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SILICON SOLAR CELL PROCESS DEVELOPMENT, FABRICATION AND ANALYSIS

SECOND QUARTERLY REPORT

FOR PERIOD COVERING

1 OCTOBER 1978 TO 31 DECEMBER 1978

BY

H. I. YOO, P. A. ILES AND D. P. TANNER

JPL CONTRACT NO. 955089

OPTICAL COATING LABORATORY, INC.
PHOTOELECTRONICS DIVISION
15251 EAST DON JULIAN ROAD
CITY OF INDUSTRY, CA 91746

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

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ABSTRACT

RTR solar cells (2x2 cm) processed from polycrystalline feedstock showed maximum AMO efficiency of 5.6%. Solar cells from single crystalline feedstock showed slightly higher efficiency than those from polycrystalline feedstock, indicating maximum efficiency of about 6.6% with SiO AR coating. Single crystalline control cells gave 11-12% AMO efficiencies demonstrating that the poor performance of the RTR solar cells was due to the low quality of material itself (this conclusion was backed up by the separate measurement of minority carrier diffusion length).

Dendritic web solar cells (2x2 cm) from the standard process showed maximum AMO efficiency (with SiO AR coating) of 9.8% while efficiency of control solar cells were around 11-12%. Web solar cells from back surface field (BSF) process indicated maximum AMO efficiency of 10.9%. Some improvement in open circuit voltage was noticed from the BSF process.

Small light spot scanning experiments were carried out on the solar cells from Wacker "Silso", EFG, RTR, and dendritic web ribbons. Photoresponse results provided information on localized cell performance and grain size in polycrystalline material, and agreed quite well with the cell performance data, such as efficiency, minority carrier diffusion length, and spectral response.

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I. INTRODUCTION

The objective of this program is to investigate, develop and utilize technologies appropriate and necessary for improving the efficiency of solar cells made from various unconventional silicon sheets. During this quarterly reporting period, work has progressed in fabrication and characterization of solar cells from RTR·ribbons (Motorola) and Dendritic web (Westinghouse). Silicon blanks (2x2 cm) were prepared from the ribbons and fabricated using a standard process typical of those used currently in the silicon solar cell industry. Later a back surface field (BSF) process and other process modifications were included in processing additional slices. Only the standard process was used for RTR ribbons since difficulties were experienced for the application of other processes; in particular, excessive breakage resulted from use of the alloyed aluminum paste method to provide a BSF.

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

II. TECHNICAL DISCUSSION

A. RTR SOLAR CELLS

1.0 SOLAR CELL FABRICATION

Blanks were prepared by waxing a ribbon on a ceramic block and slicing in size (2x2 cm). After removal of the individual blanks from the block, organic and chemical (standard RCA) solutions were used for cleaning the surface; the standard cell process followed thereafter. Blanks for the first batch were the ribbons from the annealed CVD feedstock while those for the second and third batches were from ribbons from CVD feedstock with and without annealing, or from single crystalline feedstock. Thickness of ribbons was 6-7 mils and the resistivity measured by four point probe was in the range between 1-3 ohm-cm with p-type conductivity. Cells from the first two batches were processed without etching of silicon. In the third batch process, about 1 um of silicon was removed from each side before the fabrication process b. etching in planar etch solution for 15 seconds. Efforts were also made to include a BSF process. However, screen printing of aluminum paste was unsuccessful due to the shattering of ribbons during the squeezing operation. Overall mechanical yield (unbroken cells) obtained from three batch processes was about 50%, indicating very low yield considering the solar cells were handled with extreme care. Table 1 shows numbers and causes of the broken cells during the processes; the number of initial starting blanks was 52. In many cases broken cells were badly shattered possibly due to the excessive mechanical stresses in the ribbons induced in the process of laser recrystallization. See reference [1] for detailed description of RTR process.

TABLE 1

MECHANICAL FAILURE OF RTR SOLAR CELLS (2x2 CM)
IN THE PROCESS OF FABRICATION

NUMBER OF BROKEN CELLS	CAUSE
6	Initial Slicing and Demounting
5	Cleaning
4	Evaporation; AR and Contact
1	Sintering
7	Electrical Test
23	TOTAL

Starting Blanks: 52

NOTE: Results are summarized from three batch processes

2.0 SOLAR CELL PERFORMANCE AND CHARACTERIZATION

Characteristics Under AMO Illumination

Parameters of finished solar cells were measured under AMO conditions (135 mW/cm^2, tungsten-xenon lamps with red and blue filters). The block temperature was 25°C and input light intensity was calibrated using a standard solar cell. The detailed parameters of the solar cells from RTR ribbons* and control cells are given in Appendix III, on the electrical data sheets. Solar cells made from CVD feedstock showed maximum efficiency of 3.9% for the annealed ribbons and 5.6% for the unannealed ribbons. Ribbon solar cells from single cyrstalline feedstock showed slightly higher efficiency than those from polycrystalline CVD feedstock, indicating maximum efficiency of about 6.6% with SiO AR coating. Generally, solar cells processed from the etched blanks (third batch) showed higher efficiency and more consistent results than those from ribbon without removal of a thin silicon layer. Single crystalline control cells showed 11-12% AMO efficiency. Large spread in values, combined with the limited sample sizes, prevented these cells from obtaining reliable summary tables or to provide statistical evaluation.

Since significant variation in performance from cell to cell was observed from these RTR cells, small mesa cells (2 mm in diameter) were fabricated using masking techniques and the individual cells were illuminated by a tungsten lamp to see the variation of cell performance within a single 2x2 cm cell. Figure 1 is the results of the mapping of open circuit voltage, and significant differences in V_{OC} were noticed. Correlation

*Motorola considered these samples as poorly representative of the RTR process. Hopefully some improved RTR samples can be evaluated later in the program.

FIGURE 1

OPEN CIRCUIT VOLTAGE MAPPING OF MESA SOLAR CELLS
WITHIN A RTR SOLAR CELL (2x2 cm)

291	208	335				331
343	354		343	280	320	290
300	358	320	255	390	497	314
341	331	350	172	272	210	265
252	388	308	338	348	419	
300	310	354	352	358	393	
160	219	268	297	189	257	
210	194	184	194	142	246	70

NOTE: 1. ILLUMINATED TUNGSTEN LAMP WITH UNKNOWN LIGHT INTENSITY
2. DIAMETER OF MESA CELLS; 2 mm
3. UNIT; MILLIVOLTS

with crystal structure indicated that areas of low open circuit voltage could be caused by fine details of the crystal structure.

Dark I-V Characteristics

Dark I-V characteristics (forward and reverse) were obtained from selected RTR cells and a control cell. The plot was made by point-by-point measurement and the results are plotted in Figure 2. "A" factor (in simple diode equation) derived at high bias condition ranged from about 1.8 to 3 while a control cell showed "A" factor of 1.4. I_0 was also obtained from the plots, ranging from 10^{-7} A/cm² to 10^{-5} A/cm². This suggests that shunting and space-charge recombination effects are serious problems in these cells.

Spectral Response

Absolute spectral response (A/W) was measured using a filter wheel set-up which is a combination of a set of narrow bandwidth filters and a light source. Response versus wavelength are plotted in Figure 3, in which very poor response at wavelength beyond 0.6 μm can be seen. This can be attributed to the poor quality (low lifetime or diffusion length) of the bulk RTR ribbons, which was confirmed by minority carrier diffusion length measurements (see next section).

Minority Carrier Diffusion Length

Minority carrier diffusion length was measured using a short circuit method for the finished solar cells. The whole area of a solar cell was illuminated by a light source through a filter wheel and the diffusion length was obtained from light intensity values at selected

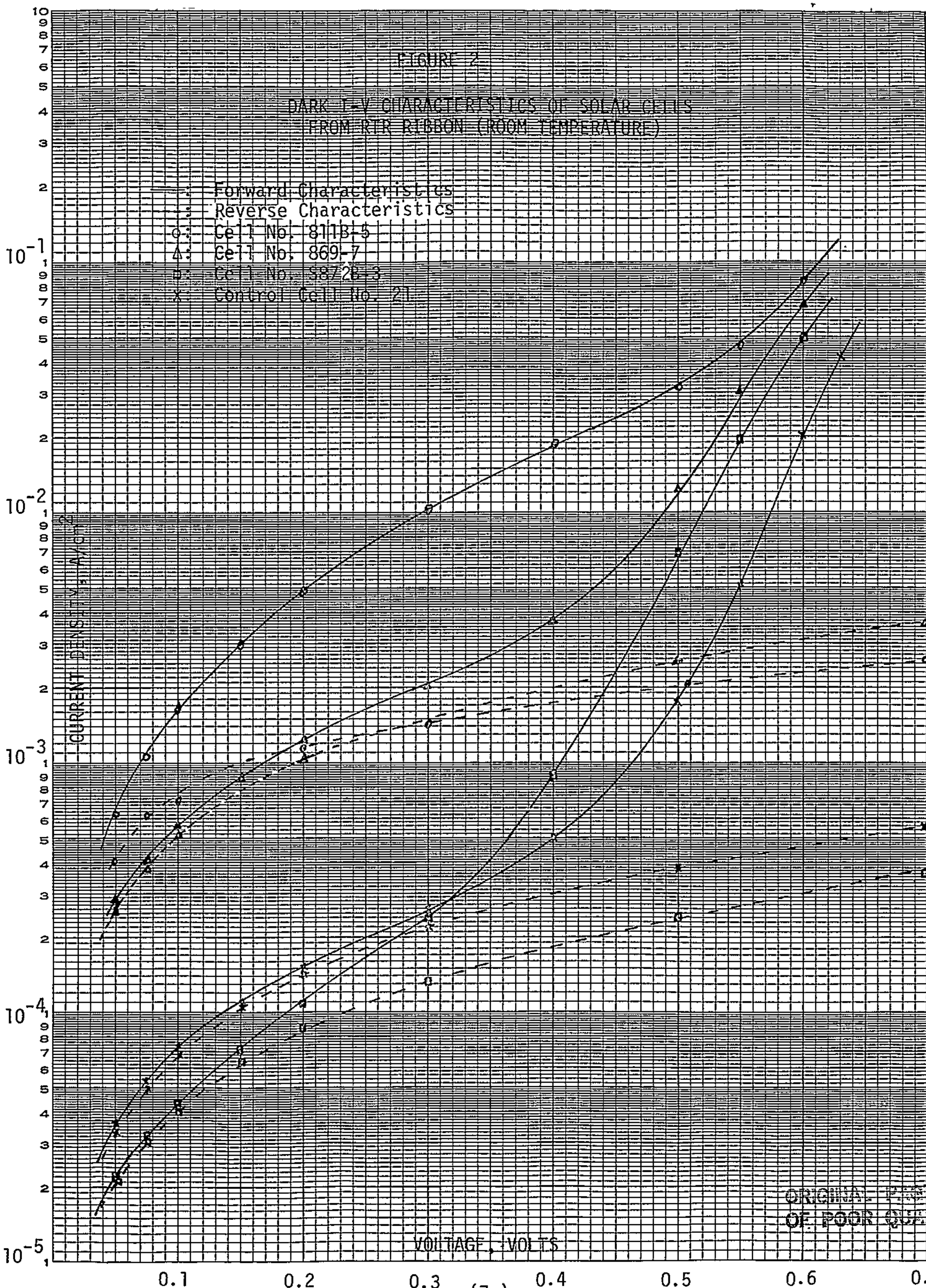
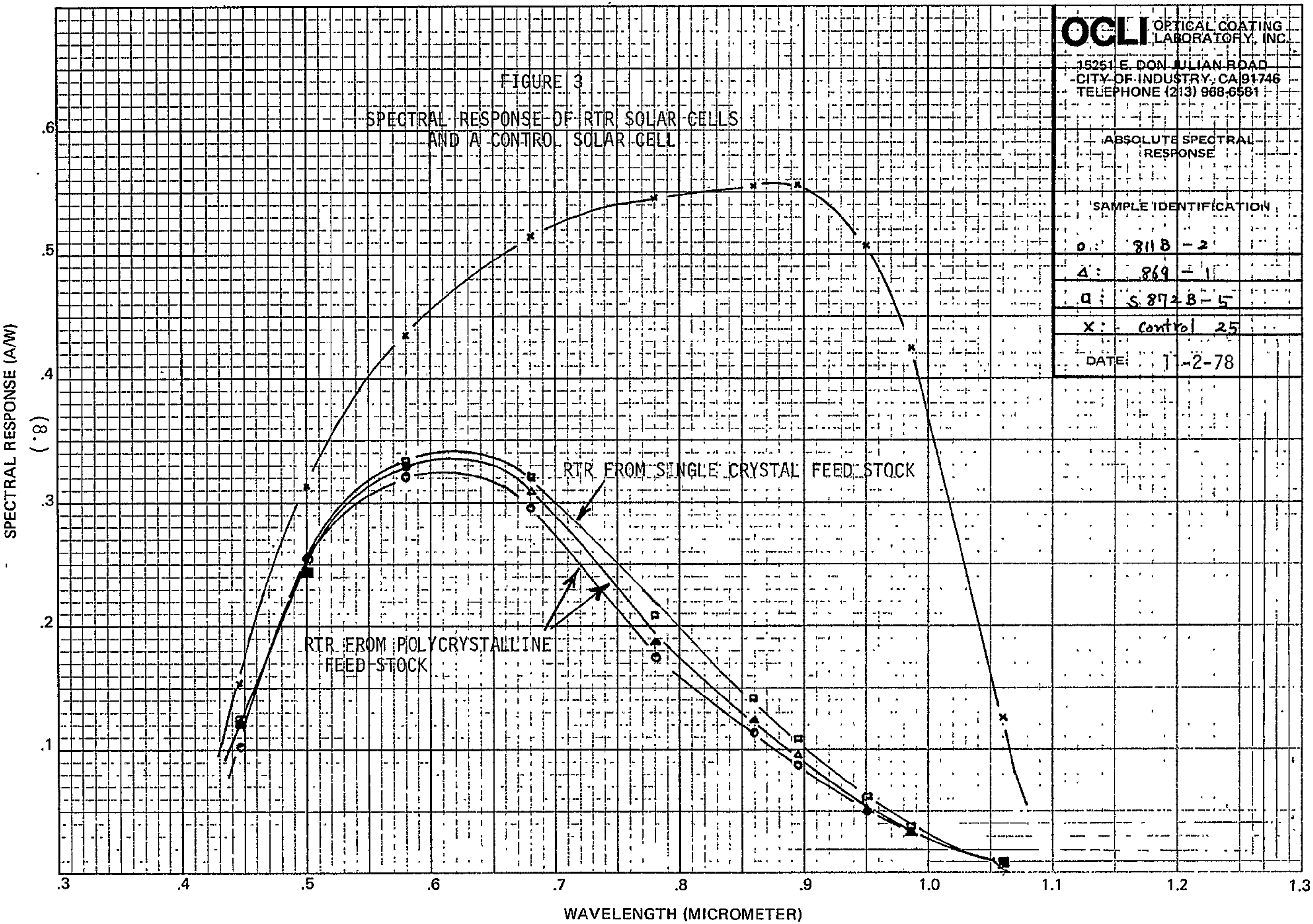


FIGURE 2
DARK I-V CHARACTERISTICS OF SOLAR CELLS
FROM RTR RIBBON (ROOM TEMPERATURE)
—: Forward Characteristics
--: Reverse Characteristics
o: Cell No. 811B-5
Δ: Cell No. 869-7
□: Cell No. S872B-3
x: Control Cell No. 21
CURRENT DENSITY, A/cm²
VOLTAGE, VOLTS
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0.1
0.2
0.3
0.4
0.5
0.6
0.7


OCLI OPTICAL COATING LABORATORY, INC.
15251 E. DON JULIAN ROAD
CITY OF INDUSTRY, CA 91746
TELEPHONE (213) 968-6581
ABSOLUTE SPECTRAL RESPONSE
SAMPLE IDENTIFICATION
o : 811B - 2
Δ : 869 - 1
□ : S 872 B - 5
x : control 25
DATE 11-2-78
FIGURE 3
SPECTRAL RESPONSE OF RTR SOLAR CELLS
AND A CONTROL SOLAR CELL
RTR FROM SINGLE CRYSTAL FEED STOCK
RTR FROM POLYCRYSTALLINE
FEED STOCK
SPECTRAL RESPONSE (A/W)
(.8)
WAVELENGTH (MICROMETER)
.1
.2
.3
.4
.5
.6
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3

wavelengths (wavelengths used for this measurement were 0.78, 0.86, 0.895 and 0.95 µm). Diffusion lengths of around 7-9 µm were obtained from measurement on seven cells. Diffusion length was also measured using small beam size illumination (∿3-4 mm beam diameter). Typical results are given in Figure 4. No significant variations from spot to spot were observed, showing consistently low diffusion length. It is also noteworthy that diffusion lengths of the cells from single crystalline feedstock were not impressively better than those of the cells from CVD feedstocks. This suggests there might be some problems associated with the recrystallization process, either due to the contamination from the process environment or the laser recrystallization process itself.

Small Spot Scanning Measurements

Results on RTR samples (and also dendritic web samples) are included in a separate section (c) below.

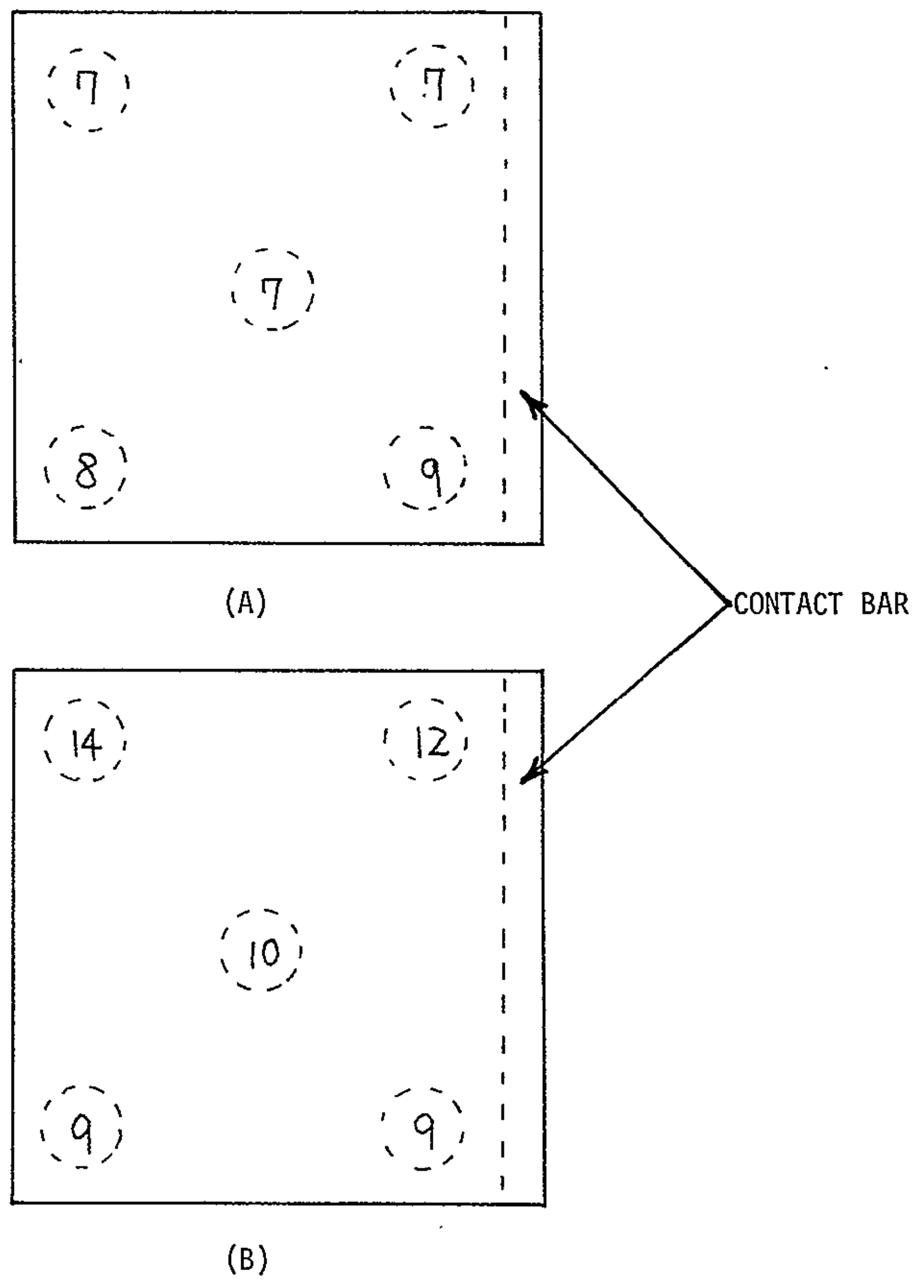


FIGURE 4

MINORITY CARRIER DIFFUSION LENGTH (μm)
VARIATION WITHIN RTR SOLAR CELLS (2x2 cm);

(A) A CELL FROM CVD FEEDSTOCK (CELL NO. 869-7)

(B) A CELL FROM SINGLE CRYSTALLINE FEEDSTOCK (CELL NO. S872B-3)

B. DENDRITIC WEB SOLAR CELLS

1.0 SOLAR CELL FABRICATION

Blanks (2x2 cm) were prepared by waxing a web section on a ceramic block and slicing in size. After removal of the individual blanks from the block, efforts were made to remove SiO, deposited on the surface during the web growing process, by chemical methods, such as boiling in nitric and sulfuric acid followed by dipping in HF. None of the methods worked except scrubbing by a cotton tip, which caused some breakage of the webs, especially of thin webs (∿6 mils). The breakage could have been minimized if the scrubbing were done before the blank shaping process since bounding dendrites could provide mechanical support for the scrubbing process. Also, steam oxidation was carried out to eliminate the mechanical scrubbing process for the removal of SiO deposit. Webs were oxidized in steam at 1100°C for an hour (with ramp-down cooling, at a cooling rate of about 3°C/minute down to 500°C), to recover minority carrier lifetime due to higher temperature heat treatment. The oxidized webs were finally dipped in HF and the surface deposits were completely removed.

NOTE: Solar cells were fabricated from the oxidized blanks and the cell performance is given in Section B, 2.0.

Organic and chemical (standard RCA) solutions were used for the final cleaning of the surface.

Thickness of the webs, as received, ranged from 5.6 mils to 9.6 mils and resistivity by four point probe was measured to be around 20-25 ohm-cm with p-type conductivity. SPV measurement of effective minority carrier diffusion length indicated values between 90-120 μm. See reference [2] for detailed description of dendritic web process.

The first batch of solar cells were fabricated using standard processing. A BSF process was applied for the second batch (see First Quarterly Report of this contract for detailed description of standard and BSF processes). A space-cell type of fabrication process was used in the third batch process. This process included a shallow junction (∿0.2 μm) formation (ten minutes oxidation and ten minutes diffusion) and application of fine front contact lines using photoresist techniques (retaining about 93% active area). The fourth batch were standard process solar cells of two types; (a) Cells with front contact bars on the bounding dendrites, and (b) Solar cells processed from steam oxidized blanks.

Mechanical yield (unbroken cells) of the relatively thick web solar cells, (with thickness between 8 to 10 mils), were generally high (about 90% yield) for both standard and BSF processes. However, thin web cells, thickness between 5-6 mils, showed lower yield (less than 50%), mainly because of breakage in the initial blank shaping stages and in removal of excess aluminum following the BSF process. Detailed causes of the breakage are listed in Table 2.

2.0 SOLAR CELL PERFORMANCE AND CHARACTERIZATION

Charactertistics Under Illumination

Solar cell parameters, such as I_{SC}, V_{OC}, CFF and η were measured under an AMO solar simulator at 25°C. Electrical data sheets in Appendix IV give detailed information on individual cells. Table 3 and Table 4 summarize

STANDARD PROCESS

CAUSE \ WEB THICKNESS	9.6 MILS	5.6 MILS
SLICING IN SIZE	---	2
SCRUBBING FOR REMOVAL OF SIO DEPOSIT	1	4
FINAL BLANK CLEANING	---	1
ELECTRICAL TEST	1	---
STARTING NUMBER OF BLANKS	12	10

BSF PROCESS

CAUSE \ WEB THICKNESS	8.6 MILS	5.6 MILS
REMOVAL OF ACCESS ALUMINUM	---	3
ELECTRICAL TEST	2	---
STARTING NUMBER OF BLANKS	12	4

TABLE 2

MECHANICAL FAILURE OF DENDRITIC WEB
SOLAR CELLS IN THE PROCESS OF FABRICATION

TABLE 3

SUMMARY OF PARAMETERS OF SOLAR CELLS
FABRICATED FROM DENDRITIC WEB; STANDARD PROCESS

WAFERS		WEB "A"	WEB "B"	CONTROL
V_{OC} (mV)	AVERAGE	534 (525)	518 (508)	595 (584)
	STANDARD DEVIATION	3.3 (1.0)	--- ---	3.2 (2.3)
	RANGE	529-537 (523-526)	514-520 (506-510)	589-598 (581-587)
J_{SC} (mA/cm²)	AVERAGE	33.8 (24.3)	32 (22.8)	33.3 (23.5)
	STANDARD DEVIATION	0.3 (0.2)	--- ---	0.7 (0.4)
	RANGE	33.3-34 (24-24.5)	31.5-32.3 (22.5-23)	32.2-34.3 (23-24.3)
CFF (%)	AVERAGE	72 (72.7)	73 (73)	78 (78)
	STANDARD DEVIATION	0.9 (1.2)	--- ---	0.8 (1.7)
	RANGE	71-73 (71-74)	72-75 (72-75)	77-79 (79-80)
η (%)	AVERAGE	9.6 (6.8)	9.0 (6.3)	11.3 (8.0)
	STANDARD DEVIATION	0.1 (0.1)	--- ---	0.3 (0.3)
	RANGE	9.5-9.8 (6.7-6.9)	8.9-9.1 (6.3-6.4)	10.8-11.8 (7.5-8.3)

NOTE: 1. Measured under AMO condition at 25°C.

2. Cells (2x2 cm) with SiO antireflective (AR) coating), parenthesis numbers are for the parameter before AR coating.

3. Web "A": Six solar cells from Web No. RE12-3.3 (Thickness ∿9.6 mils).
Web "B": Three solar cells from Web No. J65-3.4 (Thickness ∿5.6 mils).
Control: Six solar cells.

TABLE 4

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED FROM DENDRITIC WEB; BSF PROCESS

WAFERS		WEB "C"	WEB "D"	CONTROL
V_{OC} (mV)	AVERAGE	564 (552)	565 (551)	588 (573)
	STANDARD DEVIATION	16.8 (15.9)	--- ---	9.2 (14.1)
	RANGE	521-578 (511-567)	--- ---	575-598 (552-588)
J_{SC} (mA/cm²)	AVERAGE	35.5 (25.4)	34.5 (24.6)	34.3 (25)
	STANDARD DEVIATION	0.8 (0.5)	--- ---	0.3 (0.3)
	RANGE	33.2-35.9 (23.9-25.7)	--- ---	33.8-34.7 (24.5-25.4)
CFF (%)	AVERAGE	71 (74)	67 (67)	66 (63)
	STANDARD DEVIATION	2.7 (1.4)	--- ---	7 (8.7)
	RANGE	65-73 (70-75)	--- ---	56-73 (51-71)
η (%)	AVERAGE	10.4 (7.6)	9.6 (6.7)	9.9 (6.7)
	STANDARD DEVIATION	0.6 (0.4)	--- ---	1.2 (1.1)
	RANGE	9.2-10.9 (6.7-8.1)	--- ---	8.2-11.0 (5.2-7.7)

NOTE:
1. Measured under AMO condition at 25°C.
2. Cells (2x2 cm) with SiO antireflective (AR) coating, parenthesis numbers are for the parameter before AR coating.
3. Web "C": Ten solar cells from Web No. RE24-1.5 (Thickness ∿8.6 mils).
   Web "D": One solar cell from Web No. J64-1.6 (Thickness ∿5.6 mils).
   Control: Six solar cells.

the results for the cells of two process types; standard process and BSF process. BSF solar cells showed improved performance compared with the cells from standard process, average efficiency 10.4% versus 9.6%, with overall increase in both V_{OC} and I_{SC} (mainly in V_{OC}).
However, this improvement by BSF process was not as high as observed for starting silicon of this high resistivity. This possibly indicates that the minority carrier diffusion length of the starting web was not long enough to provide significant improvement in V_{OC} and I_{SC}. It is generally believed that diffusion length greater than 120 μm* is required to achieve significant improvement in V_{OC} and I_{SC} by the BSF process. The relatively low open circuit voltage of standard cells, (average $V_{OC} \sim 530$ mV), was due to the low doping level of the starting webs (∿20 ohm-cm bulk resistivity) and the low curve fill factor, about 72% in both cases, seems to be due to the increased series resistance resulting from increased bulk resistance. Maximum efficiencies obtained were 9.8% for the standard cells and 10.9% for the BSF cells. Low performance of web "B" cells in Table 3, compared with web "A" cells, was suspected to be coming from the difference in lifetime of two webs (Westinghouse lifetime data; 13 us for web "B" and 41 us for web "A") and partly the difference in web thickness, 9.6 mils for web "A" versus 5.6 mils for web "B".

Electrical data sheets for solar cells fabricated by other process modification, such as space type process, cells with contact bars on bounding

*This is an empirical observation. Work is in progress to establish a more definite relationship.

dendrites and cells from steam oxidized webs, are also given in Appendix IV. Space type cells showed low performance, mainly due to the low V_{OC} (about 510-520 mV), indicating that the BSF process was not effective in this case. Parameters of the cells with contact bars on bounding dendrites and the cells from steam oxidized webs (in an effort to remove SiO deposit without mechanical scrubbing) are summarized in Table 5. Both cells showed about the same performances. However, these are considerably lower values than those with the previous standard process (refer to Table 3). This could be due to low lifetime of the starting webs or contamination in the process of cell fabrication.

Some control cells (first control group) started to show degradation in curve fill factor, mainly due to shunting problems. This was suspected to be caused by the diffusion process since the second control group, which were diffused in a separate furnace, didn't indicate any significant degradation in CFF by shunting. Thus, the diffusion tube was cleaned and control cells were processed using standard process. Their electral parameters are given in the last page of Appendix IV, showing no degradation in CFF with consistent results.

Dark I-V Characteristics

Dark I-V characteristics (forward and reverse) were obtained from selected web cells. The plots were made by point-by-point measurement and the results are plotted in Figure 5 for the standard cells and Figure 6 for the BSF cells. "A" factors in the simple diode equation ranged from about 1.7 to 2.0 while control cells showed "A" factor ranges between 1.2 and 1.7. Saturation current (I_0) were found to be around 10^{-7} A/cm²

TABLE 5

SUMMARY OF PARAMETERS OF SOLAR CELLS FABRICATED FROM DENDRITIC WEB; STANDARD PROCESS (SPECIAL RUN)

WAFERS		WEB "E"	WEB "F"
V_{OC} (mV)	AVERAGE	514	515
	STANDARD DEVIATION	1.7	---
	RANGE	512-515	513-516
J_{SC} (mA/cm^2)	AVERAGE	30.7	30.6
	STANDARD DEVIATION	0.4	---
	RANGE	30.1-31	30.1-31.2
CFF (%)	AVERAGE	70	71
	STANDARD DEVIATION	3.4	---
	RANGE	65-73	69-73
η (%)	AVERAGE	8.2	8.2
	STANDARD DEVIATION	0.4	---
	RANGE	7.7-8.5	8.1-8.3

NOTE: 1. Measured under AMO condition at 25°C

2. Cells (2x2 cm) with SiO antireflective (AR) coating.

3. Web "E": Four solar cells with contact bars on bounding dendrites from RE28-5.3 (Thickness ∿7 mils).

Web "F": Two solar cells from steam oxidized web blanks RE28-5.3.

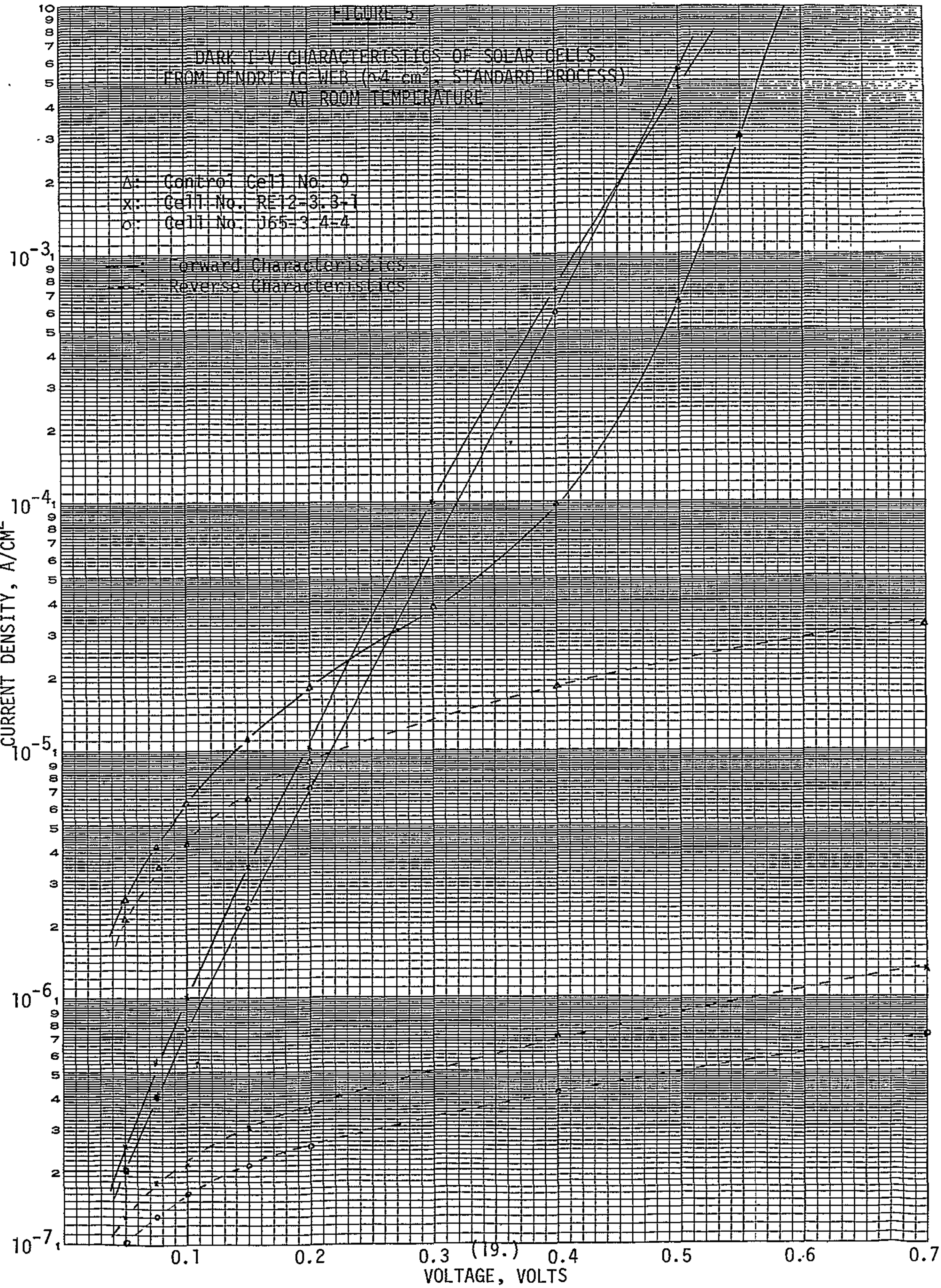


FIGURE 5
DARK I-V CHARACTERISTICS OF SOLAR CELLS
FROM DENDRITIC WEB (∿4 cm², STANDARD PROCESS)
AT ROOM TEMPERATURE
Δ: Control Cell No. 9
x: Cell No. RE12-3.3-1
o: Cell No. J65-3.4-4
Forward Characteristics
Reverse Characteristics
CURRENT DENSITY, A/CM²
VOLTAGE, VOLTS
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0.1
0.2
0.3
0.4
0.5
0.6
0.7

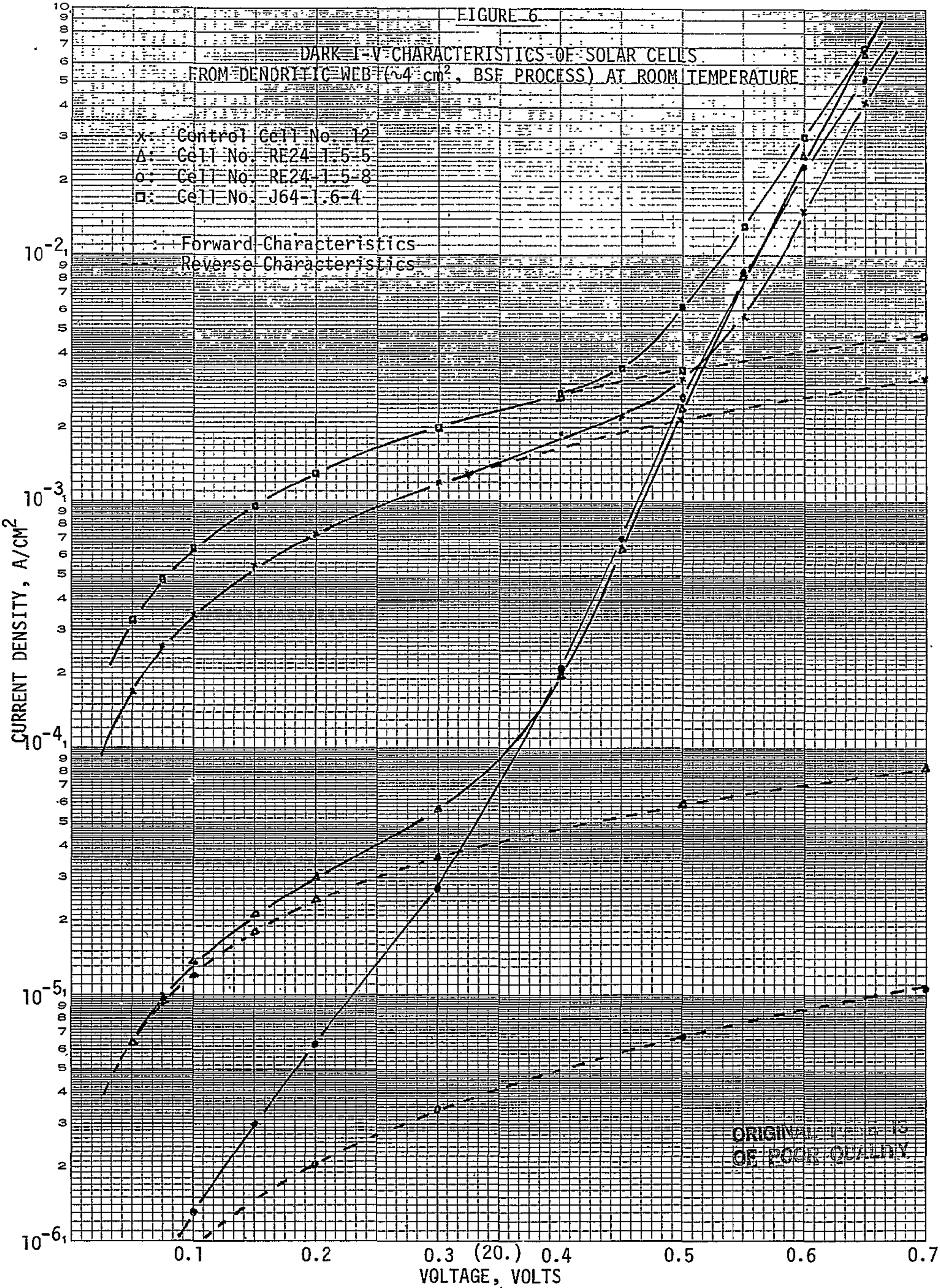


FIGURE 6
DARK I-V CHARACTERISTICS OF SOLAR CELLS
FROM DENDRITIC WEB (~4 cm², BSF PROCESS) AT ROOM TEMPERATURE
x: Control Cell No. 12
Δ: Cell No. RE24-1.5-5
o: Cell No. RE24-1.5-8
□: Cell No. J64-1.6-4
Forward Characteristics
Reverse Characteristics
CURRENT DENSITY, A/CM²
VOLTAGE, VOLTS
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶

for the standard web cells and 10^{-10} A/cm² for the control cell in standard process, and this higher I_0 for the web cells can be partly explained by lower doping level of the webs (∿20 ohm-cm resistivity) than the control blanks (1-3 ohm-cm). Generally cells from BSF process showed slightly leaky characteristics, consequently leading to increase in "A" factor and saturation current (I_0). Web solar cells showed relatively good junction characteristics, especially in low leakage at small forward bias condition (less than 0.4 volts), showing agreement with the earlier reports from Westinghouse.

Spectral Response

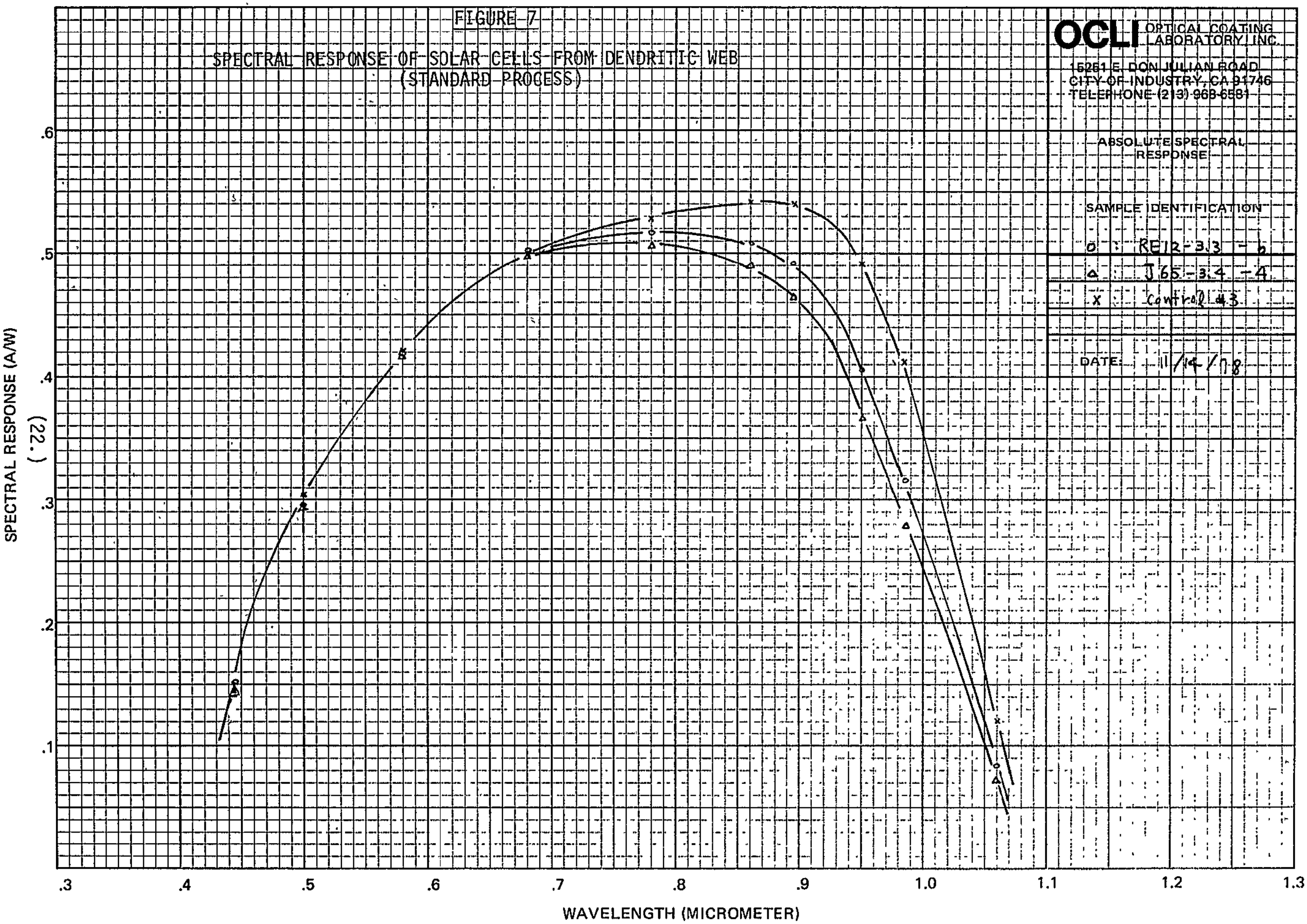
Absolute spectral response (A/W) was measured using a filter wheel set up. Response versus wavelength for the standard cells and BSF cells are given in Figure 7 and Figure 8, respectively. Web solar cell showed responses very close to those of the control cells (this is more pronounced in the case of BSF process cells) and this was in good agreement with the minority carrier diffusion length measurement of the finished solar cells in the following section.

Minority Carrier Diffusion Length

Minority carrier diffusion length was measured using the surface photo-voltage (SPV) method for the bulk webs and a short circuit current method (briefly described in Section A, 2.0) for the finished solar cells. The exposed beam (monochromatic) size on the bulk sample in SPV mode was about 2-3 mm in diameter and diffusion lengths were around 90-120 μm, measured from the number of selected webs; RE 24-1.5, J 64-1.6 and RE 28-5.4.

FIGURE 7

SPECTRAL RESPONSE OF SOLAR CELLS FROM DENDRITIC WEB (STANDARD PROCESS)



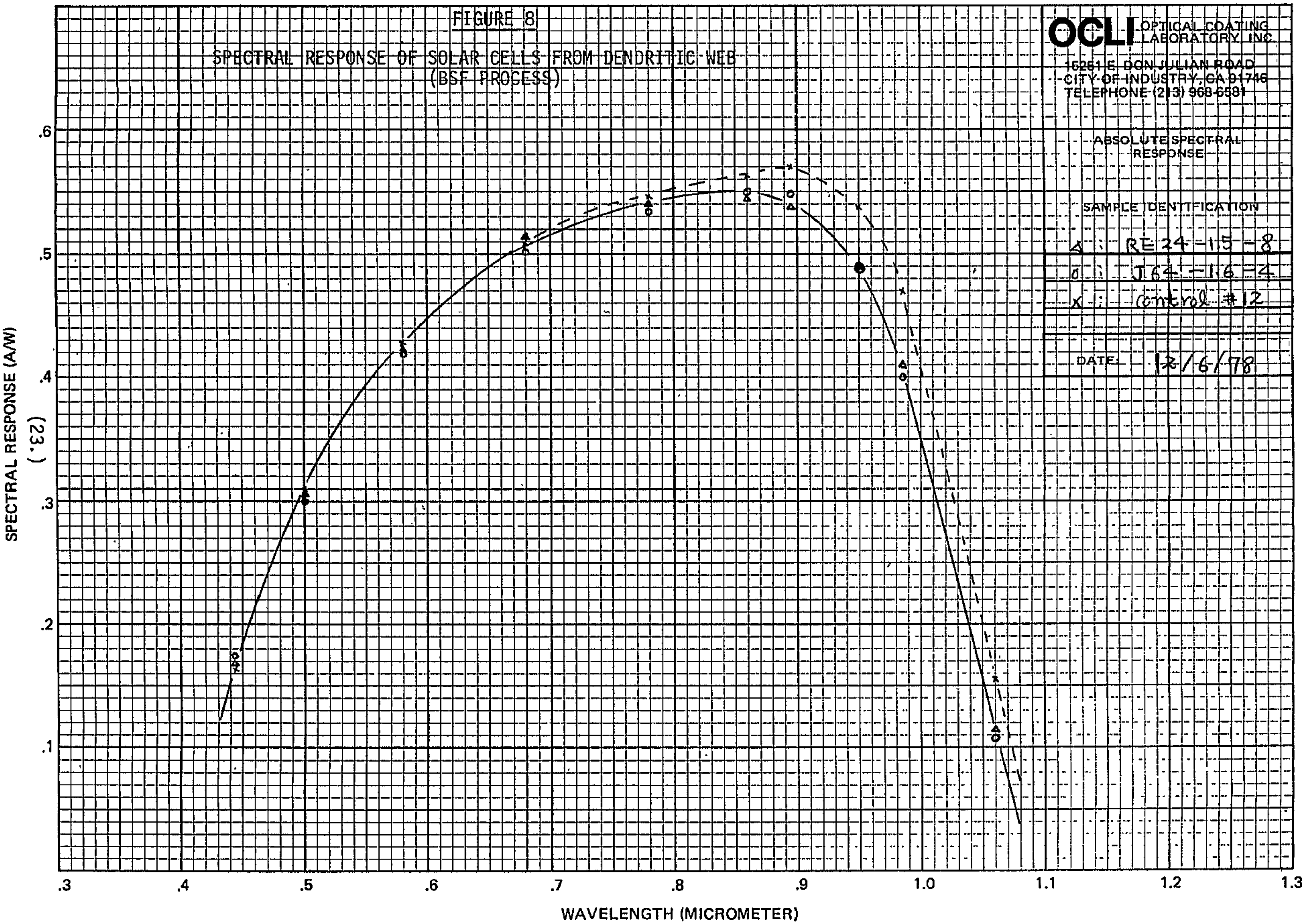


FIGURE 8

SPECTRAL RESPONSE OF SOLAR CELLS FROM DENDRITIC WEB (BSF PROCESS)

The finished cells were illuminated on the whole cell area and on spots (spot size about 3-4 mm in diameter) to see the localized variation of diffusion length, and the results are summarized in Table 6. BSF cells showed higher diffusion length than the standard cells, which agrees well with the spectral response plots (compare Figures 7 and 8) in the previous section. BSF cells also showed significant variation in diffusion length from cell to cell (i.e. 70 μm for the cell RE 24-1.5-3 versus 130 μm for the cell RE 24-1.5-8) and from spot to spot within a cell (i.e. 210 μm versus 110 um in cell RE 24-1.5-3), which could be due to inhomogenity of bulk webs or possibly a process induced effect. Diffusion length measurement on spots in standard cells indicated slightly higher values than those of the whole area measurement on same sample but this could possibly be caused by the measurement error.

Diffusion length was also checked on the cells from space type process (third batch) and both web and control cells showed low diffusion length; about 40-50 μm for the web cells and 80 μm for the control cells. This strongly indicated that these cells were contaminated in the process of fabrication, mostly likely in the diffusion step.

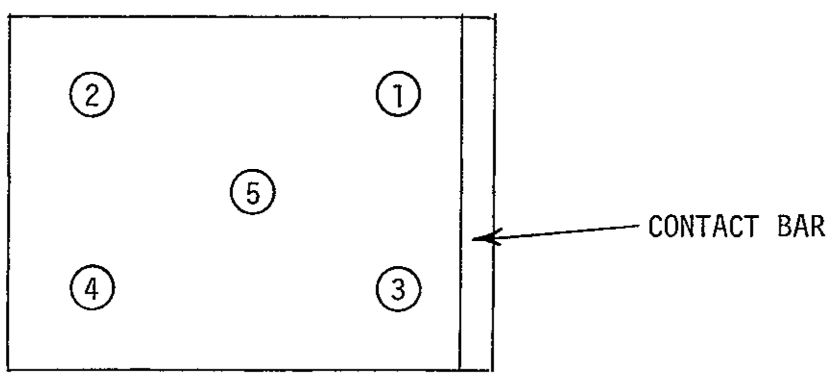
TABLE 6

SUMMARY OF MINORITY CARRIER DIFFUSION LENGTH
OF THE DENDRITIC WEB CELLS, MEASURED BY I_{SC} METHOD

	CELL NO. \ POSITION	1	2	3	4	5	WHOLE AREA
STANDARD CELL	RE 12-3.3-3	---	---	---	---	---	74
	RE 12-3.3-6	90	90	90	90	76	74
	J 65-3.4-4	---	---	---	---	---	62
	J 65-3.4-7	72	72	72	80	80	62
	CONTROL NO. 3	---	---	---	---	---	122
BSF CELL	RE 24-1.5-3	90	60	90	85	60	70
	RE 24-1.5-8	160	160	150	210	110	130
	J 64-1.6-4	---	---	---	---	---	130
	CONTROL NO. 12	---	---	---	---	---	150

NOTE: Unit; um

IDENTIFICATION OF BEAM SPOT (BEAM SIZE 3-4 MM IN DIAMETER)
FOR DIFFUSION LENGTH MEASUREMENT ON LOCALIZED AREAS OF A 2x2 CM CELL



C. PHOTORESPONSE BY SMALL LIGHT SPOT SCANNING

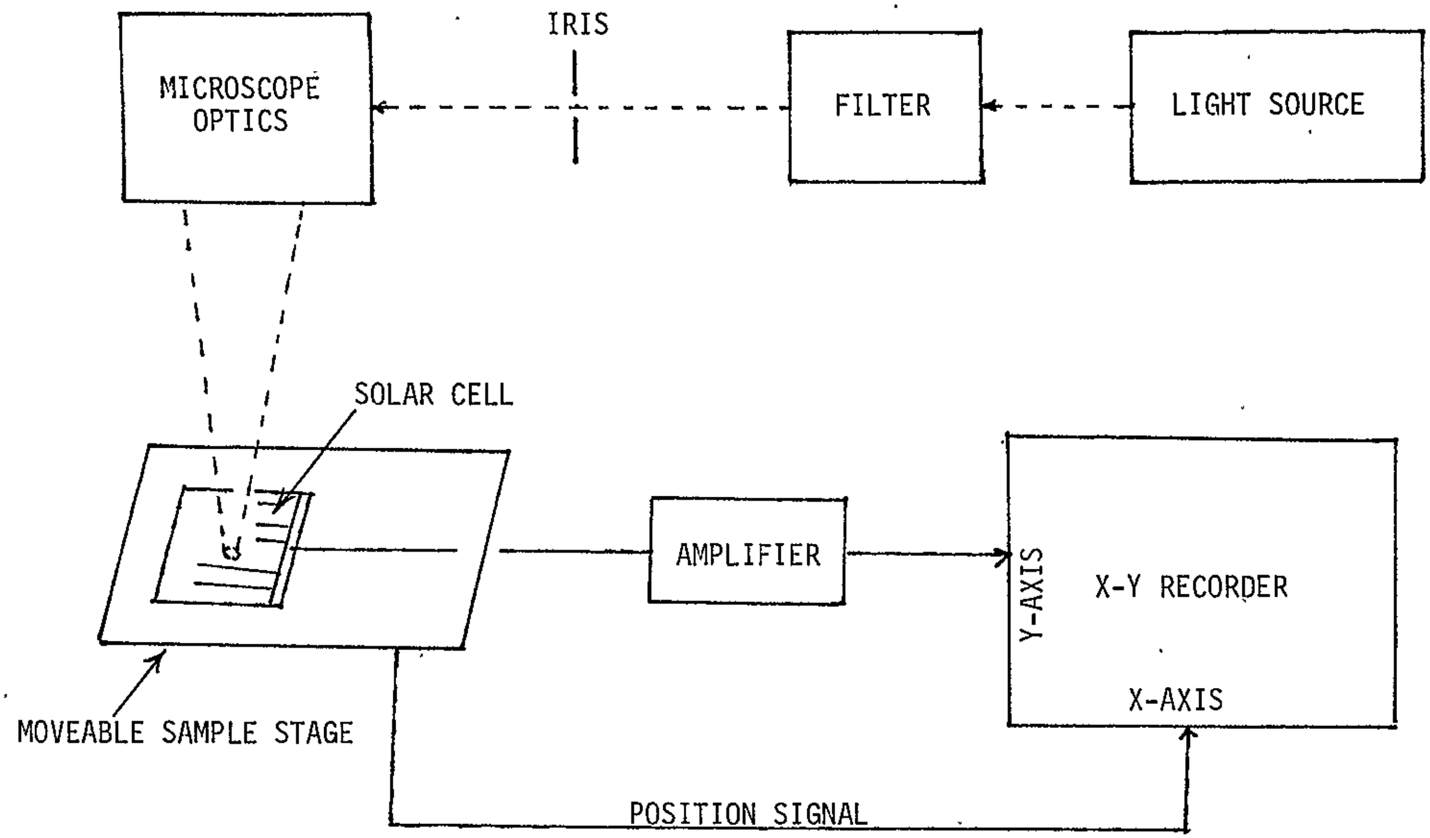
1.0 DESCRIPTION OF MEASUREMENT

A useful addition to analytical methods used to evaluate silicon sheet material for solar cell use is the small light spot scanner. This provides readout of the photosensitivity in small regions across the sheet (usually by moving a spot across a cell made from the sheet). In this way, the following information can be provided.

(i) Direct comparison of the output from different regions, can show the relative values of minority carrier diffusion lengths in those regions. In this way, spatial inhomogeneities can be seen and attempts made to correlate the different response with visual features, either present in the processed sheet silicon, or developed after additional chemical etching.

(ii) A particular case of interest is that when crystalline grains are present, where the response for different grains, and near or at the grain boundaries can evaluated.

The light spot scans shown in this report have provided useful backup to the overall assessment, and provide a more realistic indication of the reasons for sheet behavior, e.g. whether reduced response was obtained as a function of the grain size or in relatively small areas across the sheet. Below, in discussing the equipment we will indicate the possible features which can provide quantitative data. The measurement equipment is shown in Figure 9 in the form of block diagram and detailed techniques are discussed below.



A BLOCK DIAGRAM OF A FINE LIGHT SPOT SCANNING APPARATUS

FIGURE 9

Discussion of Components

(a) The light source should preferably contain long wavelength components, to allow sampling of the silicon quality away from the surface. For alignment, a He-Ne laser has been used. For most measurements, a tungsten light is used, with a very thin Si filter to remove short wavelength components. Low intensities are useable. Even with the optical losses caused by the filter, the distance from the source to the cell ($\sim$6 ft), and the iris and demagnification through the microscope optics, the use of a built-in low noise amplifier near the cell stage provides sufficient signal to drive the x-y recorder.

(b) The use of a microscope provides direct observation of the area being scanned, to aid in correlation with visual features on the cells. The use of higher power objectives (with the irises) can provide spot sizes below 10 μm. However, at such small spot sizes, the depth of focus of the objectives is very small, and thus causes problems for sheet samples which do not have a high degree of flatness because the variable spot size provides variable areas of sampling. Therefore, a moderately high magnification objective was used mostly providing a spot $\sim$20-50 μm in diameter. (For more detailed investigation in localized areas, it is planned to use smaller spots.)

(c) Even with the direct observation possibility, we use the gridlines on the cells as built-in distance (and locating) markers. Also by careful measurements of gridline width, and the shape of the intensity decrease while scanning over the gridline, an estimate can be made of the effective spot size.

(d) The cell is held in a pressure contact holder, on a platform which moves in and out, with speed adjusted by a variable control. The linear movement of the platform is fed into the x-axis of the controller; the amplified cell signal is fed into the y-axis.

(e) The x-y recorder is "calibrated" by using a control cell of good output; keeping the gain and light spot conditions fixed, the cell under test is substituted and a comparison trace made.

It is possible to improve the quantitative comparison on this set-up, to calibrate the y-signal directly against the local diffusion length measurement. However, mostly the equipment has been used for broad-scale comparisons and overall confirmation of the results have been obtained from I-V curves, spectral response, or from separate diffusion length measurements.

In summary, this equipment has revealed additional details of the various sheet materials, both to backup other measurements, made on cells, and also to indicate the possible causes for sheet performance which differs from cells using control silicon. In the following section, results of light scans are given for sheet samples covered in the first quarterly report (Wacker "Silso" sheet, EFG ribbons) as well as for the sheets covered in the present report.

2.0 PHOTORESPONSE OF SHEET SOLAR CELLS

Photoresponse of solar cells processed from Wacker "Silso" wafers, EFG ribbons, RTR ribbons and dendritic webs were obtained using the small light spot scan techniques and the results are presented in this section. The light source for the scanning light spot was a white light from a tungsten lamp (filtered with a thin transparent layer of silicon) the spot size on the sample was estimated to be around 50 µm. Relative photoresponse of sheet solar cells (standard process) are given in Figure Figure 10 for a Wacker "Silso" cell, Figure 11 for a EFG cell, Figure 12 for a RTR cell and Figure 13 for a web cell. Response of a control (Czochralski singe crystal silicon) cell is given on all curves for comparison. Spacing between grid (or finger) lines is about 2.5 mm except the EFG cell, which has a grid spacing of 0.7 mm, and this provided reference for the scanned distance and width of electrically active defect sites or boundaries.

The Wacker cell showed lower response than the control cell everywhere and the width of electrically active boundaries was estimated to be less than 0.2 mm for small crystallites and about 2 mm for large crystallites.

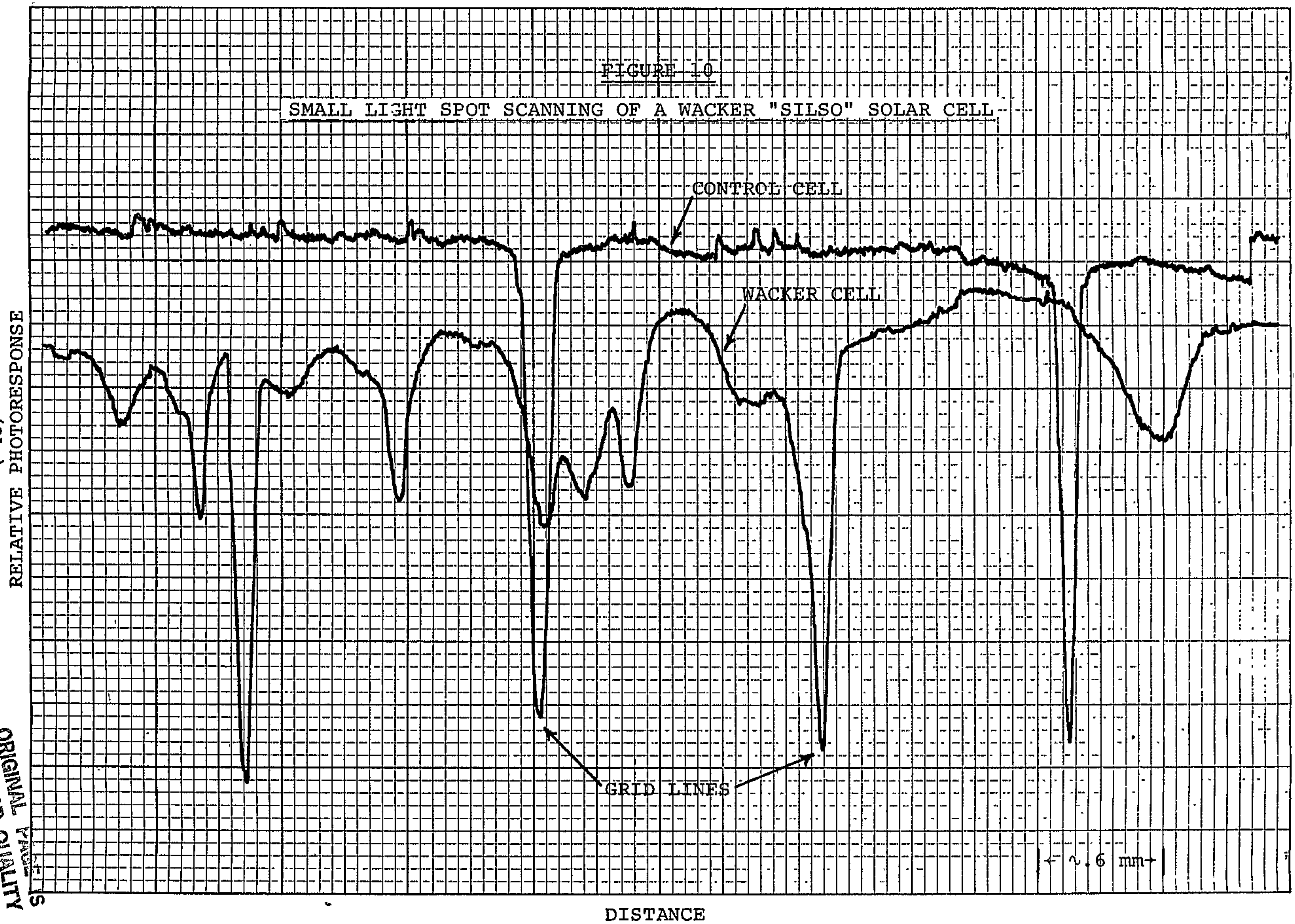
The EFG cell also indicated lower response than the control cell with the estimated grain size between 0.4 mm and 2mm. Non-uniform response from crystallite to crystallite was often found in both Wacker and EFG cells, generally low response from small crystallite, and this could possibly be due to the strain induced defects on small crystallites being more severe than those on the large crystallites.

The RTR cell showed very poor response, which made it difficult to detect electrically active defect sites.

The Dendritic Web cell indicated close response to that of the control cell and no significant number of active boundaries was noticed.

FIGURE 10

SMALL LIGHT SPOT SCANNING OF A WACKER "SILSO" SOLAR CELL



(31.)

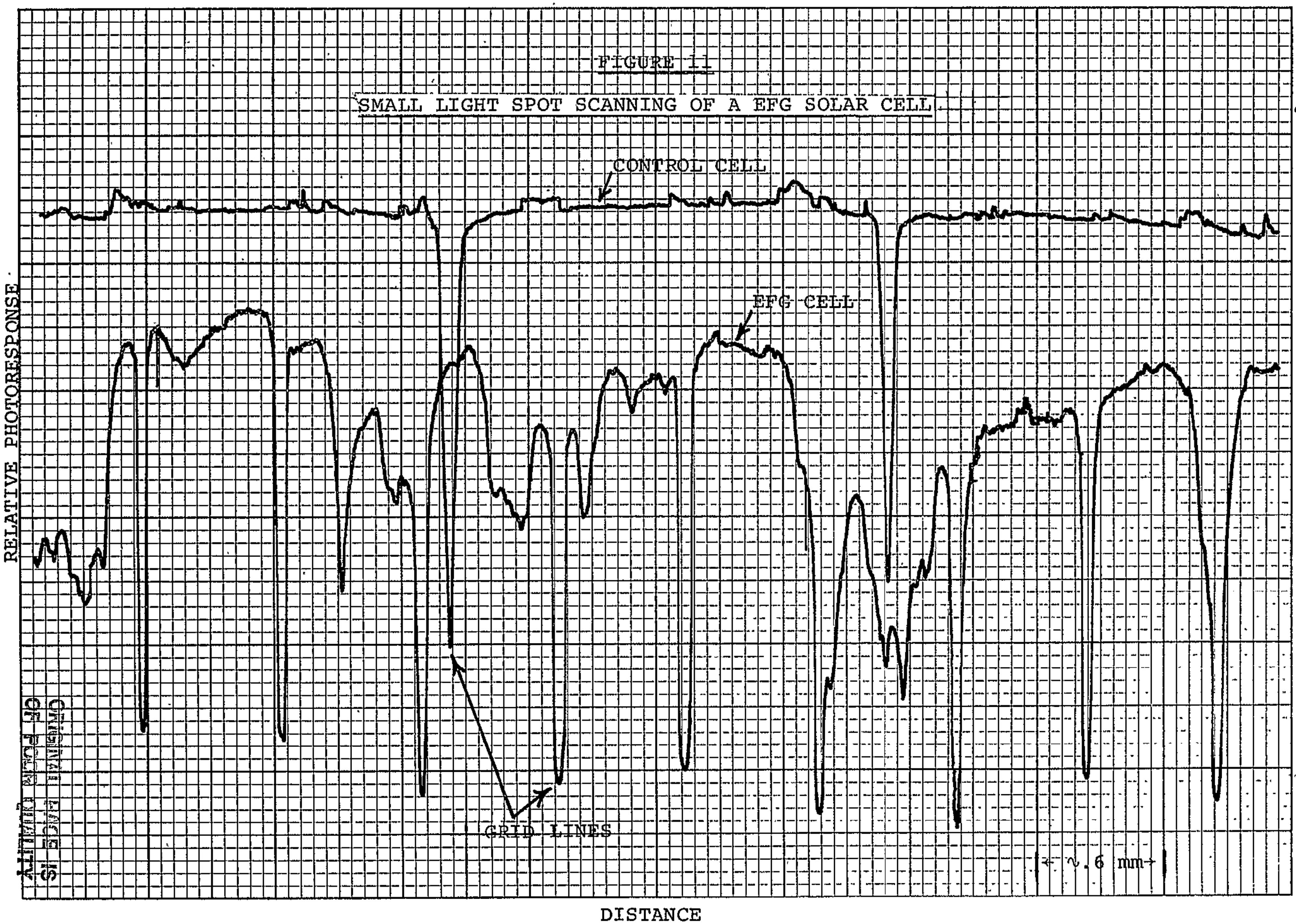


FIGURE 11

SMALL LIGHT SPOT SCANNING OF A EFG SOLAR CELL

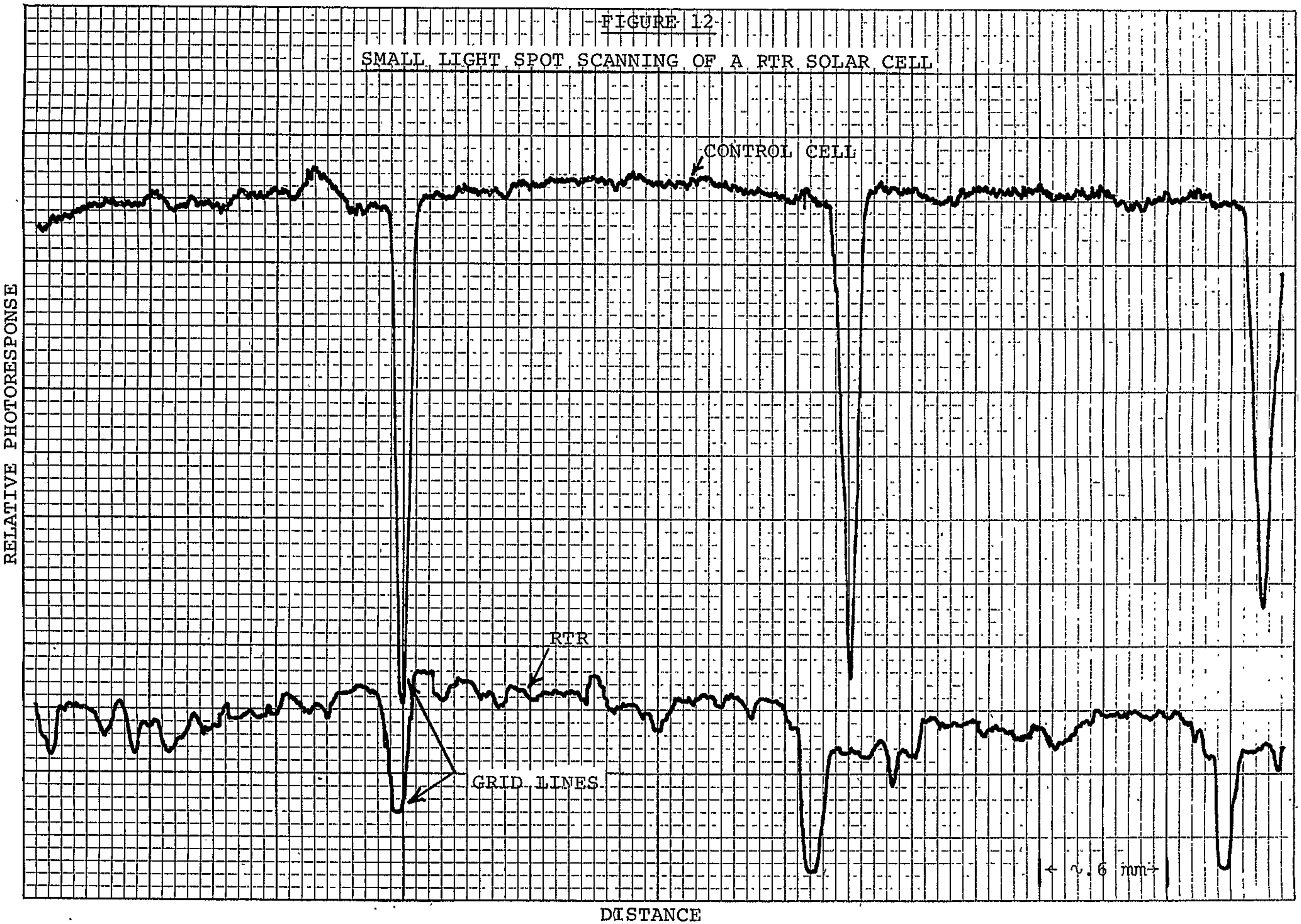
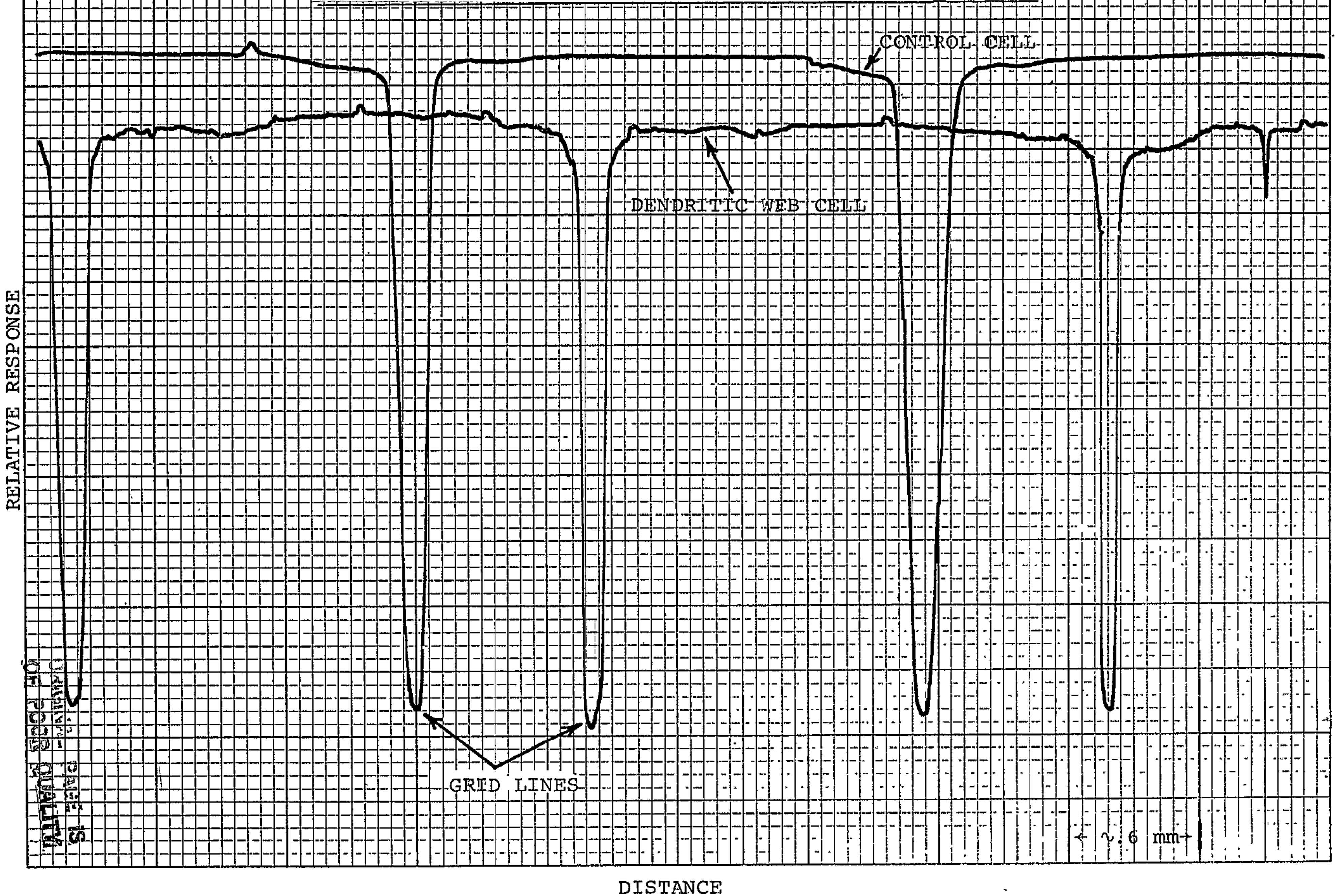


FIGURE 12

SMALL LIGHT SPOT SCANNING OF A RTR SOLAR CELL

FIGURE 13

SMALL LIGHT SPOT SCANNING OF A DENDRITIC WEB SOLAR CELL



III. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached in this work.

RTR Silicon

- The sheet showed stresses which aided breakage.

- These stresses (perhaps with residual impurities) severely reduced the I-V output, and led to reduced quality as shown by other measurements. The sheet also showed regional inhomogeneity.

- Generally the cell performance could be related to the values of diffusion length, and to the high shunt leakage seen in the dark I-V plots.

- The BSF process tried led to excessive breakage, but experience suggests that with the low diffusion lengths, no enhancement would be expected from a BSF process.

- The high stress would make fabrication of large area cells more difficult.

- Better quality RTR samples should be evaluated when available.

Dendritic Web Silicon

- Although this silicon showed spread from web to web, the better samples performance approached that of good Czochralski silicon.

- The cell quality again correlated well with all the supporting measurements.

- The dendrites were shown to have low diffusion length. Although cells were made using the dendrites as contact areas (no output anyway), in the long range this could not be economic because a good fraction of the web weight is in the dendrites, and they would probably be returned for remelting.

- BSF processing increased output, although some web samples independently processed have rivaled the best Czochralski silicon.

- In general, with greater consistency in producing good quality web, this sheet form shows good promise for combining good performance with low cost.

Small Light Spot Scanning

The inclusion of small light spot scanning has provided additional confirmation of the cell performance, both for the reported samples, and for those processed earlier. These scans will be continued. In addition, some increased information on the sheet properties is available from these scans, in providing a "picture" of the spatial variations, either in single crystal regions, or near imperfections or grain boundaries. With additional effort, these pictures can be expressed quantitatively in terms of localized diffusion length, and the variations can also possibly be correlated with visual differences across the samples.

IV. WORK PLAN STATUS

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

- Cast Silicon by Heat-Exchange Methods (Crystal Systems)
- Improved EFG Ribbon (Mobil-Tyco)
- Czochralski Silicon by Continuous or (Semi-continuous) Growth Method

Additional Measurements

Equipment is now operational which can give dark forward or reverse log I-V plots for a large number of samples in a reasonably short time. In addition, the log I-V plot under illumination can be run. This will provide a sounder estimate of the range of junction properties for a given sheet form, and after analysis a range of quantitative factors (A-values, J_o-values, shunt and series resistance) can be obtained. Again, it is hoped that these additional measurements will give more insight into the sheet silicon properties, with the goal of providing feedback information to help guide the formation of improved sheet quality.

V. REFERENCES

1. A. Baghadi, et.al., "Laser-Zone Growth in a Ribbon-to-Ribbon (RTR) process" Technical Reports for the Large Area Silicon Sheet Task of the LSA Project, JPL Contract No. 954376. Motorola.

2. C.S. Duncan, et.al., "Silicon Web Process" Technical Reports for for the Large Area Silicon Sheet Task of the LSA Project, JPL Contract No. 954654. Westinghouse.

APPENDIX I

TIME SCHEDULE

TIME SCHEDULE

TASK	MONTH												
	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL
1. PROCESS SHEET SAMPLES													
(a) 1/2 Samples → Cells	━━	━━	━━	━━	━━	━━	──	──	──	──	──	──	
(b) Analysis	━━	━━	━━	━━	━━	━━	──	──	──	──	──	──	
(c) Back Up Measurements	━━	━━	━━	━━	━━	━━	──	──	──	──	──	──	
(d) Test Alternate Process	━━	━━	━━	━━	━━	━━	──	──	──	──	──	──	
2. REPORTS													
(a) Monthly		▲	▲		▲	▲		△	△		△	△	
(b) Quarterly				▲						△			
(c) Semi-Annual							▲						
(d) Final													△
3. INTEGRATION MEETING													

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

Le: 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

MLAR: Multi-Layer Anti-Reflective

RTR: Ribbon-to-Ribbon

APPENDIX III

ELECTRICAL DATA SHEETS FOR RTR SOLAR CELLS

IDENTIFICATION INFORMATION ON PROCESSED RTR RIBBONS

First Batch:	838E	CVD feedstock, annealed
	840L	CVD feedstock, annealed
Second Batch:	850D	CVD feedstock, not annealed
	857A	CVD feedstock, not annealed
	S868C	Single crystal feedstock, not annealed
Third Batch:	811B	CVD feedstock, annealed
	869	CVD feedstock, not annealed
	S872B	Single crystal feedstock, not annealed

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2x2 cm) from RTR Ribbon, standard process 1st batch
NO A.R

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE: 10/10/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
838E-1	369	59	30	29	36	215	7.7	35	1.4
" -3	298	54	29	25	35	180	6.3	39	1.2
-5	327	53	28	25	36	200	7.2	42	1.3
-6	398	52	27	26	36	245	8.8	42	1.6
840L-3	254	55	26	30	37	145	5.4	38	1.0
" -5	270	56	28	28	37	140	5.2	34	1.0
" -6	192	54	27	27	45	65	2.9	28	0.5
		Control solar cells (2x2 cm)							
2	582	94	35	60	87	465	40.2	73	7.5
3	584	98	37	61	93	480	44.6	78	8.3
4	583	96	35	61	90	475	42.8	77	7.9

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (2x2cm) from RTR Ribbon Standard process 1st batch
SiO A.R coating

TEST CONDITION: AMO

TEMPERATURE: 25° C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
838E-3	331.2	72	37	35	50	210	10.5	44	9
" -5	359	72	37	34	51	235	12.0	47	2.2
84CL-3	271	63	29	34	42	165	6.9	40	1.3
" -5	289	67	32	34	41	180	7.4	38	1.4
" -6	225	66	33	33	45	110	5.0	33	0.9
			control	solar cells	(2x2cm)				
2	594	129	49	81	118	495	58.4	76	10.8
3	593	135	52	83	121	500	60.5	76	11.2
4	591	132	50	82	124	505	62.6	80	11.6

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2x2 cm) from RTR Ribbon, standard process 2nd batch
NO. A.R

TEST CONDITION: AM 0

TEMPERATURE: 25°C DATE:

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
850D-2	179	38	19	18	24	80	1.9	29	0.4
" -3	242	58	29	28	37	140	5.2	37	1.0
857A-2	481	56	27	28	40	355	14.2	53	2.6
" -5	227	55	28	26	38	130	4.9	40	0.9
S868C-2	519	63	31	32	54	435	23.5	72	4.4
" -3	469	56	27	~~33~~ 28	25	360	9.0	34	1.7
" -5	515	58	28	~~28~~ 29	50	420	21.0	70	3.9
" -7	479	48	23	24	33	370	12.2	54	2.3
		control solar cells (2x2 cm)							
12	581	97	36	62	87	490	42.6	75	7.9
13	583	98	36	62	87	490	42.6	75	7.9
14	589	99	37	62	92	500	46.0	79	8.5
15	587	99	38	62	86	495	42.6	73	7.9

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (2x2 cm) from RTR Ribbon, standard process 2nd batch
SiO A.R Coating
TEST CONDITION: AMO
TEMPERATURE: 25°C DATE:

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
8517A-2	499	76	35	39	58	375	21.6	54	4.0
S868C-2	528	91	44	45	80	435	34.8	73	6.4
" -4	496	47	25	25	23	400	9.2	39	1.7
" -5	522	81	38	41	69	422	29.2	69	5.4
			control	solar	cells	(2x2 cm)			
12	587	134	51	84	124	485	60.5	77	11.2
13	588	135	50	85	124	490	60.5	76	11.2
14	593	136	51	86	127	490	63.5	79	11.8
15	595	134	50	85	125	500	62.5	78	11.6

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (2x2 cm) from RTR Ribbon. Standard process 3rd batch
NO. A.R

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE:

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
811B-1	205	58	30	27	39	95	3.7	16	0.7
" -2	454	57	30	26	35	315	11.0	43	2.0
" -4	160	56	29	26	41	55	2.3	25	0.4
" -5	345	59	30	28	35	215	7.5	37	1.4
" -6	480	55	29	26	36	380	13.7	52	2.5
869-1	489	61	31	29	53	405	21.5	72	4.0
" -2	388	59	30	28	24	250	6.0	26	1.1
" -5	474	56	30	26	38	385	14.6	55	2.7
" -6	453	57	30	27	29	345	10.0	38	1.9
" -7	475	57	30	26	39	400	15.6	58	2.9
5872B-3	515	65	31	33	57	425	24.0	72	4.5
" -4	424	64	31	33	33	260	8.6	32	1.6
" -5	513	65	32	32	57	425	24.0	73	4.4
" -6	514	67	34	33	57	425	24.7	70	4.5
" -7	495	61	30	30	51	405	20.7	68	3.8

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2x2cm) from RTR Ribbon standard process 3rd batch
SiO AR
TEST CONDITION: AM0
TEMPERATURE: 25°C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
811B-1	251	80	42	37	54	120	6.5	32	1.2
" -2	487	79	40	36	51	345	17.6	46	3.3
" -4	199	77	41	36	44	70	3.1	20	0.57
" -5	398	82	43	38	53	245	12.9	40	2.4
" -6	508	76	41	34	53	400	21.2	55	3.9
869-1	503	84	44	39	74	405	29.9	71	5.6
" -2	447	82	43	38	39	300	11.7	32	2.2
" -5	492	79	43	36	58	370	21.5	55	4.0
" -6	478	82	43	38	49	370	18.1	46	3.4
" -7	492	80	43	36	62	400	24.8	63	4.6
S872B-3	528	92	45	46	82	430	35.3	72	6.5
" -4	483	91	45	45	48	330	15.8	36	2.9
" -5	527	91	45	45	81	430	34.8	73	6.5
" -6	528	93	46	46	82	435	35.7	72	6.6

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control solar cells (2x2 cm) for RTR Ribbon. standard process, 3rd batch
No. A.R & SiO A.R

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
21	581	94	36	59	86	485	41.7	76	7.7
22	580	97	37	60	87	490	42.6	76	7.9
24	584	94	36	60	86	485	41.7	75	7.7
25	578	98	37	61	90	485	43.7	77	8.1
26	582	100	38	62	92	490	45.1	78	8.3
			After	SiO	A.R coating				
21	593	132	52	80	122	485	59.2	76	11
22	588	136	55	81	122	485	59.2	74	11
24	594	134	54	81	121	485	58.7	74	10.9
25	586	137	54	83	126	480	60.5	75	11.2
26	591	140	50	84	129	485	62.6	76	11.6

APPENDIX IV

ELECTRICAL DATA SHEETS FOR DENDRITIC WEB SOLAR CELLS

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar Cells (2x2 cm) for Dendritic Web, Standard Process (1st batch) with SiO A.R coating (Parenthesis numbers for before A.R coating)

TEST CONDITION: AMO

TEMPERATURE: 25 °C

DATE: 11/9/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
1	596	133	52	81	123	495	60.9	77	11.3
	(581)	(94)	(36)	(59)	(86)	(495)	(42.6)	(78)	(7.9)
2	589	129	50	79	118	495	58.4	77	10.8
	(582)	(92)	(35)	(58)	(83)	(490)	(40.7)	(76)	(7.5)
3	598	134	53	82	124	500	62.0	77	11.5
	(586)	(95)	(36)	(60)	(86)	(495)	(42.6)	(76)	(7.9)
4	597	131	52	80	121	500	60.5	77	11.2
	(587)	(93)	(35)	(58)	(87)	(495)	(43.1)	(79)	(8.0)
5	594	132	52	80	122	505	61.6	79	11.4
	(584)	(94)	(36)	(59)	(88)	(495)	(43.6)	(80)	(8.1)
6	596	137	55	82	127	500	63.5	78	11.8
	(585)	(97)	(37)	(61)	(91)	(495)	(45.1)	(79)	(8.3)
7	593	130	49	81	118	485	57.2	74	10.6
	(586)	(92)	(34)	(58)	(84)	(495)	(41.6)	(77)	(7.7)
8	598	133	51	82	121	505	61.1	77	11.3
	(588)	(95)	(35)	(60)	(89)	(500)	(44.5)	(80)	(8.2)
9	601	136	53	83	127	515	65.4	80	12.1
	(590)	(97)	(36)	(61)	(90)	(505)	(45.5)	(80)	(8.4)

Note: # 1 – 6 First control Group
7 – 9 Second " "

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2x2 cm) from Dendritic Web, Standard Process (1st batch)
No A.R coating, ≈ 90 % active area.

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 11/9/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
RE 12-33-1	525	97	37	60	86	435	37.4	74	6.9
" -2	526	97	37	59	86	435	37.4	74	6.9
" -3			Shorted						
" -4	525	97	37	59	85	430	36.6	72	6.8
" -5	525	96	37	59	85	430	36.6	73	6.8
" -6	525	97	37	60	85	430	36.6	72	6.8
" -7	521	86	32	53	75	430	32.3	72	6.0
" -8	523	82	31	51	71	430	30.5	72	5.7
" -9	521	88	34	54	75	430	32.3	71	6.0
" -10			shorted						
" -11	523	98	38	60	84	430	36.1	71	6.7
J65-3,4-4	508	92.0	37	55	81	425	34.4	73	6.4
" -7	506	90	36	54	81	420	34.0	75	6.3
" -10	510	92	37	55	81	420	34.0	72	6.3

Note ; RE 12-3,3-7, -8, -9 cells with Bounding Dendrites.

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (2x2 cm) from Dendritic Web, Standard Process (1st batch) with SiO A.R. coating, ≈ 90 % active area.

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 11/9/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
RE12-3.3-1	529	133	53	79	119	435	52	73	9.6
" -2	537	136	54	81	120	440	52.8	73	9.8
" -4	536	138	55	80	121	435	52.6	72	9.7
" -5	531	134	53	81	118	435	51.3	72	9.5
" -6	536	135	53	82	118	435	51.3	71	9.5
" -7	533	120	47	72	106	440	46.6	73	8.6
" -8	516	114	43	71	98	440	43.1	73	8.0
" -9	531	121	47	74	106	440	46.6	72	8.6
" -11	532	135	53	82	117	440	51.5	71	9.5
"									
J65-34-4	514	129	52	78	116	415	48.1	73	8.9
" -7	520	126	51	74	114	430	49.0	75	9.1
" -10	520	128	52	76	116	415	48.1	72	8.9

Note: RE12-3.3-7, -8, -9 cells with Bounding Dendrites

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar Cells (≈ 2x2 cm) for Dendritic Web, BSF process (2nd batch)
With SiO A.R coating (Parenthesis numbers for before A.R coating), ≤90% active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE: 12/6/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	Area cm^2
10	578	131	48	83	100	448	44.6	59	8.5	3.88
	(560)	(96)	(36)	(61)	(67)	(435)	(28.9)	(54)	(5.5)	
11	592	132	49	83	110	485	53.4	69	10.2	3.88
	(581)	(95)	(35)	(61)	(75)	(475)	(35.6)	(64)	(6.8)	
12	598	138	52	86	120	485	58.2	71	10.7	4.00
	(588)	(100)	(37)	(63)	(85)	(480)	(40.6)	(69)	(7.5)	
13	591	134	50	84	115	485	55.8	70	10.7	3.88
	(582)	(97)	(36)	(62)	(83)	(475)	(39.4)	(70)	(7.5)	
14	593	131	50	82	116	485	56.3	73	11.0	3.78
	(577)	(96)	(35)	(61)	(83)	(475)	(39.4)	(71)	(7.7)	
15	575	134	50	84	96	450	43.2	56	8.2	3.89
	(552)	(98)	(36)	(62)	(67)	(410)	(27.5)	(51)	(5.2)	
17	596	131	49	82	122	490	60.0	76	10.9	4.03
	(585)	(95)	(34)	(61)	(88)	(495)	(43.6)	(79)	(8.0)	
18	599	133	50	84	124	500	62.0	78	11.3	4.06
	(589)	(96)	(35)	(62)	(88)	(475)	(41.8)	(74)	(7.6)	
Note:	# 10 - 15	First	control	Group						
	# 17 & 18	Second	"	"						

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈2x2 cm) from Dendritic Web, BSFi process (2nd batch)
NO A.R coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE:

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	area
	mV	mA	mA	mA	mA	mV	mW	%	%	cm²
RE24-15-3	511	93	36	56	85	415	35.3	75	6.7	3.89
" -4	548	98	36	62	90	440	39.6	74	7.7	3.83
" -5	567	99	36	62	91	460	41.9	75	8.1	3.86
" -6	557	101	37	64	89	440	39.2	70	7.4	3.94
" -7	559	100	36	64	91	446	40.6	73	7.7	3.90
" -8	563	99	36	63	93	445	41.4	74	7.9	3.87
" -9	557	98	36	62	92	435	40.0	73	7.7	3.85
" -10	561	100	37	63	93	435	40.5	73	7.7	3.89
" -11	544	98	37	62	92	430	39.6	74	7.5	3.89
" -12	551	98	36	62	92	435	40.0	74	7.6	3.87
J64-1.6-4	551	95	36	59	79	445	35.2	67	6.7	3.86

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2x2 cm) from Dendritic Web, BSF process (2nd batch) with SiO A.R coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 11/29/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	Area
	mV	mA	mA	mA	mA	mV	mW	%	%	cm²
RE24-1.5-3	521	129	50	79	119	405	48.2	72	9.2	3.89
" -4	561	136	50	86	125	445	55.6	73	10.8	3.83
" -5	578	137	51	87	124	460	57.0	72	10.9	3.86
" -6	569	140	52	89	124	440	54.6	68	10.3	3.94
" -7	574	139	51	88	125	455	56.9	71	10.8	3.90
" -8	575	139	52	87	125	455	56.9	71	10.9	3.87
" -9	571	136	51	85	122	415	50.6	65	9.7	3.85
" -10	573	139	52	87	126	430	54.0	68	10.3	3.89
" -11	554	138	52	86	127	440	55.9	73	10.6	3.89
" -12	561	137	51	85	125	445	55.6	73	10.6	3.87
J64-1.6-4	565	133	51	82	111	450	50.0	67	9.6	3.86

ORIGINAL PAGE IS OF POOR QUALITY

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar Cells (≈2x2 cm) for Dendritic Web, Space Process (3rd batch) With SiO A.R coating (Parenthesis numbers for before A.R coating)

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 12/8/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	Area cm²
19				Shunted	badly					
20	547	129	52	77	84	380	31.9	45	6.3	3.7~~85~~ 6
	(518)	(94)	(37)	(57)	(63)	(325)	20.5	(42)	(4.0)	
21				Shunted	badly					
22	582	129	53	76	111	490	54.4	73	10.6	3.785
	(574)	(94)	(37)	(57)	(77)	(490)	(37.7)	(70)	(7.4)	
23	577	131	53	78	102	485	49.5	65	9.6	3.82
	(566)	(95)	(38)	(57)	(67)	(460)	(30.8)	(57)	(6.0)	
24	580	130	52	79	96	480	46.1	61	9.0	3.78
	(569)	(96)	(39)	(58)	(66)	(460)	(30.4)	(55)	(5.9)	
25	593	125	46	80	116	505	58.3	79	11.3	3.82
	(587)	(91)	(33)	(59)	(85)	(500)	(42.5)	(79)	(8.2)	
26	596	128	47	82	120	505	60.4	79	11.5	3.88
	(587)	(93)	(33)	(60)	(85)	(500)	(42.5)	(78)	(8.1)	
27	599	122	44	78	116	505	58.3	80	11.5	3.755
	(591)	(89)	(32)	(57)	(84)	(495)	(41.6)	(80)	(8.2)	
Note;	# 19 –	24	First	Control	Group					
	# 25 –	27	Second	Control	Group.					

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (≈ 2x2 cm) from Dendritic Web, Space process (3rd batch)
No A.R coating, ≈ 93 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 12/6/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	Area cm²
RE28-5.4-1	509	93	39	54	83	420	35	74	6.8	3.805
" -2	505	93	39	54	85	415	35.1	75	6.7	3.88
" -3	510	94	40	54	86	425	36.6	77	7.0	3.845
" -4	509	93	39	54	85	415	35.1	74	6.9	3.77
RE28-53-1	510	89	38	52	83	420	34.9	77	7.1	3.62
" -2	510	81	34	47	74	425	31.5	76	7.0	3.34
" -4	505	89	37	52	80	420	33.6	75	6.6	3.77
" -5	507	65	27	38	59	425	25.1	76	6.8	2.74
" -6	508	92	39	54	85	430	36.6	78	7.2	3.775
" -7	512	94	39	55	85	425	36.1	75	7.1	3.795
" -8	508	93	39	54	84	420	35.3	74	6.8	3.83

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2x2cm) from Dendritic Web. Space Process (3rd batch) with SiO A.R coating, ≈ 93 (%) active area

TEST CONDITION: AM0

TEMPERATURE: 25°C

DATE: 12/

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	Area
	mV	mA	mA	mA	mA	mV	mW	%	%	cm²
RE28-5.4-1	517	127	54	73	116	420	48.7	74	9.5	3.805
" -2	512	127	53	74	115	415	47.7	74	9.1	3.88
" -3	517	126	52	75	117	425	49.7	76	9.6	3.845
" -4	514	125	51	74	113	415	46.7	73	9.2	3.77
RE28-5.3-1	516	121	50	71	112	425	47.4	76	9.7	3.62
" -2	516	111	46	64	101	430	43.2	76	9.6	3.34
" -4	514	123	51	71	112	425	47.6	75	9.4	3.77
" -5	516	90	38	52	82	430	35.3	76	9.5	2.74
" -6	517	125	52	73	116	430	49.7	77	9.7	3.775
" -7	518	127	51	75	114	425	48.5	74	9.5	3.795
" -8	514	126	52	74	114	420	47.7	74	9.2	3.83

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar Cells (≈ 2X2 cm) for Dendritic Web, Standard Process (4th batch, special Run) with SiO A.R coating, ≈ 90 (%) active area

TEST CONDITION: AMO

TEMPERATURE: 25 °C DATE:

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	Area cm^2
28	576	117	46	72	94	475	44.4	66	8.6	3.83
29	588	127	50	77	114	475	53.9	72	10.4	3.83
30	553	115	46	69	75	400	29.8	47	6.0	3.69
31	588	127	50	77	115	465	53.5	72	10.3	3.86
32	589	127	51	78	117	475	55.6	74	10.8	3.83
33	591	118	48	71	108	490	52.9	76	10.5	3.74
34	588	117	44	73	104	475	49.4	72	9.8	3.75
35	589	124	47	76	105	480	50.4	70	9.6	3.87
36	590	121	47	75	111	495	55.0	77	10.8	3.785

Note: # 28 — 33 First Control Group

34 — 36 Second " "

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (≈ 2x2 cm) from Dendritic Web, standard Process (4 th batch. Special Run) with SiO A.R coating (Parenthesis Numbers for before A.R), ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25 °C

DATE: 12/8/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η	Area
	mV	mA	mA	mA	mA	mV	mW	%	%	cm²
RE28-53-9	512	126	50	76	103	410	42.2	65	7.7	4.06
	(507)	(93)	(36)	(57)	(79)	(405)	(32)	(68)	(5.8)	
" -10	512	122	48	74	109	410	44.5	71	8.4	3.94
	(503)	(90)	(35)	(56)	(75)	(405)	(30.4)	(67)	(5.7)	
" -11	515	122	48	74	108	410	44.3	70	8.1	4.05
	(505)	(90)	(35)	(55)	(79)	(405)	(32)	(70)	(5.9)	
" -12	515	108	42	65	97	415	40.3	73	8.5	3.53
	(507)	(81)	(32)	(49)	(71)	(405)	(28.8)	(70)	(6.0)	
RE28-53-14	516	115	46	69	105	410	43.1	73	8.3	3.83
	(510)	(83)	(32)	(51)	(76)	(415)	(31.5)	(75)	(6.1)	
" -15	513	120	48	71	107	395	42.3	69	8.1	3.85
	(506)	(89)	(35)	(54)	(79)	(405)	(32.0)	(71)	(6.2)	

Note: Cell # 9 - 12 Cells with contact (Front) bars on bounding Dendrites

Cell # 14 & 15 Cells from steam oxidized Web blanks to remove surface SiO layer deposited in Growth process

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control cells (2x2 cm), Standard Process (Control Test after cleaning diffusion tube)
No A.R coating, ≈ 90 (%) active area

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 12/18/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %	AREA cm²
CT-1	588	98	37	61	91	495	45.1	78	8.3	4
" -2	585	99	37	62	90	490	44.1	76	8.2	"
" -3	585	97	37	61	90	490	44.1	77	8.2	"
" -4	585	98	37	62	89	495	44.1	77	8.2	"
" -5	584	97	37	61	89	495	44.1	78	8.2	"
" -6	583	97	37	61	89	495	44.1	78	8.2	"
" -7	586	98	37	61	90	490	44.1	77	8.2	"
" -8	586	97	37	61	89	490	43.6	76	8.1	"
" -9	587	98	37	61	91	495	45.1	79	8.3	"
" -10	585	97	37	61	89	490	43.6	77	8.1	"
" -11	586	99	37	62	92	495	45.5	79	8.4	"
" -12	584	99	37	62	90	495	44.6	77	8.3	"
" -13	584	99	37	62	90	493	44.1	76	8.2	"
" -14	587	100	38	62	93	495	46.0	79	8.5	"
" -15	587	97	37	61	89	500	44.5	78	8.2	"
" -16	586	97	37	61	89	498	44.3	78	8.2	"
" -17	583	98	37	61	89	490	43.6	76	8.1	"
" -18	586	98	37	61	89	490	43.6	76	8.1	"