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SILICON SOLAR CELL PROCESS

DEVELOPMENT, FABRICATION AND ANALYSIS

FIRST QUARTERLY REPORT

FOR PERIOD COVERING

15 JUNE 1978 to 30 SEPTEMBER 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

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ABSTRACT

Solar cells were fabricated from unconventional silicon sheets, (Wacker "Silso" wafers and EFG ribbon, RF furnace grown), and the performances were characterized with an emphasis on statistical evaluation. A number of solar cell fabrication processes were used and conversion efficiency was measured under AMO condition at 25°C. "Silso" solar cells using standard processing showed an average efficiency of about 9.6%. Solar cells with back surface field (BSF) process showed about the same efficiency as the cells from standard process. Solar cells from grain boundary passivation process did not show any improvements in solar cell performance. These efficiency values are about 2% lower than those of the single crystalline control solar cells of about the same resistivity. A number of cells were fabricated using space technology (applying photolithographic techniques for the finer contact lines, multilayer AR coating and BSF), to see the limit of "Silso" sheets; these solar cells showed an average efficiency of 10.8%. Solar cells (2x2 cm) from corners and edges of the original "Silso" wafer (10x10 cm) showed considerably lower efficiency than those of the cells from the middle part, mainly due to the difference in grain size, and this result agrees well with the result of the minority carrier diffusion length and spectral response measurements.

EFG solar cells (area area about 506 cm^2) were fabricated using standard and BSF processes. Average efficiency of the standard and BSF solar cells were around 7.8% and 8.5%, respectively, indicating about

*All efficiencies quotes in this report refer to AMO conditions.

3% lower efficiency than those of the single crystalline control cells. This is about 1% lower efficiency than that of the "Silso" solar cells, due to lower curve fill factor and open circuit voltage, and was suspected to be due to shunting caused by silicon carbided particles from die material. Minority carrier diffusion length stayed about the same in both sheets, showing about 40-60 μm range.

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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 Wacker "Silso" wafers and EFG ribbons from Mobil Tyco. Silicon blanks (2x2 cm) were prepared from "Silso" wafers and fabricated using a standard process typical of those used currently in the silicon solar cell industry, a back surface field (BSF) process and other process modification attempting to achieve grain boundary passivation. About 1" x 1" solar cells were fabricated from EFG ribbons using standard and back surface field process.

Performance parameters, including open circuit voltage, short circuit current, curve fill factor, conversion efficiency, spectral response, dark I-V characteristics, and minority carrier diffusion length, were characterized and the results were compared to the properties of cells made from the conventional single crystalline silicon, and processed with the sheet samples. Statisical evaluation was emphasized; the results indicated that cell performance depends strongly on the grain size (for "Silso") and the foreign inclusions, such as SiC, etc. in the EFG ribbons.

II. TECHNICAL DISCUSSION

A. Wacker "Silso" Solar Cells

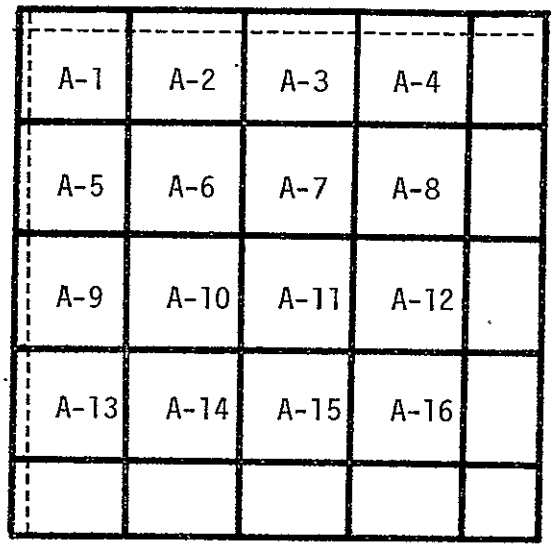
1.0 Preparation and Description of Blanks

Wacker wafers were sliced into 2x2 cm silicon blanks using an O.D. diamond saw. The wafers and the location of the blanks in each wafer were identified with letters and numerals, respectively. Figure 1 shows how these blanks were prepared from a "Silso" wafer (in this case wafer A). Identification of each blank on a wafer is very important since the cell blanks have different grain size depending on the location of the blanks on the original wafers (10x10 cm). Edges of the wafer showed smaller grain size than the middle since nucleation starts at edges during solidification of molten silicon. Grains were mm size in the middle and were less than mm in area close to edges.

The blanks were chemically polished in planar etch (2:15:5 = $HF:HNO_3:CH_3COOH$) for about 10 minutes, which removed about 1.5 mils of silicon from each face of the blanks. Four point probe measurement indicated that resistivities were in the range of 5-11 ohm-cm with p-type conductivity (four point probe measurement of polycrystalline material might introduce error in bulk resistivity reading due to the potential drop at the grain boundaries).

Surface photovoltage measurement for these "Silso" blanks indicated minority carrier diffusion lengths in the range of

40 to 80 μm (measurement used a light beam size of around 3-4 mm in diameter). Single crystalline control blanks were prepared in the same way with the measured resistivity range 1-3 ohm-cm and minority carrier diffusion length between 100-200 μm.



Classification of Blanks

Corner: A-1

Edge: A-2, A-3, A-4, A-5, A-9, and A-13

Middle: A-6, A-7, A-8, A-10, A-11, A-12, A-14, A-15, and A-16

FIGURE 1

Preparation and Classification of Silicon Blanks
(2x2 cm) From a Wacker "Silso" Wafer (A Wafer, 10x10 cm)

2.0 Fabrication of Solar Cells

Cells were made from the prepared blanks, along with control cells using Czochralski silicon. The rationale for the control cells is given in the following section.

2.1 Control Cell Rationale

For evaluation of a wide range of silicon, use is made of control cells, made from silicon previously shown to yield good cells. Even with a well established sequence of processes, the use of these control cells can serve as a useful check that the processing has been satisfactorily completed. These control slices (along with the test samples) are previously scribed with an individual code, and can be identified when the cells is completed.

If the silicon under evaluation does <u>not</u> lead to any chance of contamination of furance tubes etc., a set of control slices added at the slice preparation stage and processed along with the group to be evaluated can show that the processing has proceeded to plan (the control cell properties are known from earlier tests) and it can be verified that in the run under study, that this baseline performance has been obtained. The use of control cells effectively provides a evaluation of the integrated effect of all the process steps on the cell performance.

Should any deviation have occurred in the process steps it is convenient to determine the step(s) leading to deviation by analysis of the differences in the control cell performance.

If any cross-influence is suspected from the test silicon (e.g. contamination from high concentration of impurities), then the control cell performance can indicate this contamination. Usually such contamination is most likely to occur during the high temperature processes (especially diffusion and annealing) and in this case, use of a second group of control slices can bracket the step at which contamination occurred. This second group of control slices is formed from a similar well-behaved ingot, and is additionally diffused in a separate furnace. Should this group of cells perform well, whereas the original group showed poorer performance this indicates that the test silicon is indeed a source of contamination.

To check if the furnace itself has been contaminated, use of another group of undiffused control slices can be processed alone, to see if the output is decreased on exposure to the suspect tube.

Clearly if some of the later steps are suspected to be the cause of reduced output, additional groups of control slices, processed in acceptable equipment

up to the suspect steps, can serve to indicate degradation caused by the suspect step. [In many cases, the primary control group can serve this function.]

In addition to indication of suspect step(s), the control cells also provide quantitative estimates of the amount of degradation. Analysis of the photovoltaic parameters can show the extent of degradation in the key cell properties, e.g. decreased V_{oc} can show possible shunting or other PN junction deterioration, decreased I_{sc} can show reduced diffusion length in the silicon, or perhaps problems in the diffusion conditions or the AR coating.

The use of control cells provides a direct check of the effects of the process steps, with the information provided directly in the solar cell performance characteristics. This is often preferable to attempts to use related parameters which must still be assessed for their actual effect on cell properties. The control cells provide a constant baseline to evaluate the silicon under test, allowing direct comparison in solar cell efficiency rather than inferred comparison using cell-related physical factors.

For forms of silicon where inhomogeneity is expected (polycrystalline or ribbon silicon) the control cells can also be useful; if measurements are made of

localized small areas, comparison of the spread across the control slices and the test slices again provides a baseline indication of the degree of inhomogeneity.

In the ideal case (most usual), the control cells provide cell output as expected, and this adds confidence to any direct comparisons made on the silicon under test. In a few cases, very small deviations in control cell performance after analysis have revealed similar small deviations in the processing of the test silicon, and again necessary small adjustments were made to the process sequence (and confirmed for their effectiveness) using more control slices.

In the present work, a stock of previously acceptable silicon has been identified and retained for use as control material for the different batches of test silicon. Part of the stock has been pre-diffused for insertion with the test group and the first control group, immediately after these groups have been diffused. These are called second control group and identified in electrical data sheets of control cells in Appendices III and IV.

2.2 Standard Process

The first group of test samples is subjected to a "standard process", (which will be described in this section) to allow uniform evaluation of all the different sheet forms.

After applying a diffusion mask on the back surface, the silicon blanks, both Wacker (63 pieces) and the controls (10 pieces) were loaded in a furnace, with 12" temperature zone at 875°±1°C and oxidation was carried out in dry oxygen atmosphere for five minutes. Following the oxidation step, (in the same furnace) slices were diffused for 20 minutes by passing $POCl_3$-saturated oxygen gas and dry nitrogen gas (carrier gas) over the blanks. Finally the boat loaded with these diffused blanks was slowly pulled out of the furnace (within 10 minutes manually). After removing the glassy-layers formed during the diffusion process, sheet resistance was measured from selected samples; values of 30-60 ohm/square for Wacker silicon and 22-25 ohm/square for single crystalline controls were measured.

Front and back contacts were applied by successive evaporation of Ti, Pd and Ag in a vacuum chamber (pressure around 10^{-6} Torr) using resistively heated coils as sources. Front contacts were applied by evaporation of metals through a metal shadow mask which had grid finger density of four lines per centimeter. About 90% active area of the solar cells was obtained after evaporation. The thickness of the evaporated front metals was 1000Å for Ti, 250Å for Pd and 4-6 μm for Ag, while the thickness of Ag in the back contact was around 2-3 μm. To

minimize peeling of metal contacts during preliminary measurement of solar cell parameters (measurement without anti-reflective coating) a post metallization heat treatment was carried out at 400°C for 10 minutes in hydrogen atmosphere.

An anti-reflective coating was applied on the finished solar cells by evaporation of silicon monoxide in a vacuum chamber pressure maintained at around 10^{-6} Torr. The thickness of the evaporated SiO_x layer was around 750Å with stoichiometric factor x close to one. Finally the solar cells with anti-reflective coating were sintered again at 500°C for five minutes in hydrogen atmosphere. A block diagram of this process is given in Figure 2.

Final mechanical yield of the finished cells was around 94%. Table 1 shows the number and cause of the broken cells during process; the number of initial starting blanks was 64.

The control cells from this initial standard process showed lower open circuit voltage and higher series resistance than expected. This was suspected to be due to high contact resistance at the back metal-silicon interface. Thus, back contacts were applied first (before front contacts) and sintered in H_2 atmosphere for 10-15 minutes at 600°C. Then front contacts were

FIGURE 2

SOLAR CELL STANDARD PROCESS

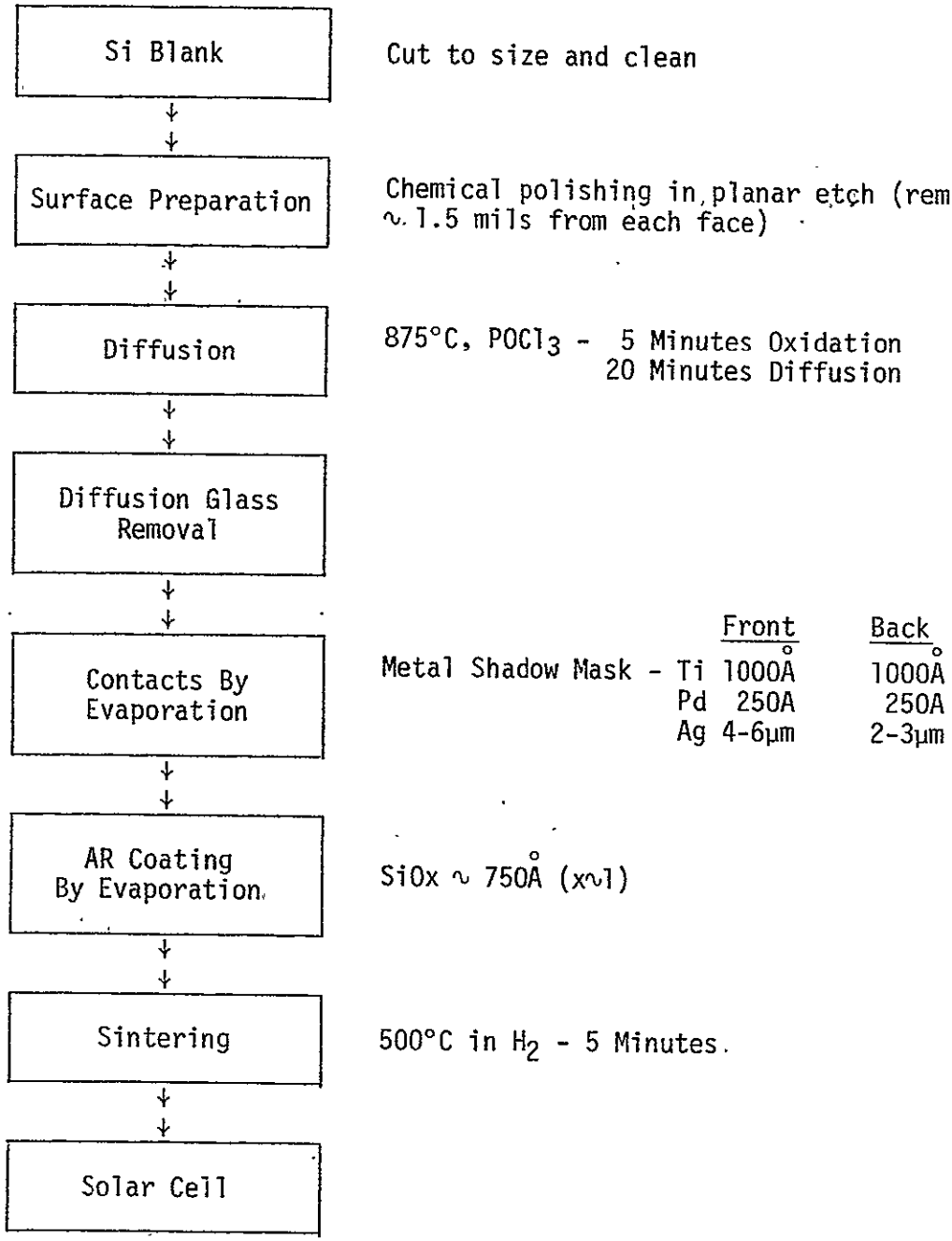


TABLE 1

NUMBER OF BROKEN CELLS	CAUSE
1	Dropped While Demounting 2x2 cm Blanks
2	Corner Chipped While Clamping Metal Shadow Mask In Evaporation Process
1	Shattered in Post-Metallization Heat Treatment in a Furnace

Mechanical Failure of "Silso" Solar Cells
in the Process of Fabrication (Standard Process)

applied and the standard process followed thereafter, the 400°C heating step was retained to minimize front contact peeling during pre-coating measurements.

NOTE: This modified process sequence (using the 600°C sintering of the back contact was used from this stage in the contract and became the "standard process".

2.3 Back Surface Field (BSF) Process

Back surface field was provided by evaporation of a thin Al layer followed by screen printing of Al paste, and an alloying step at an elevated temperature (∿800°C). This process step was added after removal of diffused oxides in the standard process. Back and front contacts (Ti, Pd and Ag) were evaporated after the alloying step.

Two "Silso" wafers were processed in this way; the sheet resistance of the diffused layers was measured to be 27-31 ohm/square for the controls and 26-28 ohm/square for the "Silso" wafers. One cell was broken in the metallization process and two cells were damaged in electrical testing, resulting in an overall mechanical yield of around 90% (twenty-eight starting blanks).

2.4 Grain Boundary Passivation Process

Tests were made to try and increase the carrier collection efficiency in polycrystalline silicon by

means of a heavily doped region near (or in) the grain boundaries (1). Phosphorus dopant is preferentially introduced into the grain boundaries of p-type material by a low temperature diffusion process. A subsequent high temperature diffusion forms a heavily doped skin which covers the surface of each grain. The resulting junction around each grain surface collects electrons which might otherwise recombine at the undoped grain boundaries. This grain boundary doping (passivation) scheme offers possibility of an increase of conversion efficiency in polycrystalline silicon solar cells especially if the grain structure is columnar.

An experiment was performed in an effort to improve the conversion efficiency using this method. An N-type, (phosphorus-dopant) source (Emulsitone) was spun on 2x2 cm wafers. After drying on a hot plate, those wafers were loaded in a furnace and heated at 600°C for about 24 hours in N_2 atmosphere. After removing glass layers on the spin-on side of the wafers, standard process was used. to complete the cells.

One "Silso" wafer was fabricated using this process with no breakage (mechanical yield of 100%). Sheet resistance of the diffused layers of both control and "Silso" wafers were in the range of 23-28 ohm/square and 28-30 ohm/square, respectively.

The next section summarizes the results obtained using the standard process, BSF, and attempted grain boundary passivation.

3.0 Solar Cell Performance and Characterization

3.1 Characteristics Under Illumination

Parameters of the finished solar cells were measured under AMO conditions* (135 mW/cm^2, tungsten-xenon lamps with red and blue filters) before and after applying anti-reflective coating. The measurement block temperature was 25°C and the input light intensity was calibrated using a standard balloon-flown solar cell.

Standard Solar Cells

The detailed parameter of the individual control cells and Wacker "Silso" cells are given in Appendix III, electrical data sheets. Four (4) "Silso" wafers (A, B, C and D) were processed and their average values, standard deviation and ranges are summarized in Table 2. Slightly different performance from wafer to wafer is noticed from the summary table. To see the dependence of the parameters on the location of the cells on each "Silso" wafer, mainly due to the difference in grain structure, solar cells were classified as corner cells, edge cells, and middle cells depending on the location (see Figure 1; 1 corner cell, 6 edge cells, and 9 middle cells were obtained from each wafer). From data obtained from four Wacker wafers (standard process) dependence of cell parameters on location is

*Detailed description of OCLI AMO Solar Simulator is given in Appendix II.

TABLE 2

Summary of Parameters of Solar Cells
Fabricated From Four Wacker "Silso" Wafers (A, B, C & D); Standard Process*

WAFERS		CONTROL	A	B	C	D
V_{oc} (mV)	AVERAGE	552 (545)	532 (526)	528 (523)	541 (533)	541 (533)
	STANDARD DEVIATION	4.2 (4.7)	5.5 (7.2)	6.7 (8.3)	5.2 (4.3)	8.4 (6.8)
	RANGE	544-557 (539-553)	524-543 (512-537)	513-537 (496-532)	534-549 (529-541)	532-555 (524-546)
J_{sc} (mA/cm^2)	AVERAGE	33.3 (25.6)	30.8 (22.7)	31 (23.2)	31 (23.6)	31 (24.0)
	STANDARD DEVIATION	1.3 (0.7)	0.7 (0.4)	0.6 (0.6)	0.9 (0.5)	0.8 (0.3)
	RANGE	30.5-34.5 (25-27)	29.3-31.8 (21.8-23.3)	29.8-31.8 (22-24)	29-32 (22.8-24.3)	30-32.5 (23.5-24.5)
CFF (%)	AVERAGE	73 (73)	65 (66)	67 (67)	69 (69)	68 (68)
	STANDARD DEVIATION	1.3 (1.1)	2.4 (3.3)	2.6 (3.6)	1.8 (1.8)	3.2 (2.0)
	RANGE	70-74 (71-74)	61-68 (60-70)	61-70 (58-71)	66-71 (66-72)	65-76 (65-72)
η (%)	AVERAGE	9.9 (7.5)	7.9 (5.9)	8.0 (6.0)	8.6 (6.4)	8.5 (6.6)
	STANDARD DEVIATION	0.6 (0.2)	0.4 (0.4)	0.4 (0.2)	0.4 (0.3)	0.6 (0.5)
	RANGE	8.7-10.3 (7.3-7.8)	7.1-8.6 (5.2-6.4)	7.4-8.7 (4.9-6.5)	8.1-9.2 (6.1-6.9)	7.8-9.6 (6.1-7.1)

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

2. Cells (2x2cm) with SiO anti-reflective (AR) coating, parenthesis numbers are for the parameter before AR coating.

*Later (Table 4) results are given for the modified standard process.

summarized in Table 3. As expected, due to smaller grain size at the corners and edges of Wacker wafer, solar cell efficiency clearly increases in order corner-edge-middle. All four Wacker wafers contained visible inclusions near the middle of the wafer, showing fine grain structures surrounding the inclusions and consequently producing poor solar cell performance compared with the rest of the wafer area; i.e. see cells A-10 and D-11 in Appendix III. Figure 3 shows a microscopic photograph of these inclusions which might have introduced from the container used for casting of Wacker silicon. An average conversion efficiency for the whole Wacker wafer can be estimated by considering the total area of corner cells (16 cm^2), edge cells (48 cm^2) and middle cells (36 cm^2). An average efficiency of around 8.1% (AMO) was obtained from the four Wacker wafers. In this case, the area occupied by the inclusion was <u>not</u> considered. However, the average efficiency will be lower than the above value if the area of poor performance were considered.

The initial standard process showed lower open circuit voltage and higher series resistance than expected. This was suspected to be due to a Schottky barrier formed at the back metal-silicon interface. A modified standard process (addition of a heat treatment step after back contact evaporation as described above)

TABLE 3

Dependence of Solar Cell Parameters on the Locating of a 2x2cm Blank Prepared From a Wacker "Silso" Wafer; Standard Process

		CORNER	EDGE	MIDDLE
V_{oc} (mV)	AVERAGE	532	532	538
	STANDARD DEVIATION	4.2	7.4	9.3
	RANGE	528∿538	513∿545	520∿555
J_{sc} (mA/cm^2)	AVERAGE	29.8	30.8	31.5
	STANDARD DEVIATION	0.7	0.6	0.5
	RANGE	29.3∿30.8	29.8∿32	30.5∿32.5
CFF (%)	AVERAGE	66	67	68
	STANDARD DEVIATION	3.6	1.8	3.2
	RANGE	62∿71	65∿69	61∿76
η (%)	AVERAGE	7.7	8.1	8.5
	STANDARD DEVIATION	0.5	0.3	0.5
	RANGE	7.1∿8.2	7.4∿8.7	7.3∿9.6

NOTE: Cells (2x2cm) with SiO AR coating measured under AMO condition at 25°C.

FIGURE 3

A Microscopic Photograph of Inclusions in Wacker Wafer (200X Magnification)

significantly improved the characteristics under illumination for both "Silso" cells and controls; average conversion efficiency increased from 8.1% to 9.6% for "Silso" cells and from 9.9% to 11.2% for control cells. Electric data sheets are in Appendix III and Table 4 summarizes parameters of these cells. Open circuit voltage of control cells showed greater improvement than those using Wacker silicon (compare V_{oc} in Table 4 and Table 2). The dependence of the parameters on the location of the cells on each "Silso" wafer was also obtained in Table 5, showing similar results with Table 3.

BSF Wacker Silicon Solar Cells

Back surface field solar cells showed an average efficiency of about 9.5%, about the same efficiency as the standard solar cells (modified); slightly improved short circuit current was offset by the decrease in open circuit voltage. However, efficiencies of the controls increased to 12.1% (about 1% conversion efficiency increase over the modified standard process cells) by improvement in both short circuit current and open circuit voltage. Individual cell parameters are listed in Appendix III and statistics are summarized in Table 6. In an effort to see the upper limit of efficiency of the Wacker sheets, fine contact lines (active area of the cell is around 93%) and multilayer

TABLE 4

Summary of Parameters of Solar Cells
Fabricated From a Wacker "Silso" Wafer (J); Modified Standard Process

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	558 (549)	30.5 (22.2)	77 (77)	9.6 (6.9)
STANDARD DEVIATION	6.1 (7.4)	0.8 (0.6)	1.3 (2.0)	0.5 (0.4)
RANGE	549-565 (539-555)	29.3-31.5 (21.3-23)	73-79 (72-79)	8.8-10.2 (6.3-7.3)

Control Cells

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	593 (586)	32.9 (24)	78 (78)	11.2 (8.2)
STANDARD DEVIATION	N.A.	N.A.	N.A.	N.A.
RANGE	591-595 (584-588)	32.8-33 (23.8-24.3)	77-79 (76-80)	11.1-11.3 (8.0-8.2)

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

2. Cells (2x2cm) with SiO AR coating, parenthesis numbers are for the parameters before AR coating.

TABLE 5

Dependence of Solar Cell Parameters on the Location of a 2x2cm Blank Prepared From a Wacker "Silso" Wafer (I); Modified Standard Process

		CORNER*	EDGE	MIDDLE
V_{oc} (mV)	AVERAGE	N.A.	551	563
	STANDARD DEVIATION	N.A.	1.8	1.5
	RANGE	N.A.	549∿554	561∿565
J_{sc} (mA/cm^2)	AVERAGE	N.A.	29.6	31
	STANDARD DEVIATION	N.A.	0.2	0.2
	RANGE	N.A.	29.3∿29.8	30.8∿31.5
CFF (%)	AVERAGE	N.A.	76	78
	STANDARD DEVIATION	N.A.	1.5	0.7
	RANGE	N.A.	73∿77	76∿79
η (%)	AVERAGE	N.A.	9.2	10.0
	STANDARD DEVIATION	N.A.	0.2	0.2
	RANGE	N.A.	8.8∿9.4	9.8∿10.2

NOTE: Cells (2x2cm) with SiO AR coating measured under AMO condition at 25°C.

*Cell broken, could not evaluate.

TABLE 6

Summary of Parameters of Solar Cells Fabricated From Wacker "Silso" Wafers (E & F); Back Surface Field (BSF) Process

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	545 (536)	31.5 (22.6)	75 (74)	9.5 (6.6)
STANDARD DEVIATION	8.4 (8.3)	0.9 (0.7)	1.8 (2.7)	0.5 (0.4)
RANGE	528-557 (518-547)	29.5-33 (21.3-23.8)	71-79 (66-77)	8.2-10.2 (5.7-7.2)

Control Cells

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	602 (593)	35.5 (25.8)	77 (75)	12.1 (8.6)
RANGE	601-602 (591-593)	35.3-35.8 (25.8-26)	75-78 (72-78)	12.0-12.3 (8.2-8.9)

Cells With Fine Contact Line and MLAR Coating

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	556	34.2	77	10.7
RANGE	550-561	33.6-34.8	75-78	10.6-10.8

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

2. Cells (2x2cm) with SiO AR coating, parenthesis numbers are for the parameters before AR coating.

anti-reflective coating were applied to three of the BSF cells, resulting in an average conversion efficiency of 10.7%. Results are summarized in a bottom table of table 6. Positional dependence of BSF cell performance is given in Table 7 with the similar results with the solar cells from the other processes.

Grain Boundary Passivated Solar Cells

Solar cells from the grain boundary passivation process showed very close performance characteristics with the cells from the standard process, indicating no improvement was achieved by using this process modification. Electrical data sheets and summary tables are given in Appendix III and Table 8, respectively.

3.2 Dark I-V Characteristics

Dark I-V characteristics (forward and reverse) were obtained from the selected solar cells. The plot was made by point-by-point measurement using digital multimeters. Room temperature plots of the dark I-V curves for solar cells from various processes are given in Figures 4 through 7. Sometimes dark diode currents of a solar cell can be expressed in a simple way,

$$I_D = I_o \left(\exp \frac{qV}{AkT} - 1\right)$$

This could be the case at high forward bias condition (V>0.4 volts) in which diffusion component dominates

TABLE 7

Dependence of Solar Cell Parameters on the Location of a 2x2cm Blank Prepared From Wacker "Silso" Wafers (E & F): BSF Process

		CORNER	EDGE	MIDDLE
V_{oc} (mV)	AVERAGE	531	540	552
	STANDARD DEVIATION	N.A.	2.6	4.2
	RANGE	528∿533	534∿541	547∿557
J_{sc} (mA/cm^2)	AVERAGE	29.6	31.0	32.0
	STANDARD DEVIATION	N.A.	0.4	0.5
	RANGE	29.5∿29.8	30.5∿31.8	31.3∿33
CFF (%)	AVERAGE	72	75	75
	STANDARD DEVIATION	N.A.	1.2	1.6
	RANGE	71∿72	74∿77	73∿79
η (%)	AVERAGE	8.4	9.4	9.9
	STANDARD DEVIATION	N.A.	0.2	0.3
	RANGE	8.2∿8.5	8.9∿9.6	9.4∿10.2

NOTE: Cells (2x2cm) with SiO AR coating measured under AMO condition at 25°C.

TABLE 8

Summary of Parameters of Solar Cells Fabricated From a Wacker "Silso" Wafer (I); Grain Boundary Passivated Process

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	554 (543)	30 (22)	76 (75)	9.4 (6.6)
STANDARD DEVIATION	9.0 (9.0)	5.3 (1.0)	0.5 (3.2)	0.6 (0.5)
RANGE	536-565 (524-552)	27.5-31.5 (20-23)	76-77 (65-78)	8.2-10.1 (5.8-7.2)

Control Cells

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	592 (582)	32.8 (24.2)	78 (76)	11.2 (7.9)
STANDARD DEVIATION	N.A.	N.A.	N.A.	N.A.
RANGE	590-593 (580-585)	32.5-33.3 (24-24.3)	77-79 (74-79)	10.9-11.6 (7.6-8.3)

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

2. Cells (2x2cm) with SiO AR coating, parenthesis numbers are from the parameters before AR coating.

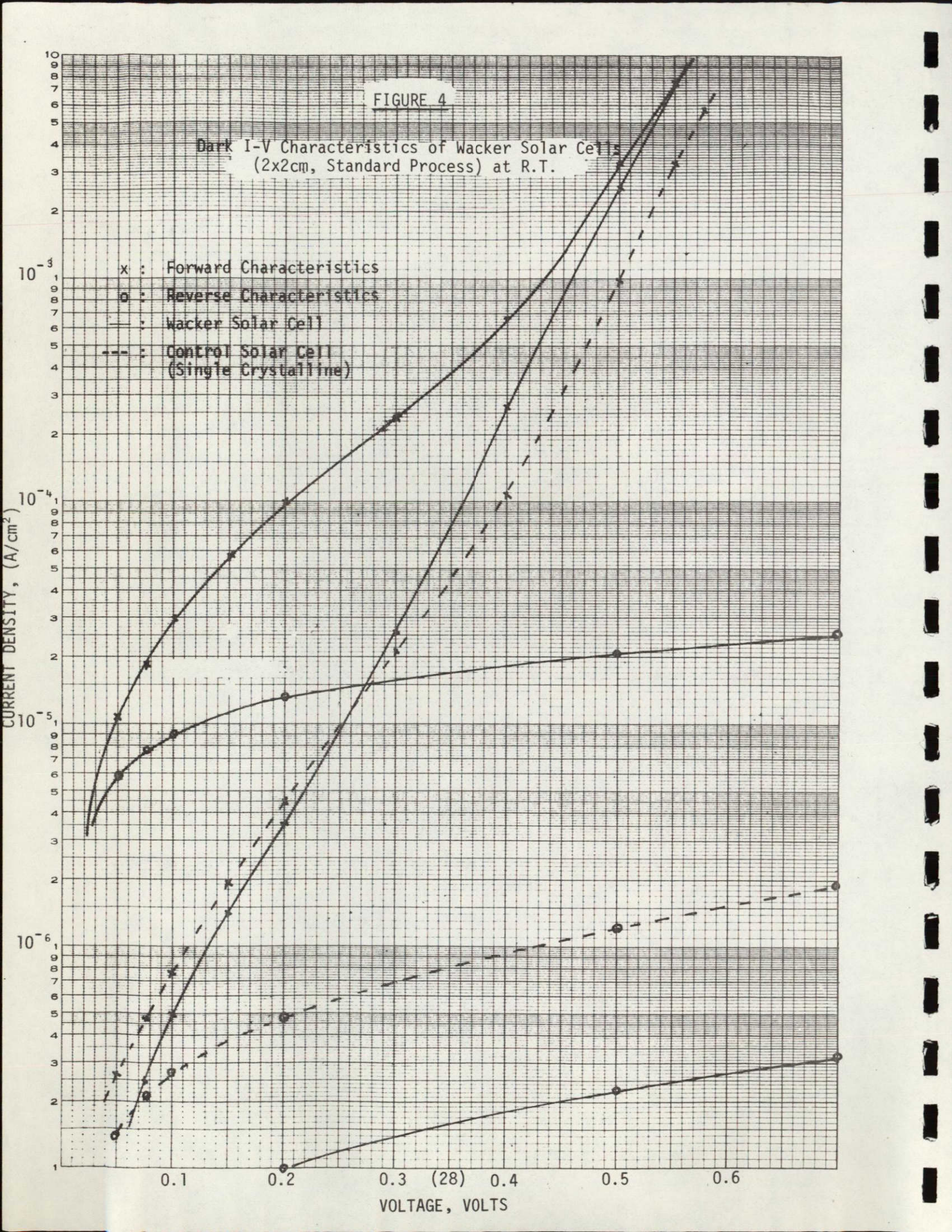


FIGURE 4
Dark I-V Characteristics of Wacker Solar Cells
(2x2cm, Standard Process) at R.T.
x : Forward Characteristics
o : Reverse Characteristics
— : Wacker Solar Cell
--- : Control Solar Cell
(Single Crystalline)
CURRENT DENSITY, (A/cm²)
VOLTAGE, VOLTS
0.1
0.2
0.3
0.4
0.5
0.6

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FIGURE 5

Dark I-V Characteristics of Wacker Solar Cells
(2)2cm, Modified Standard Process) at R.T.

x: Forward Characteristics

o: Reverse Characteristics

——: Wacker Cells

---: A Control Cell (Single Crystalline)

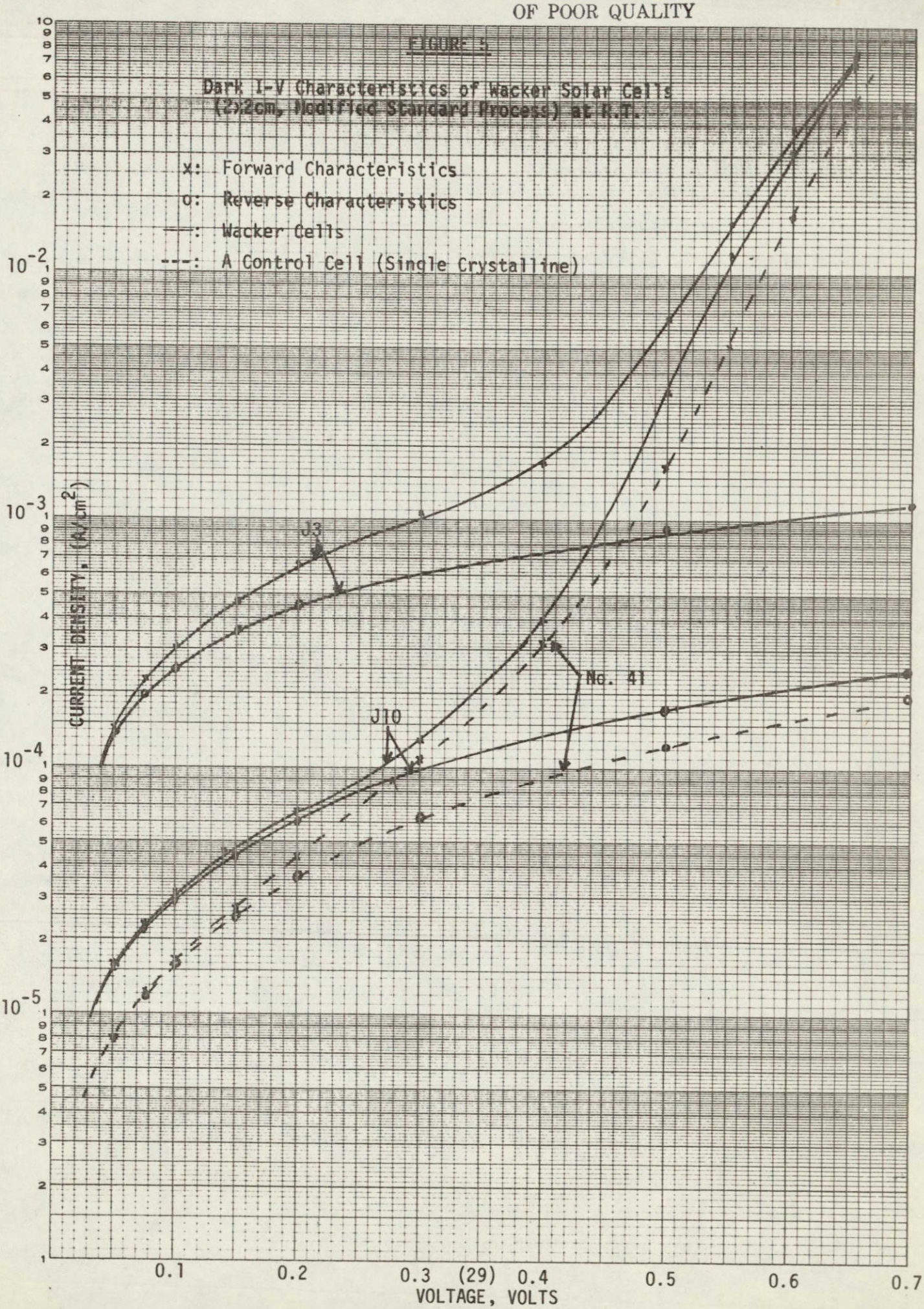

FIGURE 6

Dark I-V Characteristics of Wacker Solar Cells
(2x2cm, BSF Process) at R.T.

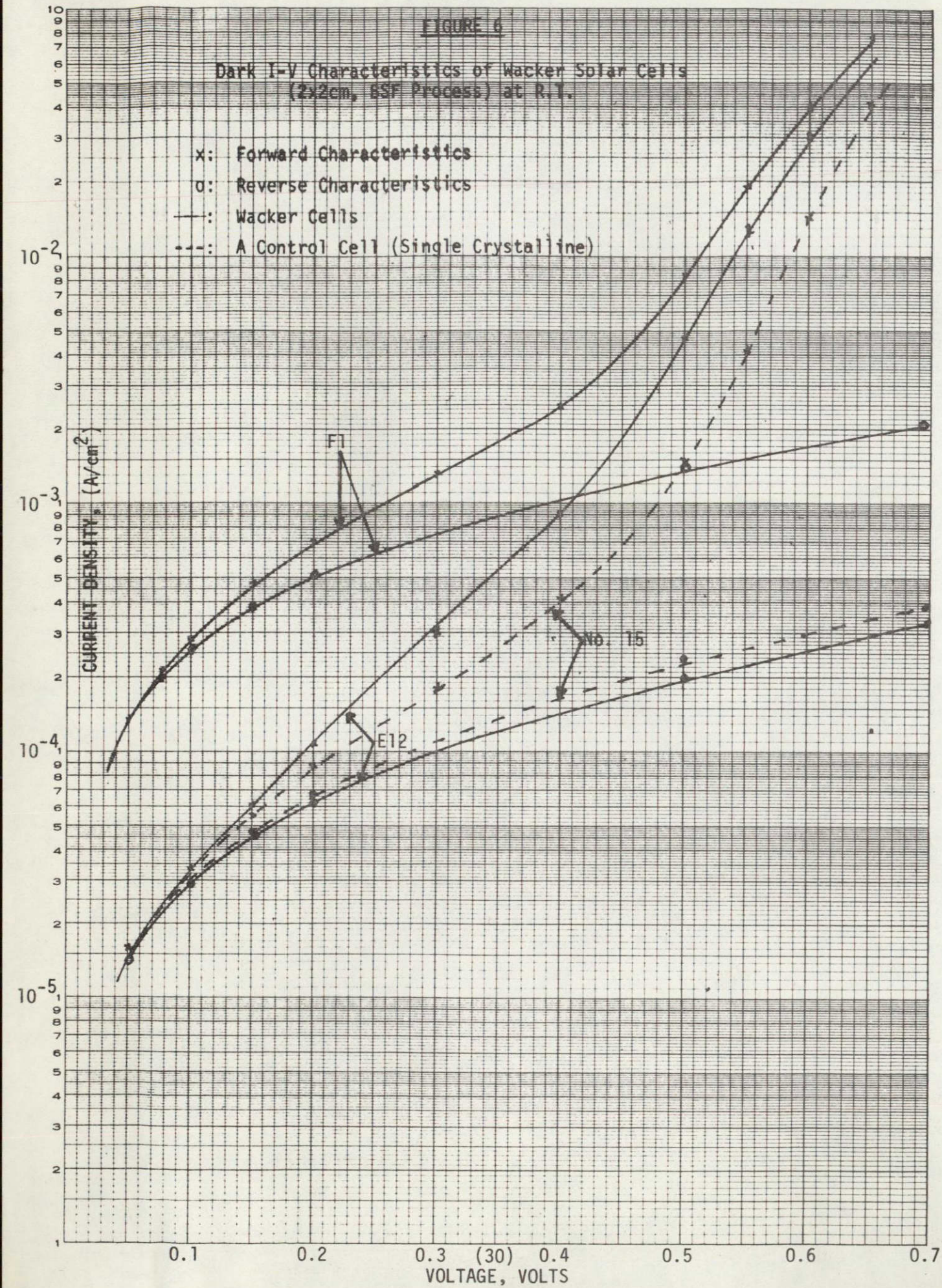

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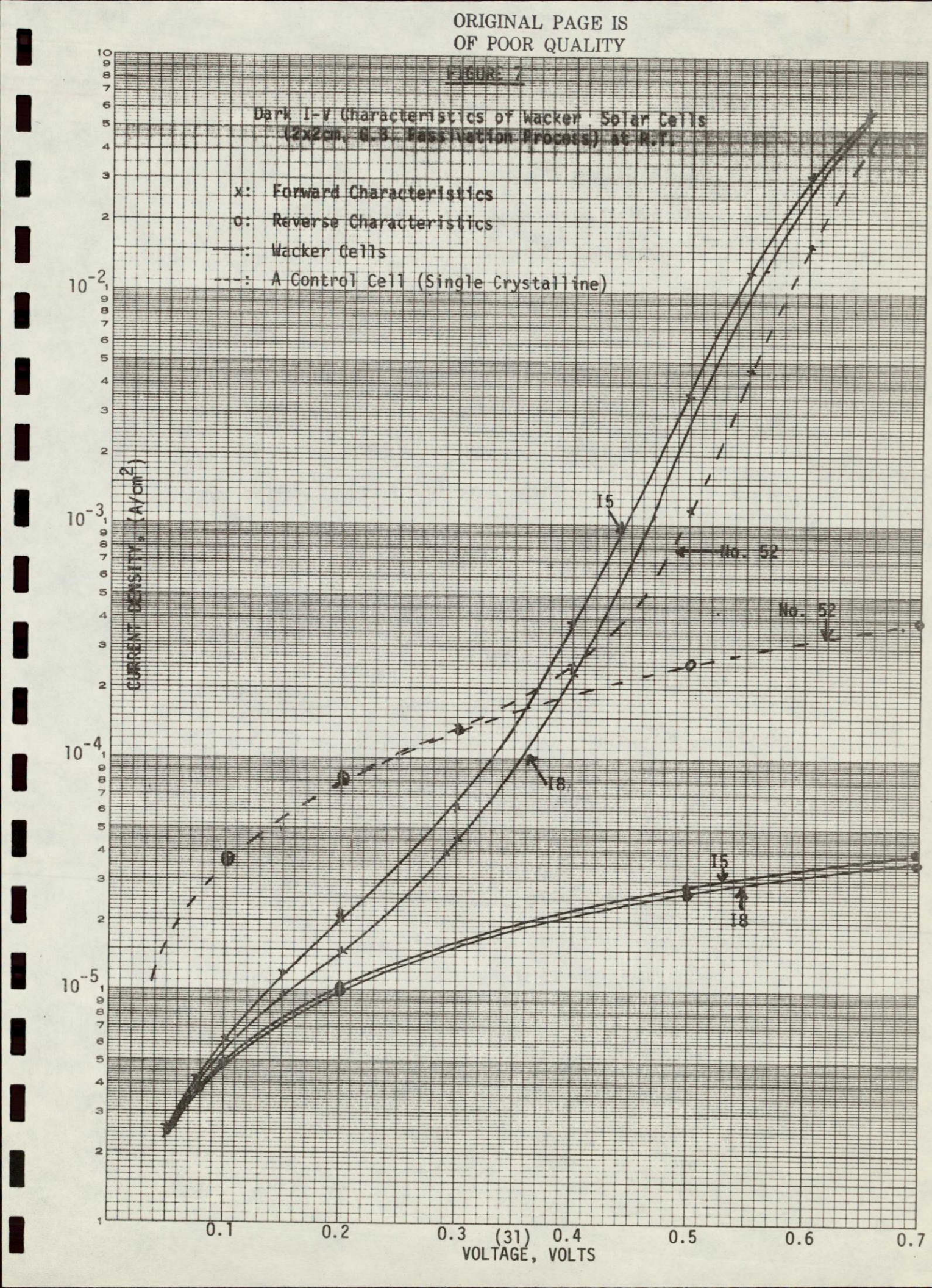
FIGURE 7

Dark I-V Characteristics of Wacker Solar Cells
(2x2cm, G.E. Passivation Process) at R.T.

x: Forward Characteristics
o: Reverse Characteristics
——: Wacker Cells
---: A Control Cell (Single Crystalline)



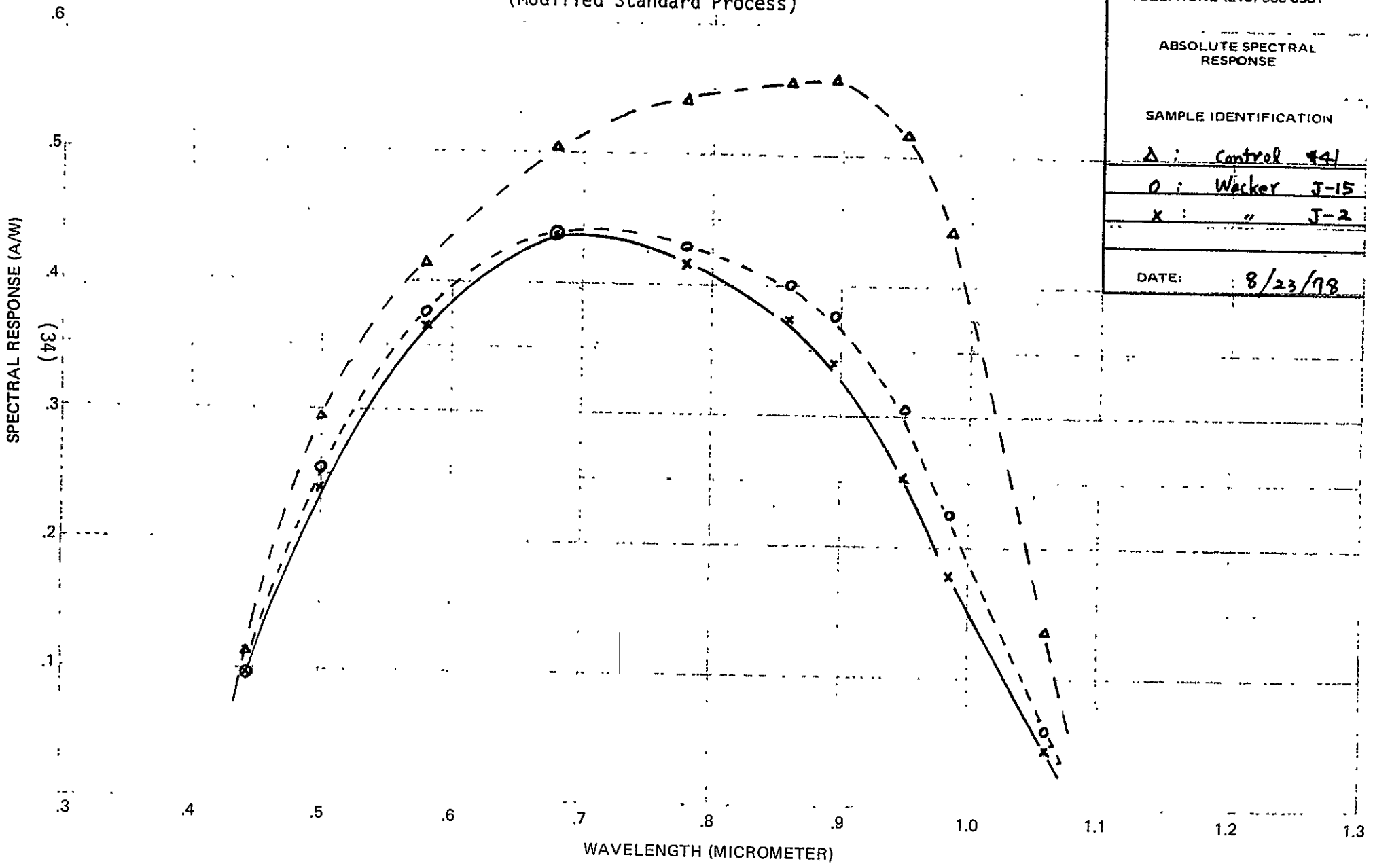
diode current. In this case "A" factor in the equation shows deviation from ideal diode characteristics, i.e. it indicates the degree of influence from the space charge recombination and shunt component of the current. Calculated "A" values from the curves ranged from 1.4 to 2.2, indicating significant deviation from the ideal diode case in which the "A" factor is unity. I_o was also obtained from the plots. A relatively wide range of I_o was observed, from 10^{-6} A/cm^2 to 10^{-9} A/cm^2; solar cells with small grain structure, such as corner cells and edge cells, showed larger values. This indicates that low open circuit voltage of the cells with small grain size is due to the large value of I_o.

3.3 Spectral Response

Absolute spectral response (A/W) was measured using a filter wheel which is a combination of a set of narrow bandwidth filters and a light source (tungsten lamp operated at color temperature of 2800°C). Spectral response of the solar cells was obtained by reading the current (short circuit) of the cells (to be measured) at known wavelengths and by calibrating this current to the current of a cell of known spectral response (standard cell of known spectral response). The active area of the solar cells was included in the calculation. Figures 8 through 11 show spectral response of Wacker cells and typical

FIGURE 9

Spectral Response of Wacker Solar Cells
(Modified Standard Process)



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CITY OF INDUSTRY, CA 91746
TELEPHONE (213) 968-6581

ABSOLUTE SPECTRAL RESPONSE

SAMPLE IDENTIFICATION

Δ : Control #4
O : Wacker J-15
X : " J-2

DATE: 8/23/78

FIGURE 10

Spectral Response of Wacker Solar Cells
(BSF Process)

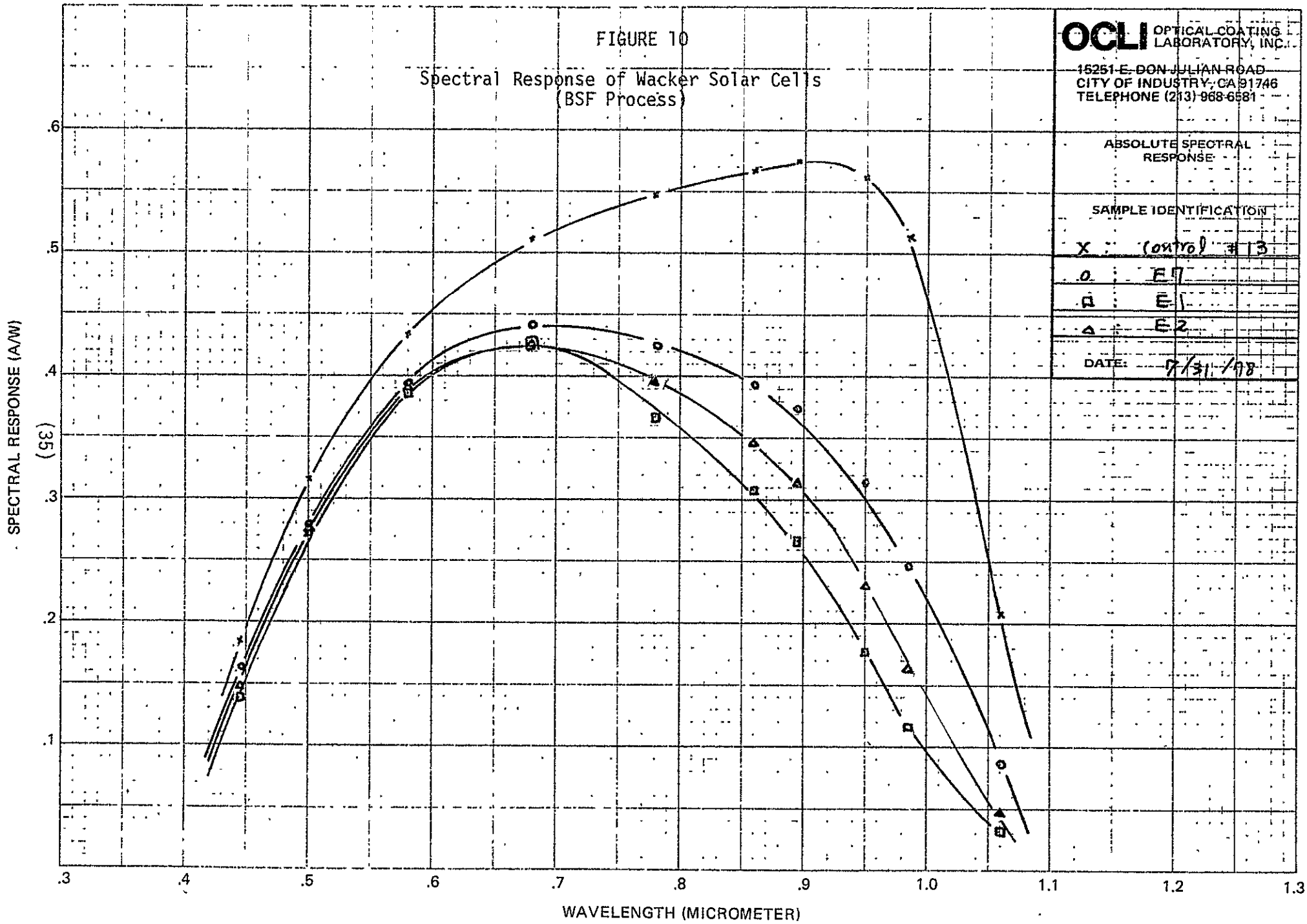

FIGURE 11

Spectral Response of Wacker Solar Cells
(G.B. Passivation Process)

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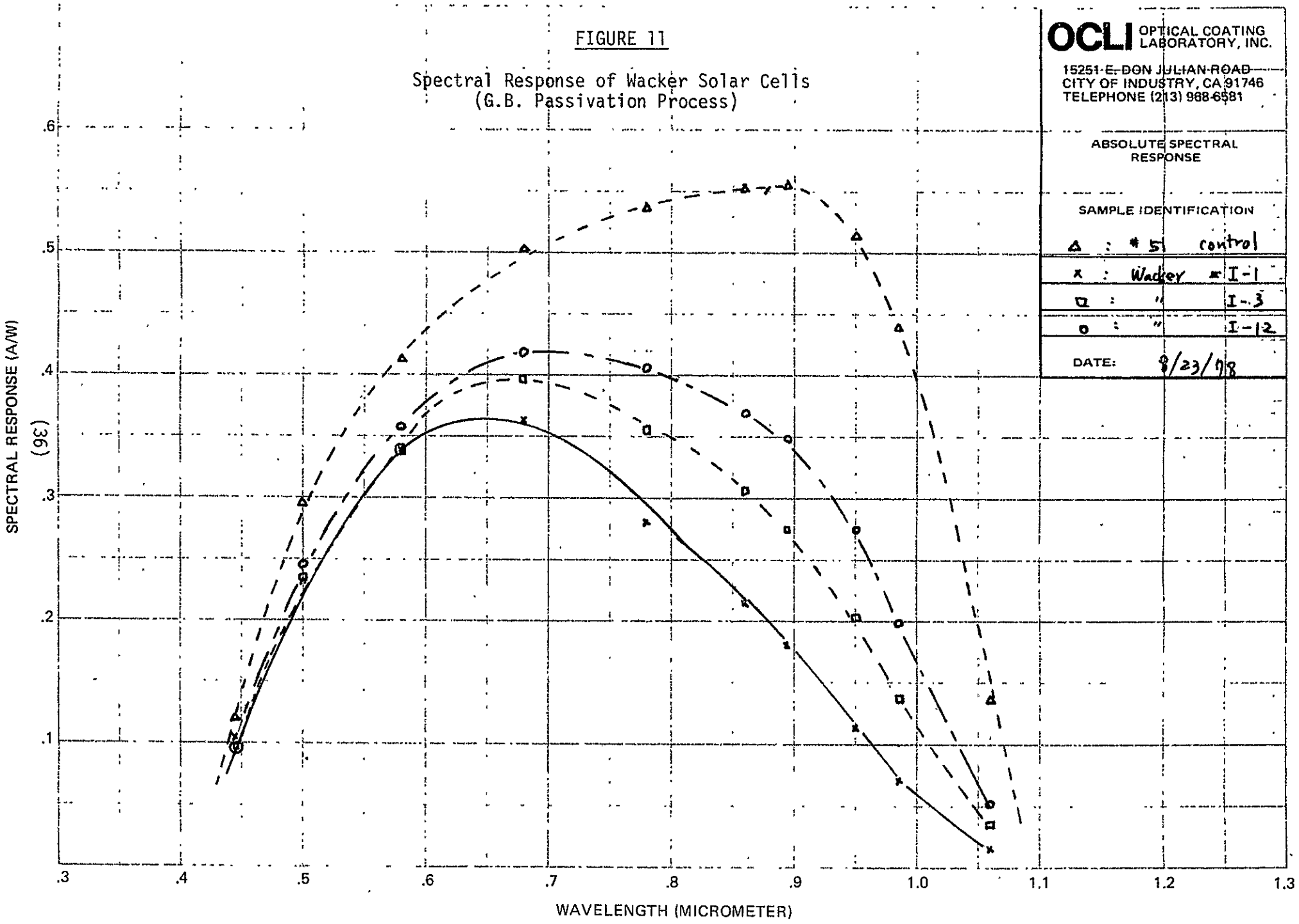
ABSOLUTE SPECTRAL RESPONSE

SAMPLE IDENTIFICATION

Δ : # 5 control
x : Wacker # I-1
□ : " I-3
○ : " I-12

DATE: 8/23/78



control cells of different process modification. Cells made from Wacker wafers indicated lower spectral response than single crystalline control cells at longer wavelengths (>0.6 μm), mainly due to smaller minority carrier diffusion length caused by grain boundary effects. The Wacker cells with lower spectral response were located in the edge (small grain size) while Wacker cells with higher response were located in the middle (large grain size) of the Wacker wafers, confirming the effect of grain size on spectral response of solar cells. The spectral response variations also agreed with the cell performance variations. However, no significant difference in spectral response was noticed from Wacker cells taken through the process variations tried (BSF, GB passivation).

3.4 Minority Carrier Diffusion Length

Minority carrier diffusion length (D.L.) was measured using the surface photovoltage (SPV) method on both bulk "Silso" wafers and diffused wafers. The exposed filtered beam size was about 2-3 mm in diameter and the results are summarized in Table 9. Generally middle blanks showed higher D.L., showing D.L. in some spots as close to those of single crystalline silicon. No significant change in D.L. before and just after the diffusion step were observed. Diffusion length measurement was also carried out using a short circuit current method

TABLE 9

Minority Carrier Diffusion Length
Measurement on Bulk Wacker Wafers

	CORNER & EDGE	MIDDLE
AVERAGE	43 (35)	75 (88)
STANDARD DEVIATION	5 (5)	15 (19)
RANGE	40-55 (30-40)	60-130 (55-120)

NOTE: 1) Parenthesis numbers for the diffused wafers without contacts.

2) Measurement by SPV method with a light beam size ~2-3 mm diameter.

3) Unit; μm.

(2) for the finished solar cells. The whole area of a solar cell was illuminated by light source through a filter wheel and the effective minority carrier diffusion length of a solar cell was obtained from light intensity values at selected wavelengths. Wavelengths used for this measurement were 0.78, 0.86, 0.895 and 0.95 μm. The wavelength dependence of reflection and absorption in anti-reflective coating layer was not considered for simplicity (generally, a straight line plot could be achieved). Table 10 summarizes the diffusion length values of solar cells made from four Wacker wafers (A, B, C and D) and Table 11 indicates the dependence of diffusion length on location of each cell in a wafer, such as corners, edges and middle. Diffusion length of solar cells (2x2 cm) ranged from 30-65 μm, showing lower diffusion length for the cells fabricated from either corners or edges of a wafer. Diffusion length measurement using small beam size (∿3-4 mm beam diameter) indicated that significant variation in the values are observed even within a single solar cell (2x2 cm). These are well illustrated in Figure 12, again indicating smaller diffusion length at spots close to edge due to small grain structure.

Diffusion length measurement was performed on areas of the wafer containing inclusions (as in A-10 and D-11 solar cells). Diffusion length values were about the

TABLE 10

Minority Carrier Diffusion Length of Solar Cells (2x2cm) Fabricated From Four Wacker Wafers (A, B, C and D)

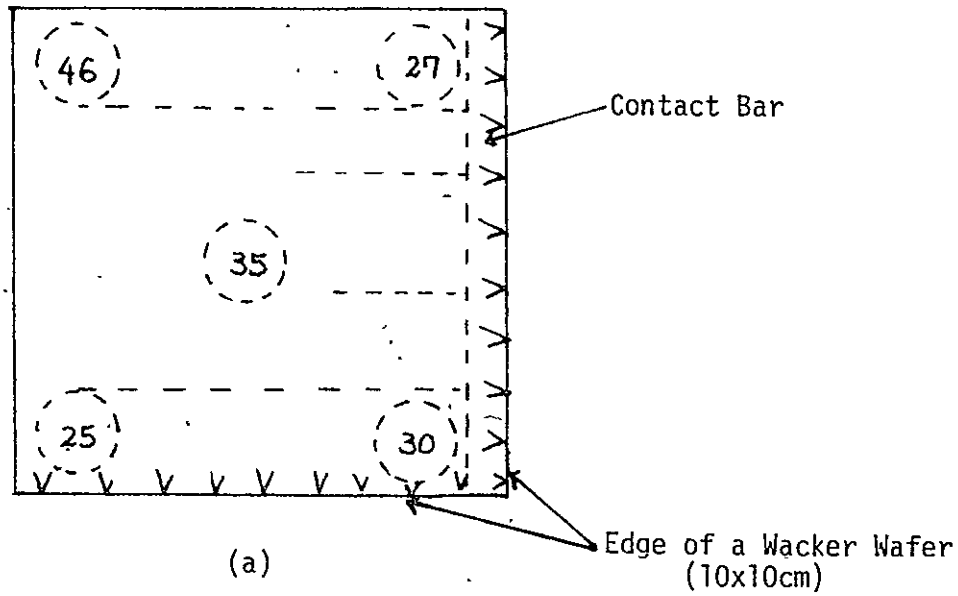
WAFERS		CONTROL	A	B	C	D
Le (μm)	AVERAGE	130	47	46	52	51
	STANDARD DEVIATION	N.A.	7.7	11.7	10	9.5
	RANGE	130-140	33-56	33-61	35-65	31-60

TABLE 11

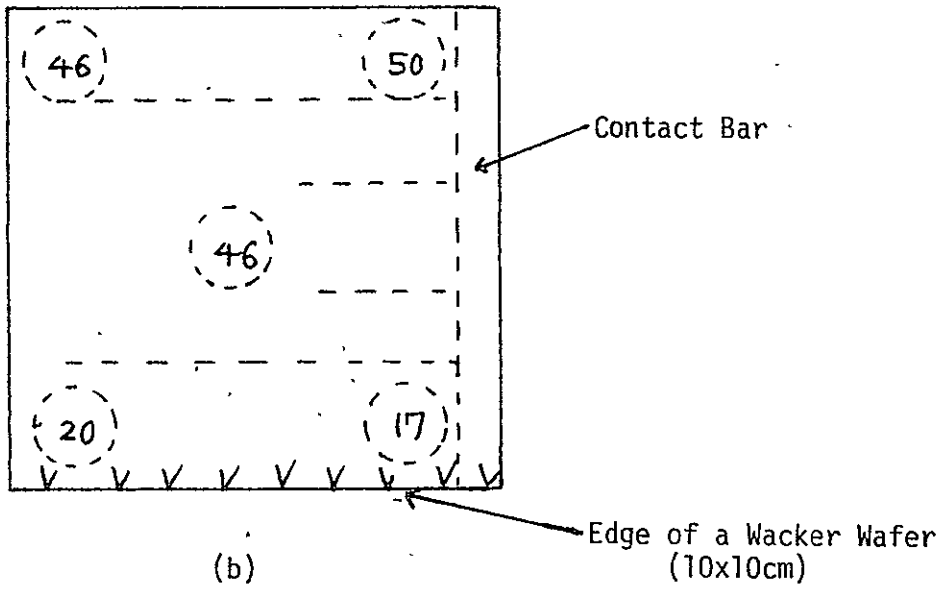
Dependence of Diffusion Length of Solar Cells on the Location of a 2x2 cm Blank Prepared From a Wacker Wafer

LOCATION		CORNER	EDGE	MIDDLE
Le (μm)	AVERAGE	33	44	56
	STANDARD DEVIATION	1.6	5.4	5.4
	RANGE	31-35	34-51	49-65

NOTE: 1) Measurement by I_{sc} method.
2) Illuminated whole area of 2x2cm cells.
3) Unit; μm.



(a)



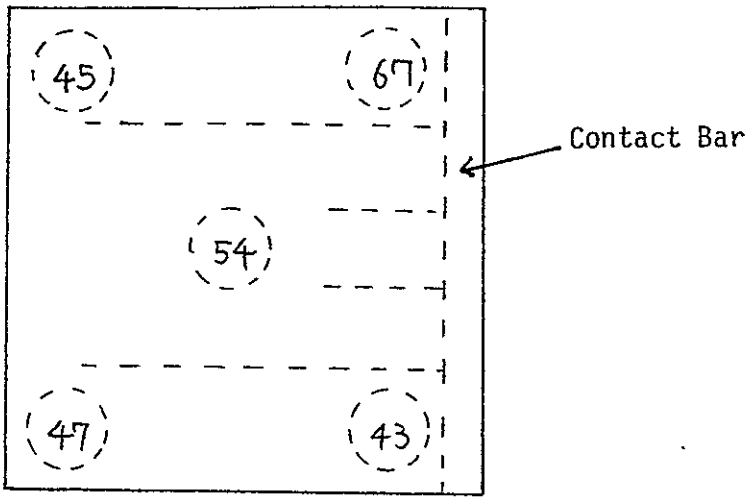
(b)

FIGURE 12

Minority Carrier Diffusion Length (μm) Variation
Within a Wacker Solar Cell (2x2cm), Measured by I_{sc} Method
With an illuminated Beam Size of ∿3-4mm Diameter

a) A Corner Solar Cell (A1)

b) A Edge Solar Cell (A3)



(c)

FIGURE 12

Minority Carrier Diffusion Length (μm) Variation
Within a Wacker Solar Cell (2x2cm), Measured by I_{SC} Method
With an Illuminated Beam Size of ∿3-4mm Diameter

c) A Middle Solar Cell (A11)

same as the rest of the cell area. This indicated that the poor performance of these cells are not due to the small grain structure, but due to shunting caused by those inclusions.

B. EFG Ribbon Solar Cells

1.0 Preparation and Description on Blanks

The EFG ribbons delivered were of the R.F. furnace grown type with visible surface undulations and inclusions from the die materials. The ribbon was about one inch wide and was sliced into approximately 1x1 inch blanks. Thickness was measured (by micrometer), at several locations of each blank, indicating around 13 mils at the edges and 10 mils in the middle. To obtain detailed information on the surface profile of the ribbons, a Dektak (Sloan) was used to scan thickness across the width of the ribbons. Figure 13 shows a typical profile of a ribbon surface, indicating significant variation in thickness across the ribbon width.

NOTE: In the worst case, thickness could be around 6 mils or less at certain localized areas, indicating problems of handling in the process of cell fabrication.

Since most of the blanks showed warpage, a bow gauge (Brown & Sharp) was used to show the degree of warpage (this may not be the proper way to check the warpage of such blanks). From 15 samples of 1" x 1" blanks bows were averaged to be around 2.0 mils with the range of 0.4->3.0 mils.

Resistivity measurement by four point probe ranged between 0.8-2.8 ohm-cm with p-type conductivity. This might not necessarily indicate accurate bulk resistivity because of thickness variations and possible grain boundary effects.

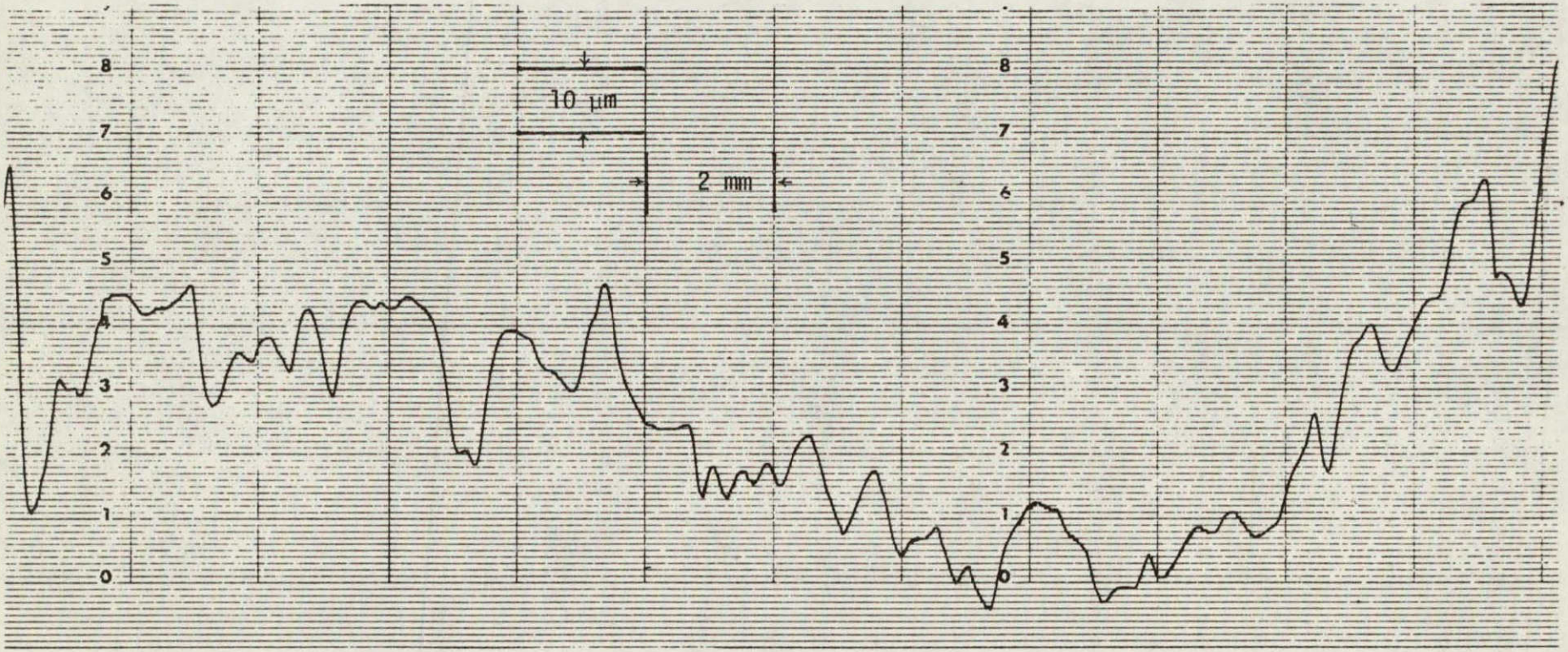


FIGURE 13

A Typical Surface Profile Across the Width of a EFG Ribbon
(Ribbon Width ∿1") by Dektak (Sloan)

SPV measurement of minority carrier diffusion length from a number of measurements with the beam size of 3-4 mm in diameter indicated values between 30-70 μm.

Initial cleaning of the blanks was done by organic solvent in ultrasonic cleaner, to remove most of the contaminants from wafer handling. However, a hazy color on the surface was difficult to eliminate without removing some silicon. Following efforts were made to remove hazy surface features.

1. Dip in HF.
2. Boil in hot D.I. water followed by HF dip (since haze was suspected to be a thin SiO layer).
3. Clean in H_2SO_4; H O = 1:1
4. Standard RCA Clean
   Solution 1 - NH_4oH; H_2O_2; H_2O = 1:1:5
   Solution 2 - HCL; H_2O_2; H_2O = 1:1:5

None of the above procedure succeeded in removing the haze. Thus, the standard wafer cleaning procedure was chosen to be the initial organic solvent cleaning procedure which will remove all the surface contamination from wafer handling.

breakage are listed in Table 12. An analysis indicated that the most of the breakage are closely related with the non-flat features of the ribbons and possibly to residual stress in the blanks. This is considered to be a significantly low yield compared with either the single crystalline or "Silso" cells.

2.2 Back Surface Field Process

The same BSF process, described in Section A.2.3, was used for EFG sheets with the modification of front contact formation by photolithographic techniques as described in the previous section (B.2.1).

Finished EFG solar cells showed a mechanical yield of about 54%; again 13 cells out of 28 starting sheets were broken in this process. Detailed cause of the breakage are given in Table 13, and again are attributed to the properties of the starting ribbon.

TABLE 12

Mechanical Failure of EFG Solar Cells
in the Process of Fabrication; Standard Process

NUMBER OF BROKEN CELLS	CAUSE
3	TEST Diamond Scribing 1 Back Contact 2
2	FRONT CONTACT Photoresist Spin 1 Develop & Rinse 1
1	BACK CONTACT
2	EDGE TRIMMING OR CUTTING USING DICING SAW
2	ELECTRICAL TEST

Starting: 22 Wafers

TABLE 13

Mechanical Failure of EFG Solar Cells
in the Process of Fabrication; BSF Process

NUMBER OF BROKEN CELLS	CAUSE
1	INITIAL CLEANUP PROCESS
4	BSF PROCESS Al Screen Printing 1 Al Alloy (Al Penetration) 1 Al Scrubbing (Residual) 1 Acid Clean (Remove Excess Al) 1
2	FRONT CONTACT, PHOTORESIST EXPOSURE
4	ELECTRICAL TEST
1	EDGE TRIMMING
1	PROCESS MISTAKE

Starting: 28 Wafers

3.0 Solar Cell Performance and Characterization

3.1 Characteristics Under Illumination

Solar cell parameters, such as I_{sc}, V_{oc}, CFF and η, were measured under AMO solar simulation at 25°C. Electrical data sheets in Appendix IV give detailed information on individual cells and Table 14 and Table 15 summarize the results for cells of two process types, standard process and BSF process, respectively. BSF solar cells showed improved efficiency compared with standard solar cells, 8.5% versus 7.8%, with the overall increase in I_{sc}, V_{oc}, and CFF.

Conversion efficiency of EFG solar cells was less than those of "Silso" solar cells and also less than recently reported results with EFG ribbon, mainly due to lower V_{oc} and CFF. This was suspected to be due to shunting by SiC (die material), which can be detected visually on the surface of the ribbon in many cases. Thus, a number of experiments were done to eliminate the effect of those particles by isolating and dicing off the area possessing the inclusions. In one case open circuit voltage increased from 525 (mV) to 545 (mV) while curve fill factor improved from 58% to 66% after removal of some inclusions. A typical inclusion, which is presumed to have orginated from die material, is shown in Figure 14 (from Cell No. 13). However, improvement in either V_{oc} or CFF was not always obtained after the

TABLE 14

Summary of Parameters of Solar cells
Fabricated From EFG Ribbons; Standard Process

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	540 (529)	28.8 (21.4)	67.8 (64.8)	7.8 (5.5)
STANDARD DEVIATION	12.5 (14.4)	1.2 (1.4)	8.9 (11.6)	1.3 (1.2)
RANGE	517-556 (496-549)	26.3-30.2 (18.8-22.9)	52-79 (43-80)	5.8-9.6 (3.5-7.1)

Control Cells

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	596 (589)	33.65 (24.3)	79 (78)	11.8 (8.3)
STANDARD DEVIATION	0 (0)	0.1 (0.1)	1.1 (1.8)	0.2 (0.2)
RANGE	596 (589)	33.5-33.8 (24.3-24.5)	78-80 (76-80)	11.6-12 (8.0-8.5)

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

2. Cells ($\sim$5-6cm^2 in area) with SiO AR coating, parenthesis numbers are for the parameters before AR coating.

TABLE 15

Summary of Parameters of Solar Cells
Fabricated From EFG Ribbon; BSF process

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	549 (538)	29.4 (22.4)	71 (70)	8.5 (6.2)
STANDARD DEVIATION	14 (17.5)	1.3 (1.2)	7.4 (7.5)	1.1 (0.9)
RANGE	533-572 (506-565)	26-31.2 (19.9-24.3)	55-78 (51-77)	6.5-10.3 (4.4-7.8)

Selected EFG Cells With MLAR Coating

	V_{oc} (mV)	J_{sc} (mA/cm^2)	CFF (%)	η (%)
AVERAGE	572 (562)	32.3 (24.2)	78 (76)	10.6 (7.7)

Control Cells

AVERAGE	603 (597)	33.9 (24.8)	76 (75)	11.5 (8.2)

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

2. Cells ($\sim$5-6cm^2 in area) with SiO AR coating (middle table is for the selected EFG cells with MLAR coating), parenthesis numbers are for the parameters before AR coating.

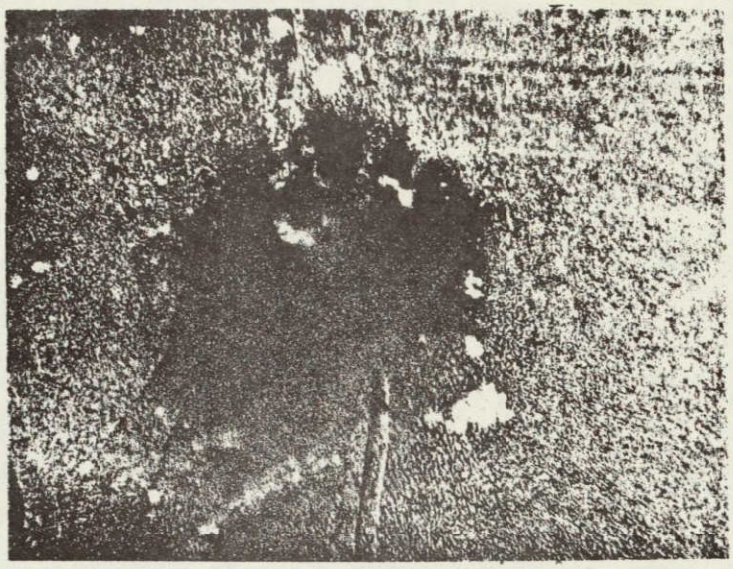


FIGURE 14

A Microscopic Photograph of a Typical Surface Inclusion in EFG Ribbon (50x Magnification)

removal of specific surface inclusions. This indicated that either there are microscopic particles that cannot be detected by eye or it may depend on the way that the particle is embedded in silicon matrix. For example, a particle might not cause any shunting problem if the particle is completely isolated by the coverage of a thin silicon layer all over the surface of the particle.

Selected solar cells from BSF process were coated with MLAR coating (instead of SiO AR coating) to show the improvement of the performance. The results are given in the middle table of the Table 15. Although an average efficiency of about 10.6% was obtained, improvement in short circuit current after MLAR coating was only about 33%. (Generally close to 50% current gain after MLAR coating was achieved in single crystalline solar cell case.) This reduced coating gain could be the result of the haze remianing on the starting blanks. The figures quoted for highest efficiency can be characterized as "preliminary", because of limited tests, and small sample size.

Limited solar cells (Cell Nos. 1 through 4) were fabricated from the ribbons of chemically etched surface to check the performance difference between cells with and without etching step (the ribbons were chemically etched in planar solution for about two minutes, which

will remove about 10 μm of silicon from each side of a ribbon). No significant difference in performance were observed (refer to data sheets in Appendix IV for detailed information). However, these solar cells showed slightly lower short current density than the solar cells without chemical etching. Reasons for this difference have not been identified yet.

3.2 Dark I-V Characteristics

Measurement techniqeus were described in previous Section A.3.2. Plots of the selected solar cells are given in Figure 15 for the standard process and Figure 16 for the BSF process. "A" factor and I_o in the diode equation (described in Section A.3.2) were in the range of 1.5-3 and 10^{-7}-10^{-6} A/cm^2, respectively. These are slightly increased values compared with the "Silso" solar cells, and this result agrees with the slightly lower open circuit voltage and curve fill factor of EFG solar cells.

3.3 Spectral Response

Absolute spectral response (A/W) was measured using the same method described in Section A.3.3. Plots of the response are given in Figure 17 for the standard cells and in Figure 18 for the BSF cells. Spectral response of EFG cells at long wavelength (λ >0.6 μm) was significantly lower than those of the single crystalline control cells

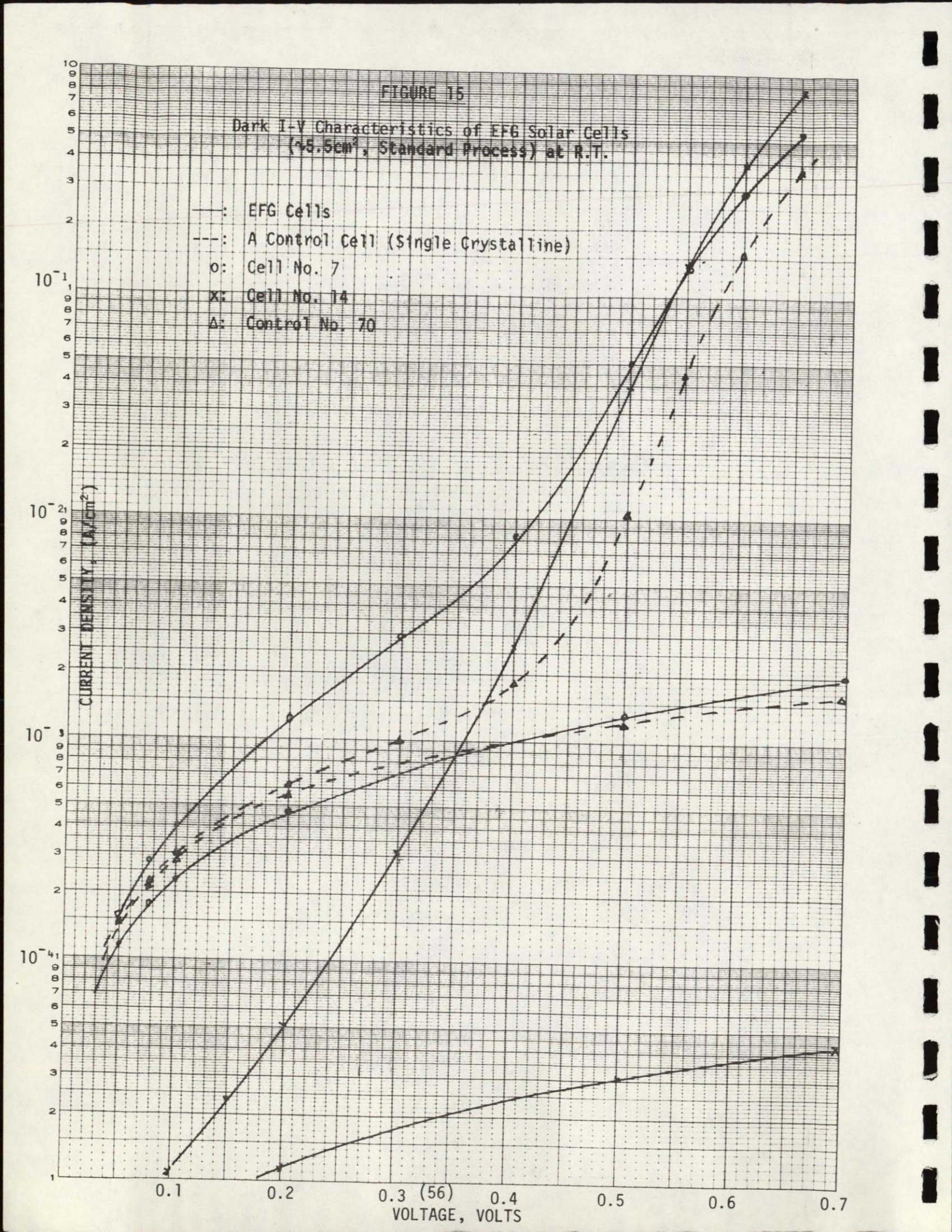


FIGURE 15
Dark I-V Characteristics of EFG Solar Cells
(48.5cm², Standard Process) at R.T.
——: EFG Cells
---: A Control Cell (Single Crystalline)
o: Cell No. 7
X: Cell No. 14
Δ: Control No. 70
CURRENT DENSITY, (A/cm²)
VOLTAGE, VOLTS
0.1
0.2
0.3
0.4
0.5
0.6
0.7

FIGURE 16

Dark I-V Characteristics of EFG Solar Cells
(~ 5.5cm², BSF Process) at R.T.

x: Cell No. 50

o: Cell No. 29

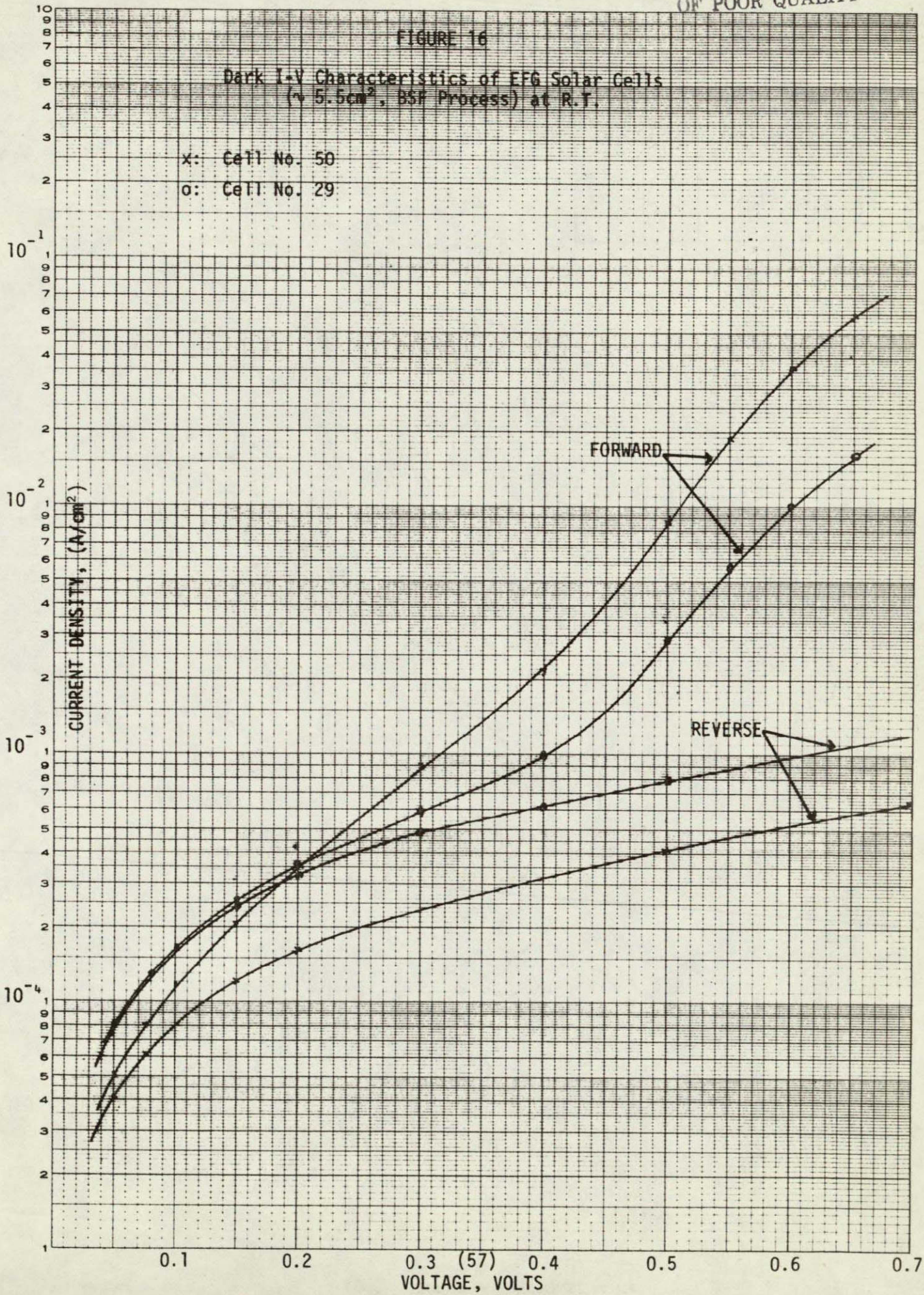


FIGURE 17

Spectral Response of EFG Solar Cells
(Standard Process)

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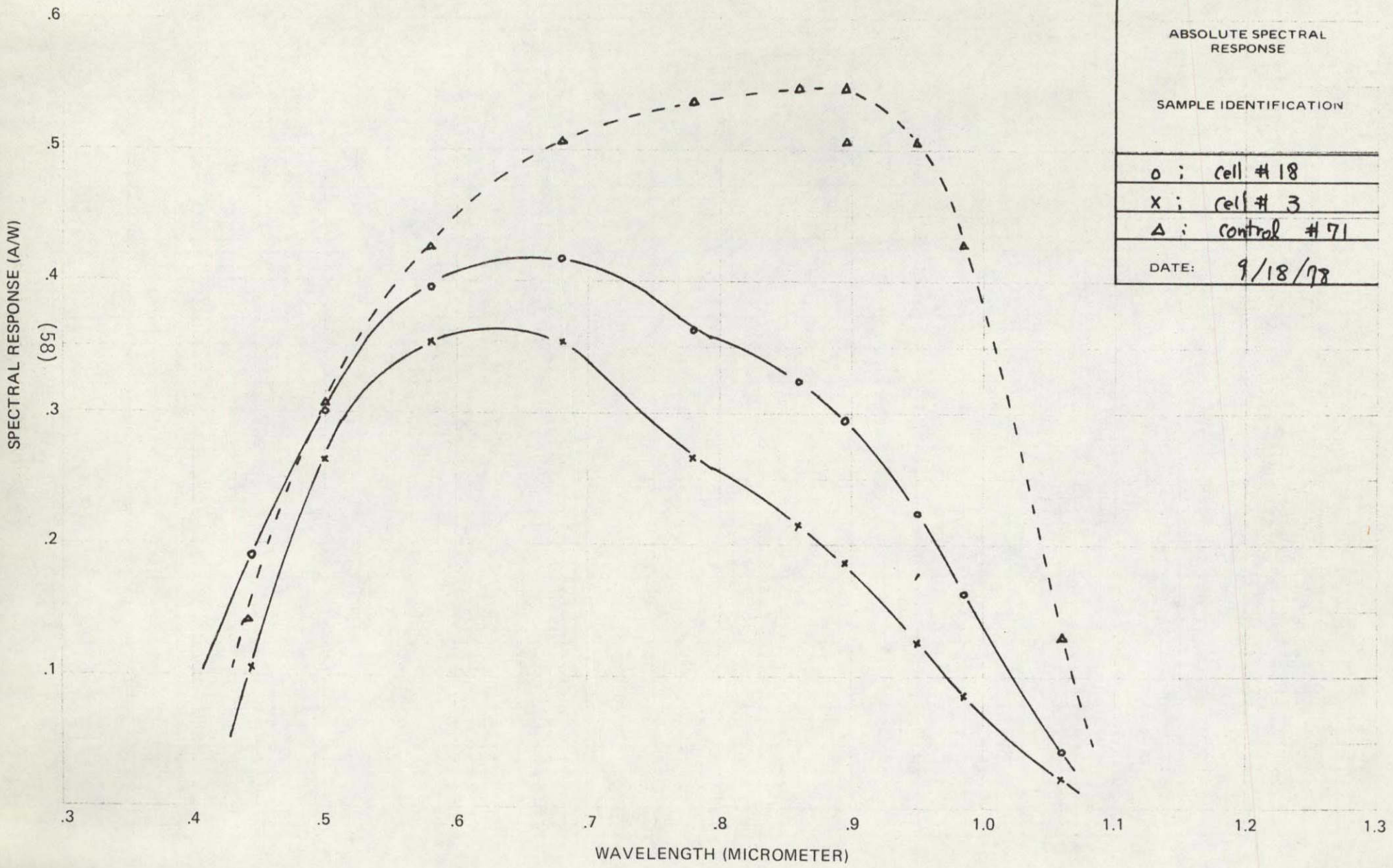
ABSOLUTE SPECTRAL RESPONSE

SAMPLE IDENTIFICATION

o ; Cell #18
x ; Cell # 3
Δ ; Control #71
DATE: 9/18/78



due to crystalline defects such as grain boundary, stacking faults, dislocations and perhaps of inclusions. The slight dip at 0.78 μm was observed for the both response figures and the origin of the dip is not known at the present time.

3.4 Minority Carrier Diffusion Length

Diffusion length was measured on the finished solar cells using the short circuit current method described in Section A.3.4. Table 16 summarizes the results of the EFG solar cells, from both standard and BSF process, measured under illumination of entire cell area, showing average diffusion length between 40 and 50 μm.

Variation of diffusion length was also detected from small beam size measurement on two solar cells and Figure 19 show results of this, indicating significant variation from spot to spot; i.e. from 20 to 50 μm in case (b). This variation in diffusion length can affect the overall carrier collection (current) obtained in the full active area of the cell.

TABLE 16

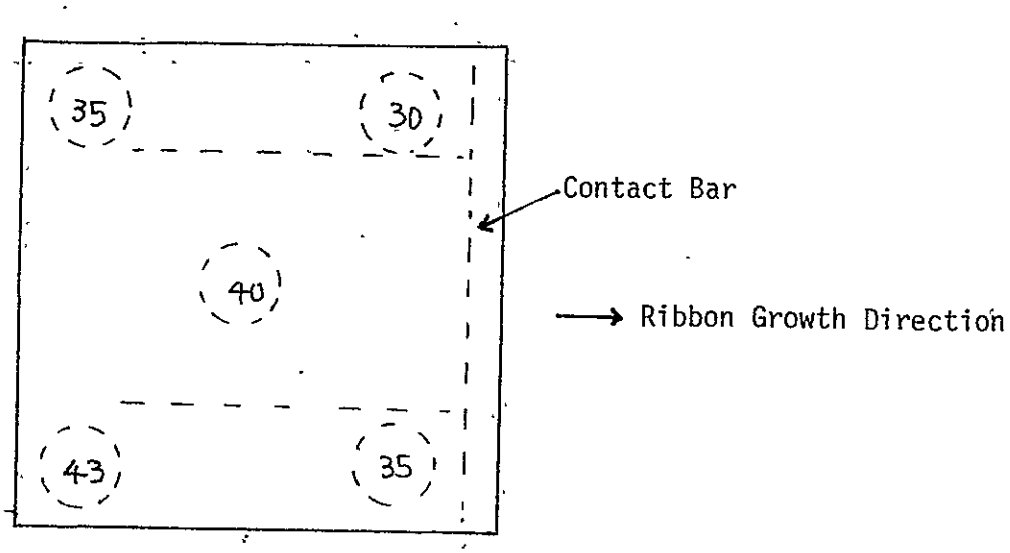
Minority Carrier Diffusion Length (μm) of EFG Solar Cells

	AVERAGE	STANDARD DEVIATION	RANGE
STANDARD CELL	40		38-41
BSF CELLS	52	11	40-65

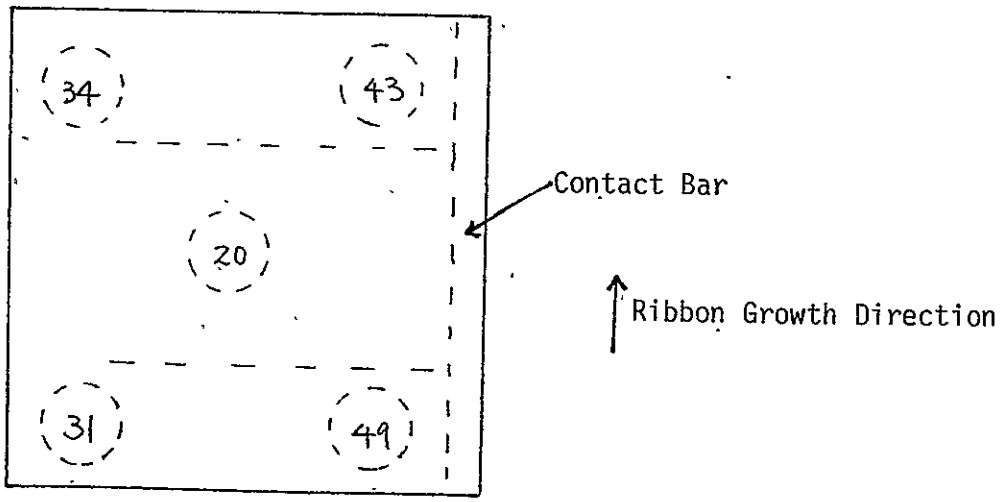
NOTE: 1) Measured by I_{SC} method illuminated whole solar cell area ($\sim 5.5 cm^2$).

2) Samples:

Standard Cells: Nos. 7 and 18
BSF Cells: Nos. 29, 32, 40,45, 49 and 55



(a)



(b)

FIGURE 19

Minority Carrier Diffusion Length (μm) Variation Within a EFG Solar Cell (∿5-6cm^2), Measured by I_{sc} Method With an Illuminated Beam Size of ∿3-4mm Diameter

a) A EFG Standard Cell (No. 7)

b) A EFG BSF Cell (No. 40)

III. CONCLUSIONS AND RECOMMENDATIONS

These conclusions reached after processing of the Wacker "Silso" wafers and EFG ribbons are as follows.

Wacker "Silso" Wafer

- o Fabrication process for conventional single crystalline solar cell can easily be adapted to this type of sheets without causing any significant process problems, in yield, or in the need for complex (expensive) process steps, etc.

- o The average conversion efficiency of solar cells (2x2 cm) under AMO condition at 25°C was about 9.5%. The maximum achievable AMO efficiency (using optimum processing, assuming material unchanged) of a solar cell (2x2 cm) from this material is predicted to be in the range between 11% and 12%.

- o The results on this sheet measured from solar cell performance, spectral response, and diffusion length showed good qualitative correlation with the average grain size. There did not appear to be any major doping impurity influence, not unexpected since the sheets are reportedly prepared from highly pure starting silicon. A secondary impurity effect was the degradation caused by "inclusions"; these were found mostly in the large grain area (middle), showing that they were not influencing the regrowth mechanism but were probably stray particles included during the casting process.

- o The BSF process indicated no improvement of performance. this could possibly be ascribed to the relatively low diffusion length (<50 μm) observed in the starting and processed sheets.

- The G.B. passivation test did not show any improvement. This does not rule out the chance of other G.B. passivation methods, but shows that there may not have been a preferential diffusion rate of phosphorus down G.B. at low temperature as required for the method used.

- For both the BSF and the G.B. passivation process, it was noteworthy that there was also no deterioration of performance. This indicates good stability of grain behavior under fairly severe process changes.

- Future improvements in cells made from Wacker "Silso" sheet appear to to lie in the increased grain size within the sheet (especially near the edge), or another method of G.B. passivation. Elimination of inclusions by better control of casting process will improve the utilization of this silicon material.

EFG Ribbon

- Warpage of the sheets and thickness variation within a sheet caused major problems in application of conventional solar cell process, especially in metallization and electrical test steps. However, with care screen printing type of metallization can possibly be applied successfully on this sheet (this is based on the experience in screen printing of Al paste in BSF process).

- An average AMO efficiency of EFG solar cells (5-6 cm^2 in area) at 25°C was about 8-9%, which was a slightly lower efficiency than the "Silso" solar cells. Maximum achievable AMO efficiency of a solar cell (1" x 1" in area) from this sheet, using optimum process steps, is estimated to be around 12%.

- The BSF process showed only slight improvement in I_{sc} and V_{oc}, probably because of the relatively low starting diffusion length and the high doping concentration ($\sim 10^{16}$ Atoms/cm^3).

- Electrically the results were only moderately good, and this was correlated with the reduced average diffusion length and possible junction shunting problem caused by the inclusions from die material (the reduced V_{oc} and CFF were thought to be due to these inclusions). The inclusions appeared more severe on this batch of ribbons than has been observed on other ribbon samples, indicating perhaps a correctable variation in the ribbon growth techniques.

- The localized areas of low diffusion length or low quality sheet will reduce one advantage of ribbon material, namely the ability to fabricate good single cells from relatively larger continous areas of ribbon.

IV. WORK PLAN STATUS

Following unconventional silicon sheets are expected to process and evaluate during the next period.

- o RTR Ribbon
- o Dendritic Web
- o Cast Silicon by HEM

Additional Meaurements

Equipment has been built to enable rapid measurement of dark forward log I-V plots, and one for fine light spot scanning of sample. This equipment will be used to aid in material evaluation; some samples from the Wacker and EFG groups will be included.

V. REFERENCES

T. H. Distefano and J. J. Cuomo, "Enhancement of Carrier Lifetime in Polycrystalline Silicon", Proceeding Workshop on Low Cost Polycrystalline Silicon Solar Cells, Southern Methodist University, Texas, May, 1976.

2. E. D. Stokes and T. L. Chu, "Diffusion Lengths in Solar Cells From Short-Circuit Current Measurement", Applied Physics Letters, 30, 425, 1977.

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		▲	▲		Δ	Δ		Δ	Δ		Δ	Δ	
(b) Quarterly				▲						Δ			
(c) Semi-Annual							Δ						
(d) Final													Δ
3. INTEGRATION MEETING													

APPENDIX II

OCLI AMO SOLAR SIMULATOR

The OCLI AMO Simulator is described under three headings; the light sources and calibration, the cell holding fixtures and the readout equipment.

(a) Light Sources and Calibration

The AMO spectrum is simulated by two separate sources.

- The blue portion of the spectrum is obtained from a xenon arc lamp with an absorption filter which attenuates the large energy spikes in the near IR region.
- The red portion of the spectrum is due to a tungsten lamp set at 2800°K color temperature with suitable filters to blend with the blue portion of the spectrum, resulting in close approximation to the AMO spectrum. Figure 1 shows the Johnson AMO spectrum (approximates closely to the Thekaekara spectrum) and also the output of the OCLI Simulator. Also shown are the separate xenon (blue) and tungsten (red) contributions.

The two light sources do not provide collimated light, the cell test plane is placed at the plane of correct convergence; the uniformity across this plane is ±2% for areas up to 8 cm^2. The deviation of the centerline of each light source from perpendicular is around 11°.

In addition to allowing cell characterization under the AMO spectrum, this simulator has an added advantage for cell evaluation. By use of suitable blocking shields, either the blue or the red spectral output shown in Figure 1 can be used to illuminate the cell. Analysis of the absolute output under

these two filters can provide a rapid indication of the process control achieved on the cell. Experience has provided guidelines for "typical" readings in these two broadband regions for a variety of cells [including intentional variations in the silicon resistivity, diffusion conditions, surface finish, contact area coverage and whether or not the cell surface has an AR coating]. Thus evaluation of the blue response can indicate the performance of a given diffusion schedule with a given resistivity silicon, and can also check the effectiveness of an AR coating. The red response can also indicate whether the final bulk output is as expected, and can thus be used to assess the minority carrier diffusion length (D.L.) achieved. Although separate methods (surface or bulk photovoltage) are used for diffusion length measurement, this broadband check is most valuable to indicate the possible range of the diffusion length. For low diffusion length values, the red response decreases and crosses over the blue response for D.L. $\sim$10 μm. Thus the red response data are most useful for scanning a larger number of samples, and can then be related to more precise D.L.-values obtained by more detailed (separate (separate) measurements.

Calibration

When first constructed the AMO Simulators were calibrated by a set of standard cells which were calibrated regularly on Table Mountain by measuring the solar spectrum incident there, and by adjusting for the measured absorption band in the spectrum, extrapolating to AMO readings. Since then, it has become common

practice to use balloon-flown and recovered standard cells to set the AMO simulator intensity, and OCLI follows this practice using either OCLI-BF cells or those supplied by customers.

(b) Cell Holding Fixture

A variety of fixtures are used, depending on the size of the cell; if the cells are very fragile (thin or stressed slices) or the contacts are wraparound, a special fixture is used.

All these fixtures include a block which is controlled at pre-set temperatures by water pumped by a thermostatically controlled water bath, with feedback from a thermocouple embedded in the test block. These blocks also have vacuum hold-down facility, and contain voltage and current probes for measurement of cell electrical output.

(c) Read-Out Equipment

The simulator has a digital meter, reading selected parameter V_{oc}, I_{sc} and the current at pre-set voltage levels. In addition, digital print out of these values plus up to three other load voltage readings are available.

Finally for development purposes, the I-V curves can be traced and from these maximum power, CFF and efficiency values can be estimated.

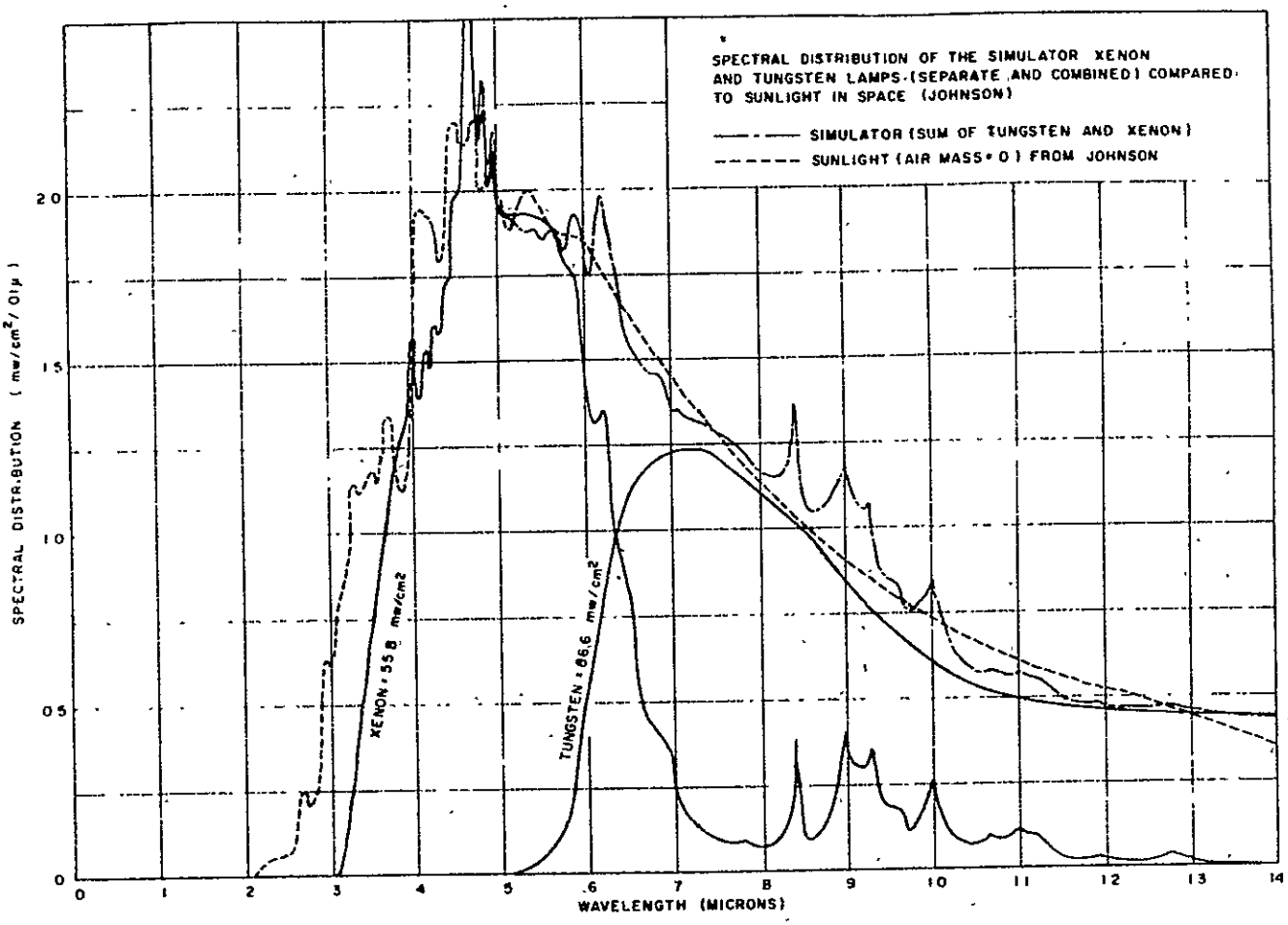


FIGURE 1

Spectral Distribution of the Simulator Xenon and Tungsten Lamps (Separate and Combined) Compared to Sunlight in Space (Johnson)

APPENDIX III

ELECTRICAL DATA SHEETS FOR "SILSO" SOLAR CELL

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2x2 cm) from Wacker Wafers (A, B, C, D) standard Process
NO A.R Coating, ≈ 90 % active Area.

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE: 6/26/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
A1	523	87	37	50	80	375	30.	60.1	5.6
A3	526	91	37	53	84	385	32.3	67.6	6.0
A4	530	90	37	53	83	390	32.4	67.9	6.0
A6	512	91	38	53	74	382	28.3	60.7	5.2
A7	537	92	38	54	85	400	34.0	68.8	6.3
A8	524	92	37	54	78	388	30.3	62.8	5.6
A9	528	90	37	53	82	388	31.8	67.0	5.9
A10	456	89	37	52	60	290	17.4	42.9	3.2
A11	532	93	38	55	86	400	34.4	69.5	6.4
A13	526	90	37	52	82	381	31.2	66.0	5.8
A14	532	91	37	54	82	405	33.2	68.6	6.2
A15	528	93	37	55	82	406	33.3	67.8	6.2
A16	514	90	37	52	75	390	29.3	63.2	5.4
B1	525	88	37	50	80	385	30.8	66.7	5.7
B2	523	91	37	53	83	380	31.5	66.3	5.8
B3	496	92	37	54	70	375	26.3	57.5	4.9
B4	52.8	92	37	54	84	395	33.2	68.3	6.1

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2 x 2 cm) from Wacker Wafers (A, B, C, D), Standard Process
No A.R coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE: 6/26/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
B5	523	89	37	52	81	395	32.0	68.7	5.9
B6	531	92	37	55	85	406	34.5	70.6	6.4
B7	532	93	37	56	85	408	34.7	70.1	6.4
B9	519	92	38	54	85	388	33.0	69.1	6.1
B10	526	96	39	56	89	395	35.2	69.6	6.5
B11	522	95	39	55	80	375	30.0	60.5	5.6
B12	523	96	39	57	88	390	34.3	68.4	6.4
B13	521	92	38	53	84	378	31.8	66.2	5.9
B14	522	94	39	55	88	380	33.4	68.2	6.2
B15	527	95	39	56	87	392	34.1	68.8	6.3
B16	526	94	39	55	86	387	33.3	67.3	6.2
C1	529	91	39	52	82	400	32.8	68.1	6.1
C2	529	93	39	54	84	400	33.6	68.3	6.2
C3	534	94	39	55	84	395	33.2	66.1	6.1
C4	533	93	39	54	85	400	34.0	68.6	6.3
C5	528	92	38	53	85	395	33.6	69.1	6.2
C7	541	97	40	57	89	420	37.4	71.1	6.9

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2x2 cm) from Wacker Wafers (A, B, C, D), Standard Process
No. A.R. coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE: 6/26/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
C8	534	95	39	56	86	410	35.3	69.5	6.5
C9	527	95	39	55	87	395	34.4	68.6	6.4
C10	539	97	40	57	90	419	37.5	71.8	6.9
C14	534	95	39	56	87	395	34.4	67.7	6.4
C15	534	96	39	56	86	390	33.5	65.4	6.2
C16	531	94	39	55	85	405	34.4	69.0	6.4
D1	528	94	41	53	86	385	33.1	66.7	6.1
D2	528	96	41	54	88	390	34.3	67.7	6.4
D3	529	96	41	55	87	395	34.4	67.7	6.4
D4	529	94	41	53	86	390	33.5	67.4	6.2
D5	529	96	41	54	83	400	33.2	65.4	6.1
D6	545	97	41	55	90	420	37.8	71.5	7.0
D8	535	97	41	56	89	410	36.5	70.3	6.8
D9	524	96	41	55	87	390	33.9	67.4	6.3
D10	537	98	41	56	90	402	36.2	68.7	6.7
D11	455	94	40	53	61	290	17.7	41.4	3.3
D14	534	97	41	55	88	397	34.9	67.4	6.5

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2 x 2 cm) from Wacker Wafers (A, B, C, D), standard Process.
NO A.R. coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25° C

DATE: 6/26/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
D15	546	97	41	56	90	425	38.3	72.2	7.1
D16	533	96	41	54	88	400	35.2	68.8	6.5

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Wacker Solar cells (2x2 cm) Standard Process
S_xO A.R coating ≈90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE: 6/27/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
A1	528	117	47	70	105	365	38.3	62.2	7.1
A3	529	124	52	72	113	380	42.9	65.7	8.0
A4	533	123	51	72	113	380	42.9	65.7	8.0
A6	526	124	52	72	103	385	39.7	60.9	7.4
A7	543	125	52	73	116	400	46.4	68.1	8.6
A8	530	126	53	73	108	390	42.1	63.3	7.8
A9	531	122	50	72	111	385	42.7	66	7.9
A10	476	119	47	71	82	315	25.8	45.6	4.8
A11	535	124	49	75	114	395	45.0	67.9	8.3
A13	527	119	48	71	108	380	41.0	65.3	7.6
A14	538	126	52	74	114	395	45.0	67.9	8.3
A15	534	127	52	75	114	395	45.0	67.9	8.3
A16	524	124	53	71	107	390	41.7	64.2	7.7
B1	531	119	48	70	107	380	40.7	64.4	7.5
B2	526	124	51	73	114	370	42.2	64.9	7.8
B3	513	125	53	72	105	380	39.9	62.2	7.4
B4	536	122	48	74	112	395	44.2	67.5	8.2

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Wacker Solar Cells (2x2 cm) standard process
SiO A.R coating, ≥ 90 (%) active area
TEST CONDITION: AM0
TEMPERATURE: 25°C DATE: 6/27/98

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
B5	528	120	48	72	110	390	42.9	67.4	7.9
B6	537	123	49	74	113	405	45.8	69.2	8.5
B7	535	126	50	76	116	405	47.0	69.7	8.7
B9	528	122	48	74	112	395	44.2	68.8	8.2
B10	530	124	47	77	113	400	45.2	68.9	8.4
B11	529	124	50	74	105	380	39.9	61.1	7.4
B12	520	127	51	76	113	390	44.1	66.7	8.2
B13	520	129	52	72	113	370	41.8	64.8	7.7
B14	521	124	48	76	115	385	44.3	68.5	8.2
B15	531	127	51	76	117	390	45.6	67.5	8.5
B16	531	123	49	74	112	390	43.7	66.8	8.1
C1	538	116	46	70	112	395	44.2	70.6	8.2
C2	537	120	47	73	112	400	44.8	69.3	8.3
C3	545	123	48	75	112	400	44.8	67.1	8.3
C4	536	124	50	74	106	410	43.5	65.7	8.1
C5	535	121	48	73	112	395	44.2	68.3	8.2
C6	547	128	51	77	118	420	49.6	70.9	9.2

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Wacker Solar Cells (2x2 cm) standard Process
S_xO A.R Coating, ≈ 90 (%) active area

TEST CONDITION: AM0

TEMPERATURE: 25°C DATE: 6/27/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	n
	mV	mA	mA	mA	mA	mV	mW	%	%
C8	544	128	54	74	117	415	48.6	69.6	9.0
C9	534	128	53	75	117	400	46.8	68.5	8.7
C10	549	128	49	78	118	420	49.6	70.9	9.2
C14	538	126	50	76	114	395	45.0	66.3	8.3
C15	546	125	48	77	115	400	46.0	67.4	8.5
C16	542	124	49	75	115	405	46.6	69.1	8.6
D1	533	123	51	71	110	390	42.9	65.7	7.9
D2	532	125	53	73	115	390	44.9	67.3	8.3
D3	534	120	46	74	109	385	42.0	65.3	7.8
D4	534	120	47	72	109	385	42.0	65.4	7.8
D5	549	124	50	74	113	410	46.3	68.7	8.6
D6	555	125	50	75	117	430	50.3	72.5	9.3
D8	546	124	48	75	113	420	47.5	70.4	8.8
D9	532	126	51	75	114	395	45.0	67.0	8.3
D10	544	130	53	76	119	410	48.8	69.1	9.0
D11	493	117	44	72	80	330	26.4	45.9	4.9
D14	542	122	47	75	110	405	44.6	67.5	8.3

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Wacker Solar Cells (2x2 cm) standard Process
Si_3O_4 A.R coating, ≈ 90 (%) active area

TEST CONDITION: AMO

TEMPERATURE: 25°C DATE: 6/27/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
D15	555	129	53	76	114	410	46.7	65.5	8.7
D16	543	126	52	74	119	435	51.8	75.8	9.6

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar Cells (2x2 cm) Wacker Standard Process (Wafer A, B, C, D)
No A.R coating, ≈ 90 % active area.

TEST CONDITION: AMO

TEMPERATURE: 25 °C

DATE: 6/26/78

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	553	100	40	60	92	435	40	72.4	7.4
2	544	101	40	61	93	428	39.8	72.4	7.4
3	552	100	40	61	89	440	39.2	70.9	7.3
4	548	101	40	61	93	425	39.5	71.4	7.3
5	539	101	40	62	94	427	40.1	73.7	7.4
6	542	101	39	61	94	425	40.	73.0	7.4
7	544	105	42	63	98	430	42.1	73.8	7.8
8	540	105	42	63	98	426	41.7	73.6	7.7
9	543	102	41	61	94	427	40.1	72.5	7.4
10	544	108	44	65	98	425	41.7	70.9	7.7

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar cells (2x2 cm) Wacker standard process
SiO A.R coating ≈90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25 °C DATE: 6/27/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	-
	mV	mA	mA	mA	mA	mV	mW	%	%
1	557	131	47	84	119	445	53	73	9.8
2	554	136	51	85	125	440	55	73.2	10.2
3	556	135	50	85	119	445	53	73	9.8
4	556	138	55	83	125	430	53.8	69.9	9.8
5	549	138	54	84	128	435	55.7	73.5	10.3
6	553	136	52	84	126	435	54.8	72.9	10.1
7	551	133	49	84	123	440	54.1	74	10.0
8	549	127	44	83	119	430	51.2	73.2	9.5
9	552	132	48	84	121	440	53.2	73.2	9.9
10	544	122	40	82	110	425	46.8	70.5	8.7

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2x2 cm) from Wacker wafer (J), Standard Process (Modified)
TEST CONDITION: NO A.R coating, ≈ 90 % active area
TEMPERATURE: AMO 25 °C DATE: 8/18/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
J2	539	85			78	445	34.7	75.8	6.4
J3	540	87			76	445	33.8	72.0	6.3
J5	540	87			80	450	36.0	76.6	6.7
J7	555	92			83	460	38.2	74.8	7.1
J8	553	89			83	465	38.6	78.4	7.1
J9	543	87			80	450	36.0	76.2	6.7
J10	558	91			84	470	39.5	77.8	7.3
J11	555	90			85	465	39.5	79.1	7.3
J13	545	87			81	451	36.5	77.1	6.8
J14	555	91			85	465	39.5	78.3	7.3
J15	555	91			85	465	39.5	78.3	7.3

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2×2 cm) from Wacker wafer (J), Standard Process (Modified) SiO A.R coating, ≈ 90 % active area.

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 8/21/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
J2	549	117	46	71	108	455	49.1	76.5	9.1
J3	551	118	45	73	106	450	47.7	73.4	8.8
J5	551	119	46	73	109	457	49.8	76.0	9.2
J7	563	123	46	77	115	460	52.9	76.4	9.8
J8	561	123	49	74	115	467	53.7	77.8	9.9
J9	552	119	47	73	110	460	50.6	76.8	9.4
J10	565	126	51	75	118	465	54.9	77.3	10.2
J11	561	124	49	74	115	467	53.7	77.4	9.9
J13	554	119	48	71	111	458	50.8	77.1	9.4
J14	563	124	50	75	118	465	54.9	78.6	10.2
J15	563	125	49	76	117	465	54.4	77.6	10.1

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar Cells (2x2 cm) Wacker (J) standard process (Modified)
S.D. A.R. coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25 °C DATE: 8/21/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
41	595	131	48	83	122	496	60.5	77.8	11.2
	(588)	(95)			(88)	(505)	(44.4)	(79.6)	(8.2)
42	593	132	49	84	122	496	60.5	77.5	11.2
	(586)	(96)			(88)	(505)	(44.4)	(79.0)	(8.2)
43	591	132	50	82	120	500	60.	76.9	11.1
	(584)	(97)			(87)	(495)	(43.1)	(76.0)	(8.0)
44	593	131	50	81	121	506	61.2	78.6	11.3
	(586)	(96)			(88)	(505)	(44.4)	(79)	(8.2)
		Following cell # 46, 47, 48 are second control Group							
46	600	131	49	82	123	511	62.9	79.9	11.6
	(592)	(95)			(89)	(505)	(45.0)	(79.9)	(8.3)
47	597	133	49	84	124	510	63.2	79.8	11.7
	(590)	(97)			(90)	(505)	(45.5)	(79.4)	(8.4)
48	596	132	49	84	123	510	62.7	79.7	11.6
	(589)	(97)			(87)	(505)	(43.9)	(76.9)	(8.1)
*	Parenthesis Numbers for before A.R coating.								

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (2x2 cm) from Wacker Wafer (E, F), BSF process
TEST CONDITION: No A.R coating, ≥ 90 % active area
TEMPERATURE: AMO
25°C
DATE: 7/26/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
E1	521	85			75	422	31.7	71.5	5.9
E2	530	87			79	435	34.4	74.5	6.4
E4	530	89			82	440	36.1	76.5	6.7
E5	531	88			78	440	34.3	73.4	6.4
E6	543	93			83	455	37.8	74.8	7.0
E7	543	95			85	455	38.7	75.0	7.2
E8	536	92			78	440	34.3	69.6	6.4
E11	542	91			82	450	36.9	74.8	6.8
E12	547	94			84	455	38.2	74.3	7.1
E13	525	87			75	435	32.6	71.4	6.0
E14	542	92			85	450	38.3	76.7	7.1
E15	545	93			85	456	38.8	76.5	7.2
F1	518	85			72	425	30.6	69.5	5.7
F2	530	89			79	445	35.2	74.5	6.5
F3	530	89			79	440	34.8	73.7	6.4
F5	527	88			79	445	35.2	75.8	6.5
F6	536	92			80	447	35.8	72.5	6.6

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2x2 Cm) from Wacker Wafer (E, F), BSF process
NO A.R Coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 7/26/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
F7	539	92			74	442	32.7	65.9	6.1
F8	544	93			84	450	37.8	74.7	7.0
F9	531	90			82	442	36.2	75.8	6.7
F11	473	91			55	281	15.5	35.9	2.9
F12	544	92			85	450	38.3	76.4	7.1
F14	543	90			80	455	36.4	74.3	6.7
F16	540	90			80	448	35.8	73.7	6.6

C-2

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (2x2 cm) from Wacker Wafer (E, F), BSF process
TEST CONDITION: SiO A.R coating, ≈ 90 % active area
TEMPERATURE: AMO 25°C
DATE: 7/27/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
E1	533	119	51	68	105	432	45.9	72.4	8.5
E2	541	123	51	71	111	450	50	75.1	9.3
E4	540	125	52	72	115	445	51.2	75.9	9.5
E5	541	124	52	71	111	446	49.5	73.8	9.2
E6	553	129	53	75	118	455	53.7	75.3	9.9
E7	555	132	53	78	122	452	55.1	75.2	10.2
E8	548	128	52	75	114	447	51.0	72.7	9.4
E11	552	126	52	74	115	453	52.1	74.9	9.7
E12	557	131	53	78	120	458	55.0	75.4	10.2
E13	534	123	52	71	110	440	48.2	73.4	8.9
E14	543	128	52	76	118	450	53.1	76.4	9.8
E15	555	129	52	77	120	460	55.2	77.1	10.2
F1	528	118	51	67	103	427	44	70.6	8.2
F2	541	124	52	72	114	445	50.7	75.6	9.4
F3	541	125	52	173	115	450	51.8	76.6	9.6
F5	537	122	51	71	112	450	50.4	76.9	9.3
F6	547	128	52	75	116	450	52.2	74.6	9.7

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2x2 cm) from Wacker Wafer (E, F), BSF Process
SiO A.R coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 7/27/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
F 8	553	129	52	77	118	450	53.1	74.4	9.8
F 9	541	127	52	74	115	450	51.8	75.4	9.6
F 12	555	125	51	73	118	460	54.3	78.6	10.1
F 14	555	128	52	76	115	455	52.3	73.6	9.7
F 16	549	125	51	74	115	450	51.8	75.5	9.6

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (≈ 2x2 cm) from Wacker wafers (E, F) , BSF process
TEST CONDITION: MLAR coating , Fine contact line ≈ 93 % active area
AMO
TEMPERATURE: 25°C DATE: 8/28/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	n
	mV	mA	mA	mA	mA	mV	mW	%	%
E16	561	135	55	79	124	467	57.9	76.7	10.8
F4	550	133	56	77	123	460	56.6	77.5	10.6
F10	561	139	56	83	127	461	58.6	74.9	10.8

Note: Area of cells

E16 ; 3.966 cm^2
F4 ; 3.956 cm^2
F10 ; 3.992 cm^2

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar cells (2x2 Cm), Wacker (E, F) BSF process
SiO A.R coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25 °C DATE: 7/27/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
11	602	142	55	87	132	503	66.4	77.8	12.3
	(593)	(104)			(96)	(500)	(48.0)	(77.8)	(8.9)
12	602	141	56	86	130	500	65.0	76.6	12.0
	(593)	(103)			(92)	(505)	(46.5)	(76.1)	(8.6)
13	601	143	56	87	131	495	64.8	75.4	12.0
	(591)	(103)			(88)	(500)	(44.0)	(72.3)	(8.2)
	Following cell # 15 and 17 are second control group								
15	603	137	53	84	129	500	64.5	78.1	11.9
	(594)	(99)			(89)	(500)	(44.5)	(75.7)	(8.2)
17	599	139	53	87	131	500	65.5	78.7	12.1
	(592)	(99)			(90)	(505)	(45.5)	(77.5)	(8.4)
	※ Parenthesis numbers for before A.R coating								

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar cells (2x2cm) from Wacker Wafer (I), Grain Boundary (G.B) passivation proc
No. AR coating, ≈ 90 % active area

TEST CONDITION: AMO
TEMPERATURE: 25 °C

DATE: 8/18/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	r
	mV	mA	mA	mA	mA	mV	mW	%	%
I 1	524	80			72	432	31.1	74.2	5.8
I 2	540	85			78	447	34.9	76.0	6.5
I 3	536	83			76	442	33.6	75.5	6.2
I 4	540	85			78	450	35.1	76.5	6.5
I 5	540	86			78	450	35.1	75.6	6.5
I 6	550	90			80	450	36.0	72.7	6.7
I 7	552	92			85	456	38.8	76.3	7.2
I 8	551	91			85	456	38.8	77.3	7.2
I 11	535	91			75	420	31.5	64.7	5.8
I 12	552	92			84	463	38.9	76.6	7.2
I 13	530	84			78	443	34.6	77.6	6.4
I 14	546	90			81	460	37.3	75.8	6.9
I 15	550	91			82	458	37.6	75.0	7.0
I 16	550	90			82	465	38.1	77.0	7.1

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Solar Cells (2×2 cm) from Wacker wafer (I), Grain Boundary (G.B) Passivation Process. SiO A.R coating, ≈ 90 % active area

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 8/21/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
I 1	536	110	46	62	101	440	44.4	75.7	8.2
I 2	549	117	47	69	110	450	49.5	77.1	9.2
I 3	548	114	46	68	106	450	47.7	76.2	8.8
I 4	548	116	47	69	109	450	49.1	76.9	9.1
I 5	550	117	48	69	109	450	49.1	76.1	9.1
I 6	558	121	47	74	111	460	51.1	75.5	9.5
I 7	562	126	50	76	118	460	54.3	76.8	10.1
I 8	561	125	51	73	117	460	53.8	77.1	10.0
I 11	546	123	49	74	104	430	44.7	66.5	8.3
I 12	565	125	49	76	116	465	53.9	76.4	10.0
I 13	544	114	45	69	107	445	47.6	76.6	8.8
I 14	558	122	47	74	114	455	51.9	76.4	9.6
I 15	564	124	49	75	115	460	52.9	75.6	9.8
I 16	562	126	51	74	116	465	53.9	76.4	10.0

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar Cells (2x2 cm) Wacker (I) G.B. passivation Process.
SiO A.R coating, ≈ 90 % active area
TEST CONDITION: AMO
TEMPERATURE: 25°C
DATE: 8/28/98

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
50	590	130	49	81	120	490	58.8	76.9	10.9
	(580)	(96)			(86)	(490)	(42.1)	(75.7)	(7.8)
51	592	131	50	82	118	503	59.4	76.5	11.0
	(580)	(97)			(84)	(492)	(41.3)	(73.5)	(7.6)
52	593	133	52	81	124	503	62.4	79.3	11.6
	(585)	(97)			(90)	(498)	(44.8)	(79.0)	(8.3)
		Follows cell # 61 and 62 are second control group							
61	597	132	49	84	124	510	63.2	80.2	11.7
	(587)	(98)			(91)	(495)	(45.0)	(78.3)	(8.3)
62	594	131	50	81	117	500	58.5	75.5	10.8
	(586)	(96)			(84)	(493)	(41.4)	(73.6)	(7.7)
*	Parenthesis numbers for before A.R coating.								

APPENDIX IV

ELECTRICAL DATA SHEETS FOR EFG SOLAR CELLS

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Cells from EFG Ribbon, standard Process
TEST CONDITION: NO A.R coating, ≈ 88 % Active area
TEMPERATURE: AMO
25°C
DATE: 9/6/78

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	%	%	cm^2
1	520	109	46	62	75	386	29.0	51.1	3.7	5.81
3	532	80	33	46	60	403	24.2	56.8	4.3	4.15
4	539	113	47	65	97	435	42.2	69.3	5.3	5.95
5	532	122	52	70	106	440	46.6	71.9	6.0	5.71
6	534	105	45	60	98	445	43.6	77.8	6.8	4.755
7	540	123	52	70	115	443	50.9	76.7	6.8	5.578
8	531	128	54	72	108	437	47.2	69.4	6.1	5.75
9	532	127	55	72	118	431	50.9	75.3	6.6	5.935
10	515	121	52	67	90	415	37.4	59.9	4.7	5.952
12	518	125	53	71	90	395	35.6	54.9		
13	509	134	58	75	92	370	34.0	49.9	4.2	5.93
14	549	114	48	65	108	465	50.2	80.2	7.1	5.22
16	535	135	57	76	106	423	44.8	62.1	5.6	5.89
18	547	128	56	71	114	452	51.5	73.6	6.6	5.813
21	496	127	54	72	80	340	27.2	43.2	3.5	5.815

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Cells from EFG Ribbon, Standard Process
SiO A.R coating, ≈88 % active area
TEST CONDITION: AMO
TEMPERATURE: 25°C DATE: 9/8/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
3	546	109	48	60	85	430	36.6	61	6.5
4	546	158	67	90	138	450	61.1	71	7.6
5	541	164	69	93	143	445	62.6	71	8.1
6	543	139	58	80	129	455	57.8	76	9.0
7	548	162	70	91	151	435	65.6	74	8.7
8	540	168	71	96	142	460	65.3	72	8.4
9	535	169	73	94	150	460	69.0	76	8.9
10	527	163	71	89	128	435	55.7	65	6.9
13	518	175	74	99	130	360	46.8	52	5.8
14	556	153	65	87	144	470	67.7	79	9.6
16	547	178	77	100	142	420	59.6	61	7.5
18	555	173	76	95	152	455	69.2	72	8.8
21	517	170	73	96	110	415	45.7	52	5.8

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar Cells (2x2 cm) EFG Ribbon Standard Process
Si O A.R coating, ≈ 90 % active area.

TEST CONDITION: AMO

TEMPERATURE: 25 °C DATE: 9/8/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
70	596	134	52	82	126	515	64.8	81	12
	(589)	(97)	(36)	(61)	(91)	(505)	(46.0)	(80)	(8.5)
71	596	135	53	83	127	500	63.5	79	11.8
	(589)	(98)	(37)	(61)	(90)	(495)	(44.6)	(77.2)	(8.3)
72	596	134	53	81	128	500	64.0	80	11.9
	(589)	(97)	(36)	(61)	(91)	(500)	(45.5)	(79.6)	(8.4)
73	596	134	52	82	124	505	62.6	78	11.6
	(589)	(97)	(36)	(61)	(88)	(498)	(43.8)	(76.7)	(8.1)
74	596	134	53	81	125	500	62.5	79	11.6
	(589)	(97)	(36)	(61)	(88)	(493)	(43.4)	(75.9)	(8.0)
76	597	134	54	81	125	505	63.1	78	11.7
	(590)	(97)	(36)	(61)	(89)	(500)	(44.5)	(77.8)	(8.2)
77	597	137	54	84	130	510	66.3	80	12.3
	(590)	(99)	(37)	(62)	(93)	(502)	(46.7)	(79.9)	(8.6)
78	598	137	53	84	129	510	65.8	80	12.2
	(591)	(98)	(36)	(61)	(91)	(507)	(46.1)	(79.7)	(8.5)
79	597	136	53	83	129	510	65.8	81	12.2
	(588)	(97)	(36)	(61)	(91)	(507)	(46.1)	(80.9)	(8.5)

cell # 76, 78, 77 and 79 are second central group

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SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Cells from EFG Ribbon, BSF process
NO A.R coating, ≥ 88 % active area
TEST CONDITION: AMO
TEMPERATURE: 25°C DATE: 9/26/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	-	AREA
	mV	mA	mA	mA	mA	mV	mW	%	%	cm^2
26	547	125	53	71	94	450	42.3	62	5.8	5.42
28	564	133	56	76	121	470	56.9	76	7.6	5.55
29	565	134	56	77	122	475	58.0	77	7.8	5.56
31	547	125	53	72	112	455	51.0	74	6.8	5.58
32	538	120	51	68	103	435	44.8	69	6.1	5.42
33	506	115	42	65	87	345	30.0	51	4.4	5.07
36	529	127	54	71	88	410	36.1	54	4.8	5.62
38	532	116	50	64	104	435	45.2	73	6.1	5.49
40	515	111	47	62	92	415	38.2	67	5.4	5.28
41	555	128	54	72	109	460	50.1	71	6.2	6.01
43	529	106	44	61	96	440	42.2	75	6.5	4.80
44	555	122	53	68	103	465	47.9	71	6.6	5.35
45	529	121	51	69	107	435	46.6	73	6.3	5.52
46	526	122	52	70	112	435	48.7	76	6.7	5.37
49	524	112	47	65	100	430	43.0	73	5.7	5.62
50	524	116	49	66	100	420	42.0	69	5.9	5.29
55	558	134	56	77	119	470	55.9	74	7.5	5.52

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Cells from EFG Ribbon, BSF Process
TEST CONDITION: SiO A.R coating, ≈ 88 % active area
TEMPERATURE: AMO 25°C
DATE: 9/27/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
28	572	173	74	97	158	490	77.4	78	10.3
31	555	166	71	94	154	465	71.6	78	9.5
32	551	161	69	90	140	460	64.4	73	8.8
33	533	153	66	85	114	390	44.5	55	6.5
36	548	167	73	93	124	435	53.9	59	7.1
40	534	152	66	84	126	440	55.4	68	7.8
41	566	168	72	94	148	475	70.3	74	8.7
43	542	144	61	81	132	460	60.7	78	9.4
44	567	163	72	90	142	475	67.5	73	9.3
45	546	162	70	90	149	450	67.1	76	9.0
49	534	146	62	83	126	450	56.7	73	7.5
50	534	154	68	84	134	445	59.6	72	8.4

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Cells from EFG Ribbon, BSF process
MLAR coating, ≈ 88 active area.

TEST CONDITION: AMO

TEMPERATURE: 25°C

DATE: 9/27/78

NO.	V_{OC}	I_{SC}	I_{SCB}	I_{SCR}	I_{Max}	V_{Max}	P_{Max}	CFF	η
	mV	mA	mA	mA	mA	mV	mW	%	%
29	576	180	77	102	164	490	80.4	78	10.7
55	567	178	76	102	160	485	77.6	77	10.4

SOLAR CELL ELECTRICAL DATA

CELL DESCRIPTION: Control Solar cell (2x2 cm), EFG Ribbon BSF process
SiO A.R coating, ≥ 90 % active area
TEST CONDITION: AMO
TEMPERATURE: 25 °C DATE: 9/27/78

NO.	V_{OC} mV	I_{SC} mA	I_{SCB} mA	I_{SCR} mA	I_{Max} mA	V_{Max} mV	P_{Max} mW	CFF %	η %
80	603	136	52	84	123	505	62.1	7.6	11.5
	(597)	(99)	(36)	(63)	(88)	(505)	44.4	75	8.2

* Parenthesis numbers for before A.R coating

APPENDIX V

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 μm

I_{SCB}: Short Circuit Current (Blue Response) at Wavelength Below $\sim$.6 μm

CFF: Curve Fill Factor

η: Solar Cell Conversion Efficiency

Le: Minority Carrier Diffusion Length

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

D.L.: Minority Carrier Diffusion Length