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**SILICON SOLAR CELL PROCESS DEVELOPMENT, FABRICATION
AND ANALYSIS**

Annual Report (Phase II) for Period July 1, 1979—June 31, 1980

By
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Optical Coating Laboratory, Incorporated
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FABRICATION AND ANALYSIS

ANNUAL REPORT (PHASE II)

FOR PERIOD COVERING
1 JULY 1979 TO 31 JUNE 1980

By

H.I. YOO, P.A. ILES, F.F. HO, AND D.C. LEUNG

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OPTICAL COATING LABORATORY, INC.
PHOTOELECTRONICS DIVISION
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ABSTRACT

Solar cells were fabricated from EFG (RH) ribbons from multiple dies, silicon on ceramic (SOC), dendritic web, cast silicon by HEM, and semi-continuous CZ from both VARIAN and HAMCO. Baseline and improved solar cells were made from the sheets.

Baseline solar cells processed in both Phase I and Phase II, involving cells from EFG, SOC, dendritic web, and HEM, indicated that no significant improvement in silicon sheet quality has been achieved in Phase II. Solar cells from semi-continuous CZ showed cell performance close to the conventional CZ control cells, although the cells from the semi-continuous CZ have shown wider performance range because of variation in crystalline perfection. Generally, process "upgrading" provided improvement in cell performance, the improvement depending on the process used and the quality of the sheet silicon.

Study of the effect of grain size on solar cell performance suggested that the minimum grain size to make solar cells of 10% AMO efficiency is about $500\mu\text{m}$, which is expected to provide minimum module efficiency of 10% AM1. If other harmful impurities are added in the process of sheet growth, the minimum grain size must be increased.

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 also because of the higher initial values of minority carrier diffusion length. This study also suggested that proper control of the back-surface field (BSF) process could minimize the junction shunting problems often introduced by the BSF processing.

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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 sheets. During the second phase of the program, work has progressed in fabrication and characterization of solar cells from silicon on ceramic (SOC, Honeywell), EFG (RH) ribbons (Mobil-Tyco) from multiple-die, dendritic web (Westinghouse), cast silicon by heat exchanger method (HEM, Crystal Systems), and semi-continuous growth CZ from both Varian and Hamco processes. Solar cells were fabricated using a baseline process typical of those used currently in the silicon solar cell industry. Other process modifications were included to give indications of the possible improved performance obtainable from various sheets. Process variations used included gettering by diffusion glasses and mechanical damage, a two step annealing to improve bulk quality, grain boundary passivation by preferential diffusion through grain boundaries, surface treatment (etching and texturizing), shallow junction formation, application of fine front grid lines, formation of BSF and back surface reflectors (BSR) and application of better AR coating (i.e. MLAR).

The parameters measured included open circuit voltage, short circuit current, curve fill factor, and conversion efficiency (all taken under AMO illumination). Additional measurements at AM1 have been included, for direct evaluation and to collect information on the AM1/AMO conversion factors for the various sheet materials. Also measurements for typical cells included spectral response, dark I-V characteristics, minority carrier diffusion length, and photoresponse by fine light spot scanning. The results were compared to the properties of cells made from conventional single crystalline Czochralski silicon with an emphasis on statistical evaluation.

In consideration of the development of low cost polycrystalline silicon sheet technologies, such as casting and ribbon growth technologies, and the corresponding requirement of minimum solar module performance, it is becoming important to establish a baseline for the grain size which will meet the requirement. Thus, experiments were carried out to establish a minimum grain size which will meet the minimum module performance and to observe the variation of cell parameters as a function of grain sizes (grain sizes of interest were about 0.5-10 mm).

The BSF process is a well-known and widely used technique to improve silicon solar cell performance by increasing V_{OC} and I_{SC} . A common method to form a BSF is to screen print aluminum paste, followed by an alloy formation step at an elevated temperature. 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. Work has progressed to identify the leakage problems using an ion microprobe/SIMS and an optical microscope. The effectiveness of the BSF process was tested as a function of starting silicon resistivities, crystal orientation, growing method and quality of silicon. Finally efforts were made to analyze the effectiveness of the (BSF) process to improve solar cells.

II. TECHNICAL DISCUSSION

A. Fabrication and Performance Characteristics of the Solar Cell

1.0 EFG (RH) SOLAR CELLS

The EFG ribbons delivered were of the RH furnace type grown with multiple (five) dies. Measured resistivity of the ribbons was about 1 ohm-cm with p-type conductivity; micrometer thickness measurements ranged from 14--19 mils. SPV measurement using an illuminated beam size around 3mm diameter showed that the diffusion length (D.L.) of the bulk starting EFG blanks averaged $45\mu\text{m}$, with a range of 20-100 μm . D.L. of the diffused EFG wafers showed an average of about 30 μm , slightly lower values than those measured on the starting EFG ribbons. (Reference (1) provides technical details of the EFG process.)

Ribbon blanks (2x2cm) were formed and the baseline solar cells were fabricated. Efforts have continued in an attempt to improve cell efficiency by using various modified process steps. The ribbon blanks were sliced and divided into two groups; one for the baseline process and the other for the modified processing. In each case, silicon blanks of about the same resistivity were added and processed with the EFG blanks. This provided a direct check of the effect of each additional processing step. Details of the process variations and performance results are described in the following sections.

Solar cell parameters, such as I_{SC} , V_{OC} , CFF and η were measured under AMO and AM1 solar simulators. (Descriptions of the simulators and calibration methods used are discussed in Appendix IV of reference (2) for the AMO

conditions and Appendix III of this report for the AM1 conditions.) The measured test block temperature was 28°C , which test show correspond to an exposed surface cell temperature of about 28°C . However, problems of accurate cell temperature measurement were experienced for EFG cells since it was difficult to make good thermal or electrical contact to the test block because of ribbon surface unevenness. To solve the electrical contacting problem, a conducting rubber was placed between the cell and test block. However this rubber pad gave temperature control problems due to its relatively poor thermal conductivity compared with a metal. Thus the temperature of the cooling test block was adjusted in such a way that the V_{OC} of a flat control cell was about the same with the conducting pad as measured for 25°C block temperature with no pad. This might not be the best way to eliminate thermal and electrical contacting problems, but is thought to minimize temperature measurement errors because of uneven surfaces.

1.1 Baseline Solar Cells

Baseline solar cells were fabricated on 2x2 cm blanks using a process sequence, representing a conservative selection of processes currently used to make good quality silicon solar cells. Typical end results of these processes are; 1) relative deep junction depth, about $0.3\text{-}0.4\mu\text{m}$ (sheet resistance 25-30 ohms/square), 2) Ti-Pd-Ag metallization scheme, evaporated through a metal shadow mask, providing about 90% active area, and 3) SiO anti-reflective (AR) coating. (See Appendix III of reference (2) for the details of the baseline process.)

Illumination Characteristics

Two batches of the baseline solar cells were fabricated. The first baseline run was intended to show the performance variation of ribbon cells as a

function of dies and growth sequences. Front contact peeling-off, particularly for the control cells, prevented these cells from providing reliable data. However, there seemed to be no specific correlation between cell performance, growth sequence, and different die location. The second baseline process was repeated and a statistical evaluation was obtained from the run. Table 1 summarizes the important solar cell parameters from the baseline process, showing an average AMO efficiency of about 6.1%. The average AM1 efficiency of these cells was about 6.7%

Dark I-V Characteristics

Measurements were carried out by the point-by-point and the resulting forward and reverse characteristics are plotted in Figure 1. The "A" factor in the simple diode equation was 1.9 for an EFG cell and 1.6 for a control cell. Saturation current density (J_0) (in the diode equation) of the EFG cell and the control cell was about $4 \times 10^{-7} \text{ A/cm}^2$, and $6 \times 10^{-9} \text{ A/cm}^2$, respectively.

Spectral Response

Absolute spectral response (A/W) of the EFG cells was measured using the filter wheel set-up (described in Appendix V-A of reference (2)). Plots of the response are given in Figure 2. The EFG cells gave lower response than single crystalline control cells at long wavelengths ($> 0.6 \mu\text{m}$), mostly due to the smaller minority carrier diffusion length.

Minority Carrier Diffusion Length

Minority carrier diffusion length (L) was obtained using the surface photovoltage (SPV) method for the bulk EFG ribbons and the short circuit current (I_{SC}) method for the finished solar cells. The SPV method indicated an average

L of about $45\mu\text{m}$ for the EFG blanks. The size of the illuminated monochromatic beam was about three (3) mm in diameter and generally an L-variation of 20-100 μm was measured from spot-to-spot. D.L. by the I_{SC} method (for the finished cells) showed slightly lower L values; an average of $30\mu\text{m}$ with a range of 18 to $50\mu\text{m}$.

Photoresponse By Small Light Spot Scanning

Localized photoresponses of solar cells were obtained by small light spot scanning, (using a set-up described in Appendix V-C of reference (2)). A typical result is given in Figure 3. The light scanning direction was perpendicular to ribbon growth, i.e. across the ribbon width. A significant number of electrically active defect sites is identified from the figure, and photoresponse of the EFG cell is considerably lower than that of the conventional CZ control cell.

1.2 Baseline Solar Cells with Pre-Treatments

In an effort to improve the solar cell performance, pre-treatments were applied on the starting EFG blanks before the fabrication of the baseline solar cells. The treatments used included; 1) surface treatments, such as wet chemical polishing (etching) and texturizing, and 2) gettering by diffusion glasses, mechanical damage, etc.

Surface Treatments

Surface etching was carried out by chemical polishing the EFG blanks in a planar etch solution for about thirty (30) seconds. This step is expected to remove about $1\text{--}2\mu\text{m}$ of the surface silicon layer which might be contaminated during the ribbon growth environment or handling.

Surface texturizing processes using orientation-dependent etching techniques have been developed to reduce the reflection of incident light from the front surface, leading to an improvement in solar cell efficiency. Single crystal solar cells fabricated in this fashion have shown a significant increase in short-circuit current under illumination. An experiment was performed to assess the feasibility and the effect of surface texturizing process on the performance of solar cells made from the EFG ribbons. The texture etching apparatus used in this experiment included a hot plate and a solution container. EFG ribbon blanks were placed vertically in a plastic carrier, and immersed for about 20 minutes in a texturizing solution (2% NaOH + 8% Isopropyl Alcohol in DI water) maintained at 80°C. A partially textured surface was observed, indicating a large variation in crystal orientation over the surface of the EFG ribbons.

Baseline solar cells were fabricated from EFG blanks having undergone surface treatments. Table 2 summarizes solar cell parameters under AMO illumination. The table suggests that there is no significant change in performance between cells with the treatment and the cells without the treatment. An average AMO efficiency of EFG control is around 6%. Figure 4 is the plot of the spectral response of EFG cells with surface etching. No significant change has been observed over the cells without surface etching (See Figure 2 for comparison).

Gettering

The objective of this experiment was to determine whether gettering steps, introduced prior to baseline cell fabrication, either by diffusion glass or mechanical damage, could improve cell output by removing the undesired impurities close to the surface, the impurities contributed by the dies or the

growth chamber conditions. Gettering by diffusion glass was carried out by growing a phospho-silicate glass layer using a standard POCl_3 diffusion at 875°C , followed by subsequent removal of the glass layer and a thin surface layer (about $1\text{--}2\mu\text{m}$) before the standard cell process. Deposition of the glass layer lasted for ten (10) minutes in one case and forty (40) minutes in the other. Table 3 summarizes the result of the gettering, indicating no consistent results in two cases; the first run (GET^1) did show significant improvements in both J_{sc} and V_{oc} , while the second run (GET^2) did not show any performance improvement. No clear explanation for the results has been reached yet.

It is well known that the mechanical damage on the silicon surface can getter bulk impurities and defects when proper process steps are used. EFG ribbons were sand blasted on the back side and then cleaned in Aqua Regia to remove possible contaminants from the sand blasting step. Solar cells were fabricated by forming junctions both front and back, etching off the back damaged layer, and then evaporating contacts. A standard diffusion cycle, contact pattern and AR coating were used for this process. These solar cells were tested under illumination, showing poor performance (low V_{oc} and CFF) mainly due to insufficient removal of the damaged layer in the back.

A Two Step Annealing

Minority carrier diffusion lifetime by a two-step annealing has been demonstrated on Czochralski grown silicon wafers (3). A two step annealing included an heat treatment at 800°C for 64 hours in a dry O_2 ambient, followed by a second 1050°C annealing in N_2 atmosphere for 16 hours. Standard solar cells were fabricated after removal of the surface oxides and a thin silicon layer (about $5\text{--}10\mu\text{m}$). Performance of these solar cells showed degradation in bulk

property; average short circuit current density decreased to 16.2 mA/cm^2 from 16.6 mA/cm^2 of the EFG control cells (EFG cells without the annealing step). Czochralski cells undergoing the same annealing process showed even more severe degradation than the EFG cells. This degradation could possibly be due to improper curing of the crystallographic defects generated during heat treatment at relatively high temperatures.

1.3 BSF Solar Cells

Solar cells (2x2 cm) were fabricated using the BSF process described in Appendix III of reference (2). Metallization used the Ti-Pd-Ag system, was applied using metal shadow masks, which are expected to provide about 90% front active area. SiO₂ was the AR coating used.

The BSF cells were tested under AMO conditions and Table 4 summarizes the results, indicating a remarkable improvement in conversion efficiency (an average AMO η of 7.3%). Especially, short circuit current density of the BSF cells showed a significant increase over the baseline cells, which is beyond a value normally expected from a material of relatively low minority carrier lifetime. This could possibly be from the other features of the process (formation of shallow junction and better AR coating gain, etc.) and from better quality of silicon. (Inhomogeneity of the EFG ribbons was quite often observed.) Spectral response of a BSF EFG cell is shown in Figure 5 and the spectral response of a baseline EFG cell is given for comparison. The BSF cell shows an increase in both short and long wavelength responses.

1.4 Solar Cells From Grain Boundary Passivation

Attempts were made to enhance carrier collection efficiency for the EFG ribbons by utilizing a preferential diffusion along boundaries at low temperature.

This scheme (so called grain boundary passivation GBP) offers the possibility of an increase in conversion efficiency of the EFG cells. The test was carried out by deposition of a dopant source (20 minutes POCl_3 diffusion at 875°C), followed by drive-in at low temperature (600°C for 24 hours in N_2 atmosphere). Finally, the Glass layer was removed and a baseline process was used to complete the cells. (NOTE: Efforts to passivate grain boundaries of Wacker "Silso" wafer were tried using a spin-on diffusion source. The results were reported in reference (2)).

Average cell parameters from the first GBP run are summarized in Table 5, in which the baseline cell parameters from Table 1 are given for comparison. Solar cells from the GBP process did show significant improvement in efficiency, indicating an average AMO efficiency of 7.5%. Figure 6 is the spectral response plots of the cells from the process, showing significant improvement in long wavelength response (compared with the response of the baseline cell in Figure 2).

Reproducibility tests on performance of the cells utilizing the grain boundary passivation process were carried out on EFG (RH) ribbons from different batches. Since the significant improvement in performance by the process could possibly be due either to the curing of crystallographic bulk defects or from impurity redistribution in the bulk at the low temperature heat treatment step (600°C in N_2 for 24 hours), attempts were made to separate these effects from the effect of the preferential diffusion through the G.B. Thus, one group of the EFG ribbons followed the same GBP process steps described above, and the other group of the EFG had heat treatment (HT) first, 600°C in N_2 for 24 hours, followed by junction formation and other standard process steps. Baseline control cells were also fabricated from the EFG ribbons.

The cell parameters under AMO were obtained. Table 6 summarizes average cell parameters without AR coating. Parameters of CZ control cells are given in the table for comparison. The table suggests that there is no improvement in cell parameters by either the GBP process or the HT process.

Minority carrier diffusion length (L) was measured on these solar cells using the short circuit current method, indicating about the same L for the GBP, the HT, and the EFG control cells. All showed an average L of about 25-30 μm . This result does not coincide with the previous results of the GBP process in the first batch run. No clear explanation has been reached at present.

1.6 Solar Cells From Pre-Characterized EFG

EFG (RH) ribbons pre-characterized by MRI (Utah), in terms of dislocation density, twin density and grain boundary length, were supplied to ASEC to fabricate standard solar cells (2x2cm) and to correlate defect densities with solar cell parameters. Difficulties were experienced in dicing the substrates to 2x2 cm blanks, mainly due to excessive breakage in the dicing step. (NOTE: These EFG ribbons were not only thinner than usual, but also had severe surface undulations. These EFG ribbons have undergone surface treatment, including thinning, for analysis at MRI.) The cell fabrication process was slightly modified to overcome this problem; the diffusion step used the standard five minutes of oxidation and twenty minutes of carrier gas. Front contact lines were formed using photoresist techniques. Finally, mesa cells of various sizes were defined by waxing and etching techniques.

Most of these EFG solar cells suffered from junction shunting problems, generally showing CFF less than 70%. Control cells from both EFG and CZ

silicon were fabricated. Measurements were done under AMO conditions without AR coating and parameters of individual cells are obtained. The control Cz-Si cells were as expected. Despite the low CFF, the precharacterized thin EFG cells showed comparable efficiencies to the control EFG cells; some of this was the result of the higher active area, resulting from the photo mask grid formation. Since shunting problem prevented these cells from obtaining reliable data on overall cell parameter (J_{sc} , V_{oc} , and CFF) as a function of defect densities, especially for V_{oc} and CFF, efforts were made to correlate the density of various defects with J_{sc} , more precisely the active area short circuit current density. Information of defect densities supplied by MRI is given in Table 8 for each EFG cell made from them. Figures 7,8, and 9 show the active area J_{sc} plotted as a function of dislocation density, twin density and grain boundary length, respectively. No strong correlation between the defects and J_{sc} were observed at present, which could be due to the fact that the area under investigation for defect study at MRI represents a relatively small portion of the whole cell area. The short circuit current density shows a tendency to decrease as the dislocation density increases if one or two data points (in Figure 7) are discarded. However, the figures indicated that J_{sc} rather strongly depends on the batch numbers from which the EFG ribbons are grown. Also, as the silicon thickness decreases, it is more difficult to obtain high J_{sc} values without use of a BSF.

In conclusion it appears that the major cause of J_{sc} variation in EFG Si is the varying diffusion length from impurity contamination obtained in different batches rather than the density of defects characterized at MRI. This is a preliminary result and further work is needed for a conclusive result.

TABLE 1
SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED FROM
EFG (RH) MULTI-RIBBONS; BASELINE PROCESS

		EFG		CONTROL	
		AM0	AM1	AM0	AM1
V_{OC} (mV)	Average	507	500	591	583
	Standard Deviation	6	5	2	2
	Range	502-519	497-510	588-592	580-584
J_{SC} (mA/cm ²)	Average	22.3	18.5	33.1	27.9
	Standard Deviation	.6	.5	.5	.4
	Range	21.8-23	18-19	32.3-33.5	27.3-28.3
CFF(%)	Average	72.5	72.5	77.1	77.2
	Standard Deviation	1	1.1	1.2	1.8
	Range	71.1-73.9	71-74	75.2-78.2	74-78
η (%)	Average	6.1	6.7	11.1	12.5
	Standard Deviation	.3	.3	.3	.4
	Range	5.8-6.5	6.5-7.2	10.6-11.4	11.8-12.7

NOTES:

- Cells (2x2 cm) with SiO AR coating, measured at 25°C test block temperature.
- Sample cells from Run No. 5. Sample size: EFG - 6 cells
Control - 5 cells

TABLE 2

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED FROM EFG (RH) MULTI-RIBBONS AFTER SURFACE TREATMENTS

		SURFACE ETCHING		SURFACE TEXTURIZING	
		EFG	Control ²	EFG	Control ²
V_{OC} (mV)	Average	514	505	519	512
	Standard Deviation	12	12	---	---
	Range	502-538	495-511	516-524	506-517
J_{SC} (mA/cm ²)	Average	23.2	23.5	21.9	21.2
	Standard Deviation	2.4	1.6	---	---
	Range	19.8-26.3	22.7-25.1	21.4-22.6	20.7-21.9
CFF (%)	Average	66	69	70	69
	Standard Deviation	5	4	---	---
	Range	58-73	65-74	70-71	66-72
η (%)	Average	5.8	6.0	5.9	5.6
	Standard Deviation	0.5	0.6	---	---
	Range	5.2-6.5	5.8-7.0	5.7-6.2	5.1-5.8

- NOTES: 1. Cells with baseline process (2x2 cm, SiO AR coating) measured under AM0 conditions at 25°C test block temperature.
2. Control cells mean EFG cells fabricated without surface treatment.
3. Sample Size: Surface Etching - EFG: 11 cells
EFG Control: 6 cells

TABLE 3

Summary of Parameters of Standard EFG (RH) Solar Cells Fabricated After
Diffusion Glass Gettering

	GET ¹	GET ²	STD EFG ³
Voc (mv)	AVERAGE 528	503	507
	S.D. -	9	6
	RANGE 523~535	487~516	502~519
Jsc (mA/cm ²)	AVERAGE 27.3	22.4	22.3
	S.D. -	0.8	.6
	RANGE 26.8~27.5	21~23.3	21.8~23
CFF (%)	AVERAGE 68	70	73
	S.D. -	5	1
	RANGE 65~70	59~74	71~74
η (%)	AVERAGE 7.2	5.8	6.1
	S.D. -	0.6	.3
	RANGE 6.9~7.4	4.7~6.3	5.8~6.5

NOTE: 1. Cells (2x2cm) with SiO AR coating under AMO conditions at 25°C test block temperature.

2. GET¹: Ten minutes of diffusion glass deposition.
GET²: Forty minutes of diffusion glass deposition.

STD EFG: From Table 1 (STD EFG cells without the gettering steps).

3. Sample sizes:

GET¹: 3 Cells

GET²: 6 Cells

EFG Control: 6 Cells

TABLE 4
SUMMARY OF PARAMETERS OF BSF SOLAR CELLS FABRICATED
FROM EFG (RH) RIBBONS.

		BSF EFG	STD. EFG *
V_{OC} (MV)	AVERAGE	532	507
	S.D.	7	6
	RANGE	519 ~ 549	502 ~ 519
J_{SC} (mA/cm ²)	AVERAGE	26.2	22.3
	S.D.	0.8	0.6
	RANGE	24.8 ~ 27.3	21.8 ~ 23
CFF (%)	AVERAGE	71	73
	S.D.	4	1
	RANGE	61 ~ 74	71 ~ 74
η (%)	AVERAGE	7.3	6.1
	S.D.	0.6	.3
	RANGE	6.0 ~ 7.9	5.8 ~ 6.5

- NOTE: 1. Cells (2x2cm) with SiO₂ AR coating measured under AMO conditions at 25°C test block temperature.
2. Sample sizes:
BSF - 10 cells
STD - 6 cells
3. STD cells from Table 1. (*).

TABLE 5

PARAMETER (AVERAGE) OF EFG SOLAR CELLS FROM GRAIN BOUNDARY
PASSIVATION (GP): FIRST RUN

	G.P.	STD*
Voc (mV)	537	507
Jsc(mA/cm ²)	25.9	22.3
CFF (%)	73	73
η (%)	7.5	6.1

- NOTE: 1. Cells (2x2 cm) with SiO AR coating measured under AMO conditions at 25°C test block temperature.
2. STD* cell data from Table 1.

TABLE 6

PARAMETER (AVERAGE) OF EFG CELLS FROM GRAIN BOUNDARY PASSIVATION
(GP): SECOND RUN

	G.P.	H.T.	EFG CONTROL	CZ CONTROL
Voc (mV)	505	511	512	581
Jsc (mA/cm ²)	16.6	17.3	17.2	24.3
CFF (%)	60	60	65	74
(%)	3.7	3.9	4.3	7.8
SAMPLE SIZE	10	6	7	6

NOTE: 1) Cells (2x2 cm) with NO A.R. coating measured at 28°C test block temperature.

2) H.T.: Heat Treatment

3) EFG cells from EFG Run I.D. #187-3C-3S.

TABLE 7

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED FROM
EFG (RH) MULTI-RIBBONS; SHALLOW JUNCTION PROCESS

		EFG		CZ CONTROL	
		AM0	AM1	AM0	AM1
$V_{OC}(mV)$	Average	525	525	588	585
	Standard Deviation	11	14	5	5
	Range	506-538	495-539	581-592	579-590
$J_{SC}(mA/cm^2)$	Average	28	23.5	36.5	30.6
	Standard Deviation	1.6	1.4	.6	.4
	Range	25.4-31	21.3-26	36-37.2	30.1-31.1
CFF(%)	Average	69.4	64.9	74	71
	Standard Deviation	3.6	6.9	3.7	4.5
	Range	63-75	53-78	70-78	67-77
$n(\%)$	Average	7.6	8	11.7	12.6
	Standard Deviation	.6	1	.7	1
	Range	6.6-8.4	6.5-9.9	11-12.6	11.9-14.1

NOTES:

1. Cells ($\sim 2 \times 2$ cm) with MLAR coating and shallow junction (from Run No. 3), measured at 25°C test block temperature.
2. Sample size: EFG - 10 cells
CZ Controls - 4 cells
3. Problems of temperature control and contacting were experienced during AM1 measurements.

TABLE 8

INFORMATION ON DETECT DENSITIES SUPPLIED BY MRI

EFG I.D.	TWINS /mm ²	DISLOCATION /μm ²	G B LENGTH cm/cm ²
88G	577	.037	3.0
69A	774	.023	4.1
69B	390	.027	3.1
69C	703	.019	3.6
33A	284	.056	4.0
33B	435	.021	3.6
33D	246	.024	2.6
33E	293	.037	3.3

FIGURE 1

Dark I-V Characteristics of a EFG (RH)
Multi-Ribbon Solar Cell at R.T.
(4cm² in area, baseline cell)

- x: A Control Cell No. 4
- o: A EFG Cell No. 5-1092-7-5
- : Forward Characteristics
- : Reverse Characteristics

Figure 2

Spectral Response of EFG (RH) Multi-Ribbon Solar Cells
(Baseline Process)

SPECTRA RESPONSE (A/V)

WAVELENGTH (MICROMETER)

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ABSOLUTE SPECTRAL
RESPONSE

SAMPLE IDENTIFICATION

X: Control Cell #1

O: EFG 5-1092-7-1

Δ: EFG 5-1092-7-5

DATE:

FIGURE 3

Small Light Spot Scanning of a EFG (RH) Multi-Ribbon Solar Cell
(Baseline Process, Run #5)

FIGURE 4

SPECTRAL RESPONSE OF SOLAR CELLS FROM EFG (RH); SURFACE ETCHING PROCESS

FIGURE 5

SPECTRAL RESPONSE OF A BSF/EFG (RH) SOLAR CELL

FIGURE 6

SPECTRAL RESPONSE OF SOLAR CELLS FROM EFG (RH) RIBBONS;
GRAIN BOUNDARY PASSIVATION PROCESS

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FIGURE 7: SHORT CIRCUIT CURRENT DENSITY (ACTIVE AREA) VS. DISLOCATION DENSITY OF EFG (RH) RIBBON SOLAR CELLS.

FIGURE 8: SHORT CIRCUIT CURRENT DENSITY (ACTIVE AREA) VS. TWIN DENSITY OF
EFG (RH) RIBBON SOLAR CELLS

FIGURE 9 : SHORT CIRCUIT CURRENT DENSITY (ACTIVE AREA) VS. GRAIN BOUNDARY LENGTH OF EFG (RH) RIBBON SOLAR CELLS.

2.0 Dendritic Web Solar Cells

Dendritic webs delivered were from several batch runs with varying thickness (about 6 to 10 mils). Four point probe measurements indicated a resistivity of about 7-10 ohm-cm, with p-type conductivity. The SPV measurement of minority carrier diffusion length (L) showed a variation of L from web to web. An average L value was about 65 μm with a range of 40 - 120 μm . (Reference (4) provides technical details of Westinghouse's dendritic web process.)

Solar cells (2x2cm) were fabricated using the baseline process; other process modifications, such as the best-of-state-of-the-art process and a two step annealing, were used to indicate possible improved performance. Larger area cells (1"x1") were also fabricated.

2.1 Baseline Solar Cells

Blank shaping (2x2cm) and removal of the surface deposit were carried out using the same method described in Section E of reference (2). Baseline solar cells were fabricated using process steps described in Appendix III of Reference (2).

Illumination Characteristics

Table 9 summarizes the cell parameters from the baseline process (Run No. 2). Both AMO and AM1 parameters are given in the table, indicating an average efficiency of web cells about 10.1% for AMO and 11.5% for AM1. The average AMO and AM1 efficiency of the control cells was 11.2% and 12.5%, respectively, which is an efficiency approximately 1% higher than those of the web cells.

Compared with the previous results on the baseline web cells (2), performance variation from web to web was noticed mainly due to the variation of sheet quality, specifically in variation in minority carrier diffusion length.

Dark I-V Characteristics

Dark I-V characteristics (forward and reverse) were obtained from selected samples at room temperature. The plots were made from the point-by-point measurements and a typical result is given in Figure 10. "A" factors of both the web cells and the control cell were about 1.6 and the saturation current densities (J_0) were 9×10^{-9} A/cm² for the web cell and 5×10^{-9} A/cm² for the control cell. The web cells showed consistently low leakage characteristics, observed from the current level at low bias voltages (V_B 0.3 volts).

Spectral Response

Absolute spectral response was obtained using a filter wheel set-up described in Appendix V-A of reference (2). The wavelength dependence of the response of the standard web solar cells is given in Figure 11. The web cells showed response close to that of a control cell, with slightly lower long wavelength response than the control cells.

Minority Carrier Diffusion Length

Minority carrier diffusion length (L) was measured using the SPV method for the bulk webs and the short circuit current (I_{SC}) method for the solar cells (Refer to Appendix V-B of reference (2) for details). Both methods showed an average L of about 65 μ m.

Photoresponse by Small Light Spot Scanning

Localized photoresponse of the sheet cells was obtained by light scanning (Refer to Appendix V-C of reference (2) for details). A typical scanning result from a standard web cell is given in Figure 12. The web cells showed response close to that of the controls and no significant number of active defect sites were observed.

2.2 The Best-State-Of-The-Art Solar Cells

Efforts were directed toward making the best-state-of-the-art solar cells from dendritic webs on 2x2cm blanks. The key process steps used were; 1) formation of shallow junction to improve blue response (sheet resistance was about 50 ohms/square) (2) application of fine front grid lines using photoresist techniques, which gave about 92% active area, (3) formation of back surface field (BSF) by alloying screen printed aluminum paste, (4) formation of back surface reflector (BSR) by evaporation of a thin aluminum layer in the back, and (5) a good quality (a multi-layer) AR coating was evaporated on the cells to minimize reflection from the surface.

Solar cell parameters, such as I_{sc} , V_{oc} , CFF, and η , were measured under AMO and AM1 conditions at 25⁰C test block temperature. Table 10 summarizes the results, showing an average AMO efficiency of 12.8%. A web cell showed an AMO efficiency as high as 14.2%, which corresponds to measured AM1 efficiency of 15.5%.

Absolute spectral response (A/W) was made using a filter wheel set-up from a good web cell and a bad cell. Response versus wavelength is given in Figure 13, indicating significant improvement in short wavelength response compared with those of the standard cells in Figure 11. The response at

wavelength 0.45 μm indicates a quantum efficiency higher than 100%. This could either be due to a measurement error due to low light level at this wavelength along with a reduced response from the standard cell, or possibly to impact ionization.

2.3 Solar Cells From Other Processes

Large Area Cells

Larger area solar cells (1"x1") were fabricated from webs. Process steps used were 1) shallow junction formation, (sheet resistance about 50 ohms/square), 2) front grid lines by photoresist techniques, 3) BSF and 4) MLAR coating. Control cells were also fabricated from conventional Cz silicon of about the same resistivity.

Table 11 summarizes performance of the solar cells, indicating an average AMO efficiency of 11.1%. This is an efficiency 1% lower than the Cz control cells of about the same resistivity. Spectral responses of these cells are plotted in Figure 14. The figure indicates that significant improvement in blue response is noticed compared with the standard cells reported earlier. One web cell (#4 cell) shows lower overall response than the other (#1 cell), suggesting an inconsistency in silicon sheet quality. Czochralski control cells of about the same resistivity showed higher response in the long wavelength region.

A Two Step Annealing

Baseline solar cells were fabricated after a two step annealing described in Section 1.2. Performance of these cells showed degradation in bulk quality;

the average short circuit current density reduced to 22.4 mA/cm^2 compared to 23.5 mA/cm^2 of the web control cells (web cells without the annealing step).

TABLE 9

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED
FROM DENDRITIC WEB: BASELINE PROCESS

		WEB		CONTROL	
		AMO	AM1	AMO	AM1
V_{oc} (mV)	AVERAGE	551	543	591	583
	STANDARD DEVIATION	5	5	2	2
	RANGE	546-556	533-548	588-592	580-584
J_{sc} (mA/cm ²)	AVERAGE	32.7	27.7	33.1	27.9
	STANDARD DEVIATION	1	.7	.5	.4
	RANGE	30.3-34	26.3-28.5	32.3-33.5	27.3-28.3
CFF (%)	AVERAGE	76	76	77	77
	STANDARD DEVIATION	1	1	1	2
	RANGE	73-77	74-78	75-78	74-78
η (%)	AVERAGE	10.1	11.5	11.2	12.5
	STANDARD DEVIATION	.4	.4	.2	.4
	RANGE	9.3-10.7	10.5-12.1	10.8-11.4	11.8-12.7

NOTES:

- Cells (2x2 cm) with SiO AR coating, measured at 25°C Test Block.
- Sample Size: Web - 16 Cells
Control - 5 Cells

TABLE 10

SUMMARY OF PARAMETERS OF WEB SOLAR CELLS FABRICATED
FROM THE BEST-STATE-OF-THE-ART PROCESS.

		B
		WEB
Voc (mV)	Average Standard Deviation Range	585 11 569-604
Jsc (mA/cm ²)	Average Standard Deviation Range	39.4 0.9 37.8-41.0
CFF (%)	Average Standard Deviation Range	75 3 70-78
η	Average Standard Deviation Range	12.8 0.7 11.6-14.2

- NOTES: 1. 2 x 2 cm cells with shallow junction, MLAR, BSF and BSR process.
2. Cells measured under AMO conditions at 25°C test block temperature.
3. Sample Size: 10 cells

TABLE 11

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED
FROM LARGE AREA DENDRITIC WEBS (1" x 1")

		A	
		WEB	CONTROL
Voc (mV)	Average Standard Deviation Range	564 23 520-588	584 --- 580-588
Jsc (mA/cm ²)	Average Standard Deviation Range	36.2 1.7 32.9-37.8	37.6 --- 37.5-37.8
CFF (%)	Average Standard Deviation Range	73 2 71-77	75 --- 73-77
η (%)	Average Standard Deviation Range	11.1 1.1 9.4-12.6	12.1 --- 11.9-12.6

- NOTES: 1. 1" x 1" cells with shallow junction, MLAR coating and BSF process.
2. Cells measured under AMO conditions at 25°C test block temperature.
3. Sample Size: A - Web: 7 cells
Control: 3 cells
4. Control cells mean cells fabricated from CZ silicon of about the same resistivity.

Figure 10

Dark I-V Characteristics of a Dendritic-Web Solar Cell at R.T.
(4 cm² in area, baseline process)

- x: A Control Cell No. 4
- o: A Web Cell No. 17-1152-4
- : Forward Characteristics
- : Reverse Characteristics

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SAMPLE IDENTIFICATION

x : Control #4

o : Web 17-1152-4

Δ : Web 17-1155-1

DATE:

FIGURE 11

Spectral Response of Solar Cells From Dendritic Webs
(BASELINE Process)

FIGURE 12

Small Light Spot Scanning of a Dendritic Web Solar Cell
(Baseline Process)

FIGURE 13

SPECTRAL RESPONSE OF SOLAR CELLS FROM DENDRITIC WEB;
2x2 CM CELLS WITH SHALLOW JUNCTION, BSF AND BSR PROCESS

FIGURE 14

SPECTRAL RESPONSE OF SOLAR CELLS FROM DENDRITIC WEB;
1"x1" CELLS WITH SHALLOW JUNCTION AND BSF PROCESS

3.0 Silicon on Ceramic (SOC) Solar Cells

SOC substrates delivered to ASEC, were grown at an average growth rate of about 0.06 cm/sec. with an average thickness around 300 μ m. The substrates were doped with boron concentration of about $1 \times 10^{16}/\text{cm}^3$ (1.5 ohm-cm P-type). Minority carrier diffusion lengths of the bulk SOC by the SPV method were in the range between 20-40 μ m. (See reference (5) for the detailed description on SOC process.)

Baseline solar cells of varying sizes were fabricated using the baseline processes modified to fit to these substrates (same diffusion conditions and AR coating were used). Efforts were given to improve cell performance by making the junction shallower and applying better AR coating, etc.

3.1 Baseline Solar Cells

Baseline SOC solar cells were fabricated using the same process sequences, described in the annual report (2) (a p^+ layer in the back was formed by alloying of thin aluminum layers during the diffusion step). 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 7cm² and 19cm², were fabricated using waxing techniques. Evaporated SiO was used as AR coating, and indium solder was pressed into the back opening for electrical tests.

Illumination Characteristics

Solar cell parameters, such as I_{sc} , V_{oc} , C_{ff} , 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.) Table 12 summarizes the results of the baseline 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 (2), 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.

3.2 Shallow Junction Solar Cells

Shallow junction solar cells were fabricated using a short diffusion time than the standard diffusion step, (10 minutes of diffusion instead of 20 minutes) resulting in sheet resistance of about 40-50 ohms/square. Selected solar cells were coated with evaporated multi-layer AR coating to minimize surface reflection. All other process steps were same as the baseline process described in Section 3.1.

Illumination Characteristics

Table 13 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% of the standard cells), mainly due to increase in I_{sc} , specifically from increase in blue response of the cells (I_{scb}).

In conclusion, with more careful processing, SOC cells were similar to those fabricated earlier. The addition of 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 12

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

		SOC		CZ CONTROL
		AM1	AMO	AMO
$V_{OC}(mV)$	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:

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

TABLE 13

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

4.0 Solar Cell From Cast Silicon By Heat Exchanger Method (HEM)

Blanks (2x2cm) were prepared by slicing the cast silicon blocks using an ID saw. The silicon blocks were prepared from three casting experiments at Crystal Systems: run numbers 342C, 349C, and 314C. Measured resistivity of the sliced blanks ranged between 0.5 ohm-cm and 1.5 ohm-cm with p-type conductivity. One cast ingot (Run #314C) showed resistivity variations between 0.8 and 1.5 ohm-cm from end-to-end of the 3" block. Approximately half of the blanks showed some degree of polycrystallinity while the other half was single crystal. Minority carrier diffusion lengths (SPV method) were in the range 30 to 80 μm . (Reference (6) provides details of the HEM process.)

Baseline and BSF solar cells were fabricated from both single crystalline and poly crystalline HEM. Efforts to improve bulk properties of HEM silicon were also carried out; gettering by diffusion glasses and two step annealing, etc.

4.1 Baseline Solar Cells

The thickness of the as-sawn starting blanks was 16 mils, thinned down to about 13 mils using a planar etching solution. Two batches of solar cells were fabricated using the baseline process (see Appendix III of reference (2) for the details of the proces); One batch contained single crystalline HEM and the other batch was polycrystalline HEM.

Illumination Characteristics

Solar cell parameters, such as I_{sc} , V_{oc} , CFF, and η , were measured under AMO and AM1 solar simulation at 25°C test block temperature. Table 14 summarizes the cell parameters of the two batch processes, showing an average AMO efficiency of 9.5% for the single crystalline HEM cells and 7.6% for the

polycrystalline HEM cells. Significant difference in performance between the two batches was due to the difference in CFF; an average CFF of 73% for the single crystal HEM cells versus 63% for the poly HEM cells. Low CFF of the poly HEM was partly due to the inclusions observed in the bulk HEM material. Figure 15 shows microscopic photographs of the inclusions (or possibly precipitates); (a) for the precipitates at the grain boundary and (b) for the precipitates in the bulk. NOTE: The inclusions were observed on the poly section of ingot run number 314C, specifically at the position close to the last part of solification.

4.2 Baseline Cells with Gettering

Gettering by diffusion glasses was added to the baseline 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 POCl_3 source). After this step, chemical polishing removed the diffused layers (and if successful, removed some gettered impurities) and the saw-cut damage layer simultaneously; baseline processing followed thereafter to fabricate 2x2cm solar cells.

Illumination Characteristics

Parameters of solar cells using the gettering process are summarized in Table 15. 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 baseline cell performance results in the previous section (4.1) using the same silicon and process conditions.

Spectral Response

Figure 16 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 baseline cells, 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 (2) for the detailed description on measurement procedure).

Solar cells utilizing the gettering step showed an average diffusion length of about $70\text{ }\mu\text{m}$ which is an improvement over the cells without the gettering treatment. Typical L -values of the HEM cells without gettering and for the Cz control cells were about $50\text{ }\mu\text{m}$ and $150\text{ }\mu\text{m}$, respectively.

4.3. Large Area Solar Cells

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

Illumination Characteristics

Finished solar cells had evaporated SiO₂ AR coatings with Ti-Pd-Ag metallization. Solar cell parameters, such as I_{sc} , V_{oc} , CFF, and η , were measured under 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 (2).)

Solar cell parameters of the large area (1"x1") HEM solar cells from both baseline and shallow junction processes were obtained. Table 16 and Table 17 summarize the results for the baseline cells and for the shallow junction cells. The baseline solar cells showed an average AMO efficiency of 10% for single crystalline HEM and 9.7% for polycrystalline HEM. The shallow junction solar cells indicated a slight improvement in efficiency for both single crystalline and polycrystalline 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 polycrystalline HEM. This indicates that use of HEM silicon with such large crystallites (mm size) does not significantly reduce solar cell performance.

Spectral Response

Absolute spectral response (A/W) was measured using a filter wheel set-up (refer to Appendix V of reference (2) for the details). Responses are plotted in Figure 17 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.

TABLE 14.

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED FROM HEM; BASELINE PROCESS

		HEM (Single)	HEM (Poly)	CZ Control
V_{OC} (mV)	Average	584	584	593
	Standard Deviation	8	8	1
	Range	574-598	570-599	592-595
J_{SC} (mA/cm ²)	Average	30.1	28.2	33.4
	Standard Deviation	1.4	2.0	0.4
	Range	28.3-32.5	24.3-31.3	32.8-33.8
CFF (%)	Average	73	63	76
	Standard Deviation	4	7	2
	Range	60-77	51-73	74-78
η (%)	Average	9.5	7.6	11.1
	Standard Deviation	0.8	0.9	0.3
	Range	7.6-10.6	6.7-9.4	10.8-11.6

- NOTES: 1. Cells (2x2 cm) with SiO AR coating measured under AM0 conditions at 25°C test block temperature.
 2. Sample size: HEM (single): 20 cells
 HEM (poly): 14 cells
 CZ Control: 5 cells

TABLE 15

SUMMARY OF PARAMETERS OF SOLAR CELLS
FROM HEM: GETTERING & BASELINE 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 SiO AR coating measured under AMO conditions at 25°C test block temperature
- Sample size: Single - 11 cells
Poly - 9 cells
Control - 4 cells

TABLE 16

SUMMARY OF PARAMETERS OF SOLAR
CELLS (1"x1") FROM HEM: BASELINE 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 SiO₂ AR coating measured under AM0 condition at 25°C test block temperature.
- Sample size: HEM single - 10 cells
Poly - 10 cells
Control - 4 cell

TABLE 17

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

(a)

(b)

FIGURE 15

MICROSCOPIC PHOTOGRAPHS OF INCLUSIONS (OR PRECIPITATES)
FOUND IN HEM SILICON (CRYSTAL SYSTEMS RUN #314C); 200X

- (a) Precipitates at the grain boundary
- (b) Precipitates in the bulk

FIGURE 16 Spectral Response of Solar Cells from HEM: Gettering Process

FIGURE 17 Spectral Response of Solar Cells (1"x1")
from HEM.

5.0 Solar Cells From The Semi-Continuous CZ Silicon (Varian)

Three sections of a continuous CZ growth (Varian) ingot were delivered to ASEC and were sliced into wafer form. Resistivity of the wafers was about 3.5 ohm-cm with p-type conductivity. Minority carrier diffusion length of the bulk wafers was in the range between 130-170 μ m using SPV measurements. (Reference (7) provides technical details of the semi-continuous CZ growth from Varian.)

5.1 Baseline Solar Cells

These wafers were sliced into 2x2 cm blanks and solar cells were fabricated using baseline process. (Refer to Appendix III of Annual Report (2) for the process details.) Control blanks were prepared from conventional Cz wafers, with resistivity range and minority carrier diffusion lengths about 1-2 ohm-cm and 140 μ m, respectively.

Illumination Characteristics

Thirty-six (36) solar cells (2x2cm) were prepared from the Varian blanks using the baseline process. The majority of the baseline cells showed consistent performance, indicating an average AMO efficiency of about 10.7% at 25^oC test block temperature. A summary of parameters of the baseline cells is given in Table 18. Control solar cells showed an average efficiency of 10.9%, indicating slightly better performance than those made from the Varian material. There seemed to be no difference in cell performance between the cells from the top, middle, and bottom sections of the ingot. Lower V_{OC} of the Varian solar cells (about 20 mV lower than that of the controls) was mainly due to the slightly lower doping level of the Varian wafers; 3-4 ohm-cm for the Varian versus 1-2 ohm-cm for the controls.

Dark I-V Characteristics

Dark I-V plots (forward) were obtained using a semi-automatic plotter and sample cells were selected from this data to measure their forward and reverse dark I-V characteristics using point-by-point measurements. The plots of these measurements are given in Figure 18. Calculated "A" factors from the simple diode equation were about 1.7 for both Varian cells and a control cell. The saturation current density (J_0) obtained from the plots was about 3×10^{-8} A/cm² for the Varian cells and 2×10^{-9} A/cm² for the control cells. Based on the current at low bias voltages, the control cell showed lower shunt resistance than the Varian cell, but this shunt resistance indicated by the control cell (about 200 ohms for a 2x2 cm) did not appear to reduce either V_{OC} or CFF.

Spectral Response

Absolute spectral response (A/W) was measured using a filter wheel set-up (refer to Appendix V of reference (2) for the details of measurements). Response versus wavelength for standard process cells from a typical control and Varian wafers are given in Figure 19. Varian cells showed responses very close to those of the control cell. A Varian cell (cell No. B10-2) showed slightly higher overall response.

Photoresponse By Small Light Spot Scanning

Localized photoresponse of the solar cells was obtained by light spot scanning (refer to Appendix V of reference (2) for the details of measurements). A typical result of the scanning is given in Figure 20. The Varian cell showed response close to that of the control cell.

TABLE 18

Summary of Parameters of BASELINE
Solar Cells Fabricated From Varian Continuous CZ Wafers

PARAMETER		TOP	MIDDLE	BOTTOM	CONTROL
V_{OC} , mV	Average	573	575	574	592
	Standard Deviation	1.2	3	1.7	2
	Range	571-574	570-580	572-576	590-594
J_{SC} , mA/cm ²	Average	34.3	34	34.0	34.7
	Standard Deviation	0.2	0.4	0.3	0.3
	Range	34-34.8	33.5-34.8	33.5-34.3	34.5-35
CFF, %	Average	74	74	74	72
	Standard Deviation	2	2	1	2
	Range	71-76	71-77	73-76	70-74
η , %	Average	10.7	10.7	10.7	10.9
	Standard Deviation	0.3	0.4	0.2	0.4
	Range	10.3-11.1	10.1-11.3	10.4-10.9	10.5-11.3

NOTES:

1. Varian Ingot Identification Run 191, Ingot No. 3
2. Measured Under AMO Condition at 25°C.
3. Cells (2x2 cm) With SiO AR Coating.
4. Number of Samples:

Varian: Top: 9 Cells
 Middle: 10 Cells
 Bottom: 5 Cells
 Control: 3 Cells

FIGURE 18

Dark I-V Characteristics of
Solar Cells From Varian Continuous CZ Wafers

OCLI OPTICAL COATING
LABORATORY, INC.

15251 E. DON JULIAN ROAD
CITY OF INDUSTRY, CA 91746
TELEPHONE (213) 968-6581

ABSOLUTE SPECTRAL
RESPONSE

SAMPLE IDENTIFICATION

x: Control Cell No.

o: Cell No. B10-2

Δ: Cell No. E7

DATE:

FIGURE 19

Spectral Response of BASELINE Solar Cells
From Varian Continuous CZ Wafers

SPECTRAL RESPONSE (A/W)
-69-

FIGURE 20

Small Light Spot Scanning of a BASELINE
Solar Cell From Varian Continuous CZ Wafers

Solar Cells From The Semi-Continuous CZ (Hamco)

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

Baseline solar cells (2x2cm) were fabricated to show the effect of the ingot growth sequence on cell performance, etc. Other process variations, such as BSF, large area cells (1"x1") with shallow junction and high efficiency processes, were used to see the effects of these processes on solar cell performance. (Reference (8) provides technical details of the Cz semi-continuous Cz growth from the Hamco process.)

Baseline Solar Cells

Wafers were cut to 2x2 cm blanks and the blanks were thinned down to about 13 mils using planar etching solution. Baseline solar cells were fabricated. Refer to Appendix III of reference (2) for the process details.)

Illumination Characteristics

Solar cell parameters, such as I_{sc} , V_{oc} , CFF, and η , were measured under AMO solar simulation at 28⁰C test block temperature. Some of the selected cells were tested under AM1 conditions. Figure 21, 22, and 23 are summaries of

cell parameters of the baseline solar cells under AMO conditions, showing short circuit current density, open circuit voltage and efficiency, respectively. The figures indicate average values and ranges of the parameters as a function of ingot growth sequence. Average short circuit current density showed a tendency to decrease as the number of ingots grown increase; i.e., about $2\text{mA}/\text{cm}^2$ of J_{sc} drop is noticed in the last ingot (9M). This indicates a possibility of accumulation of impurities in the repeated charging and pulling steps. 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, efficiency should show a similar trend if CFF stays about the same. In this case, CFF showed a tendency to increase, which could possibly be due to decrease in resistivity as the number of ingots grown increase. Solar cells from polycrystalline 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.

Spectral Response

Absolute spectral response (A/W) was obtained using a filter wheel set-up (refer to Appendix V of reference (2) for the details). Responses of the baseline solar cells are plotted in Figure 24. 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 at long wavelengths; 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 spectral response measurement. L of the cells from the first ingot (1T) and the last ingot (9M), both single crystal, were about $170\mu\text{m}$ and $70\mu\text{m}$, 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 reference (2), efficiency vs minority carrier diffusion length.) The L-values correlate with spectral responses.

6.2 High Efficiency Solar Cells

Efforts were given to improve the solar cell efficiency by adding more process steps. Solar cells (2x2cm) were fabricated from single crystal HAMCO wafers using modified process steps to the baseline process. The process steps we used are:

- (1) Formation of shallow junction (sheet resistance of about 40-50 ohms/square,
- (2) Application of fine front grid lines using photoresist techniques, resulting in about 92% active area,
- (3) Addition of BSF by alloying screen printed aluminum paste, and
- (4) Application of better quality MLAR anti-reflective coating.

Illumination Characteristics

Solar Cell parameters, such as I_{sc} , V_{oc} , CFF, and , were measured under AMO simulation conditions at 28°C test block temperature. Table 19 summarizes the results of the improved performance. An average AMO efficiency of these cells was 12.6%, which is a significant improvement over that of the standard cells (about 1.5% improvement in average efficiency). The increase in I_{sc} by the process was noticeable; 39.4 mA/cm² for this process versus 35 mA/cm² for the standard process.

Spectral Response

Absolute spectral responses (A/W) of the solar cells are plotted in Figure 25. Responses of a cell from the first ingot (cell #1) and a cell from the last ingot (cell #13) are shown in the figure along with a conventional Cz control cell processed using the same process steps. The figure indicates; 1) the response improved in both short and long wavelength region compared with those of the standard cell (Figure 24), and 2) a cell from the last ingot (#13) showed lower response, especially in long wavelength, than both a control cell and a cell from the first ingot, again suggesting reduction in minority carrier diffusion length.

6.3 Solar Cells From Other Processes

Large area blanks (1"x1") were prepared and solar cells were fabricated by formation of shallow junctions (sheet resistance of about 40 ohms/square). For grid lines, metallization was applied using metal shadow mask. SiO was the AR coating. These cells showed results similar to the baseline cells (Section 6.1) in terms of efficiency and dependence of overall performance on ingot growth sequence, etc.

Solar cells (2x2cm) were fabricated from the selected Hamco wafers (1T, 3T, 5T, 7T, 8T, 8B, and 9B) using the BSF process described in Appendix III of the First Annual Report (2). Standard metallization patterns and schemes were applied and SiO was the AR coating. Performance of the individual solar cells was obtained under AMO conditions. The result suggested that no significant improvement in Voc and Jsc was achieved by the BSF process, compared with the results of the baseline cells. The BSF Hamco cells showed even slightly lower efficiencies than the baseline Hamco cells, mainly because of low curve fill factors. The low CFF was due partly due to increase in series resistance.

TABLE 19

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED
FROM HAMCO WAFERS; HIGH EFFICIENCY PROCESS.

	Voc (mV)	Jsc ₂ (mA/cm ²)	CFF (%)	η (%)
Average	591	39.4	73	12.6
Standard Deviation	3	0.6	2	0.4
Range	586-596	38.4-40.0	70-77	12.0-13.6

- NOTE:
- 1) Solar cells (2 x 2 cm) fabricated using Shallow Junction (SJ), Back Surface Field (BSF), and MLAR Coating.
 - 2) Cells measured at 28°C test block temperature under AMO conditions.
 - 3) Cells from all single crystal; 1T (3 cells), 2T (4 cells), 4T (3 cells), 5T (1 cell), and 9T (3 cells).

FIGURE 21 SHORT CIRCUIT CURRENT DENSITY (AMO) VERSUS INGOT GROWTH SEQUENCE

FIGURE 22

OPEN CIRCUIT VOLTAGE (AMO) VERSUS INGOT GROWTH SEQUENCE

FIGURE 23 - AMO EFFICIENCY (BASELINE PROCESS) , VERSUS INGOT GROWTH SEQUENCE

FIGURE 24. SPECTRAL RESPONSE OF BASELINE SOLAR CELLS FROM HAMCO WAFERS.

+ 1 T
 0 0 M
 0 0 (Control Cell)

SPECTRAL RESPONSE (A/W)

WAVELENGTH (micrometers)

-74-

FIGURE 25
SPECTRAL RESPONSE OF HIGH EFFICIENCY SOLAR
CELLS FROM HAMCO WAFERS

B. Performance Summary of the Sheet Solar Cells

1.0 Baseline Solar Cells

Figure 26 is a summary of illumination characteristics (AMO) of solar cells made by the baseline processing. Parameters of interest are J_{sc} , V_{oc} , CFF and η . Their average values and ranges are shown in the figure for the various forms of silicon sheets (average values are indicated by circles for the Phase I work and by triangles for the Phase II work). The figure suggests; 1) solar cells from semi-continuous Cz silicon, both Varian and Hamco processes, shows an average η almost the same as that of the conventional Cz control cells, although the former indicates wider ranges than the latter, 2) some sheet cells, such as Web and HEM, shows cell efficiency close to that of the Cz controls, (an average efficiency of about 9-10% versus 11%), and 3) the sheet cells generally gave wider ranges in efficiency than the control cells, mainly because of the wide ranges of CFF and J_{sc} . Solar cells from the Phase II work did not show any significant improvement over the cells in Phase I works. SOC cells showed a slight improvement in J_{sc} in Phase II, mainly due to increase in front active area by utilizing photoresist techniques. Enhancement in V_{oc} was observed from the dendritic web cells and the result was attributed to the difference in the starting substrate resistivity; about 15 ohm-cm in Phase I versus 7 ohm-cm in Phase II. Solar cells from dendritic web and HEM showed wider ranges in cell parameters in Phase II, indicating a problem of reproducing the same sheet quality.

2.0 Solar Cells From the Process Variations

Improvement in cell performance has been obtained by adding other process variations to the baseline process; i.e., formation of shallow junction (SJ), application of back surface field (BSF) and back surface reflector (BSR),

evaporation of better quality anti-reflective (AR) coating (MLAR), and addition of gettering steps to improve bulk property.

Table 20 summarizes AMO parameters of solar cells fabricated using the modified process steps, from which the best AMO efficiencies were achieved. Statistical average values and the best efficiencies achieved are given in the table with the description of the processes used. The right hand column indicates a potential efficiency, which was calculated from the best Voc, Jsc and CFF achieved independently. The table suggests that improvement in Voc and CFF is necessary for some sheet cells to obtain an average AMO efficiency of 10% or higher by improving sheet quality.

Efficiency improvements as a function of minority carrier diffusion length were also obtained for the various process steps used. Figure 27 is the result of the plots for the standard process, BSF process and shallow junction with BSF. Standard process is indicated by circles and the BSF and SJ processes are indicated by Δ and x, respectively. The figure suggests that the better the quality of the silicon sheets, i.e., the higher the L, the higher the magnitude of the performance improvement. By adding the BSF and SJ processes to the standard process, sheet solar cell efficiency improved about 1% for $L=50 \mu\text{m}$ and 2% for $L=150 \mu\text{m}$. NOTE: Baseline solar cells have two data points for each sheet cell in the curve. The lower points represent efficiencies actually obtained and upper points indicate potential efficiencies assuming that CFF can be improved to a level of about 76%.

3,0

AMO/AM1 Conversion

Solar cell parameters were measured both under AMO and AM1 solar simulator conditions. Descriptions of the simulator and calibration methods used

are discussed in Appendix IV of the First Annual Report (2) and Appendix III of this report for the AM1 conditions.

Table 21 summarizes AMO/AM1 conversion of short circuit current density (J_{sc}) and efficiency () of the baseline solar cells from the various silicon sheets. An average AMO/AM1 conversion ratio of J_{sc} ranges between 1.13 and 1.20, while an average AM1/AMO conversion ratio of ranges between 1.11 and 1.17. There seems to be no strong correlation between the ratio and the quality of the sheet silicon at present. SOC cell shows a slight deviation from the rest of the sheet cells, which could partly be due to the difficulties in temperature measurements and effect of non-uniform illumination on large area cells. (An average standard cell size of 13 cm^2 for SOC vs 4 cm^2 for the other sheet cells). Finally, it is worthwhile to emphasize that these conversion ratios obtained are only valid under the specific illumination spectrum and intensity calibration methods used.

TABLE 20

A SUMMARY OF ILLUMINATION CHARACTERISTICS OF THE
SHEET SOLAR CELLS FROM THE IMPROVED PROCESSES.

	Average Parameters				η^1 (%)	Process Used	η^2 (%)
	Voc (mV)	Jsc (mA/cm ²)	CFF (%)	η (%)			
EFG (RH)	538	26.8	75	8	9.0	SJ, MLAR	9.1
EFG (RF)	549	29.4	71	8.5	10.3	BSF	10.3
WEB	585	39.4	75	12.8	14.2	SJ, BSF, BSR, MLAR	14.3
SOC	529	26.0	68	6.9	7.3	SJ, MLAR	7.3
HEM	596	33.0	71	10.3	11.8	GETTERING + STD	11.8
SILSO	556	34.2	77	10.7	10.8	BSF, MLAR	11.3
HAMCO	591	39.4	73	12.6	13.6	SJ, BSF, MLAR	13.6

Note 1) η^1 : Best η achieved.

2) η^2 : η calculated from best Voc, Jsc and CFF achieved independently.

3) Solar cells measured under AMO illumination conditions at temperature 25 - 28°C.

4) HEM and HAMCO cells shown here are all from single crystal.

TABLE 21

AN AMO-AMI CONVERSION OF SHORT CIRCUIT CURRENT
DENSITY (J_{sc}) AND EFFICIENCY (η) OF THE STANDARD
SOLAR CELLS FROM VARIOUS SILICON SHEETS.

	J_{sc} , AMO/AMI		η , AMI/AMO	
	AVERAGE	RANGE	AVERAGE	RANGE
SOC	1.13	1.12-1.14	1.17	1.14-1.23
EFG (RH)	1.20	1.18-1.21	1.11	1.08-1.12
WEB	1.17	1.10-1.20	1.14	1.12-1.17
HEM	1.17	1.16-1.17	1.12	1.10-1.13
HAMCO	1.19	1.17-1.21	1.12	1.10-1.23

- NOTES:
1. Data based on selected sample measurement for AMI.
 2. Solar cells with SiO₂ AR coating measured at 25°C test block temperature.
 3. See Appendix IV of Reference (2) for AMO simulation conditions and Appendix III for AMI simulation conditions.

FIGURE 26

A SUMMARY OF ILLUMINATION (AMO) CHARACTERISTICS OF THE
BASELINE SOLAR CELLS FROM THE UNCONVENTIONAL SILICON SHEETS

FIGURE 27

CONVERSION EFFICIENCY VERSUS MINORITY CARRIER
DIFFUSION LENGTH FOR THE THREE PROCESS VARIATIONS

C. Effects of Grain Size on Cell Parameters

In considering the development of low cost polycrystalline silicon sheet technologies, such as casting and ribbon growth technologies, and the corresponding requirement of minimum solar module performance (generally accepted minimum efficiency is about 10% AM1), it is becoming important to establish a criterion for the grain sizes which will meet the required minimum module performance. Thus, the objective of these experiments was; 1) to establish a minimum grain size which will meet 10% AM1 module efficiency and 2) to observe the variation of cell parameters as a function of grain sizes; grain sizes of interest here were about 0.5-10mm.

1.0 Experimental

Starting substrates were prepared in such a way to obtain reliable data:

- i.e. 1) Mainly used CZ polycrystalline substrates (2x2cm): the use of pure starting silicon is expected to minimize other possible impurity effects. Other polysilicon sheets, such as SILSO and HEM, were added for comparison.
- 2) Substrates were chosen in such a way that each substrate had relatively uniform distribution of grain size. This is a very important factor in selecting the substrates since non-uniform distribution of the grain size in a substrate can easily mislead interpretation of the results obtained from the cell parameters.

Grain size was determined by small light spot scanning across a finished solar cell. The light source used was of a penetrating long wavelengths which would represent photoresponse of the bulk silicon. The light source was obtained from a tungsten lamp passing through a very thin silicon filter. Grain size was

calculated by averaging distances between dips in photoresponses; the grain sizes obtained in this way indicate electrically active grain boundaries. The average size obtained thus is larger than "visual" counts from etched slices, where both active and inactive grain boundaries are considered. Other details included:

- 1) Several scanning runs, at least four, were made on each cell.
- 2) Two to four cells of each grain size group were scanned to obtain a reliable statistically average grain size.

2.0 Results

Solar cell parameters were obtained as a function of grain size under AMO condition with AR coating. The parameters are normalized with respect to those of the single crystalline solar cells of the same resistivity. Plots of the results are given in Figure 28 (for J_{sc}), Figure 29 (for V_{oc}), Figure 30 (for CFF), and Figure 31 (for η). The effective minority carrier diffusion length (L) was also measured using the short circuit current method for the various grain sizes and the results are shown in Figure 32.

Figure 28 indicates that J_{sc} fell off fast at grain sizes below 1mm, showing about 10% reduction in J_{sc} at grain sizes around 700 μm (0.7mm).

Open circuit voltage in Figure 29 also showed a drop as the grain size decreased, about 5% reduction (-30 mv loss) at grain sizes around 1mm. V_{oc} vs grain size was also obtained with the information from dark I-V measurements and the observed short circuit current, showing a similar result. Dark I-V measurement also suggested that reduction in V_{oc} for smaller grains is not due to the junction shunting caused by grain boundaries, but by the increase in saturation current, possibly from reduction in effective minority carrier diffusion length.

Curve fill factors in Figure 30 showed no noticeable dependence on grain size. However, there was a tendency to decrease at smaller grain size, possibly from increase in sheet resistance (series resistance) by the increased potential drop at grain boundaries.

Normalized efficiencies with respect to single crystal solar cells, are plotted in Figure 3. About 20% reduction is seen at grain sizes around $700\text{ }\mu\text{m}$, mainly from reduction in both J_{sc} and V_{oc} for a smaller grain substrate. Figure 32 shows the effective minority carrier diffusion length variation, indicating L of about $50\text{ }\mu\text{m}$ for a substrate of grain size 1mm . L vs grain size shows a straight line in semi-log plots within the range of grain sizes under investigation. Finally, attempts were made to check how this work checks with earlier works. Figure 33 plots theoretical and experimental efficiencies (AM1) for various silicon grain sizes: dotted lines for the theoretical and a solid line for the experimental results. Plots of the present work (indicated by circles) were made by assuming that single crystalline solar cell efficiency is about 15% at AM1.

In summary, the results of this work suggest that the minimum grain size to make solar cells of AMO 10% efficiency is about $500\text{ }\mu\text{m}$, which is expected to provide minimum module efficiency of 10% AM1. If other harmful impurities are added in the process of sheet growth, the minimum grain size must be increased. Uniform distribution of grain size has been observed to be an important condition that has to be satisfied too. The performance of solar cells with non-uniform grain size distribution was dominated quite often by the performance of the sections of smaller grains, especially from degradation in V_{oc} and CFF.

FIGURE 28

SHORT CIRCUIT CURRENT DENSITY VERSUS GRAIN SIZE

FIGURE 29

OPEN CIRCUIT VOLTAGE VERSUS GRAIN SIZE

FIGURE 30

CURVE FILL FACTOR VERSUS GRAIN SIZE

FIGURE 31

EFFICIENCY VERSUS GRAIN SIZE

FIGURE 32

EFFECTIVE MINORITY CARRIER DIFFUSION LENGTH VERSUS GRAIN SIZE

FIGURE 33

EFFICIENCY VS GRAIN SIZE

D. Back Surface Field (BSF) Process Development

The BSF process is a well-known and widely used technique to improve silicon solar cell performance by increasing Voc and Isc. 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. (Refer to Appendix III of the First Annual Report for the details.) 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. Typical illumination characteristics of solar cells fabricated using the BSF process are given in Figure 34, in which a shunting solar cell shows performance degradation by a reduction in Voc and maximum power available from the cell. Work has been done to analyze the shunting characteristics caused by the BSF process using ion Microprobe/SIMS* and optical microscope examination.

The effectiveness and shunting characteristics of the BSF process were tested as function of: (1) starting silicon resistivities; 0.3-15 ohm-cm (2) crystal orientations; (100) vs (111), (3) crystal growing method; CZ vs FZ, and (4) quality of silicon, i.e., minority carrier diffusion length (L). Finally, using the ion microprobe, efforts were made to study effectiveness of BSF by analysis of the concentration profile aluminum (or other element, (such as boron) used for BSF process) on the back side of solar cell.

*The analysis was carried out using CAMECA Sims 3F at Charles Evans Associates (San Mateo, California).

Diagnosis

A large number of solar cells were investigated for clues for the shunting problem, using an optical microscope. Results indicated that shunted solar cells generally had surface contamination (front junction side) in the form of penetration pits and alloy patterns, indicating a high probability and degree of shunting. Figure 35 shows photographs of contaminants at high magnification, in which the crystallographic orientation dependence of contamination patterns is noticed: (a) for a (100 substrate) and (b) for a (111) substrate. Ion microprobe/SIMS was used to identify the contaminants as aluminum (Figure 10 (c) is a photograph of the aluminum image). Mechanical lapping removed the surface patterns completely, which suggests that the contaminants are located at the front junction surface. Sputtering by the ion source (oxygen) also showed the same results; i.e., the pattern in (b) of Figure 10 has disappeared after about 2 m of silicon was sputtered away (no aluminum image could be obtained after the sputtering).

The ion microprobe/SIMS was further utilized to check if surface areas, free from visual contaminants, were also contaminated. Thus, a surface profile analysis (front junction side) was performed for mass numbers up to 60 by the probe and a typical result is shown in Figure 36. The figure indicates high spikes in the ion intensity counts for elements such as B, C, O, Na, Al, K, Ca and some silicon complexes. The surface concentration was 6×10^{18} atoms/cm³, which is a concentration close to the solid solubility of aluminum (about 1×10^{19} atoms/cm³) in silicon. The depth profile of aluminum was also obtained to see how deeply

the aluminum penetrated into the bulk silicon, or towards the junction. Figure 37 is a result of the depth profile; mass numbers 14, 27, and 11 for silicon, aluminum and boron, respectively. The depth of aluminum penetration was estimated from the sputtering rate used (the junction depth was about 3000 angstroms). Calculated concentrations are also indicated in Figure 37, showing initially high concentration of aluminum close to surface (solid solubility limit down to about 300-400 angstroms), leveling off to a concentration of 4×10^{16} atoms/cm³ at a depth of 1500 angstroms. A significant concentration of boron was also observed at the surface and was thought to have originated from the aluminum paste used for the BSF process. The boron concentration of about 4×10^{15} atoms/cm³ is equivalent to the boron concentration of the starting boron-doped p-type silicon of 1-3 ohm-cm resistivity.

Past experience indicated that junction shunting by the BSF process depends on the starting silicon properties, such as doping concentration (some results were reported in the Fourth Quarterly Report), crystallographic orientation or defects. Thus, work has progressed to see if there is a difference in aluminum diffusion as a function of crystallographic orientation; (111) versus (100). About 3000 angstroms of aluminum was evaporated on the wafers of starting resistivity around 10 ohm-cm, and alloyed following the same procedure used for the paste BSF process. The samples were analyzed for aluminum depth profile on the alloyed side by the microprobe. (NOTE: This experiment was performed to save the probe operation time since depth profiling of the Al paste alloy layer takes a long time due to relatively deep penetration depth of aluminum.) The results of the profiling are given in Figure 38; (a) for (100) orientation and (b) for (111) orientation. The aluminum penetration depth in (100) is larger than that of the (111) by approximately a factor of two. The same

experiment was performed on dendritic webs which have (111) orientation and similar results were obtained as shown in (c) of Figure 38. These should be regarded as preliminary results since no extensive tests on reproducibility of the results have been done.

Since ion microprobe/SIMS analysis showed aluminum contamination near the front surface, work has progressed to protect the front surface by depositing various thickness of SiO_2 on the diffused surface before aluminum paste was applied. SiO_2 thickness of 0.5 μm , 1 μm , 1.5 μm , and 2 μm were used. The test was carried out on 3" wafers carrying a pattern of 6 2x2 cm solar cells. Each wafer was finally cut to 2x2 cm solar cells for evaluation. The results indicated that, statistically, the number of shunted cells and the degree of shunting decreased as the thickness of the protective layer increased. To back-up this result another batch of solar cells were processed, showing a similar result. Ion microprobe analysis on these solar cells suggested that the penetration depth and the front surface concentration of aluminum show a tendency to decrease as the thickness of the protective layer increased.

Dependence On The Properties Of The Starting Substrates

Shunting characteristics of the BSF process was tested 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). The BSF was applied on single crystalline 3" wafers (Table 22 gives information on the starting substrates). 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 the 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 about AR coating.

Most of the solar cells (about 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, or growing method of the starting substrates. This result does not agree with the past experience, 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.)

Conclusions

The main source of the shunting problems was identified as aluminum contamination and 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. The present experimental result indicated that junction shunting problems can possibly be minimized by proper control of the process.

2.0 Effectiveness of the BSF Process

Improvement of solar cell parameters by the BSF process was obtained 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. Baseline solar cells were made

from the same substrates without BSF and the performance results are compared with the BSF cells. (Table 22 provides information on the starting substrates). All cells were tested under AMO conditions without AR coating to minimize the effect of another variable (AR coating). The results are summarized in Table 23. Efficiencies of the baseline 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 22, improvements of cell parameters as a function of the starting substrate resistivity were obtained; Figure 39 for the open circuit voltage (V_{oc}), Figure 40 for the short circuit current density (J_{sc}), and Figure 41 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. Short circuit current density also depended on the substrate resistivity, mainly due to dependence of minority carrier diffusion length (L) on the substrate resistivities. Figure 42 plots J_{sc} vs L , indicating 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 J_{sc} and V_{oc} improvement depended on the resistivity. Figure 41 indicates that 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 23 suggested that improvement of J_{sc} and V_{oc} did not appear to be a strong function of either crystal orientation or crystal growing methods.

In summary, the BSF produced greater relative increases for higher resistivity (probably because of greater shift in Fermi levels, and the higher values of initial diffusion length). These increases were seen in both Voc and Jsc, with 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 only slight increase at the high end.

3.0 Discussion on BSF

Efforts were made to understand and check why the BSF process is so effective in improving solar cell performance, by analysis of aluminum (or other element used for BSF process such as boron) concentration profile on the back side of solar cell using the ion probe.

Aluminum depth profiling of the BSF, formed by an aluminum paste alloy process, were performed on CZ solar cells of (111) and (100) orientation and on dendritic web. The results are given in Figure 43 for CZ (100), Figure 44 for CZ (111) and Figure 45 for dendritic web. The figures suggest;

- (1) Aluminum penetration depth by the BSF process ranges between 1.5 and 4 μm .
- (2) Solid solubility limit of aluminum almost extends to the end of the penetration front, and,
- (3) Aluminum concentration falls off drastically at the interface between silicon and the alloy layer, CZ (100) orientation shows a less drastic concentration change at the interface.

NOTE: These should be regarded as preliminary results since no tests on reproducibility of the results have been done.

Depth profiles of other BSF processes utilizing boron sources on p-type starting substrates, either by boron nitride (BN) diffusion or boron ion-implantation, were performed using the ion microprobe. The results are shown in Figure 46 for the BN process and figure 47 for the implantation process, indicating;

- (1) Boron penetration depths are about 4000 angstroms, which is relatively small compared with the aluminum paste process,
- (2) Interface regions make rather smooth transitions compared with the BSF process using Al paste, and
- (3) Boron concentration in the doped regions is considerably lower than the solid solubility of boron, which is about $1-3 \times 10^{20}$ atoms/cm³ at room temperature.

Generally, the BSF, formed by either BN diffusion or boron ion-implantation, was less effective, specifically in terms of improvements in open circuit voltage; typically 10-20 mv lower than the BSF cells using the aluminum paste alloy process. This could possibly be explained in terms of (1) penetration depth; the larger the better, possibly by less influence from back surface recombination, (2) concentration profile at the interface; the more abrupt the better, possibly by high drift field generated at the back, and (3) concentration in the doped region; the higher the better, i.e., the closer the solid solubility, the better, probably because of greater shift in Fermi levels at the L/H back junction (up to a limit that band gap narrowing and Auger recombination play a significant role by heavy doping effect). Further work is expected to extend these results.

TABLE 22

INFORMATION ON SILICON
SUBSTRATES USED FOR THE BSF TEST

SUBSTRATE I.D. #	GROWTH METHOD	ORIENTATION	RESISTIVITY (OHM-CM)	L (μm)
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 23
SOLAR CELL PARAMETERS WITH AND WITHOUT THE BSF

I.D.#		V_{OC} (mv)		J_{SC} (ma/cm ²)		CFF (%)		η (%)	
		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 AM0 conditions at 25°C test block temperature.
2. STD: Baseline cells without the BSF
BSF: Baseline 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.

FIGURE 34

TYPICAL ILLUMINATION CHARACTERISTICS OF TWO BSF PROCESS
SOLAR CELLS: A GOOD CELL AND A SHUNTED CELL

SURFACE JUNCTION CONTAMINANTS FROM THE BSF PROCESS

(A)

CONTAMINANTS ON (100) WAFER

(B)

CONTAMINANTS ON (111) WAFER

(C)

ALUMINUM IMAGE (BRIGHT TRIANGLE PATTERN)
BY ION MICROPROBE/SIMS

FIGURE 36

FIGURE 38

ALUMINUM PENETRATION PROFILE (SIMS) ON

(a) A CZ (100) Wafer

FIGURE 38

ALUMINUM PENETRATION PROFILE (SIMS) ON

(b) A CZ (111) Wafer

FIGURE 38

ALUMINUM PENETRATION PROFILE (SIMS) ON

(c) A Dendritic Web

FIGURE 39

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

FIGURE 40

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

FIGURE 41

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

FIGURE 42

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

FIGURE 43

ALUMINUM DEPTH PROFILE (SIMS) OF THE BSF APPLIED ON A CZ (100) WAFER

FIGURE 44

ALUMINUM DEPTH PROFILE (SIMS) OF THE BSF APPLIED ON A CZ (111) WAFER

FIGURE 45

ALUMINUM DEPTH PROFILE (SIMS) OF THE BSF APPLIED ON A DENDRITIC WEB

FIGURE 46

BORON DEPTH PROFILE (SIMS) OF THE BSF APPLIED BY
BORON NITRIDE DIFFUSION ON CZ SILICON

FIGURE 47

BORON DEPTH PROFILE (SIMS) OF THE BSF APPLIED BY
ION IMPLANTATION ON A CZ SILICON

III. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The general conclusions reached after analyzing the cell performance and other related physical measurements are as follows:

- The baseline process serves as a useful evaluation method, and the various measurements, such as minority carrier diffusion length, spectral response, dark I-V characteristics and small light spot scanning, provide good internal consistency and repeatability.
- Sheet silicon, evaluated in both Phase I and Phase II, did not show any significant improvement in sheet quality, especially in terms of minority carrier diffusion length or short circuit current density.
- Performance improvement has been achieved by process variations, such as formation of shallow junction, BSF, BSR, better AR coatings, and application of the fine front grid lines, etc. However, the performance improvement by process optimization depended on silicon quality, i.e., minority carrier diffusion length (L); the higher the L, the higher the magnitude of the performance improvement.
- Effects of grain size on cell performance study indicated that minimum grain size of $500\mu\text{m}$ is required to make solar cells of AMO efficiency higher than 10%. If harmful lifetime killer impurities are incorporated in the process of sheet formation, the grain size should be higher than $500\mu\text{m}$.

- The BSF used produced greater relative increases for higher resistivity. It should be noted that in spite of the large relative increase for the highest resistivities tested, the final efficiencies were similar for the ranges 1-15 ohm-cm, with slight increase at the higher end.
- The main source of the shunting problems by the BSF used was identified 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 particles along the edge of a wafer. The present study indicated that the junction shunting problems by the process can possibly be minimized by proper control of the process.

Recommendations

Evaluation of the sheets suggested the following:

- The back-up measurements (spectral response, minority carrier diffusion length, diode characteristics and light scanning) should be continued because they add insight to guide choice of optimum processing, or feedback on failure modes to help manufacturers to improve the sheet performance.
- Some silicon sheets need to improve the sheet quality, i.e., increase L and reduce inclusions, to achieve AMO efficiency of 10% or greater. Some sheet cells can possibly improve V_{oc} by increasing doping levels of the starting substrates to resistivity

around 0.5 ohm-cm. This can be done on some sheets without sacrificing minority carrier lifetime. High doping can reduce the effect of grain boundaries in polycrystalline sheets.

Some lower cost processes should be started in the program to obtain early warning of possible conflicts in the process variables.

IV. WORK PLAN STATUS

Phase III of the program will extend Phase I and Phase II with an increase emphasis on improvement of solar cell efficiency by process optimization and development of new process techniques tailored to suit the specific sheet form.

V. REFERENCES

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APPENDIX I
TIME SCHEDULE

APPLIED SOLAR ENERGY CORPORATION

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TIME SCHEDULE (PHASE II)

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

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

AM1 SIMULATOR AND CALIBRATION

The following are the conditions used for AM1 simulation.

(a) Light Source

Spectrolab Model XT-10 was used as a light source for AM1 conditions. Features of the AM1 simulator consist of a 35-element lenticular optics assembly to provide spatial and temporal uniformity (intensity uniformity of $\pm 3\%$ within beam size of 8 inches) and a xenon lamp with air mass one filters. Refer to technical brochure of XT-10 for details.

(b) Light Intensity Calibration

Light intensity was calibrated by using a terrestrial secondary standard (TSS-014) from JPL. The standard cell was calibrated in accordance with the method described in NASA/ERDA Workshop Document "Interim Solar Cell Testing Procedures for Terrestrial Applications".

NOTE: Two major areas of possible errors are involved in this AM1 simulation conditions; they are 1) difference in spectrum between the simulator and real AM1 conditions, and 2) difference in spectral response between solar cells (to be measured) and a standard cell used to calibrate light intensity. Work continues to resolve these problems.