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DEVELOPMENT OF CONCENTRATOR SOLAR CELLS

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Sandia Contract 54-2191B

ABSTRACT

A limited pilot production run on PESC silicon solar cells for use at high concentrations (200 to 400 suns) is summarized. The front contact design of the cells was modified for operation without prismatic covers. The original objective of the contract was to systematically complete a process consolidation phase, in which all the process improvements developed during the contract would be combined in a pilot production run. This pilot run was going to provide a basis for estimating cell costs when produced at high throughput. Because of DOE funding limitations, the Photovoltaic Concentrator Initiative is on hold, and Applied Solar's contract was operated at a low level of effort for most of 1993. The results obtained from the reduced scope pilot run showed the effects of discontinuous process optimization and characterization. However, the run provided valuable insight into the technical areas that can be optimized to achieve the original goals of the contract.

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1.0 INTRODUCTION

This report summarizes a limited pilot production run on PESC silicon solar cells for use at high concentrations (200 - 400 suns). The cell front contact design was modified for operation without prismatic covers. The original objective of the contract was to systematically complete a process consolidation phase, in which all the process improvements developed during the contract would be combined in a pilot production run. This pilot run would demonstrate the current efficiency status of high concentration Si cells, and would provide a basis for estimating cell costs when produced at high throughput. Because of DOE funding limitations, the Concentrator Initiative is on hold, and Applied Solar's contract was operated at a low level of effort for most of 1993.

The results obtained from the reduced scope pilot run showed the effects of discontinuous process optimization and characterization. However, the run provided valuable insight into the technical areas which can be optimized to achieve the original contract goals.

2.0 TECHNICAL RESULTS

2.1 Pilot Run Details

Twenty 4-inch diameter Si wafers, with 0.2 ohm-cm resistivity, were processed in Applied Solar's Si production line. The process sequence used has been described in previous reports. Four photomasks were used to balance good cell efficiency with reduced costs. The micro-grooving, P+ and N+ diffusions, and surface passivation steps were developed earlier. The micro-grooving used an image-reversal process (to reduce the reflecting flats), but image-reversal was not used to form the front grid pattern. Previous tests showed that CFF values were higher if the back contacts were sintered at 525°C. This high temperature led to some out-diffusion of the Al layer used in the PESC back contact, and caused some

difficulties in obtaining void-free soldered joints. Also if the sintering was done after AR coating, a slight loss of J_{sc} was observed. Original plans were to replace this sinter step with a rapid thermal anneal. It was not possible to include this rapid anneal step in time for the pilot run.

2.2 Yields

Twenty percent of the starting slices were lost after metal evaporation, or after sawing to size.

Twenty percent of the wafers were rejected early in the processing because of incomplete mask registration. This gave a mechanical yield of 60%. For the remaining wafers, the electrical yield (cells $\geq 19\%$ at 150-suns, 30°C) was around 70%. i.e., overall yield was $60\% \times 70\% = 42\%$. As a result 200 cells with 150-sun efficiency $>19\%$ (and average 150-sun efficiency 20%) were delivered.

2.3 Electrical Distribution

At average 150-suns, the average value of the major I-V parameters was as follows:

TABLE 1

	V_{oc} (mV)	J_{sc} (A)	P_{max} (W)	CFF (%)	Efficiency (%)
Average Value - 200 cells	782	4.981	2.984	76.6	19.9
Average Value - 10 cells	775	5.01	3.028	78.0	20.19

The average I_{sc} at one-sun was 33.2 mA/cm^2 . For comparison, Sandia selected (at random) 10 cells and the average values (at 150x) are also included, and show good agreement.

Figure 1 and 2 show histogram plots for the efficiency and curve fill factors for the 200 cells.

2.4 Comments

The most important factor determining the one-sun output was the short circuit current density (J_{sc}). The average one-sun value for J_{sc} was 33.2 mA/cm², about 5 - 8% lower than the best J_{sc} values observed in earlier tests using Si with similar quality, and the same masks and processes. At higher concentration, the low one-sun J_{sc} value led to lower efficiency, although the major cause of reduced efficiency was CFF (see discussion in 3.4)

Within the 200 cell group, the efficiency spread was around 10%, mostly from J_{sc} variation (7%) and partly from CFF spread (3%). There was slight slice-to-slice variation in J_{sc} , since over half the slices included most of the cells with low J_{sc} . Tests below (3.1) showed that the minority carrier diffusion lengths ($\sim 150 \mu\text{m}$) were comparable to values expected from Si with resistivity around 0.2 ohm-cm. Ellipsometric measurements during processing showed that the surface passivation SiO_2 layer varied from 90Å SiO_2 to 300Å. This spread in thickness could detune the AR coating, which was designed for SiO_2 thicknesses around 100Å. Reflectance tests on 5 cells (see 3.2 below) showed average reflectance between 5% and 7% over most of the active wavelength range (0.5 - 1 μm). The grid mask used contained line widths around 5 μm (shadow loss 3.5%), but actual measurements showed that the deposited gridline width was 7 μm , around 5% shadow loss.

Considering this shading, the measured reflectance around 5 - 7% does not suggest that serious J_{sc} loss was caused by detuning of the AR coating. However, part of the J_{sc} spread could have been caused by varying line widths.

The V_{oc} values obtained at one-sun and higher concentrations were similar to those observed previously, and did not affect the cell output significantly.

3.0 CHARACTERIZATION TESTS

Sandia selected ten cells at random from the 200 delivered cells, and as seen in Table 1, the average IV parameters for those 10 cells (tested at 150-suns) agreed closely with the average values for the 200 cells delivered.

Drs. Ruby and Basore performed very thorough tests on these cells, (numbered 1 through 10). The following sections summarize these Sandia test results, and show their value in analyzing the cell performance. We have focused attention on cells 2, 4, 7, and 8 because #2 and #4 are close to the average, #7 had high shunt leakage and #8 had the best efficiency at high concentrations.

3.1 Measurements at High Concentrations

Table 2 shows the Sandia measurements at one-sun and concentration 6.2x, 12x, 50x, 150x, 250x and 400x for the four cells 2, 4, 7, and 8.

Figures 3 - 14 plot concentration on a log scale and show the variation of efficiency (Figures 3 - 6), CFF (Figures 7 - 10) and V_{oc} (Figures 11 - 14).

The peak efficiency was around 50-suns, and the peak CFF around 12-suns. The slope of the V_{oc} vs $\ln X$ plot was slightly lower than the 26 mV/decade for ideality factor $n = 1$, and decreased for concentrations above 150x. This V_{oc} variation with concentration agrees closely with previous tests and confirms that the quality of the Si and the PN junction were comparable to earlier tests.

The peak efficiency was determined mostly by the J_{sc} values (these were discussed in section 2.4).

The fall off in efficiency and CFF with concentration was caused by series resistance, and thus is discussed in more detail in Section 3.4.

3.2 Spectral Response

Measurement of cell response and reflectance as a function of wavelength, led to plots of external and internal quantum efficiencies. Using analysis developed in reference 1, Dr. Basore determined that the average bulk diffusion length was between 160 and 185 μm , and the rear surface recombination velocities were between 860 and 1,860 cm sec^{-1} . These values are considered satisfactory.

3.3 Dark Forward Diode Measurements

Two typical dark I - V curves (for cells #2 and #7) are shown in Figures 15 and 16. Three cell parameters can be defined from those curves.

3.3.1 Diode Ideality Factor

The factor n in the Boltzman factor nkT/q can be determined by the slope of the curve at medium high diode currents (injection level). Fairly consistent n -values, between 1.05 and 1.2, were found for all ten cells.

3.3.2 Shunt Leakage Currents

The current at low voltages ($\leq 0.3\text{V}$) showed the PN junction shunt leakage. For the two cells shown, #2 had high shunt resistance, and #7 had low shunt resistance. The effects of the leakage currents on cell behavior is pronounced only at low concentrations. At one-sun, the curve fill factor for #2 and #7 were respectively 0.816 and 0.612. However, for

concentrations above 10x, the generated currents are much higher than the leakage currents, and the CFF is controlled by series resistance (see 3.4).

3.3.3 Series Resistance

The fall off in linearity at high currents is an indication of voltage dropped across the series resistance, and is typically measured as the ΔV at high currents such as 10 or 15 A/cm² (ΔV is indicated on the curves, along with estimates of series resistance).

In 3.4 we discuss series resistive effects in detail, and have concluded that the r_s value derived from the dark forward characteristic is not accurate. Possibly the cause is that under forward bias in the dark, the current flow pattern is different from the illuminated cell. Also the series voltage drop has opposing effect on the voltage across the diode in the circuit equations. The analysis in the next section gave r_s values closer to predicted values, and gave guidelines for estimating the deficiencies in the current cells, and possible improvements which could be made.

3.4 Analysis of Performance at High Concentrations

3.4.1 Series Resistance from Model

Using the standard grid model for the separate contributions to series resistance, and inserting parameters used in designing the grid mask (and in processing) we obtain the following estimates:

Emitter Resistance	~	1 milli-ohm
Front Contact Resistance	~	2 milli-ohm
Bulk Resistance	~	6 milli-ohm
Gridline Resistance	~	3 milli-ohm

In addition to these 12 milli-ohms, tests had shown that the back contact resistance could be significant (1-5 milli-ohms), although the sintering cycle used was intended to reduce this resistance (as mentioned with trade-offs in ease of soldering and a small loss in J_{sc}).

3.4.2 Analysis of CFF Versus Concentration Curves

We used the same cells (2, 4, 7 and 8) discussed in 3.1.

Using Sandia's test results for concentrations of 50, 150, 250 and 400 suns, we computed the ideal fill factor (FF_0) from equation 1.

$$(1) \quad FF_0 = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1}$$

$$v_{oc} = \frac{y_{oc}}{nkT/q} \quad \text{and we assumed } n \sim 1. \text{ i.e. } v_{oc} = \frac{y_{oc}}{26}$$

These FF/FF_0 values were then used to derive the FF/FF_0 ratio from equation 2.

$$(2) \quad \frac{FF}{FF_0} = \frac{(1 - r_s)}{R_s} \quad \text{where } r_s \text{ is the series resistance}$$

$$\text{and } R_s = \frac{0.9 v_{oc}}{I_{sc}}$$

At each concentration we calculated FF/FF_0 for the 5 r_s values (0, 5, 10, 15 and 20 milli-ohms) and these are shown in Tables 3 - 6.

The values of efficiency versus concentration are plotted (on a linear scale) in Figures 17 - 20. The dashed lines show the changing efficiency as a function of concentration for five values of modeled series resistance r_s . The solid line shows the measured variation and by comparison, it can be seen that the approximate r_s values are as follows:

TABLE 7

Cell No.	2	4	7	8
Series Resistance (m-ohm)	12	9.5	13	12

We see that low series resistance slightly affects the maximum efficiency (~ 150 suns), but the maximum value is more dependent on J_{sc} .

As expected, the value of series resistance determines the rate of fall off in efficiency at higher concentrations.

3.4.3 Discussion

The spread in r_s values is consistent with deviations from the modeled values in 3.4.1. Also the analysis shows that all series resistance contributions (especially grid resistance), must be reduced to approach the slow fall off for r_s values < 10 milli-ohms. It appears that close attention to reduced r_s values must be combined with increased J_{sc} , to achieve high peak values of efficiency, and to reduce the fall off beyond the concentration giving peak efficiency.

4.0 CONCLUSIONS

This abbreviated run and the Sandia characterization tests have provided useful information on the achievable performance of these high concentration cells.

Fine-tuning of the series resistance can be completed by a systematic process consolidation and the performance validated by testing at higher concentrations.

The most important requirement is to increase J_{sc} to the levels consistent with the starting silicon. This can be confirmed by one-sun measurements using the designed masks and the processes developed by iterative testing.

5.0 REFERENCES

1. P. A. Basore, "Extended Spectral Analysis of Internal Quantum Efficiency," Conference Record of 23rd IEEE PVSC, July 1993, p. 147.

Table 2
Sandia Test Results at Different Concentrations

Cell #2

CONC	EFF	VOC	ISC	FF	VMP	IMP	MAX PWR	TEMP
6.2	19.30	.693	.208	.829	.607	.197	.120	25.0
12.0	19.78	.710	.402	.832	.620	.383	.237	25.0
50.0	20.56	.748	1.678	.819	.644	1.595	1.028	25.0
150.0	20.20	.773	5.004	.783	.640	4.737	3.030	25.0
250.0	19.12	.783	8.216	.743	.620	7.709	4.779	25.0
400.0	17.80	.791	13.334	.675	.572	12.442	7.119	25.0

Cell #4

CONC	EFF	VOC	ISC	FF	VMP	IMP	MAX PWR	TEMP
6.2	18.61	.699	.205	.887	.606	.191	.115	25.0
12.0	19.39	.716	.395	.822	.629	.370	.233	25.0
50.0	20.37	.754	1.642	.822	.652	1.562	1.018	25.0
150.0	20.25	.778	4.936	.792	.650	4.675	3.038	25.0
250.0	19.65	.787	8.248	.757	.630	7.797	4.913	25.0
400.0	18.04	.794	13.026	.698	.593	12.169	7.216	25.0

Cell #7

CONC	EFF	VOC	ISC	FF	VMP	IMP	MAX PWR	TEMP
6.2	18.11	.696	.204	.792	.689	.185	.112	25.0
12.0	18.84	.712	.392	.810	.622	.364	.226	25.0
50.0	19.88	.750	1.634	.811	.643	1.546	.994	25.0
150.0	19.38	.776	4.892	.766	.629	4.619	2.906	25.0
250.0	18.05	.786	7.983	.720	.608	7.423	4.512	25.0
400.0	16.45	.793	12.884	.644	.572	11.498	6.579	25.0

Cell #8

CONC	EFF	VOC	ISC	FF	VMP	IMP	MAX PWR	TEMP
6.2	20.79	.704	.219	.836	.616	.209	.129	25.0
12.0	21.06	.721	.422	.831	.631	.401	.253	25.0
50.0	21.83	.757	1.753	.823	.652	1.674	1.091	25.0
150.0	21.49	.782	5.283	.781	.643	5.015	3.223	25.0
250.0	20.15	.791	8.650	.736	.619	8.135	5.037	25.0
400.0	18.51	.799	13.974	.664	.593	12.495	7.404	25.0

TABLE 3

Efficiency vs. Concentration (Cell #2)

Experimental					Calculated				
Conc'n.	V _{oc} (mV)	I _{sc} (A)	FF	EFF (%)	FF _o	r _s (mΩ)	FF/FF _o	FF	EFF (%)
50	748	1.678	.819	20.56	.853	0	1	.853	21.41
						5	0.987	.842	21.14
						10	0.975	.832	20.89
						15	0.963	.821	20.61
						20	0.950	.810	20.33
150	773	5.004	.783	20.2	.856	0	1	.856	22.07
						5	0.964	.825	21.27
						10	0.928	.754	20.48
						15	0.892	.763	19.68
						20	0.856	.733	18.9
250	783	8.216	.743	19.12	.858	0	1	.858	22.08
						5	0.942	.808	20.79
						10	0.883	.758	19.51
						15	0.825	.708	18.22
						20	0.767	.658	16.93
400	791	13.334	.675	17.8	.859	0	1	.859	22.65
						5	0.905	.777	20.49
						10	0.811	.697	18.38
						15	0.716	.615	16.22
						20	0.622	.534	14.08

TABLE 4

Efficiency vs. Concentration (Cell #7)

Experimental					Calculated				
Conc'n.	V _{oc} (mV)	I _{sc} (A)	FF	EFF (%)	FF _o	r _s (mΩ)	FF/FF _o	FF	EFF (%)
50	750	1.634	.811	19.88	.833	0	1	.833	20.4
						5	0.986	.823	20.2
						10	0.976	.813	19.93
						15	0.964	.803	19.7
						20	0.952	.793	19.44
150	776	4.892	.766	19.38	.837	0	1	.837	21.2
						5	0.965	.808	20.45
						10	0.930	.778	19.7
						15	0.895	.749	18.95
						20	0.860	.720	18.2
250	786	7.983	.720	18.05	.839	0	1	.839	21.1
						5	0.944	.792	19.9
						10	0.887	.744	18.7
						15	0.831	.697	17.5
						20	0.774	.649	16.3
400	793	12.884	.644	16.45	.840	0	1	.840	21.46
						5	0.910	.764	19.45
						10	0.820	.689	17.54
						15	0.730	.613	15.6
						20	0.640	.538	13.7

TABLE 5

Efficiency vs. Concentration (Cell #4)

Experimental					Calculated				
Conc'n.	V _{oc} (mV)	I _{sc} (A)	FF	EFF (%)	FF _o	r _s (mΩ)	FF/FF _o	FF	EFF (%)
50	754	1.642	.822	20.37	.837	0	1	.837	20.7
						5	0.987	.826	20.45
						10	0.976	.817	20.23
						15	0.964	.807	19.98
						20	0.952	.797	19.73
150	778	4.936	.792	20.25	.840	0	1	.840	21.5
						5	0.965	.811	20.76
						10	0.930	.781	19.99
						15	0.894	.751	19.23
						20	0.859	.722	18.48
250	787	8.248	.757	19.65	.842	0	1	.842	21.86
						5	0.942	.793	20.6
						10	0.884	.744	19.3
						15	0.825	.695	18.04
						20	0.767	.646	16.77
400	794	13.026	.698	18.04	.843	0	1	.843	21.8
						5	0.909	.766	19.8
						10	0.818	.690	17.84
						15	0.727	.613	15.85
						20	0.636	.536	13.86

TABLE 6

Efficiency vs. Concentration (Cell #8)

Experimental					Calculated				
Conc'n.	V _{oc} (mV)	I _{sc} (A)	FF	EFF (%)	FF _o	r _s (mΩ)	FF/FF _o	FF	EFF (%)
50	757	1.753	.823	21.83	.851	0	1	.851	22.6
						5	0.987	.840	22.3
						10	0.974	.829	22.0
						15	0.961	.818	21.7
						20	0.949	.808	21.44
150	782	5.283	.781	21.49	.854	0	1	.854	23.52
						5	0.962	.822	22.64
						10	0.925	.790	21.76
						15	0.887	.758	20.88
						20	0.850	.726	19.99
250	791	8.65	.736	20.15	.856	0	1	.856	23.43
						5	0.939	.804	22.0
						10	0.879	.752	20.6
						15	0.818	.700	19.2
						20	0.757	.647	17.7
400	799	13.974	.664	18.51	.857	0	1	.857	23.92
						5	0.903	.774	21.6
						10	0.806	.691	19.3
						15	0.709	.608	16.97
						20	0.611	.524	14.63

FIGURE 1 HISTOGRAM PLOT OF EFFICIENCY

FIGURE 2 HISTOGRAM PLOT OF CFF

FIGURE 3
Efficiency Versus Concentration (Cell #2)

FIGURE 4
Efficiency Versus Concentration (Cell #4)

FIGURE 5

Efficiency Versus Concentration (Cell #7)

FIGURE 6
Efficiency Versus Concentration (Cell #8)

FIGURE 7

Curve Fill Factor Versus Concentration (Cell #2)

FIGURE 8

Curve Fill Factor Versus Concentration (Cell #4)

FIGURE 9

Curve Fill Factor Versus Concentration (Cell #7)

FIGURE 10

Curve Fill Factor Versus Concentration (Cell #8)

FIGURE 11

Open Circuit Voltage Versus Concentration (Cell #2)

FIGURE 12

Open Circuit Voltage Versus Concentration (Cell #4)

FIGURE 13
Open Circuit Voltage Versus Concentration (Cell #7)

FIGURE 14

Open Circuit Voltage Versus Concentration (Cell #8)

Cell ID=94008-02
 Comment=212

Cell area= 1.000 cm²

Cell Temp= 25.00 deg C

Minimum Current= 1.000E-06 amps

Maximum Current= 1.500E+01 amps

Ramp Sweeptime= 100 ms

Sample Interval= 2.00 ms

$$r_s = \frac{.91 - 0.807}{15} = 6.7 \text{ m}\Omega$$

$$n = 1.07$$

FIGURE 15
Dark I-V Curve (Cell #2)

Cell ID=94008-07
 Comment=94

Cell area= 1.000 cm²

Cell Temp= 25.01 deg C

Minimum Current= 1.000E-06 amps
 Maximum Current= 1.500E+01 amps

Ramp Sweeptime= 100 ms
 Sample Interval= 2.00 ms

$$r_s = \frac{.906 - .827}{15} = 5.3 \text{ m}\Omega$$

$$n = 1.21$$

FIGURE 16
Dark I-V Curve (Cell #7)

Figure 17 EFFICIENCY vs CONCENTRATION
(Cell #2)

Figure 18 EFFICIENCY vs CONCENTRATION
(Cell #4)

Figure 19 EFFICIENCY vs CONCENTRATION
(Cell #7)

Figure 20 EFFICIENCY vs CONCENTRATION
(Cell #8)

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