4	"
9T-3	588	29.5					81	73	12.6	"
9M-1	586	28.2					81	76	12.5	"
9B-2	560	24.8					67	74	10.3	"

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Cells for HAMCO SJ + STD Process

2nd Sheet

SiO AR Coating

TEST CONDITION: AM1

TEMPERATURE: 25°C Test Block

DATE:

[illegible]