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Electrical Overstress Failure in Silicon Solar Cells

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Electrical Overstress Failure in Silicon Solar Cells

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Abstract

This report presents a solar cell electrical overstress failure model and the results of experimental measurements of threshold pulsed failure currents on four types of silicon solar cells. The transient EMP field surrounding a lightning stroke has been identified as a potential threat to a photovoltaic array, yet failure analysis of solar cells in a pulsed environment had not previously been reported. Failure in the low resistivity concentrator cells at pulse widths between 1 μ s and 1 ms occurred initially in the junction. Finger damage in the form of silver melting occurs at currents only slightly greater than that required for junction damage. The result of reverse bias transient overstress tests on high resistivity (10 Ω cm) cells demonstrated that the predominant failure mode was due to edge currents. These flat-plate cells failed at currents of only 4 to 20 A which is one or two orders of magnitude below the model predictions. It thus appears that high resistivity flat-plate cells are quite vulnerable to electrical overstress which could be produced by a variety of mechanisms.

*Currently with Sandia National Laboratories

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FOREWARD

This technical report, ARMC-R-358, has been prepared by Mission Research Corporation, 1720 Randolph Road, S. E., Albuquerque, New Mexico, for Sandia National Laboratories, under contract 62-8208. Mr. Calvin B. Rogers was the Sandia Technical Monitor. The Mission Research Corporation program manager was R. L. Pease. Other major contributors to the analyses and report were J. R. Barnum, V. A. J. van Lint, W. V. Vulliet, and T. F. Wrobel.

1.0 INTRODUCTION

This final report on contract 62-8208 presents a solar cell electrical overstress failure model development and results of experimental measurements of threshold pulsed failure currents on four types of silicon solar cells. This work is a follow on to contract 13-0215, Transient Effects from Lightning.¹ Under contract 13-0215, MRC identified the transient EMP field surrounding a lightning stroke as a potential threat to a photovoltaic array. The EMP field can couple energy into the DC array cabling connecting the array with a power conditioning unit or DC load. The resultant current and voltage transients, in the form of a double exponential pulse may cause damage to the silicon solar cells in the array. In order to determine the threshold current required to damage the cells, a first order model was developed to predict the failure current from the cell characteristics. The results of the model were that the metallization would burn out at a substantially lower current than the silicon junction. Failure currents of several thousand Amperes for pulse widths of 10-100 μ s were predicted for a typical 2 1/4" diameter concentrator cell and several hundred Amperes for a typical 3" diameter flat-plate cell.¹

These model predictions did not take into account the heating of the silicon junction by conduction from the metal. Also no experimental measurements were made of pulsed overstress failure levels. A literature search performed during contract 13-0215 revealed that no pulsed overstress failure testing had been performed on solar cells. However, TRW has performed electrical overstress failure tests on silicon solar cells under steady state reverse bias.² They found the failure levels to be several Amperes to tens of Amperes with failures occurring on the edges of the cell.

The purpose of this program is to refine the transient overstress failure model and experimentally measure the pulsed current failure thresholds for several typical concentrator and flat-plate silicon solar cells.

Section 2 of this report provides background information on the development of the program. Section 3 provides details of the Solar cells that were modeled and tested for overstress failure. The model development is presented in Section 4 along with the predictions of threshold failure current for each of the cells. Section 5 presents the results of the experimental verification of the cell current distribution under high current pulses and the results of the overstress failure tests. A discussion of the results is given in Section 6 along with comparisons to model predictions. Section 7 presents the conclusions and recommendations.

2.0 BACKGROUND

In the original test plan for this program, a primarily experimental effort was proposed in which

- a) A minimum sample of 40 each of six different solar cell types would be obtained for characterization and overstress testing.
- b) Extensive electrical and physical measurements would be made to extrapolate model input parameters.
- c) Threshold failure currents would be measured on each cell type as a function of pulse width, temperature and illumination.
- d) A statistically significant sample would be tested at room temperature, 10 μ s pulse width with no illumination to determine the variability in failure level for each cell type.
- e) An extensive failure analysis would be performed to determine failure modes.

The experimental facility proposed for this test effort was the Direct Drive Lab (DDL) of the Air Force Weapons Laboratory (AFWL). Within the first few months of the program it became apparent that the overstress failure characterization of the solar cells required more of a development effort than originally conceived. There was a great deal of difficulty in obtaining the test cells and developing mounting techniques for testing. The semiautomated electrical test equipment of the DDL, which is used primarily for transistors and diodes, proved inadequate for the large area solar cell. The source impedance and short circuit current output of the square wave pulsers of the DDL proved inadequate for overstress failure testing of the concentrator cells. Also the temperature controller and

illuminator of the DDL could not easily be incorporated into the overstress test setup. In addition, a flaw was discovered in the burnout model developed under contract 13-0215.

Therefore the program was significantly revised and a new test plan generated. The new plan called for a reduced electrical characterization program aimed primarily at measuring the substrate resistivity, hence doping level, of the cells, as well as the avalanche voltage and dynamic impedance of the cells. Part of the reason for this was that nearly all of the model input parameters could be obtained either directly from the manufacturers and/or from technical reports and papers written on the development of the cells. The tests to be performed at increased temperature and illumination were dropped since the model predictions indicated that these variables would introduce only small deviations in the threshold failure currents. Since the available square wave pulsers at DDL have insufficient output to cause damage in some of the cells, the test plan was revised to include failure tests on smaller symmetrical pieces of the entire cells. The problem with this approach, however was the confidence in extrapolating failure currents to the entire cell.

A considerable amount of time and effort was expended in trying to develop the capability to perform threshold failure tests on whole cells. The alternatives considered were, a) locate and schedule an existing high current pulser facility with sufficient output to fail all cells and adequate instrumentation to get acceptable measurements of the current and voltage waveforms during the overstress tests, b) determine the time and expense involved in developing a pulser and instrumentation system with the proper characteristics, and c) designing and building a transformer to be used with an existing high voltage pulser so that adequate current would be available to fail whole cells. The decision was made to use approach c) by having AFWL design and build a transformer to be used with a Maxwell Labs 150 KV pulser available at AFWL. This decision was based primarily on the

fact that Sandia had already contracted with the AFWL DDL for experimental support for the program. This decision however, meant that instead of being able to measure the threshold damage current as a function of square wave pulse width over the range of 1-100 μ s, the failure thresholds could only be measured for a double exponential pulse with a 10 μ s decay time.

In addition to the previously mentioned difficulties, there were problems in obtaining the test cells. Although the original plan called for at least 40 each of three types of concentrator cells and 40 each of three types of flat-plate cells, Sandia was only able to supply ~40 each of two concentrator cell types, 16 of a third concentrator cell type and 60 each of one flat-plate cell type. The major limitation on the flat-plate cell was the requirement for a small area to guarantee that the failure currents would be within the capability of the pulser.

Based on the aforementioned developments during the early part of the program, the program plan evolved into the following:

- 1) Perform electrical characterization of test cells prior to over-stress tests to verify substrate doping levels and measure avalanche breakdown voltage and dynamic impedance.
- 2) Refine the failure model and predict failure modes and threshold failure currents for each of the cell types.
- 3) Perform high current pulse measurements of the voltage drops along the bus and fingers to verify the model predictions of current distribution.
- 4) Measure the threshold failure currents in each cell type for both forward and reverse bias.

- 5) Perform visual failure analysis on all cells to determine failure modes.
- 6) Compare measured failure data with predicted failure levels to determine validity of model.

3.0 CHARACTERISTICS OF THE SOLAR CELLS

As mentioned in Section II the original plan called for an experimental test program on 3 concentrator and 3 flat-plate cell types. Although 3 concentrator cell types were obtained, only one type of flat-plate cell was included. In this section a complete description of the cells is given along with the geometrical and physical characteristics and the cell mounting techniques important for modeling the overstress failure. In addition, the results of electrical tests performed to verify certain parameters will be given.

Table 3-1 is a list of the solar cells characterized along with references for the cell parameters.

TABLE 3-1

Cell Type	Manufacturer	Sample Size	Total Cell Area	Reference
Concentrator	Applied Solar Energy Corp. (ASEC)	48	5.5 cm ²	3
Concentrator	Solarex	40	15 cm ²	4
Concentrator	Sandia National Labs (SNL)	16	5.5 cm ²	5
Flat-plate	TRW (obtained from Photowatt)	60	4 cm ²	6

3.1 General Description of Cells

The ASEC concentrator cell is a point focus cell used in a Sandia National Labs prototype concentrator array system. Figure 3-1 presents top and cross section views of the cell. This cell has an active surface area of 4.2 cm^2 with 72 fingers per side.

The SNL concentrator cell is also a point focus cell with a finger pattern similar to the ASEC cell. This cell also has an active area of 4.2 cm^2 but only 54 fingers per side. MRC received two lots of SNL cells, both of which were unable to meet SNL performance specifications. The cells had a low fill factor, more than normal leakage current and metallization adhesion problems. However, these cells were used for overstress tests since cells meeting SNL specifications were not available to MRC at that time. Figure 3-2 presents top and cross section views of the Sandia cell.

The Solarex concentrator cell is a line focus cell developed under contract to SNL. This cell has an active area of 11.94 cm^2 and 106 fingers. Top surface and cross section views are presented in Figure 3-3.

The Photowatt cell is the only flat-plate cell received. This cell was manufactured by TRW and was originally intended for space applications. The cell has an active area of 8 cm^2 with 48 fingers as shown in Figure 3-4. The cells received for testing were LASER scribed and sectioned into two cells. Figure 3-5 presents top and cross section views of the two elements. Correspondence with TRW revealed that the original cells were rejected because they did not pass environmental tests.

The ASEC cell is fabricated with a blanket n^+ top surface diffusion into a $.4 \text{ ohm-cm}$ p type substrate 12 mil thick. A single main bus encircles the active area with the grid fingers perpendicular to the bus at each edge. The electrode metal on the front and back surfaces is an evaporated

TOP VIEW

CROSS SECTION OF CELL

Bus: 0.15 cm wide, 5 mil high
(including solder)

Fingers: 20 μm wide, 5 μm high

Silicon To Layer (n+): 0.4 μm thick,
 $\rho = 0.002 \Omega \text{ cm}$

Silicon Base (P): 12 mil (305 μm).
 $\rho = 0.4 \Omega \text{ cm}$

Figure 3-1. ASEC CONCENTRATOR CELL.

Figure 3-2. SANDIA SOLAR CELL.

Figure 3-3. SOLAREX SOLAR CELL.

Figure 3-4. Photowatt flat-plate cell before scribing.

FIGURE 3-5. PHOTOWATT FLAT-PLATE SOLAR CELL AFTER SCRIBING.

trimetal (Ti-Pd-Ag) with the thickness of the electrode increased to 5 μm by electroplating of Ag. The main bus cross sectional area is additionally increased approximately 5 mils by flowing solder on the bus. An anti-reflective coating is utilized to reduce surface reflectance over the usable solar spectrum.

The SNL cell is similar to the ASEC in geometry only. The cell is fabricated with a planar p+ top surface diffusion and an n+ blanket back surface diffusion utilizing a .3 ohm-cm p type substrate 12 mil thick. Figure 3-2 illustrates the cell cross section. As with the ASEC cell a single main bus encircles the active area with the grid fingers perpendicular to the bus and 5 mils of solder flowed on the bus. However, the main bus on the SNL cell is on top of an oxide which provides dielectric isolation between the bus and the Si. The metallization technique for the front and back surfaces is the same as for the ASEC cell except the resulting metallization thickness is $\sim 10 \mu\text{m}$. An anti-reflective coating is also utilized.

The Solarex cell is constructed on a .4 Ω cm p type 12 mil textured wafer and employs an n+ planar top surface diffusion. The junction extends to the edge of the cell at the ends. The front surface metallization is a dual bus configuration with the fingers perpendicular to the bus. The Solarex bus does not lie on top of an oxide, but on the Si. The front surface metallization uses a trimetal evaporation (Cr-Cr&Au-Au) and Ag electroplated to 20 μm , with approximately 5 mils of solder on the bus. The back surface metallization uses an Al alloy, Cr&Au evaporated film, and Ag electroplate. A tantalum oxide anti-reflective coating is evaporated on the front surface.

The Photowatt cell construction and specifications were obtained from personnel at TRW. The Photowatt cells were fabricated with an n+

blanket diffusion on a 10 ohm-cm p type textured substrate 8 mils thick. The metallization consists of a trimetal (Ti-Pd-Ag) contact with an Ag electroplate to 5 μm . The textured surface has an antireflective coating.

A summary of the pertinent information obtained from the manufacturers is given in Table 3-2. These values must be considered nominal for the cell types.

3.2 Verification of Nominal Parameter Values

Most of the nominal parameter values obtained from the manufacturers have been assumed correct. Spot checks of cell size, bus width, finger width and chip thickness verified the values given in Table 3-2. The upper layer resistivity and thickness are more difficult to verify. The resistivities are reasonable numbers considering the solubility of electrically active dopants in silicon. The thickness, or diffusion depth is reasonable since these values are nearly the same for the shallow emitter diffusions in microcircuits. One of the more critical parameters is the base region resistivity which was verified experimentally.

Base region resistivity can be verified by two methods, capacitance/voltage (C/V) and reverse breakdown measurements. These methods were both used to determine experimental values for substrate doping concentrations and thus base resistivity. The results from the two methods were compared to nominal substrate concentrations and were found to be within 20% of the nominal substrate doping concentrations obtained from resistivities supplied by the manufacturers shown in Table 3-2.

C/V - Method

To determine substrate doping concentrations from C/V data, either a step or a linearly graded junction is assumed. For solar cells which use a

TABLE 3-2

Characteristic	ASEC	Sandia	Solarex	Photowatt
Junction type	n+/p	p+/n	n+/p	n+/p
Symmetry	1/8	1/8	1/2	1
No. of fingers	72/side	54/side	108	24
Finger width	20 μm	23 μm	32 μm	25.4 μm
Finger thickness	5 μm	10 μm	20 μm	5 μm
Maximum finger length	1 cm	1 cm	1 cm	1.9 cm
Bus width	.15 cm	.15 cm	.236 cm	.1cm/.0686 cm
Bus length	2.35 cm/side	2.35 cm/side	6 cm	1.9 cm
Silicon base resistivity	.4 Ωcm	.3 Ωcm	.4 Ωcm	10 Ωcm
Base doping	$5.4 \times 10^{16} \text{ cm}^{-3}$	$2.65 \times 10^{16} \text{ cm}^{-3}$	$5.4 \times 10^{16} \text{ cm}^{-3}$	$1.4 \times 10^{15} \text{ cm}^{-3}$
Avalanche Voltage (From plane junction approximation)	21	33	21	245
Chip thickness	12 mils	12 mils	12 mils	8 mils
Top layer resistivity	.002 Ωcm	.002 Ωcm	.001 Ωcm	.001 Ωcm
Top layer thickness	.4 μm	.35 μm	.4 μm	.3 μm

shallow very heavily doped top surface layer a step junction assumption is reasonable. The depletion layer capacitance for a step junction is given by:⁷

$$\frac{1}{C^2} = \frac{2}{N_s q \epsilon_0 K_s} [V_{Bi} \pm V_B] \quad (1)$$

where

- C - capacitance per unit area
- N_s - substrate doping concentration
- q - electron charge
- ϵ_0 - permittivity of free space
- K_s - dielectric constant of Si
- V_{Bi} - built in voltage
- V_B - reverse bias voltage

If $1/C^2$ is plotted versus applied reverse bias voltage a straight line should be obtained. The slope of the line is found by differentiating equation (1) with respect to bias voltage. This is given by:

$$\text{SLOPE} = m = \frac{(1/C^2)}{(V_{Bi} \pm V_B)} = \frac{2}{q K_s \epsilon_0 N_s} \quad (2)$$

Equation (2) can be rearranged to give:

$$N_s = \left[\frac{q K_s \epsilon_0}{2} m \right]^{-1} \quad (3)$$

To determine N_s , C/V measurements were made for each solar cell under non-illuminated reverse bias conditions using an HP-4275A programmable digital LCR meter. The HP-4275A has a variable frequency from 10 KHz to 10 MHz. It is capable of measuring capacitance up to 35 Volts reverse bias with reverse currents up to 100 mA. The capacitance of the solar cells was measured up to the maximum voltage (35 V) or current (100 mA), whichever occurred first. The test signal frequency was set at 10 KHz. Figure 3-6 shows the set up used for the C/V measurements. Table 3-3 shows the test parameters for the solar cells tested. The column under maximum

CAPACITANCE MEASUREMENT TEST SET UP

Figure 3-6. Capacitance measurement test set up.

nominal test voltage lists the highest nominal voltage for which the leakage current was less than 100 mA.

TABLE 3-3

C/V Test Parameters

<u>Cell Type</u>	<u>No. of Cells Tested</u>	<u>Nominal Reverse Breakdown</u>	<u>Max Nominal Test Voltage V</u>	<u>Max Nominal Test Current mA</u>
ASEC	28	21	20	100
SANDIA	15	33	20	100
SOLAREX	12	21	5	100
5 FINGER SOLAREX	1	21	12	100
8 FINGER SOLAREX	1	21	12	100
11 FINGER SOLAREX	3	21	13	100
15 FINGER SOLAREX	2	21	12	100
PHOTOWATT	23	245	85	60

Results

Table 3-4 lists the results of measured substrate doping compared to predicted values. Figure 3-7 illustrates a typical $1/C^2$ versus bias voltage plot from which doping concentrations were determined.

The Solarex cell data did not follow the expected C/V dependence. The $1/C^2$ plots were nonlinear and differences were noted between complete and sectioned cells. Figure 3-8 illustrates a typical $1/C^2$ plot for the Solarex cell. The figure shows the non-linearity of the data compared to the expected $1/C^2$ behavior.

Figure 3-7. Typical $1/C^2$ vs reverse bias voltage.

Figure 3-8. Typical $1/C^2$ plot for the Solarex cell.

TABLE 3-4

C/V Measurement Results. Experimental and Nominal Values.

CELL TYPE	No. of CELLS TESTED	DIODE TYPE	NOMINAL SUBSTRATE RESISTIVITY Ω cm	NOMINAL DOING CONCENTRATION (cm^{-3})	MEAN OF MEASURED DOPING CONCENTRATION (cm^{-3})	STANDARD DEVIATION OF MEASURED CONCENTRATION (cm^{-3})
ASEC	28	n+/p	.4	5.4×10^{16}	4.44×10^{16}	$.35 \times 10^{16}$
SNL	15	p+/n	.3	2.65×10^{16}	1.70×10^{16}	$.174 \times 10^{16}$
PHOTOWATT	23	n+/p	10	1.4×10^{15}	1.52×10^{15}	$.191 \times 10^{15}$
COMPLETE SOLAREX	12	n+/p	.4	5.4×10^{16}	1.18×10^{17}	$.362 \times 10^{17}$
5 FINGER SOLAREX	1	n+/p	.4	5.4×10^{16}	8.82×10^{16}	-
8 FINGER SOLAREX	1	n+/p	.4	5.4×10^{16}	6.48×10^{16}	-
22 FINGER SOLAREX	3	n+/p	.4	5.4×10^{16}	6.182×10^{16}	$.417 \times 10^{16}$
15 FINGER SOLAREX	2	n+/p	.4	5.4×10^{16}	7.085×10^{16}	$.137 \times 10^{16}$
ALL SOLAREX SECTIONED CELLS	7	n+/p	.4	5.4×10^{16}	6.35×10^{16}	$.386 \times 10^{16}$

Since the $1/C^2$ values for the Solarex cells increase at a nearly exponential rate with increasing bias voltage, the data would not fit a $1/C^2$ or $1/C^3$ dependence or even a shift from a $1/C^2$ to a $1/C^3$ dependence as sometimes occur with epitaxial devices. Nonlinearities can result from high leakage current or parasitic capacitance. However increased leakage current results in increased capacitance at high voltage. In the case of the Solarex cells, the capacitance is decreasing. Dominance of parasitic capacitance effects is not expected since the mounting technique for the Solarex cells was similar to that of other cells and no parasitic effects were observed with the other cell types.

Even though the Solarex cell C/V data did not fit a $1/C^2$ dependence at higher voltages, it did seem to fit the expected linear behavior up to about 5 V. The doping level data shown in Table 3-4 was based on C/V measurements up to 5 V. It is evident that a much better correlation to the nominal resistivities was obtained from the C/V data on the cell sections.

Breakdown Method

Substrate doping concentration can also be determined from breakdown or avalanche voltage. The breakdown voltage as a function of doping concentration for a step junction is.⁷

$$V_B = \frac{\epsilon_s E_m^2}{2qN_s} \quad (4)$$

where:

- V_B - breakdown voltage
- N_s - substrate doping concentration
- q - electron charge
- ϵ_s - semiconductor permittivity
- E_m - maximum electric field

This relation applies to a plane junction. For planar junctions the breakdown voltage is also a function of the diffusion depth or junction radius of curvature since the breakdown is assumed to occur at the junction periphery. For bulk conduction in large area devices the plane junction approximation is reasonable.

Since the solar cells were so leaky, high current pulsed measurements were required to assure that the cell was in avalanche. Measurements were made using 100 μ s rectangular pulses. Current and voltage pulse data were taken both below and well into avalanche in order to determine the breakdown voltage. Table 3-5 presents the doping concentrations obtained from pulse measurements. No data is presented for the Photowatt cell, since avalanche could not be achieved without damage to the cell.

Table 3-6 is a list of the measured doping concentrations compared to the nominal values obtained from the manufacturers. In the case of the ASEC cells, both experimental methods gave results that were lower than the nominal value given in Reference 3. However for the Sandia and Solarex cells, one method gave results that were larger and the other method gave a result that was smaller than the nominal value used. For the Photowatt cell only the C/V method could be applied and the experimental result was within a few percent of the nominal. Because of the variation in the experimental results, there appeared to be no justification for selecting one method over the other. Hence it seemed reasonable to use the nominal value supplied by the manufacturers for the model predictions.

3.3 Mounting Techniques

There were two primary considerations regarding cell mounting: 1) to mount the cells in a similar manner to their application in a system, and 2) to have the mounting such that electrical overstress failure and

TABLE 3-5

Substrate Doping Concentration Determined from Breakdown Measurements

<u>Cell Type</u>	<u>No. of Cells Tested</u>	<u>Test Method</u>	<u>Diode Type</u>	<u>Nominal Substrate Resistivity</u>	<u>Nominal Breakdown Voltage</u>	<u>Mean Measured Breakdown Voltage</u>	<u>Standard Deviation of Measured Breakdown Voltage</u>	<u>Nominal Doping Concentration</u>	<u>Doping Concentration Extrapolated From Breakdown Voltage</u>
ASEC	5	Pulse	n ⁺ /P	.4 Ω cm	21	24.0 V	-	5.4x10 ¹⁶ /cm ³	3.2x10 ¹⁶ /cm ³
SNL	17	Pulse	P ⁺ /n	.3 Ω cm	33	24.62 V	.59	2.65x10 ¹⁶ /cm ³	3.2x10 ¹⁶ /cm ³
SOLAREX	29	Pulse	n ⁺ /P	.4 Ω cm	21	19.92 V	1.51	5.4x10 ¹⁶ /cm ³	5.0x10 ¹⁶ /cm ³

The standard derivation of substrate doping is not presented because the mean breakdown voltage was used to determine the doping concentration.

TABLE 3-6

Comparison of substrate doping values obtained from C/V and breakdown measurement to predicted values obtained from base resistivity specifications.

<u>CELL TYPE</u>	<u>TEST METHOD*</u>	<u>AVERAGE DOPING CONCENTRATION EXTRA-POLATED FROM DATA</u>	<u>DOPING CONCENTRATION DETERMINED FROM NOMINAL RESISTIVITY</u>	<u>RATIO OF MEASURED TO NOMINAL DOPING CONCENTRATION</u>
ASEC	C/V	$4.44 \times 10^{16} / \text{cm}^3$	$5.4 \times 10^{16} / \text{cm}^3$	.8148
ASEC	BV	$3.2 \times 10^{16} / \text{cm}^3$	$5.4 \times 10^{16} / \text{cm}^3$	.5926
SNL	C/V	$1.70 \times 10^{16} / \text{cm}^3$	$2.65 \times 10^{16} / \text{cm}^3$	.6415
SNL	BV	$3.2 \times 10^{16} / \text{cm}^3$	$2.65 \times 10^{16} / \text{cm}^3$	1.208
PHOTOWATT	C/V	$1.52 \times 10^{15} / \text{cm}^3$	$1.4 \times 10^{15} / \text{cm}^3$	1.086
COMPLETE SOLAREX	C/V	$1.18 \times 10^{17} / \text{cm}^3$	$5.4 \times 10^{16} / \text{cm}^3$	2.185
COMPLETE SOLAREX	BV	$5.0 \times 10^{16} / \text{cm}^3$	$5.4 \times 10^{16} / \text{cm}^3$	.9259
SOLAREX SECTIONS	C/V	$6.86 \times 10^{16} / \text{cm}^3$	$5.4 \times 10^{16} / \text{cm}^3$	1.27

*C/V Capacitance voltage method
BV Breakdown voltage method

testing is a function of the cell and not the mounting. These two constraints are met for each of the cells as described below.

The ASEC cells were supplied mounted to ceramic headers and studded copper heat sinks. This was the mounting configuration for their system application. Figure 3-9 illustrates the ASEC mounting. In mounting the cells solder is flowed on the back surface and main bus of the cell. Top surface contact is made to the cell at the four corners by soldering copper contact straps to the bus. Back surface contact is made between the entire back surface and the back surface contact bus on the ceramic header.

The SNL cell was not supplied with a mounting header. Since this cell is the same size as the ASEC cell, the ASEC ceramic header was used without the copper heat sink.

The photowatt cell was also supplied without a mounting header. Since there were no specifications as to system mounting considerations, this cell was also mounted to the ASEC ceramic header. Figure 3-10 illustrates the photowatt cell mounted on the ASEC header.

Since the Solarex cell is much larger than the other cells, it would not fit on the ASEC header. Therefore a special mount was fabricated for the cell as shown in Figure 3-11. The header material chosen was a standard 1/16 inch copper clad glass-epoxy circuit board. Although preferable, there were no ceramic substrates of the desired size readily available. A possible draw back of the glass-epoxy board is heat transfer. However, this was not a problem for overstress testing since the thermal diffusion length for a 100 microsecond current pulse is shorter than the cell thickness. The bus layout on the glass-epoxy header was chosen to have a geometry similar to the ASEC ceramic header.

FIGURE 3-9. ASEC SOLAR CELL AND MOUNTING.

FIGURE 3-10. PHOTOWATT FLAT-PLATE CELL MOUNTING.

FIGURE 3-11. SOLAREX SOLAR CELL MOUNTING.

4.0 MODEL DEVELOPMENT

A failure model was developed under Sandia Labs contract 13-0215. The main conclusion of that model was that the solar cells would fail due to metallization burnout and that junction burnout would occur at significantly higher currents. In this program the earlier model was reviewed and extended. It was discovered that a significant contribution to the heating in the silicon had been overlooked. Since the silicon junction is within a micron of the surface, heat from the metallization is conducted to the junction in times short compared to the pulse widths of interest. This conductive heating was not included in the earlier model. In addition, the model was extended to include the effects of the change in metal resistivity with temperature. In this report, the entire model is discussed including the work performed in the previous effort.

In deriving the model, the following assumptions were made:

- a) Maximum heating occurs for reverse bias.
- b) The maximum current density in the silicon, hence heating, occurs in the bulk rather than at the surface or edges for transient currents in the range of 10-100 μ s pulse widths.
- c) The threshold for failure of the silicon junction occurs when the silicon is heated to the resistivity turnover temperature which is a function of the base doping density.
- d) The threshold for metallization failure is the silver melt temperature, 960°C.

Assumption a) is valid since the power, hence increase in temperature, across the junction is equal to the current times the voltage.

Clearly for reverse bias the voltage across the junction is greater for the same current than for forward bias. Assumption b) is much more difficult to justify. In the case of reverse DC bias, failures are in fact due to surface or edge currents.² In order to justify this assumption for transient currents, an estimate of the current densities in a surface inversion region must be made. If we assume that the surface leakage currents are through a narrow inversion region at the silicon - silicon dioxide interface, then the adiabatic heating in the silicon is

$$\Delta T = \frac{P\tau}{C_s V}$$

where ΔT is the increase in temperature, P the power delivered to the inversion region, τ the pulse width of the current pulse, C_s the silicon heat capacity ($1.78 \text{ j/cm}^3 \text{ }^\circ\text{C}$) and V the volume being heated (cross sectional area times inversion layer thickness). The power, P , dissipated in the inversion region is due to the silicon resistivity, ρ_s , and is equal to $I^2 R$ where I is the total current and the resistance R is $\rho_s \ell / A$ where ℓ is the length of the current path, i. e., chip thickness for edge conduction, and A is the cross sectional area (chip perimeter times inversion layer thickness). As an example, the ASEC cell has a silicon resistivity of $.4 \text{ } \Omega\text{-cm}$, a chip thickness of $300 \text{ } \mu\text{m}$ and a perimeter of 9.4 cm . If a worst case leakage resistance, R , of $10 \text{ } \Omega$ is assumed, then the inversion layer thickness is $1.3 \text{ } \mu\text{m}$ and the inversion layer volume is $3.7 \times 10^{-5} \text{ cm}^3$. The resistivity turnover temperature, ΔT , for the silicon base region is 325°C . A current of 4.6 A would be required to heat the inversion volume to 325°C at $\tau = 100 \text{ } \mu\text{s}$. In order for this much current to flow through the inversion region, a voltage of 46 V across the inversion region would be required ($V = 4.6 \text{ A} \times 10 \text{ } \Omega$). However, the breakdown voltage of the ASEC cell is only 23 volts . Therefore if the leakage resistance is $5 \text{ } \Omega$ or greater, then current conduction should be primarily through the bulk rather than the edges. This analysis assumes that only the inversion

region is heated. However at 100 μ s the thermal diffusion length is $L = \sqrt{D\tau} = 77 \mu\text{m}$, where D is the silicon thermal diffusivity ($.6 \text{ cm}^2/\text{s}$). Since L is much greater than the inversion layer thickness, much of the heat will be conducted away from the inversion layer during the pulse and the current required to heat the inversion region to the turnover temperature will be greater. Thus a leakage resistance of less than 5Ω would be required for edge current failure to dominate.

Typical leakage resistances measured on the cells used in this study were 50-100 Ω . Therefore we expect the transient current conduction to be primarily through the bulk.

Assumption c) allows for a worst case model since the resistivity turnover temperature is the threshold for instability. In typical pulsed power failure tests on diodes and transistors, the amount of power required to cause failure in addition to the power required to reach instability is only 5-10%. Therefore assumption c) should allow the model to provide a lower bound to the failure current. Assumption d) is obvious.

4.1 Current Distribution in the Cell

Before the heating in the cell can be calculated, the cell current distribution under pulsed conditions must be determined. The ASEC cell will be used to illustrate the model.

The bus distributes current to the fingers. Since its cross sectional area is large, due to its width and the thickness of the solder, the major resistive voltage drop occurs in the fingers with the bus being at uniform potential with respect to the back surface of the cell. For the ASEC cell, the bus lies directly on the silicon, hence some of the current in the bus is conducted directly into the silicon. The majority of the current however, is into the fingers, then through the silicon to the back

surface after traversing some fraction of the finger length. This current distribution is illustrated in Figure 4-1. As shown in Figure 4-1b, current down the fingers also spreads out laterally from the finger through the low resistivity n^+ region. If we assume the junction voltage V_j is constant, then for a finger voltage $V(x)$, where x is measured from the bus, and a current per unit finger length $I_\ell(x)$ along a finger of length ℓ the following relations apply

$$\frac{dV(x)}{dx} = \frac{\rho_m}{A_m} \int_x^\ell I_\ell(x) dx \quad (1)$$

$$I_\ell(x) = \frac{W_p}{\rho_s S_s} (V(x) - V_j) \quad (2)$$

where ρ_m is the finger (silver) resistivity assumed to be $2 \mu\Omega - \text{cm}$, ρ_s is the p type base resistivity, A_m the finger cross sectional area, W_p the width of the current sheet in the n^+ region and S_s the silicon base thickness. Combining these equations gives the differential equation for the voltage along the finger

$$\frac{d^2 V(x)}{dx^2} = \frac{\rho_m W_p}{\rho_s A_m S_s} (V(x) - V_j) \quad (3)$$

which can be solved for $V(x)$:

$$V(x) = V_j + (V_0 - V_j) e^{-x/\lambda} \quad (4)$$

where V_0 is the bus voltage, assumed constant, and

$$\lambda = \sqrt{\frac{\rho_s A_m S_s}{\rho_m W_p}} \quad (5)$$

is the exponential decay length down the finger. A similar set of equations for the current and voltage distribution in the direction transverse to the finger yields a lateral decay length

a) Current Flow Under Bus and Down Length of Finger.

b) Current Flow Laterally from Finger Through Low Resistivity n+ Region.

Figure 4-1. Current distribution in the silicon.

$$\lambda_s = \sqrt{\frac{\rho_s S_{n+} S_s}{\rho_{n+}}} \quad (6)$$

where ρ_{n+} is the resistivity of the $n+$ region and S_{n+} is its thickness. The total width of the current sheet, W_p , is then equal to $2\lambda_s + W_f$ where W_f is the finger width. Using the data given for the ASEC cell the exponential decay length λ is 0.426 cm and the current sheet width W_p is 330 μm .

The current conducted down the finger can also be related to the current density of the current conducted under the bus, J_0 . This current density J_0 multiplied times an effective incremental area for current down the finger gives the incremental finger current $I(x)$.

$$I(x) = J_0 W_p \lambda (e^{-x/\lambda} - e^{-\ell/\lambda}) \quad (7)$$

The differential voltage along the finger can be derived by integrating this current to a distance x in the following manner.

$$V(x) = \frac{\rho_m}{A_m} \int_0^x I(x) dx$$

$$\Delta V(x) = \frac{\rho_m}{A_m} J_0 W_p \lambda \left[\left(\lambda (1 - e^{-x/\lambda}) - x e^{-\ell/\lambda} \right) \right] \quad (8)$$

The current density J_0 is determined by dividing the total current into the cell, I_T , by the total effective area of the fingers plus the bus area. The effective area of a finger of length ℓ is

$$A_F = W_p \lambda (1 - e^{-\ell/\lambda}) \quad (9)$$

For the ASEC cell with fingers of varying lengths the total effective area of the fingers is

$$A_{FT} = W_p \lambda N \left[1 - \frac{\lambda}{\ell} (1 - e^{-\ell/\lambda}) \right] \quad (10)$$

where N is the number of fingers.

Equation (8) is used to calculate the voltage drop along the finger from the geometrical and physical properties of the cell. Experimental values of $V(x)$ are compared to this equation in a later section.

4.2 Heating Effects in the Silicon

Once the current distribution under pulsed high current conditions is established, the heating due to this current can be determined. The current through the cell will cause heating in the silicon from the power dissipated across the junction, the I^2R power in the bulk silicon base and by conduction of heat from the metallization which lies directly on the silicon. Heating in the metal fingers occurs from the I^2R power which is position dependent due to the exponential decay of current down the finger. Maximum heating in the finger will occur near the bus where the current density is greatest. The threshold damage current is assumed to be the minimum current which will either heat the silver finger to its melting point of 960°C or heat the silicon to its resistivity turnover temperature. For the ASEC cell the ΔT required for resistivity turnover is approximately 325°C .

Junction Heating From Reverse Bias. The most severe heating effects in the silicon pn junction occur for the reverse bias case. The maximum power per unit area occurs directly under the bus where the current density is greatest. This power density is equal to the current density J_0 times the junction voltage. The junction voltage, V_j , is equal to the avalanche plus space charge voltage. The temperature rise in the silicon due to this power dissipation is

$$\Delta T = \frac{J_0 V_j \sqrt{\tau}}{C_s \sqrt{D}} \quad (11)$$

where τ is the current pulse width, C_S the silicon heat capacity (1.78 J/cm³°C) and D the silicon thermal diffusivity (0.6 cm²/S). For the ASEC cell at 100 μ s, $\Delta T = 0.045 I_T^\circ\text{C}$. Thus it would take 7,220 A to raise the temperature of the junction to its turnover temperature.

Bulk Heating of the Silicon. The heating of the silicon base region under the bus (maximum current density) due to the silicon base resistance is

$$\Delta T \approx \frac{J_0^2 \rho_S \tau}{C_S} \quad (12)$$

For the ASEC at $\tau = 100 \mu\text{s}$, $\Delta T = 1.60 \times 10^{-6} I_T^\circ\text{C}$. A current of 14,200 A is required to raise the silicon temperature 325°C.

Heating of Finger Metallization and Subsequent Heating of Silicon by Conduction. The most important source of heating in the silicon is due to conduction from the metal finger. Consequently a solution of the thermal diffusion differential equation is necessary to determine the temperature profile in the silicon. For thermal diffusion lengths, $\sqrt{D\tau}$, much less than the finger width the solution to the thermal diffusion equation using the plane wave approximation is

$$\Delta T \approx \frac{P\tau}{C_S W_f \sqrt{D\tau}} \quad (13)$$

where P is the power per unit length in the finger and W_f the finger width. For $\sqrt{D\tau}$ large compared to the finger width, the thermal wave becomes cylindrical and it is necessary to integrate the thermal conduction in cylindrical geometry to obtain the heated volume. For this case

$$\Delta T \approx \frac{P}{\pi C_S D} \ln \left(\frac{\sqrt{D\tau}}{\frac{1}{2} W_f} \right) \quad (14)$$

To find the value of P it is necessary to know the current density in the metal finger, J_m . J_m decreases along the length of the finger and is a maximum near the bus. The maximum value of J_m , which will be used in subsequent calculations, is related to the maximum silicon current density, J_0 , by the ratio of the effective finger area for current flow and the actual cross sectional area of the finger.

$$\frac{J_m}{J_0} = \frac{W_p \lambda (1 - e^{-L/\lambda})}{A_m} \quad (15)$$

where A_m is the finger cross sectional area. The power per unit length is

$$P = J^2 \rho_m A_m \quad (16)$$

Substitution of (15) into (16) and the result into (13) and (14) gives the temperature increase in the silicon in terms of the total cell current, the finger and silicon parameters and the current pulse width. The resultant equations solved for the total cell current are

$$\sqrt{D\tau} \ll \frac{1}{2} W_f \quad I_T = \frac{1}{FA_F} \frac{\Delta T A_m C_S W_f \sqrt{D}}{\rho_m \sqrt{\tau}}^{1/2} \quad (17)$$

$$\sqrt{D\tau} \gg \frac{1}{2} W_f \quad I_T = \frac{1}{FA_F} \left[\frac{\pi \Delta T A_m C_S D}{\rho_m \ln \left(\frac{\sqrt{D\tau}}{\frac{1}{2} W_f} \right)} \right]^{1/2} \quad (18)$$

where $F = (A_{FT} + A_B)^{-1}$.

Using equation (18) for the threshold failure current of the ASEC at 100 μs , we get a value of 4600 A which is smaller than the value calculated for either bulk silicon heating or junction heating.

Equations 17 and 18 provide results for the threshold failure currents for the plane and cylindrical wave approximations assuming constant silver resistivity. However the silver resistivity varies with temperature according to the relation $\rho_m = \rho_0(1+\alpha\Delta T)$ where ΔT is the increase in temperature above room temperature, α is the temperature coefficient of resistivity for silver, $.0038/^{\circ}\text{C}$ and ρ_0 is the room temperature silver resistivity.

Equation 13 is the plane wave solution for ΔT in terms of power, P . Since the power dissipated in the silver is proportional to ρ_m then $P = P_0(1+\alpha\Delta T)$ where P_0 is the power for constant resistivity. Differentiating ΔT with respect to τ we obtain

$$\frac{d\Delta T}{d\tau} = \frac{P_0(1+\alpha\Delta T)}{W_f C_s \sqrt{D\tau}}$$

thus

$$\frac{d\Delta T}{(1+\alpha\Delta T)} = \frac{P_0 d\tau}{W_f C_s \sqrt{D\tau}}$$

Integrating both sides yields:

$$\frac{1}{\alpha} \ln(1+\alpha\Delta T) = \frac{P_0}{W_f C_s} \sqrt{\frac{\tau}{D}}$$

Solving for ΔT we have

$$\sqrt{D\tau} \ll \frac{1}{2} W_f \quad \Delta T = \frac{1}{\alpha} \left[e^{\left(\frac{\alpha P_0}{W_f C_s} \sqrt{\frac{\tau}{D}} \right)} - 1 \right] \quad (19)$$

In a similar manner equation (14) can be used to derive the variable resistivity solution for the cylindrical approximation. The result is

$$\sqrt{D\tau} \gg \frac{1}{2} W_f \quad \Delta T = \frac{1}{\alpha} \left[\left(\frac{4\tau D}{W_f^2} \right) \frac{\alpha P_0}{2\pi C_s D} - 1 \right] \quad (20)$$

Equations 19 and 20 are not easily solved for I_T . However the failure current can be determined by plotting ΔT versus I_T and finding the value of I_T for which ΔT = resistivity turnover temperature.

4.3 Metallization Burnout

The maximum heating in the silver metallization occurs in the fingers near the bus. This temperature increase is given in equations (19) and (20) for the short and long pulse approximations. The threshold failure currents for metallization burnout are determined by plotting ΔT versus I_T and finding the value of I_T for which ΔT is 935°C (melting point - room temperature).

4.4 Prediction of Threshold Failure Currents

The solar cell parameters necessary to calculate first the current distribution in the cell and the threshold failure currents were presented in Section 3.0. These are nominal values obtained by the manufacturers and in some cases verified by measurements on the test cells. The predictions of failure current are based on these nominal values and do not represent either the spread in the parameters from cell to cell within a cell type nor do they represent a worst case for a given cell type. The predictions do, however, represent a lower bound to the nominal cell failure inasmuch as the prediction is based on heating only to the instability temperature and not the failure temperature.

All of the nominal parameter values necessary to calculate failure currents are given in Table 4-1. The nominal threshold failure currents

TABLE 4-1

Description	Symbol	Units	ASEC	Sandia	Solarex	Photowatt
Symmetry	-	-	1/8	1/8	1/2	1
Diode Type	-	-	n+p	p+n	n+p	n+p
No. of Fingers per Section	N	-	35	27	106	24
Finger Width	W_f	cm	2.0E-3	2.3E-3	3.2E-3	2.54E-3
Finger Thickness	S_f	cm	5.0E-4	1.0E-3	2.0E-3	5.0E-4
Max. Finger length	l	cm	1.0	1.0	1.0	1.9
Finger Spacing	S_F	cm	2.8E-2	3.7E-2	5.66E-2	7.9E-2
Finger cross sectional area	A_m	cm ²	1.0E-6	2.3E-6	6.4E-6	1.27E-6
Bus width	W_B	cm	0.15	0.15	0.236	0.1/0.0686
Bus length	l_B	cm	1.1	1.1	6.0	1.9
Bus area per section	A_B	cm ²	0.165	0.165	1.42	0.159
Silicon Base ρ	ρ_S	Ωcm	0.4	0.3	0.4	10
Silicon Base thickness	S_S	cm	3.0E-2	3.0E-2	3.0E-2	2.0E-2
Top layer ρ	ρ_+	Ωcm	0.002	0.002	0.001	0.001
Top layer thickness	S_+	cm	4.0E-5	3.5E-5	4.0E-5	3/0E-5
Silicon resistivity turnover temperature	ΔT	°C	325	325	325	175
Relaxation length down finger	λ	cm	.426	.615	.904	1.12
Width of current sheet	W_p	cm	.0330	.0274	.0470	.078
Finger effective area (longest finger)	A_F	cm ²	.0127	.0135	.0284	.0723
Total effective finger area (whole cell)	A_{FT}	cm ²	2.42	1.84	6.02	1.74
Total bus area for current flow to silicon (whole cell)	A_{BT}	cm ²	1.32	0	2.83	.159
Reciprocal of total current flow area	F	cm ⁻²	.267	.543	.113	.527
Time for thermal diffusion equal to $\frac{1}{2} W_f$	τ_b	μs	1.7	2.2	4.3	2.7

are determined from equation (19) for times, τ , small compared to the thermal diffusion length equal to 1/2 the finger width. From Table 4-1, the times for which (19) is valid are less than 1 μ s. For time much greater than τ_b equation (20) is valid. Figures 4-2 through 4-5 are plots of ΔT versus I_T for each of the four cell types. Equation (19) was used for 100 ns and 1 μ s and equation (20) was used for 100 μ s and 1 ms. These equations should be valid for the concentrator cells since the maximum temperature increase in the silicon is principally due to conductive heating from the fingers. However, in the case of the Photowatt cell, the heating from reverse bias is appreciable since the avalanche voltage is about 245 V. From equation (11), the heating of the silicon under the bus, where the current density is a maximum, is

$$\Delta T = 93.6 I_T \sqrt{\tau}$$

The failure currents calculated from the reverse bias heating are thus lower than those predicted from equation (20) for $\tau \geq 100 \mu$ s. However for the shorter pulse widths, equation (19) gives lower threshold currents.

Figure 4-6 is a plot of the threshold failure currents for each of the four cell types versus the pulse width. Since neither of the approximations are valid in the range of 10 μ s the failure currents at this pulse width are found by merely connecting the predicted results at 1 and 100 μ s.

The failure predictions are presented in terms of current rather than current density. The variations in area could be normalized out if the failure data were for current density. However it is difficult to accurately present the data in terms of current density since in the case of the concentrator cells, the heating of the silicon is due to current density in the fingers, and in the Photowatt cell at long pulse widths, the heating is due to the current density under the bus.

Part of the reason the failure currents in the Solarex cell are high is due to the much greater cross sectional finger area, A_m . Also the

Figure 4-2. ΔT versus total cell current at different pulse pulse widths for ASEC cell.

Figure 4-3. ΔT versus total cell current at different pulse widths for Sandia cell.

Figure 4-4. ΔT versus total cell current at different pulse widths for Solarex cell.

Figure 4-5. ΔT versus total cell current at different pulse widths for Photowatt cell.

Figure 4-6. Threshold failure current versus pulse width for solar cells.

reason for the low failure currents in the Photowatt cell is the small value of A_m and the high base resistivity, hence high avalanche breakdown voltage. The Sandia and ASEC cells are the same area. However the Sandia has a lower failure current due to the fact that the bus sits on an oxide layer thus forcing all of the current down the fingers. This difference offsets the larger value of A_m in the Sandia cells compared to the ASEC cell.

The metallization burnout threshold failure currents can be determined from Figures 4-2 to 4-5. For the concentrator cells, all of which have a resistivity turnover ΔT of 325°C , the failure currents are about 37% higher than the silicon junction failure currents. For the Photowatt cell, with $\Delta T = 175^\circ\text{C}$, the metallization burnout current is about 73% higher at the short pulse widths. At the longer pulse widths, $\tau \geq 100 \mu\text{s}$ the failure current is governed by the reverse bias heating. In this case the difference between the silicon junction failure current and the metallization failure current is even greater.

5.0 EXPERIMENTAL VERIFICATION OF CELL CURRENT DISTRIBUTION

As described in the section on model development, an important aspect of predicting transient failure currents is the prediction of the current distribution in the cell. Once the current distribution is established, the maximum heating in the various regions can be determined. Equation (8) is the predicted differential voltage down the fingers as a function of the current density in the finger and the finger resistivity. The position dependent current density in the finger is a function of the current under the bus and the effective area for current into the silicon. This effective area involves the width of the current sheet along the finger, W_p , and the decay length, λ . Good correlation between the measured values of $\Delta V(x)$ and the predicted values provides confidence that the model properly describes the current distribution.

Therefore a rather extensive set of measurements was made on the concentrator cells in order to verify the current distribution. $\Delta V(x)$ measurements were made down the bus on the ASEC cells to verify the assumption that the bus is at an equipotential. $\Delta V(x)$ measurements along the fingers were made on all of the concentrator cells as a function of current up to 600 A. These tests were performed for both reverse bias and forward bias in order to compare the current distributions. At these current levels the cell fingers did not experience significant heating, hence the temperature variation in both silver and silicon resistivity did not have to be considered. However, in order to determine the effects of temperature on $\Delta V(x)$, some tests were conducted on smaller sections of cells. For the smaller sections, currents of 300-600 A cause significant heating and hence produce nonlinear results.

In the remainder of this section, the development of a special pulser is described along with the experimental setup for measuring $\Delta V(x)$. Results of $\Delta V(x)$ measurements will be presented and correlation with predicted response discussed.

Because a rather large volume of data was generated, only representative data will be presented in the main text. The remainder of the data is included in Appendix A.

5.1 Experimental Test Set-up and Procedure

Measurements were performed using the test setups shown in Figures 5-1 and 5-2. A device under test (DUT) is forward or reverse biased by a 10-100 μ s, 0-600 A current pulse from a pulser designed and built by MRC especially for this program. The current pulse generates voltage drops on the cell fingers and bus which are measured with microprobe contacts. The current pulse also generates a magnetic H field close to the solar cell. The H field will generate B coupling effects on the microprobes and their respective cables. These effects must be minimized by careful microprobe and test circuit layout.

The pulser developed by MRC is capable of delivering a 10 to 100 μ s, 0 to 600 A pulse into a load impedance $\leq .1 \Omega$. The pulser utilizes MOS power transistors (IR130 Hexfets) in parallel for wave shaping and switching of a capacitor bank. The initial pulser used 10 IR130 Hexfets and a 11500 μ f capacitor bank and had an output of 200 A. The modified pulser uses 30 IR130 Hexfets and a 34500 μ f capacitor bank and delivers a 600 amp output. Figure 5-3 illustrates the circuit for the modified pulser. The circuit for the initial pulser is the same except for 20 fewer capacitor - switch sections. There is no charging supply or triggering circuitry built into the pulsar. The charging supply used was an HP-6227B dual power supply which is limited to 100 mA and 90 volts for physical protection of the pulser. The trigger supply used was an HP-214 pulser which provides a 10 volt variable width output pulse. The trigger pulse width determines the high current output pulse width which is varied from 10 μ s to 100 μ s.

Figure 5-1. Initial test setup for current distribution tests.

Figure 5-2. Test setup for current distribution tests using modified pulser.

Figure 5-3. Schematic diagram of the high current pulser.

To assure accurate measurements of the relatively small voltage drops along the fingers, differential voltage measurements were made. The measurements were made using a Tektronix 7A13 differential comparator plug-in, which has a common mode rejection ratio of 86 dB. Contact to the cell surface was made with Micro-Manipulator microprobes. Two different measurement set ups were used. The initial pulser set up is shown in Figure 5-4 and the modified pulsar set up is shown in Figures 5-5 through 5-7.

Due to the type of measurement being performed, close attention was paid to the CMRR of the 7A13 and $\dot{B}$ coupling into the microprobes and cables. In reverse bias mode, the total cell voltage was approximately 25 volts for the ASEC cells. In order to make sure the common mode voltage was less than the maximum specified for the 7A13, 5X attenuators terminated in 50 ohms were used on the input to the 7A13. To keep the $\dot{B}$ coupling to a minimum, measurements were made on fingers which are perpendicular to the main current loop. The microprobes are positioned perpendicular to the main current loop and parallel to the fingers as shown in Figures 5-5 and 5-7. The coax cables from the microprobes were also routed through ferrite cores and twisted slightly to minimize common mode voltage on the cable shields. The microprobe cables were also routed perpendicular to the main current loop to minimize coupling.

The test method consisted of pulsing the cell with a current pulse and making differential voltage measurements between various points on the metallization. Data was taken on current through the cell, voltage across the cell and differential finger and bus voltages at currents between 20 and 600 A. Differential finger voltage measurements were made with respect to distance down the finger and relative to bus position. Differential bus voltage measurements were made with respect to finger number.

Figure 5-4. Solar cell measurement used with initial MRC pulser.

Figure 5-5. Solar cell test fixture used with modified pulser.

Cross Section View of Test Set Up for ASEC Cell

Cross Section View of Test Set Up For Sandia and Solarex Cells

Figure 5-6. Cross section view of test set up and cells.

Figure 5-7. Solar cell and probe position for reverse bias current distribution measurement. (Rotate cells 180° for forward bias.)

5.2 Experimental Results and Comparison With Model Predictions

As stated in Section 4, the model was developed with the assumption that the bus was essentially at an equipotential and that the current down the fingers decayed exponentially according to equation (7). Equation (8) was derived to express the differential finger voltage as a function of distance from the bus to the finger end and is applicable for reverse biased. Table 5.1 is a summary of the experimental measurements that were made to verify equation (8), investigate the differential voltage down the bus and to determine the effects of heating on the current distribution.

TABLE 5-1

Current Distribution Tests Performed

Test Conditions	Test Cells	Test Conditions		
		Current	Pulse Width	Bias
Bus potential	ASEC	20 A, 200 A	30 μ s	R
$\Delta V(x)$ vs. finger number	ASEC	20-200 A	50 μ s	R
$\Delta V(x)$ on longest finger (small ΔT)	ASEC, SNL SOLAREX (Section)	50-600 A	100 μ s	R, F
$\Delta V(x)$ on longest finger (large ΔT)	1/8 section ASEC	200-600 A	100 μ s	R, F

Unfortunately all of the Photowatt cells were used for failure tests in order to investigate the failure current versus pulse width. Thus no current distribution tests were performed on this cell type.

5.2.1 Bus Voltage

The voltage drop down the bus was considered to be quite small, hence the bus was treated as an equipotential in the model predictions. Measurements of the differential voltage drop down the bus were made on the ASEC cell on two opposite sides. These measurements were made in San Diego using the initial MRC pulser. The data is presented for a 20 A pulse in Figure 5-8 for one side and a 200 A pulse in Figure 5-9 for the opposite side. As expected, the maximum ΔV is roughly linear with total cell current. However, the results shown in Figure 5-8 for the left side indicate that the bus voltage is not symmetrical. The peak drop occurs near finger 45 rather than finger 36. This asymmetry was not observed on the right hand side bus. The reason for this asymmetry is presently not understood. The voltage drop down the bus is due to the bus resistance and the total current in the bus. If we assume that the current down the bus decays linearly then

$$I(x) = \frac{I_T}{8} \frac{(\ell_B - x)}{\ell_B}$$

where $I_T/8$ represents the current in one section and ℓ_B is the bus length of one section (1 cm). The differential voltage drop measured from a corner is thus

$$\Delta V(x) = \frac{\rho_{mB}}{8A_{mB}} I_T \int_0^x \frac{\ell_B - y}{\ell_B} dy$$

$$\Delta V(x) = \frac{\rho_{mB} I_T}{8A_{mB} \ell_B} (\ell_B x - \frac{1}{2} x^2)$$

where ρ_{mB} is the bus metal resistivity and A_{mB} is the bus cross sectional area. The resistivity of 50-50 solder is $15 \mu\Omega\text{-cm}$. The bus cross sectional area is formed by assuming that the cross section is a segment of a circle with base equal to bus width and height equal to 5 mil as shown in Figure 5-10.

Figure 5-8. Bus voltage drop versus finger number at $I_B = 20$ A, $\tau = 30$ μ s. Left side bus.

Figure 5-9. Bus voltage drop versus finger number at $I_B = 200$ A,
 $\tau = 20$ μ s. Right side bus.

Area of segment = $\frac{R^2}{2} \left(\frac{\pi\alpha}{180} - \sin\alpha \right)$ where R is radius of circle and segment is subtended by angle α .

Figure 5-10. Bus cross sectional area.

Using this approach, the bus area is found to be $.00128 \text{ cm}^2$. Thus

$$\Delta V_B(x) = 1.46 \times 10^{-3} I_T \left(x - \frac{1}{2} x^2 \right) \quad (21)$$

A comparison of the differential bus voltage from equation (21) to the experimental data at 200 A is given in Figure 5-11. The difference between the predicted curve and the measured curve shows an increasing value down the length of the bus. This is due to the voltage drop on the outer bus to which the copper contact bridges are soldered. The offset is about 25 mV at the end of the bus. If this offset were proportionally added to the predicted curve the agreement would be excellent.

The results of the bus voltage measurements demonstrate that there is a small but measurable voltage drop down the bus and a more thorough analysis would have to account for this difference in the prediction of failure current. However, accounting for the current distribution down the bus would significantly complicate the analysis of threshold failure current without changing the results appreciably. Therefore no attempt was made to modify the analysis to include bus voltage drops.

5.2.2 Voltage Down Fingers of Varying Length

An extensive amount of data was generated for the value of $\Delta V(x)$ near the intersection of the bus and finger for fingers of varying lengths.

Figure 5-11. Comparison of experimental and calculated bus voltage drop vs finger number @ $I_B = 200$ A, $\tau = 30$ μ s. Right side bus.

On each side of the cell there are 72 fingers, hence the center finger is No. 36. The fingers with low and high numbers are near the bus ends and are proportionately shorter. In Figure 5-12 the differential finger voltage is plotted versus distance down the finger up to .3 cm. Curves for every 5th finger are shown. This data was generated in San Diego using the initial MRC pulser. The data was taken on a whole ASEC cell on the left side at 200 A and 30 μ s. The slope of the $\Delta V(x)$ near the bus is a measure of the relative amount of current entering the finger. The figure illustrates that the longer fingers (near the center) are receiving more current as predicted by the model. This data verifies that even though the bus voltage drop at 200 A is appreciable, the model prediction that the current in the finger is proportional to finger length still holds.

Figures A-1 through A-4 show data similar to Figure 5-12 at total cell currents of 20A, 40A and 80A for the left side. Figure A-4 is a plot of $\Delta V(x)$ versus x at 200 A for every 5th finger on the right side of the same ASEC cell. This data demonstrates that the center finger, number 36, has the maximum current. This is consistent with Figure 5-9, for the bus voltage on the right side bus. For the right side bus the differential voltage was symmetric.

5.2.3 Results of $\Delta V(x)$ Measurements on Longest Fingers

The most extensive current distribution measurements were performed on the longest fingers as a function of current for both reverse and forward bias on the ASEC cells, SNL cells and small sections of the Solarex cells. $\Delta V(x)$ measurements were taken .25 ℓ , .5 ℓ , .75 ℓ and ℓ where ℓ is the length of the finger. Measurements were taken at currents between 50 and 600 A for a 100 μ s pulse. The ΔV data was typically read from the photos at 80 μ s. Figure 5-13 is a reproduction of typical current and voltage waveforms.

Figure 5-12. Differential finger voltage drop vs position @ $I_B = 200$ A, $\tau = 30 \mu s$, (left side).

Top Trace - voltage across the
cell 10 V/d, 20 μ S/d

Differential finger voltage
50 mV/d, 20 μ S/d

bottom trace - current through
the cell 50 A/d, 20 μ S/d

Figure 5-13. Current and voltage waveforms for current distribution tests.

For this illustration, the test was performed on an ASEC cell at 200 A. The voltage waveform is shown in the upper oscilloscope trace on the left. The lower trace is the total cell current and the photo on the right is the differential finger voltage. $\Delta V(x)$ versus current, plotted parametrically with x for each ASEC cell, for both forward and reverse bias is given in Figures A-5 through A-8 in the appendix. This data is followed by representative waveform photos at each of the current levels in Figures A-9 through A-14. The data is summarized and presented in Figures 5-14 and 5-15 as $\Delta V(x)$ versus x at 200 A and 400 A respectively. Along with the experimental data, the predicted curves from equation (8) are shown for the assumed thin film silver resistivity of $2 \mu \Omega \text{ cm}$ and the Handbook value for bulk silver of $1.6 \mu \Omega \text{ cm}$.

Figure 5-14. Complete ASEC cell differential finger voltage versus distance down the finger for a 200 amp $100 \mu\text{s}$ square pulse.

Figure 5-15. Complete ASEC cell differential finger voltage versus distance down the finger for a 400 amp $100 \mu\text{s}$ square pulse.

There is a rather unexpectedly large variation from cell to cell in the measured data along with a peculiar shape in the curve for unit 21. However the data do in general follow the exponential shape predicted by equation (8) and the absolute values of $\Delta V(x)$ agree reasonably well with the predicted values. A better fit is obtained using the bulk resistivity of silver rather than the assumed thin film value of $2 \mu \Omega \text{ cm}$.

The forward biased $V(x)$ measured on cell 47 is less than half the value measured for reverse bias. This indicates that either the decay length is significantly lower for forward bias, hence the current less uniformly distributed down the finger, or the total current into the finger is much less. The predicted value of $V(x)$ assuming that the current were proportionately lower is compared to the forward bias curve. Since the data shows a reasonably good fit to this curve it may be assumed that the total current flowing under the bus, J_0 is much higher in the forward biased case. However, no experiments were performed to directly verify this assumption. The $V(x)$ values for forward bias were in all cases much lower than for reverse bias.

In Figure 5-15, similar data is shown for the whole ASEC cells but at 400 A. Again there is a large variability from cell to cell and the predicted $V(x)$ curve for $\rho_m = 1.6 \mu \Omega \text{ cm}$ fits the data better than the curve using $2 \mu \Omega \text{ cm}$.

Although the variability in data is somewhat greater than expected, the experimental data appear to validate the current distribution predictions represented by equation (8).

Another comparison of the measured and predicted data was made by calculating the decay length, λ , from the experimental data using equation (8) and assuming $\rho_m = 2 \mu \Omega \text{ cm}$. These results are shown in Figure 5-16. The calculated λ from the experimental data is plotted versus x and

Figure 5-16. λ 's obtained from experimental data using equation (8) for whole ASEC cells.

compared to the predicted value of λ . This analysis indicates that the agreement between the calculated and measured λ is reasonably good, especially for the data taken at x , the end of the finger. The departure of the measure λ near the bus indicates that the experimental data did not follow the precise functional form of equation (8) over the entire finger length. However the agreement is still good enough to verify the exponential behavior.

$\Delta V(x)$ data was also taken on several whole SNL cells. The results of these tests were extremely erratic. The noise voltages caused by $\dot{B}$ coupling were minimized in the same manner as for the ASEC cells however they were much greater for the SNL cells resulting in unacceptable signal to noise ratios. This made the data analysis much more difficult. Even with the efforts to sort the data from the coupling noise the results appeared to be nonphysical with the $\Delta V(x)$ increasing and decreasing over the length of the finger. One feasible explanation for the erratic results is that the SNL cells were known to have contact resistance problems from poor adhesion. Whatever the cause of the erratic data, it was determined that no useful information could be derived from the data and hence it is not presented.

The $\Delta V(x)$ measurements on the Solarex cells were performed on 11 finger sections rather than whole cells. The reason for this was that the Solarex cells were too large to fit in the fixture and even at 600 A the ΔV values were too small to measure accurately. As with the ASEC cells, the $\Delta V(x)$ versus current plots are included in Appendix A along with the current and voltage waveform photos. Figures A-15 through A-20, contain the $\Delta V(x)$ plots and Figures A-21 and A-22 are typical oscilloscope photos.

A summary of the data, plotted as $\Delta V(x)$ versus x is given in Figure 5-17 for 200 A and Figure 5-18 for 400 A for both reverse and forward bias. Predicted data are shown for both $2 \mu \Omega \text{ cm}$ and $1.6 \mu \Omega \text{ cm}$. Again the

Figure 5-17. 11 Finger SOLAREX cell differential finger voltage versus distance down finger for 200 A 100 ms pulse (voltages taken at $80 \mu\text{s}$).

Figure 5-18. 11 Finger SOLAREX cell differential finger voltage versus distance down the finger for 400 amp 100 microsecond square pulse.

forward biased $\Delta V(x)$ values are much less than for the reversed bias case. The reverse biased tests were performed on two samples. The results for cell #18 are quite erratic for both the right hand side and the left hand side, whereas the results for cell #13 are well behaved.

The reason for this erratic behavior is not known. Although the data has not been corrected for coupling noise, a review of that data shows that there was no difference in the coupling voltage for unit #13 and unit #18. The coupling voltage was about 75 mV at 200 A and 125 mV at 400 A. This noise voltage is small compared to the $\Delta V(x)$ values and hence could not account for the shape of the curves for unit #18.

Although the data for the Solarex cells is not as well behaved as for the ASEC cells, it does support the current distribution prediction reasonably well. As with the ASEC cells, the data seem to fit the prediction based on the $1.6 \mu \Omega \text{ cm}$ resistivity better than the $2 \mu \Omega \text{ cm}$ predictions.

A plot of the λ 's calculated from the measured data is shown in Figure 5-19. This data demonstrates the erratic behavior of the Solarex cell sections but does verify that the theoretical predictions are reasonable.

5.2.4 $\Delta V(x)$ Measurements on ASEC Cell Sections

Current distribution measurements were made on a 1/8 section of an ASEC cell as shown in Figure 5-20, to confirm the nonlinear effects due to temperature dependent resistivity. Measurements were made on several 1/8 sections under forward and reverse bias conditions on the longest finger of the 1/8 section. This corresponds to the center finger on the complete cell. One cell was taken far into the nonlinear mode to the point of over-stress. This occurred in the reverse bias direction for a 600 A pulse.

Figure 5-19. λ 's obtained from experimental data using equation (8) for Solarex cell sections.

Figure 5-20. 1/8 SECTION OF ASEC CELL.

Damage was observed where the finger contacts the bus. Overstress damage did not occur in the forward direction at 600 A. Since the purpose of this section was not to generate overstress effects, but current distribution measurements, currents for the remaining 1/8 sections were limited to 400 A.

Differential voltage drop versus current for the 1/8 section ASEC cells are presented in Appendix A, Figures A-23 through A-26. Figures A-27 through A-30 illustrate typical waveforms. Figures A-31 and A-32 present the data on the ASEC sections as $\Delta V(x)$ versus x at 200 A and 400 A respectively.

Figure 5-21 is a plot of $\Delta V(x)$ versus current for the reverse bias tests made on the longest finger of unit #19B. The dashed line illustrates the predicted behavior for a constant silver and silicon resistivity. The measured results show a dramatic increase in $\Delta V(x)$ starting at currents above 100 A. This increase in $\Delta V(x)$ is due to the temperature dependent increase in ρ_m and the changes in W_p and λ due to both the temperature dependent silver and silicon resistivities. The cell section is observed to fail at 600 A. This implies that the temperature rise in the metal was at least 325°C which is the silicon resistivity turnover temperature. The temperature coefficient of resistivity for silver is .0038/°C which means that a temperature increase of 263°C will cause ρ to double. However at 600 A the value of $\Delta V(x)$ is seen to be less than twice the linear value. This implies that either W_p or λ or both decrease with increasing temperature.

No attempt was made to predict the temperature dependence of W_p or λ . However it does appear that the effective area for current flow down the fingers decreases with increasing temperature. The effect of this decrease on the threshold failure current is difficult to determine. Reference to equations (17) and (18) show that the failure current is

ASEC 19A 1/8 SECTION
 .4" UP FROM BUS REVERSE BIAS

Figure 5-21. Differential voltage at end of longest finger on 1/8 ASEC cell section versus cell current.

proportional to the ratio of the total effective area to the effective area of the longest finger. Both of these effective areas are seen to decrease with increasing temperature.

In conclusion, the results of the current distribution tests support the general conclusions used in the derivation of the failure model. The functional form of the exponential current decay is verified along with the absolute value of the predicted $\Delta V(x)$ curves. Since the derivation of the current distribution was based on bulk current conduction as opposed to surface or edge conduction, the assumption that transient currents up to 100 μ s pulse width are primarily through the bulk seems to be verified at least for the ASEC and Solarex cells. This assumption was not verified for the SNL cells since the data was too erratic to give meaningful results or for the Photowatt cells since no $\Delta V(x)$ tests were performed.

The results of the bus voltage test showed that the voltage drop was appreciable but should not invalidate the analysis. Another interesting result was that the forward biased $\Delta V(x)$ tests on the ASEC and Solarex cells resulted in much smaller voltage drops than for the reverse biased case. This result can be explained by a much larger component of J_0 for forward bias. If the value of J_0 is much larger for forward bias then the current in the fingers would be reduced proportionately. This would result in larger threshold failure currents under forward bias for the ASEC and Solarex cells.

6.0 OVERSTRESS FAILURE TESTING

The results of the model predictions were given in Section 4.0. Predicted failure currents for the concentrator cells were several thousand Amperes (A) for 10-100 μ s pulse widths, whereas the predictions for the Photowatt cell were a few hundred Amperes. As mentioned earlier, a great deal of time was spent in developing a suitable pulser for the overstress testing. The desired requirements were a fast rise and fall time square wave pulser with variable pulse width between 1 μ s and 1 ms capable of delivering at least 30,000 A into a short circuit. The desired instrumentation was a current transformer or current viewing resistor setup capable of measuring the current waveform through the cell up to 30,000 A with resolution at low current of approximately 1 A. In addition, a voltage probe was desired capable of measuring the voltage waveform across the cell up to approximately 300 V with a resolution at low voltages of about .1 V.

An investigation of available pulsers at both AFWL and other government and contractor facilities indicated that we had two options.

- a) Use an available high voltage, 50 Ω pulser and construct a transformer capable of delivering the high currents to the low impedance cell, or
- b) Contract the use of a lightning simulator facility.

Neither of these options would provide a variable pulse width square wave pulser, however they would provide the necessary current.

Since Sandia Labs had already contracted with the AFWL to support our testing with the DDL facility we opted to have the AFWL build a suitable transformer to be used in conjunction with an available high voltage double exponential wave pulser. This facility was designed to provide the

necessary current for the failure tests on the concentrator cells and available square wave pulsers were used for additional tests on the flat-plate cell.

6.1 Description of Pulsers and Instrumentation Used for Overstress Testing

Because of the high currents required for overstress failure, most of the tests were performed on a Maxwell labs high voltage pulser for which the special transformer was built. In addition to the Maxwell, two square wave pulsers were used; a Velonix 360 and a custom pulser built for AFWL by the BDM Corporation called the SPG-200.

The Maxwell pulser is a high voltage capacitor discharge pulser. The pulse shape is double exponential with a variable rise time of 10 to 1000 ns and a variable decay time of .5 to 10 μ s. The charging voltage is continuously variable from 50 to 150 KV. Additional control of the output voltage is accomplished with the use of 3x and/or 10x attenuators. The pulser output is through a 100 foot length of RG-220 cable with a nominal source impedance of 50 Ω . Figure 6-1 is a typical output waveform into a 50 Ω load.

A transformer was designed and built by the AFWL for the Maxwell pulser. The input impedance was specified to be 50 Ω and the output impedance $\sim$.1 Ω to match the dynamic impedance of the solar cells. The design is coaxial with the shield forming a single turn secondary (output) and the center conductor forming a 22 turn primary (input). In order to achieve a pulse duration correlating to the lightning environment, the pulser was adjusted to 1 μ s rise time and 10 μ s decay time. Figures 6-2 and 6-3 show typical output pulses from the transformer into a short circuit and .1 Ω load. The maximum output current measured into a short circuit was $\sim$ 30 kA.

Typical voltage waveform of Maxwell pulser into $50\ \Omega$ load for 10 ns rise and 10 μ s decay time.

Figure 6-1.

Current Waveform

Transformer output into short circuit.
226 A/d 5 μ s/d

Figure 6-2.

Voltage Waveform

Transformer output into $.1\ \Omega$ load.
50 v/d 5 μ s/d

Figure 6-3.

The transformer output was designed to provide instrumentation and function as a test fixture. Figure 6-4 A, B and C illustrate the transformer output and appearance. Figure 6-5 illustrates the Maxwell transformer test set up. Current measurements were made by employing a milled out section in the copper bus bar as a current viewing resistor, (CVR). The precision $50\ \Omega$ resistor is similar to a voltage probe and functions as a matching impedance on a $50\ \Omega$ coax cable. The $50\ \Omega$ coax cable is also terminated in $50\ \Omega$ at the scope input. The voltage across the cell is monitored by a Tektronix P6009, 100x voltage probe. Voltage measurements were also made with two P6009 probes in a differential mode and using a custom made $50\ \Omega$ differential probe. The single P6009 probe set up shown in Figure 6-5 worked as well as the more complicated probe arrangement, therefore the simple set up was used.

Instrument calibration was performed using a known $.1\ \Omega$ load across the transformer output. An integrator was used to adjust the CVR wave form to correspond to the voltage waveform. The final calibration factor was 45.2 A/mv. The minimum scope sensitivity of 5 mv/division gives a current of 226 A/division with a maximum resolution of $\sim \pm 6\ \text{A}$.

The Velonix 360 has a nominal output impedance of $200\ \Omega$. The 360 is supplied with several transformers to match load impedances down to $3\ \Omega$. Two different configurations of this pulser were used as shown in Figures 6-6 and 6-7. The two different configurations were necessary because low output impedance transformers were not available for 50 and 100 μs pulse widths. For these test configurations the output pulse from the 360 is transformer coupled to the desired output impedance. For the $3\ \Omega$ transformer a $1\ \Omega$ CVR is used. For the $50\ \Omega$ system a commercial $50\ \Omega$ coaxial current and voltage T&M probe was used. This probe uses a 1:1000 voltage divider and a $.01\ \Omega$ CVR.

The SPG-200 is a 30 kV $50\ \Omega$ charge line square wave pulser. This pulser was used for the short pulse width, 1.5 μs , testing of the Photowatt

Figure 6-4A. Maxwell transformer input and instrumentation.

Figure 6-4B. These photos show the transformer output bus bar configuration. They also show typical cell mounting and instrumentation connections.

Figure 6-4C. These photos illustrate the physical appearance and relative size of the transformer (Note 4" x 3" photos in top photo).

Figure 6-5. Test setup for Maxwell pulser and matching transformer.

Figure 6-6. Test setup for Velonix (2 & 10 μ s output pulse, 3 Ω matching transformer).

Figure 6-7. Test setup for Velonix. (10 μ s, 50 μ s, and 100 μ s output pulse, 50 Ω matching transformer.)

cell. As with the Velonix 360 two test setups were used as shown in Figures 6-8 and 6-9. Testing was originally performed with the setup in Figure 6-8. However the dynamic impedance of the solar cell caused unacceptable reflections. To reduce these reflections, the setup in Figure 6-9 was tried. Although there was no great reduction in the reflections, instrumentation is somewhat cleaner, therefore the setup of Figure 6-9 was used for the remainder of the SPG-200 tests.

6.2 Overstress Failure Criteria

In overstress failure testing of most semiconductor electronic components the failure criteria is defined as

- a) A distinct break in the current and voltage waveforms during the overstress pulse with a rapid increase in current and a rapid decrease in voltage. (Breakpoint criteria) or
- b) A measureable degradation of the electrical performance parameters after the overstress pulse, e.g. decrease in transistor current gain, increase in leakage current, or
- c) A catastrophic failure after the overstress pulse. Examples are a short circuit due to junction burnout or an open circuit due to a metallization burnout. (Metallization damage is normally implied from electrical tests since the semiconductor chip is not visible unless the package has been opened.)

Since a solar cell is a semiconductor diode, a similar set of failure criteria were implemented in this test program. Where possible the breakpoint criteria was employed. Unfortunately for most of the failure tests no obvious breakpoints were observed. The important electrical

Figure 6-8. Test setup for SPG-200. (1.5 μ s pulse, 1 Ω CVR.)

Figure 6-9. Test setup SPG-200. (1.5 μ s pulse, 50 Ω system, .01 Ω CVR.)

performance parameters of the solar cell are open circuit voltage, short circuit current, efficiency and fill factor. Since these tests are rather time consuming and we did not have the test setups for making these measurements, we relied on the reverse DC current-voltage characteristic of the cell to measure cell degradation. The major problem with this approach is that cell leakage currents were 10's to 100's of mA, compared to typical bulk junction leakage currents of nA to μ A. Thus the surface or edge currents dominated. In order to observe an increase in leakage in the bulk, a change large enough to overcome the initial surface leakage is required. This would correspond to an increase of several orders of magnitude.

Catastrophic failures observed either by visual inspection of the cell surface or by a short circuit in the I-V characteristic.

Since solar cells are not packaged, visual examination after each overstress pulse was relatively easy. Cells were observed with a microscope at 90x. I-V characteristics were monitored with a curve tracer.

In summary, the failure criteria for the solar cells was:

- a) A distinct break in the voltage and current waveforms during the overstress pulse.
- b) A 10% or greater change in the reverse leakage current after the overstress pulse.
- c) A visual defect after the overstress pulse. Examples are metallization melting or rupturing or burned regions in the silicon.

6.3 Test Procedure

A summary of the overstress failure tests performed on the solar cells is given in Table 6-1. Listed in the table are the sample sizes, pulser and test setup used and the test conditions.

TABLE 6-1

Summary of Overstress Failure Testing

<u>Cell Type</u>	<u>Sample Size</u>	<u>Pulser (1) and test setup (Figure No.)</u>	<u>Pulse (2) Type</u>	<u>Bias Test (3) Condition</u>
ASEC	28	MAX, 6-5	DE, 10 μ s	R
ASEC	8	MAX, 6-5	DE, 10 μ s	F
SNL	13	MAX, 6-5	DE, 10 μ s	R
SNL	3	MAX, 6-5	DE, 10 μ s	F
Solarex	25	MAX, 6-5	DE, 10 μ s	R
Solarex	7	MAX, 6-5	DE, 10 μ s	F
Photowatt	17	MAX, 6-5	DE, 10 μ s	R
Photowatt	9	MAX, 6-5	DE, 10 μ s	F
Photowatt	5	SPG 200, 6-8, 6-9	SW, 1.5 μ s	R
Photowatt	3	VELONIX, 6-6	SW, 10 μ s	R
Photowatt	4	VELONIX, 6-7	SW, 50 μ s	R
Photowatt	8	VELONIX, 6-7	SW, 100 μ s	R

(1) MAX - Maxwell pulser with AFWL transformer

(2) DE - Double exponential, SW - square wave

(3) F - Forward, R - reverse.

The failure tests were performed using the step stress method. An initial peak current level was selected which was, hopefully, below the

threshold failure current for the cell. This initial level was generally 1/2 the predicted threshold failure current. A photograph of the reverse I-V characteristic was taken prior to pulsing and the cell was inspected visually at 90x to determine any initial defects or abnormalities. The cell was then mounted to the fixture and given the initial current pulse at room temperature and normal test room lightning. Current and voltage waveforms were recorded and inspected for breakpoint failure. The cell was then removed from the fixture and tested on the curve tracer to determine if any change took place in the I-V characteristic. The cell was also inspected visually to determine silicon and/or metal damage. If the cell did not fail according to the criteria outlined in Section 6-2, then the current level was increased and another pulse applied. This procedure was continued until the cell failed. In many cases where the failure was due to an increase in the leakage current as determined from pre-post curve tracer measurements, the current was further increased until metallization damage occurred.

All of the failure tests on the concentrator cells were performed with the Maxwell pulser. However, for the reverse biased tests on the Photowatt cell the results using the Maxwell pulser were not satisfactory. The breakdown voltage of the Photowatt cells is about an order of magnitude higher than the concentrator cells. Once the charging voltage on the Maxwell was increased to the point where sufficient voltage was delivered to the cell to cause avalanche, the available current was several hundred Amperes. No current limiting resistors were employed, hence the cell current could not be sufficiently controlled. Since the failure currents for the Photowatt cells turned out to be far below the predicted level of about 200 A, the failures occurred early in the pulse and were in some cases below the resolution of the instrumentation.

Since the failure currents for the Photowatt cells were difficult to measure accurately on the Maxwell pulser and were low enough to be measured

on the square wave pulsers, it was decided that failure tests on the remaining cells should be done using the SPG-200 and Velonix pulsers.

The use of these pulsers also allowed a measure of failure current versus pulse width. The SPG-200 is capable of pulse widths up to 1.5 μ s and the Velonix up to 100 μ s.

6.4 Results of Failure Tests on the Concentrator Cells

All of the failure tests on the concentrator whole cells were performed on the Maxwell Labs pulser with the AFWL transformer. The pulse shape is a double exponential with a rise time of approximately 1 μ s and a decay time of 10 μ s. A summary of the threshold failure data on the concentrator cells is given in Table 6-2. The threshold failure currents are the lowest currents for which the cells failed by the criteria given in Section 6.2. The minimum, maximum, average and standard deviation are shown for each of the cell types for both reverse biased and forward biased testing. In addition, a predicted threshold failure current is shown based on the variable resistivity model. The predictions were made for constant current or square wave pulses. In order to compare the measured failure currents to the predicted failure currents, a conversion between a double exponential and a square wave is required. If the conversion is based on the average power in the wave, then an exponential wave with peak current I_0 and decay time τ is equivalent to a square wave of amplitude I_0 and pulse width $.4 \tau$. Thus the predicted threshold failure current was taken from Figure 4-6 at 4 μ s in order to compare to the Maxwell pulser results.

There are several general features of the experimental results that require comment. First the spread in the data is much greater than would be expected from the variation in the important cell parameters that influence the predicted failure thresholds. The ratio of maximum threshold failure to minimum threshold failure ranges from 2 greater than 5 for

TABLE 6-2.

Summary of failure tests on concentrator cells

(All current values are in Amperes)

	ASEC	Sandia	Solarex
Reverse Bias			
Average failure current	6636	3146	18819
Std. Dev.	1367	766	5678
Sample Size	28	13	25
Minimum I_F	3164	2305	5880
Maximum I_F	9300	4926	31200
Predicted I_F	4700	3400	15000
Forward Bias			
Average failure current	12871	4896	22406
Std. Dev.	2807	1643	2886
Sample Size	8	3	7
Minimum I_F	8362	3751	19400
Maximum I_F	16300	6780	25990

reverse bias and 13 to 33% for forward bias. Concentrator cells typically have rather tight controls on most of the variables important in the model predictions such as finger cross sectional area and base doping level. The C/V and breakdown voltage measurements, discussed in Section 3.2 indicated that variations in base doping concentration from cell to cell within a cell type were quite small. Thus the wide variations in failure threshold must be due either to defects or nonuniformities in the cells that are difficult to detect (e.g., variations in finger sectional area from finger to finger or along a finger) or multiple failure modes not predicted by the model.

Another feature of the data is the difference in threshold failure current for forward bias and reverse bias. In all cases the failure currents for forward bias were substantially higher than for reverse bias. This suggests that the current distribution under forward bias was different than for reverse bias assuming that the failure mode is that of junction failure due to heat conducted from the fingers.

As mentioned in Section 4, the model is based on the assumption that at current levels sufficient to cause failure the current is primarily through the bulk rather than the surface or edges. Since the model also assumes that failure occurs when the silicon is heated to the resistivity turnover temperature, the predictions should be conservative since actual failure occurs when the instability results in hot spots which extend across the base and cause local silicon melt regions or filaments. No estimates were made for the additional energy required to go from resistivity turnover to actual filamentation. Therefore the model should predict a nominal lower bound to the failure current. Any failures that occur at currents below the predicted value should be due to either a different failure mode or due to a variation the cell parameters that would substantially lower the predicted threshold current for that particular cell.

In all three of the concentrator cell types the minimum failure current was below the predicted failure level, and in fact for the SNL cells the average failure level was below the predicted value. Therefore a much closer look at the data is required in order to determine the nature of the unexpected low failures.

In order to investigate the low failures, the data was plotted as histograms of frequency of occurrence versus threshold failure current for each cell type. Since most of the cells were tested at currents above where they first failed, histograms of first fail, second fail, and final fail were plotted. The histogram for the reversed biased ASEC cells is shown in Figure 6-10 for first fail, 6-11 for second fail and 6-12 for final fail. Included in each block of the histogram are the cell number, criteria by which the cell failed and the failure current level.

There are two cells, units # 1 and 8 which failed below the predicted level of 4700 A. The cause of failure was an increase in the reverse leakage current for both cells. The reverse leakage current in the cells prior to overstress testing is due to surface or edge currents as discussed in Section 6.2. In order to detect a change in the leakage current, increases of several mA were required since the initial leakage currents were 10's to 100's of mA. This would correspond to several orders of magnitude increase in bulk leakage current. In order to cause such an increase in the bulk leakage severe junction damage would be required in a small fraction of the junction. If a region of the junction did undergo filamentation then it is reasonable to assume that the local current density in this region would be increased sufficiently to cause metallization damage in the fingers directly above where the filamentation occurred. It was pointed out in Section 4.0 that an increase of only 37% in the current density in the finger would raise the temperature of the silver from the silicon resistivity turnover value to the silver melt value.

Figure 6-10. Histogram of reversed bias ASEC failure currents for first fail.

Figure 6-11. Histogram of reverse bias ASEC failure currents for second fail.

Figure 6-12. Histogram of reverse bias ASEC failure currents for final pulse.

Thus, if enough junction damage occurred in the bulk to cause a measurable increase in the leakage current, one would expect to see finger melts at about the same total cell current. In the case of units #1 and #8, increases in the reverse leakage current were observed without any accompanying finger melts. This observation suggests that the increase in leakage current could have been a surface or edge effect. If surface effects were the cause of the increase in leakage then the model predictions would not apply. Therefore a closer look at the data is required to determine if any failures occurred in the bulk at currents below those predicted by the model. In Figure 6-11 the current levels for second observed failure are given. Again units #1 and #8 failed below 4700 A. However, both failures were again due to further increases in leakage without any finger melts. In Figure 6-12 the final fail data is given. Unit #8 exhibited a short circuit for reverse bias and finger melts were observed. This occurred at 4248 A which is again below the predicted failure level. Thus unit 8 does fail from bulk current conduction at a level below where the model predicts a lower bound.

Unit #8 received a total of 4 overstress pulses. No anomalies were noted in the pretest data on unit #8. Its breakdown voltage was 21 V and the pretest leakage was 225 mA at 15 V. After 3160 A the leakage increased by 300 mA. After the 2nd shot of 3525 A the leakage increased an additional 400 mA at 15 V. Shot 3, at a current of 3890 A, caused an additional increase of 150 mA at 15 V, again with no finger melts. On the last shot, at 4248 A the reverse I-V characteristic became essentially a short circuit and finger melts were observed. The finger melts are located near the bus as predicted by the model but do not occur on the longest fingers. It is possible that the low failure level is caused by a reduction in the cross sectional area of the particular affected fingers, however a failure analysis could not provide such information because of the melt damage.

The conclusion that can be drawn from the reversed biased overstress tests on the ASEC cells is that the model works well in predicting a lower

bound to the bulk failures produced by electrical overstress. Only one device had a confirmed bulk related failure at a level below the prediction and it occurred at 90% of the predicted threshold. However, there were failures that occurred as low as 67% of the predicted threshold that appear to be due to a different failure mode. The rather unexpected failure mode is apparently excessive surface or edge conduction causing a significant increase in reverse leakage current.

The forward biased overstress data on the ASEC cells is shown in Figure 6-13. The lowest first fail was observed at 8360 A, well above the predicted lower bound. The lowest failure which involved finger melts, hence bulk damage, occurred at 10,400 A or more than twice the predicted threshold for reverse-bias. It seems reasonable that the current distribution under forward bias is substantially different than for reverse bias. As suggested in Section 5, a much greater fraction of current may be directly under the bus under forward bias. This would substantially lower the amount of current down the fingers hence increase the threshold failure current. Although the data is not conclusive the $\Delta V(x)$ measurements on the ASEC fingers under forward bias seem to confirm this idea.

The conclusion drawn from the forward bias overstress tests on the ASEC cells is that the model developed for reverse bias is quite conservative in predicting a lower bound for forward bias. No cells were observed to have failure levels below that predicted.

The SNL cells were received in two lots and the test results indicate a difference in response of the two lots. Therefore the data is plotted separately. In Figure 6-14, data is shown for first, second and final fail levels for the reversed biased tests on the first lot of SNL cells. In Figure 6-15, similar data is given for the second lot.

ASEC FORWARD BIAS FIRST FAIL

Figure 6-13. Histogram of forward biased ASEC failure currents.

SANDIA REVERSE BIAS FIRST GROUP OF CELLS

Failure Code:

IV - Change in IV

FM - Finger Damage at Bus

Figure 6-14. Histogram of SNL lot 1 reverse bias failure currents.

Figure 6-15. Histogram of SNL lot 2 reverse bias failure currents.

All of the first fail currents for lot 1 were below the predicted threshold failure level of 3400 A. However all of these failures were due to increases in the leakage current without any accompanying finger melts, suggesting that the failures may be related to surface effects.

These apparent surface related failures occurred at currents as low as 2300 A. However the second fail data shows that cell 01 exhibited a finger melt at 3160 A, below the predicted threshold. No finger melts were observed in the other four cells until the final fail data. Thus there was only one of the five cells which had a confirmed bulk related failure at a current below the predicted threshold. The first fail current levels on lot 2 were much higher than for lot 1 as shown in Figure 6-15. Two of the units had first failure currents below the predicted values, however both of these were due to increased leakage. The final fail data, however, shows that unit #3 had finger melts at 3070 A, well below the predicted threshold.

Thus one unit from each lot of SNL cells had a confirmed bulk related failure below the predicted threshold. No obvious abnormalities were noted in the pretest characterization of these cells which would explain the low failure levels. However as mentioned in Section 3, all of the SNL cells were rejects because of low performance and contact problems. Therefore it is reasonable to assume that the low failures may be due to imperfections or metallization contact problems which could significantly alter the current distributions. This was verified by the difficulty in measuring $\Delta V(x)$ as was described in Section 5.

Because of the small sample size of SNL cells, only three cells were tested for forward biased overstress failure. The histogram for forward bias failures is given in Figure 6-16. The lowest failure, which occurred at 3750 A was apparently surface related. Since the bus on the SNL cells lies on top of an oxide layer all of the current is forced to flow through

SANDIA FORWARD BIAS

Figure 6-16. Histogram for forward bias SNL failure currents.

the fingers. Because of this, one would expect the bulk related failure levels for reverse and forward bias to be the same. Although the sample sizes are too small to be statistically significant, the range of confirmed bulk related failure levels for reverse bias was 3070-5290 whereas for forward bias the range was 4880-6780. Thus the forward bias failure levels were clearly higher. At present we do not have a reasonable explanation for why this occurred.

Histograms for reversed biased first fail, second fail and final fail levels for the Solarex cells are given in Figures 6-17, 6-18 and 6-19 respectively. Five cells had first fail currents below the predicted threshold of 15,000 A, one occurring as low as 5876 A. Although four of these five failures were due to leakage current increases, one cell, which failed at 12,000 A had a finger melt. The melt occurred on the finger next to the edge where the current entered from the pulser. On the next pulse, at 12,650 A, several fingers near the same end melted. As the current was further increased, more and more fingers at the same end showed melts. The final current pulse was 15,800 A. The failures were due to bulk current flow with the number of affected fingers increasing with each pulse. This cell had a pretest leakage of 800 mA at 15 V and a breakdown voltage of ~17 V. Nothing was noted in the pretest characteristics of this cell that would explain its low failure level. However, a survey of the finger melt data shows that in nearly all cases the finger melts occur at the end nearest where the current enters the back surface of the cell. As described in Section 6.1, the Solarex cell was mounted to the transformer terminals between the center of the cell and one end since the cell was too long to fit between the two terminals. This asymmetry caused a larger fraction of the current to pass through the two contacts on the one end mounted between the terminals. Since the one contact was placed at the end of the cell, if the current through the two contacts was approximately equal then the failures would be expected to occur near the end contact because fewer fingers feed the end contact. This would cause a greater current density in the fingers nearest the end, hence a lower total cell failure current.

Figure 6-17. Histogram of reverse bias Solarex failure currents for first fail.

SOLAREX REVERSE BIAS SECOND FAIL

Fail Code:

I/V - Change in I/V

FM - Finger Damage at Bus

SC - I/V Short Circuit

Figure 6-18. Histogram of reverse bias Solarex failure currents for second fail.

Unit number 31 had a first fail current level well below the other cells. On the first pulse, at 5876 A, the cell showed an increase in the leakage current at 10 V of 50 mA. The pretest leakage at 10 V was 120 mA. However no finger melts were observed on this device until a current of 16,500 A. Thus it appeared that the early failure was surface related.

The conclusion for the reversed biased Solarex cells is that the model does predict a reasonable lower bound for the failure even though failures were observed at currents below the predicted threshold. The lowest bulk related failure occurred at about 80% of the threshold. The reason for the low failures appears to be due to the asymmetry of the current flow resulting from the mounting technique.

The first fail forward-biased current levels for the Solarex cell are shown in Figure 6-20. All of the failures occurred well above the threshold failure level predicted for reverse bias. As with the ASEC cells the reason for the higher failure currents appears to be due to the differences in current distribution between reverse and forward bias. Thus the model adequately predicts a lower bound to the failure threshold.

6.5 Results of Failure Tests on the Photowatt Flat-plate Cell

As discussed in Section 4, the predicted failure levels for the Photowatt cell were much lower than for the concentrator cells. There are several reasons for this. The Photowatt cell has a small junction area as well as a small cross sectional finger area. The substrate resistivity of $10 \Omega \text{ cm}$ is much higher in the Photowatt cells than in the concentrator cells. This high resistivity results in a breakdown voltage of ~245 Volts which causes much greater heating due to reverse bias. At pulse widths of 100 μs and greater the predominate failure mechanism is reverse biased junction heating under the bus.

SOLAREX REVERSE BIAS FINAL FAIL

Fail Code:

I/V - Change in I/V

FM - Finger Damage at Bus

Figure 6-19. Histogram of reverse bias Solarex failure currents for final pulse.

SOLAREX FORWARD BIAS FIRST FAIL

Failure Code:

I/V - Change in I/V

FM - Damage to Fingers at Bus

Cell number 2 had damage to the fingers at the bus at 26668 A and a change in I/V.

Cell number 17 was also pulsed in the reverse bias mode first. The failure to the fingers was independent of the reverse testing.

Figure 6-20. Histogram of forward bias Solarex failure currents.

The initial reverse biased failure tests on the Photowatt cells were performed on the Maxwell Labs pulser. A total of 17 cells were tested to failure using the 10 μ s double exponential pulse. The charging voltage on the pulser was increased until the cell approached avalanche. Once this voltage was reached, the current in the cell increased rapidly. Since no current limiting was employed, the current increased well beyond the initial failure current. A distinct breakpoint occurred in the current and voltage waveforms indicating initial failure. Since the resolution of the current waveform was on the order of 5 A, an accurate measure of failure current was not possible. The cells unexpectedly failed at currents on the order of 4-20 A, between .75 and 5 μ s into the pulse. The predicted failure level at a pulse width of 1 μ s is 450 A and at 10 μ s about 300 A.

Figure 6-21 illustrates a typical current and voltage waveform for the reversed biased failure tests on the Maxwell pulser. The current waveform at the top shows a very slight increase in current up to about 4 μ s. At that point the current increases rapidly to a peak of about 250 A, then decays back to zero. The voltage waveform at the bottom shows a rapid increase to a peak of about 130 volts. This is well below the breakdown voltage of 245 V. At 4 μ s the voltage decreases sharply from about 110 V to about 70 volts. A histogram of the failure currents is presented in Figure 6-22. Each block in the histogram shows the approximate fail current, the time to failure, the cell number and the failure mode. The primary failure mode is a hole in the bus near the edge accompanied by an increase in the reverse leakage current. These failure modes indicated in the blocks were determined by a detailed visual examination at 500 x after the pulse. They are not representative of the type of failure that occurred at the breakpoint. From the oscilloscope photo of the current waveform presented in Figure 6-21, it was evident that after the failure occurred, a large current was dumped into the cell. Therefore it is not possible to determine the nature of the failure that occurred at the breakpoint. The failure modes listed for the post-test analysis are increases

Current through cell: 226 A/d
5 μ s/d

Start of Pulse
Failure Point

Voltage across cell: 20 v/d
5 μ s/d

Figure 6-21. Current and voltage waveforms for reverse bias failure tests on Photowatt cell using Maxwell pulser.

PHOTOWATT REVERSE BIAS DOUBLE EXPONENTIAL PULSE FIRST FAIL

Figure 6-22. Histogram of reverse bias Photowatt failure current on Maxwell pulser.

PHOTOWATT 1.5 μ s

REVERSE BIAS

Failure Code:

I/V - Change in I/V

HB - Bus Metallization Damage at Edge

EF - End of Finger Damage

FE - Finger at Edge Damage

Figure 6-23. Histogram of reverse bias Photowatt failure currents on SPG-200.

outside fingers next to the edge, increases in leakage current and bus damage at the outside of the bus next to the edge. Figures 6-24 through 6-26 give the results of the Velonix tests at 10 μ s, 50 μ s and 100 μ s respectively. All of the cells tested on the Velonix failed at voltages much less than the breakdown voltage, hence they never reached a bulk avalanche condition. Again all failures were surface or edge related. A plot of the failure current versus time to failure for all of the reverse biased square wave pulse tests on the Photowatt cells is shown in Figure 6-27. Although there is a lot of scatter in the data for short times, all of the failure currents were between 4 and 15 A for time to fail greater than 2 μ s.

Comparisons between the experimental results and the predicted threshold failure is inappropriate since all of the observed failures were apparently due to edge effects and the model predicts failure currents for bulk conduction. It was apparent from the voltage waveforms that only a few cells, those tested on the SPG-200, actually reached avalanche.

The forward biased overstress tests were performed on the Maxwell Labs pulser. A histogram of the test results is given in Figure 6-28. The predicted threshold failure level for reverse bias at 4 μ s (corresponding to a 10 μ s exponential) is 340 A. Although most of the forward biased failures levels were well above the predicted threshold, one cell failed at 322 A, exhibiting a finger melt near the bus. Since no $\Delta V(x)$ tests were performed on the Photowatt cells, no comments can be made concerning the current distribution under forward bias. However if it is similar to that of the ASEC and Solarex cell, we would expect forward biased failure current to be higher than that predicted for reverse bias. Thus it is rather surprising that a bulk related forward biased failure would occur below the predicted threshold for bulk related reverse biased failure.

Figure 6-24. Histogram of reverse bias Photowatt failure currents on Velonix at 10 μ s.

PHOTOWATT 50 μ s REVERSE BIAS

Figure 6-25. Histogram of reverse bias Photowatt failure currents at 50 μ s.

PHOTOWATT 100 μ s REVERSE BIAS

Testing at these cells was stopped at the first fail

Failure Code:

- NC - No change in I/V or Visual
- EF - End of Finger Damage
- FE - Finger at Edge Damage
- I/V - I/V Change

Figure 6-26. Histogram of reverse bias Photowatt failure currents on Velonix at 100 μ s.

Figure 6-27. Failure current versus time to fail for reverse bias tests on Photowatt cells.

PHOTOWATT FORWARD BIAS DOUBLE EXPONENTIAL PULSE FIRST FAIL

Failure Code:

FM - Finger melt at the bus

I/V - Change in I/V curve

HB - Hole in bus

Figure 6-28. Histogram of forward bias Photowatt failure currents.

One possible explanation is that due to the texturing of the silicon surface, the finger metallization is uneven. Thus the cross sectional area of the fingers may vary significantly along the length of the finger. Since the failure current is directly proportional to the square root of the finger cross sectional area, a factor of two reduction in finger cross sectional area would cause a 30% decrease in the predicted failure current.

6.6 Results of Post-test Visual Inspection

At the conclusion of all of the overstress testing a detailed visual inspection of all of the cells was conducted under high power magnification in order to determine the nature and location of all of the failures. Each cell was scanned over the entire surface at 500 x. The results of this visual inspection are presented as visual composites of the damage locations and damage types for each cell type for each different test condition. Also presented are drawings of the cell test configurations showing the direction of positive current during the overstress test. Electron current would of course be in the opposite direction of the conventional positive current. Photomicrographs of the various types of visual damage are presented in Appendix B.

Figure 6-29 illustrates the results of the visual analysis for the ASEC cells tested under reverse bias on the Maxwell pulser. Figure 6-30 shows the direction of positive current for reverse bias. The results clearly indicate that finger melts occurred on the longer fingers near the intersection of the finger and the bus as the model predicts.

Figure 6-31 illustrates the location of visual failures for the ASEC cells under forward bias on the Maxwell pulser. The current under forward bias is shown in Figure 6-32. It is clear that the distribution of failures under forward bias is significantly different than under reverse bias. All of the failures occur in the corners near the bus contacts rather than

- Finger Heating
- Finger Melt
- Finger melt and open circuit
- ▲ Finger melt, open circuit, and hole into the junction
- Hole through the bus into the junction

Figure 6-29. Location of visual damage on ASEC cells after reverse bias overstress tests.

Figure 6-30. Test configuration and direction of positive current for reverse bias ASEC tests.

- Finger Heating
- Finger Melt
- ◆ Finger melt and open circuit
- ▲ Finger melt, open circuit, and hole into the junction

Figure 6-31. Location of visual damage on ASEC cells after forward bias overstress tests.

Figure 6-32. Test configuration and direction of positive current for forward bias ASEC tests.

on the longer fingers. Also, the failures are heavily weighted towards the side where the electrons enter from the pulser. The distribution of the failures reinforces the assumption that under forward bias the bulk of the current flows directly from the bus into the silicon with a small fraction of the current in the fingers. The preferred current path for electrons seems to be from the pulser through the contacts on the right hand side (Figure 6-32) spreading very little from the bus contacts through the silicon and out the back surface contact. Since the outer bus on the ceramic substrate offers some resistance, less current enters the contacts on the left hand side. Hence there are fewer damage centers located near the left side contacts.

The results of the visual defect location for the SNL cells under reverse bias are shown in Figure 6-33. The direction of positive current is shown in Figure 6-34. As with the ASEC cells, the failures are primarily finger melts near the bus and are more heavily weighted toward the longer fingers. This further confirms the model predictions of bulk related failure. The results for forward bias on the SNL cells are shown in Figure 6-35 with the direction of positive current shown in Figure 6-36. These results are distinctly different from the ASEC results under forward bias. In the SNL cells, the bus is not in contact with the silicon hence the current cannot be conducted under the bus. Since the current is forced down the fingers, there is a much more uniform distribution of finger melts. The finger melts seem to be slightly weighted toward the right side. In the case of the SNL cell, which is p^+ on n , the electrons enter from the back surface of the silicon and flow out the bus to the bus contacts. Again the failures are weighted toward the side where the electrons enter from the pulser but the bias toward the electron entry point is not as great as for the ASEC cells.

The results for the Solarex cells under reverse bias are shown in Figure 6-37. The direction of positive current is shown in Figure 6-38.

- Finger Melt
- Finger Melt and Open Circuit
- ▲ Finger melt, open circuit and hole into the junction

Figure 6-33. Location of visual damage on SNL cell after reverse bias overstress tests.

Figure 6-34. Test configuration and direction of positive current for reverse bias SNL tests.

- Finger Melt
- Finger Melt and
Open Circuit
- ▲ Finger melt, open
circuit, and hole
into the junction

Figure 6-35. Location of visual damage on SNL cells after forward bias overstress tests.

Figure 6-36. Test configuration and direction of positive current for forward bias SNL tests.

- Finger melt
- Finger melt and open circuit
- ▲ Finger melt, open circuit and hole into the junction
- Finger lifted up from the surface

Figure 6-37. Location of visual damage on Solarex cells after reverse bias overstress tests.

Figure 6-38. Test configuration and direction of positive current for reverse bias Solarex tests.

With the exception of one device, all of the visual failures occurred on one end within the first 15-20 fingers. The reason for this asymmetry in failure location was discussed in Section 6.4. It is apparently due to the mounting technique required for the pulser configuration. The highest current density occurs in the fingers nearest the point of entry of the electron current from the pulser. These results further verify the model predictions of failure type and location.

The results of the visual inspection of the Solarex cells for forward bias tests are given in Figure 6-39. The direction of positive current is shown in Figure 6-40. The location of the failures under forward bias is nearly identical to that for reverse bias. The proximity of the failures to the bus end contacts is evident for both bias conditions. In both cases this asymmetry is due to the mounting configuration.

The Photowatt overstress tests under reverse bias were performed on the Maxwell pulser, the SPG-200 and on the Velonix pulser at several pulse widths. Drawings indicating the visual failure type and location will be presented for each of these tests. For the tests conducted on the Maxwell Labs double exponential pulser, the cells failed early in the pulse but were subjected to a large current surge after failure. Thus the post-test visual defects are a result of high surge currents received after initial failure. Since the Photowatt cells were originally 4 cm x 2 cm cells which were sectioned in two equal parts, there are two bus configurations. Therefore in order to reproduce the actual failure locations, the data is presented in two figures, one for each bus configuration. Figures 6-41 and 6-42 show the type and location of the visual defects for reverse biased Maxwell Labs pulser tests. Figure 6-43 shows the mounting configuration and direction of positive current. Nearly all of the failures occurred on the bus and consisted of bus melts in the center of the bus and holes in the silicon at the bus edges. The surge currents, after initial failure, were typically 200-500 A.

- Finger Melt
- Finger Melt and Open Circuit
- ▲ Finger Melt, Open Circuit and Hole into the Junction
- Finger Lifted up from the Surface

SOLAREX - Post fail visual inspection
Forward bias, maxwell pulser

Figure 6-39. Location of visual damage on Solarex cells after forward bias overstress tests.

Figure 6-40. Test configuration and direction of positive current for forward bias Solarex tests.

Figure 6-41. Location of visual damage for reverse bias Photowatt tests on Maxwell pulser.

Figure 6-42. Location of visual damage for reverse bias Photowatt tests on Maxwell pulser.

Figure 6-43. Mounting configuration and direction of positive current for reverse bias Photowatt tests.

The reverse bias square wave visual failure results are given in Figures 6-44 through 6-49 for the SPG-200 and Velonix tests. The failures are predominately edge related. Finger melts usually occurred on the edge fingers or at the end of the fingers next to the edge. Bus failures usually occurred at the outside bus edge. There were also tracks in the silicon from the bus edge or an edge finger to the silicon edge.

The results of the post-test visual defect analysis on the Photowatt cells tested under forward bias on the Maxwell are shown in Figures 6-50 and 6-51. The direction of positive current through the cell is shown in Figure 6-52. With the exception of one hole in the bus at the edge, all failures were finger melts near the bus as predicted by the model developed for bulk conduction under reverse bias. All of the failures were clustered near the wide part of the bus where the bus contact was made. This further confirms that under forward bias, when the bus lies directly on the silicon, most of the current enters the silicon either under the bus or within a short distance of the bus.

- Hole through the bus and into the junction
- ▲ Finger melt, open circuit and hole into the junction
- ⊙ Defect in the bus. Bus melt and open circuit.

Figure 6-44. Location of visual damage for reverse bias Photowatt tests on SPG-200

- Hole through the bus and into the junction

Finger Number Down Bus

Figure 6-45. Location of visual damage for reverse bias Photowatt tests in SPG-200.

Track in Si from bus or finger
to edge of the cell

• Finger melt

Figure 6-46. Location of visual damage for reverse bias Photowatt tests on Velonix at 10 μ s.

Figure 6-47. Location of visual damage for reverse bias Photowatt tests on Velonix at 50 μ s.

Figure 6-48. Location of visual damage for reverse bias Photowatt tests on Velonix at 50 μ s.

Figure 6-49. Location of visual damage for reverse bias Photowatt tests on Velonix at 100 μ s.

Figure 6-50. Location of visual damage for forward bias Photowatt overstress tests.

• Finger Melts

Figure 6-51. Location of visual damage for forward bias Photowatt overstress tests.

Figure 6-52. Mounting configuration and direction of positive current for forward bias Photowatt tests.

7.0 SUMMARY AND CONCLUSION

The goal of the program was to develop a model to predict the threshold failure currents for pulsed electrical overstress in silicon solar cells and to experimentally verify the model on several concentrator and flat-plate cell types. The model has been developed and presented in detail. Calculations of threshold failure currents have been made for three concentrator cells and one flat-plate cell. The model calculations were based on nominal values of cell parameters obtained from the manufacturers and partially verified by physical and electrical measurements. The model was developed for reverse bias on the assumption that the primary mode of current conduction during the transient overstress environment is through the bulk silicon. The threshold failure current is derived assuming that silicon damage occurs once the instability temperature (silicon resistivity turnover) is reached. This provides a lower bound to the failure current.

Three types of concentrator cells (ASEC, SNL and Solarex) and one type of flat-plate cell (Photowatt) were obtained for testing. Each of these cell types was modeled for threshold failure current.

The results of the model predictions are the following:

- a) Failure in the concentrator cells under reverse bias at pulse widths between 1 μ s and 1 ms occurs initially from the silicon junction being heated to instability by conduction from the metal fingers.
- b) Initial failure occurs under the longest fingers near the intersection of the finger and bus.

- c) Finger damage in the form of silver melting should occur at currents only slightly greater than that required for silicon junction failure.
- d) Failure in the high resistivity flat-plate cell should occur in the same manner as for the concentrator cells at pulse widths below 10 μ s.
- e) For the longer pulse widths the primary failure mode in the high resistivity cell should be due to reverse bias heating of the junction to the instability temperature. This would occur where the current density in the silicon is greatest, i. e., under the bus.

A significant part of the model development involved a detailed description of the current distribution under transient high currents. An experimental setup was developed in order to verify the current distribution under pulsed conditions. This setup involved the development of a high current square wave pulser capable of delivering a 600 A, 100 μ s pulse at up to 100 volts. The current distribution was experimentally verified by measuring the voltage distribution along the bus and down the fingers from the bus to the finger end. These measurements were made using microprobe contact to the metallization and monitoring the voltage with a differential preamplifier. Both the functional form of the voltage distribution and the magnitude of the voltage drops down the fingers were verified for reverse bias on the ASEC and Solarex cells. However excessive coupling voltages prevented the acquisition of meaningful data on the SNL cells, which was apparently due to contact problems with the cells. No measurements were taken on the Photowatt cells as they were all utilized for failure tests. The results of the current distribution tests under forward bias were quite different than for reverse bias. Although it was not verified directly, the results implied that a much greater fraction of

the current was directly into the silicon under the bus rather than down the fingers and into the silicon. If the total current into the finger were reduced from that predicted for reverse bias, then both the form and magnitude of the voltage down the finger could be predicted by the model. The conclusion of the current distribution tests was that the model was verified for reverse bias and under forward bias the current distribution was significantly different, apparently with less current into the fingers.

All cell types were tested for transient overstress failure under both reverse and forward bias. Because of the high currents required for failure, a special transformer was built to be used in conjunction with a high voltage pulser. The resultant pulser test configuration was capable of delivering a double exponential pulse with a maximum 10 μ s decay time and with a peak current of 30,000 A into a short circuit. This pulser was used for the overstress failure tests on all cells under both bias conditions. However additional reverse bias tests on the flat-plate cell were performed using square wave pulsers.

The failure criteria established for the cells was one or more of the following, whichever occurred first;

- a) A breakpoint in the current and voltage waveform during the overstress pulse, i.e., rapid increase in current and decrease in voltage.
- b) A post-test to pre-test change in the reverse current of 10% or more.
- c) Post-test visual damage in the form of metallization melts or silicon damage.

The only case where a clear breakpoint occurred was for the reverse bias tests on the Photowatt cells. In all other cases failure was determined by either criteria b) or c). Post-test electrical and visual examination was performed after every pulse. In most cases the overstress testing was continued until some visual damage occurred, even though the cell failed at lower currents due to increases in leakage.

The results of the reverse bias tests on the concentrator cells verified that the model works well in predicting a lower bound to the threshold failure current for failures resulting from bulk current conduction. Out of 66 concentrator cells tested under reverse bias, only four cells had confirmed bulk related failures below the predicted threshold. The lowest bulk related failure occurred at 80% of the predicted value. Possible explanations for these low failures are discussed in Section 6. However in several instances for all three cell types failures that are apparently due to surface or edge effects occurred below the predicted threshold. All of these "failures" were increases in leakage current. It is doubtful that degradation of leakage current would affect cell performance. Thus the failure model seems to work very well in predicting both the nature of the failures and a lower bound for the threshold failure current.

The threshold failure currents for forward bias transient overstress on the concentrator cells were much larger than for reverse bias. No cells failed at currents below the threshold predicted for reverse bias. The failure mode for forward bias was predominately finger melts near the bus indicating bulk current conduction. However it was verified that the current distribution was significantly different in the ASEC cell where the bus lies directly on the silicon. Failures occurred very close to the bus contacts. In the SNL cells, the failures were evenly distributed along the fingers near the bus since the bus lies on an oxide layer thus forcing current through the fingers. Due to the asymmetry of the mounting configuration on the Solarex cells, current conduction occurred preferentially at

one end of the cell and hence the failure locations were the same for forward and reverse bias. The failure model developed for reverse bias proved to be conservative as a lower bound for the threshold failure current for forward bias.

The results of the reverse bias transient overstress tests on the flat-plate cell demonstrated that the predominate failure mode was due to edge currents, hence the model did not adequately predict a lower bound to the failure threshold. Failure currents for pulse widths greater than about 2 μ s ranged from 4-20 A which is one to two orders of magnitude below the model predictions. Therefore the assumption of bulk current conduction does not apply to transient currents in high resistivity flat-plate cells and a different model based on edge currents is required. It appears that high resistivity flat-plate cells are quite vulnerable to transient overstress damage and could present a major problem for photovoltaic arrays in the lightning environment.

The results of the forward bias transient overstress tests on the flat-plate cell indicate that the model developed for reverse bias provides a reasonable lower bound to the forward bias failure current.

It is recommended that on the basis of the reverse bias transient overstress tests on the flat-plate cell, further work be performed to develop a model based on edge conduction and to characterize a variety of flat-plate cells.

Based on the model predictions, which have been verified for concentrator cells under reverse bias, there are several parameters which can be controlled to increase the tolerance of the cell in the overstress environment. One major factor is, of course, total cell area. As with other semiconductor devices, the tolerance to overstress failure increases with increasing active area. The other major factor is the cross sectional area

of the fingers. The failure current scales with the square root of the finger cross sectional area. Since the total surface area of the fingers must be minimized, in order to increase efficiency then the finger thickness can be increased to maximize cross sectional area. Another conclusion is that the overstress tolerance can be increased by placing the bus directly on the silicon. This not only increases the total active area, but allows a large fraction of the current to be conducted directly into silicon hence reduces the current density in the fingers.

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APPENDIX A

ADDITIONAL DATA

Figure A-1. DIFFERENTIAL FINGER VOLTAGE DROP VS POSITION
 @ $I_B = 20$ A, $\tau = 30 \mu s$ (LEFT SIDE).

Figure A-2. DIFFERENTIAL FINGER VOLTAGE DROP VS POSITION
 @ $I_B + 40$ A, $\tau = 30 \mu s$, (LEFT SIDE).

Figure A-3. DIFFERENTIAL FINGER VOLTAGE DROP VS POSITION
@ 80 A, $\tau = 30 \mu s$, (LEFT SIDE).

Figure A-4. DIFFERENTIAL VOLTAGE DROP VS POSITION @ $I_B + 200$ A, $\tau = 30 \mu s$ (RIGHT SIDE).

Figure A-5. ASEC CELL #21, REVERSE BIAS, RIGHT SIDE DIFFERENTIAL FINGER VOLTAGE VS CURRENT FOR 100 μ s PULSE.

Figure A-6. ASEC #25 CELL, REVERSE BIAS, RIGHT SIDE DIFFERENTIAL FINGER VOLTAGE VS CURRENT FOR 100 μ s PULSE.

Figure A-7. ASEC #47 CELL, REVERSE BIAS, RIGHT SIDE DIFFERENTIAL FINGER VOLTAGE VS CURRENT FOR 100 μ s PULSE.

Figure A-8. ASEC #47 cell, forward bias left side differential finger voltage versus current for 100 μ s pulse.

50 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 20 A/d

Differential Finger
Voltage 50 mV/d

100 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 50 A/d

Differential Finger
Voltage 50 mV/d

150 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 50 A/d

Differential Finger
Voltage 100 mV/d

Figure A-9. Typical voltage, current and differential finger voltage waveforms for an ASEC cell under reverse bias conditions. For currents of 50 to 150 A.

200 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 100 A/d

Differential Finger
Voltage 100 mV/d

200 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Voltage 100 A/d

Differential Finger
Voltage 250 mV/d

400 A PULSE

Top Trace. Cell Voltage 20 V/d
Bottom Trace. Cell Voltage 200 A/d

Differential Finger
Voltage 250 mV/d

Figure A-10. Typical voltage, current and differential finger voltage waveforms for an ASEC cell under reverse bias conditions. For currents of 200 to 400 A.

500 A PULSE

Top Trace. Cell Voltage 20 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 250 mV/d

500 A PULSE

Top Trace. Cell Voltage 20 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 250 mV/d

600 A PULSE

Top Trace. Cell Voltage 20 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 250 mV/d

Figure A-11. Typical voltage, current and differential finger voltage waveforms for an ASEC cell under reverse bias conditions. For currents of 500 to 600 A.

50 A PULSE

Top Trace. Cell Voltage 5 V/d
Bottom Trace. Cell Current 20 A/d

Differential Finger
Voltage 25 mV/d

100 A PULSE

Top Trace. Cell Voltage 5 V/d
Bottom Trace. Cell Current 50 A/d

Differential Finger
Voltage 25 mV/d

150 A PULSE

Top Trace. Cell Voltage 5 V/d
Bottom Trace. Cell Current 50 A/d

Differential Finger
Voltage 50 mV/d

Figure A-12. Typical voltage, current and differential finger voltage waveforms for an ASEC cell under forward bias conditions. For currents of 50 to 150 A.

200 A PULSE

Top Trace. Cell Voltage 5 V/d
Bottom Trace. Cell Current 100 A/d

Differential Finger
Voltage 50 mV/d

300 A PULSE

Top Trace. Cell Voltage 5 V/d
Bottom Trace. Cell Current 100 A/d

Differential Finger
Voltage 50 mV/d

400 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 100 mV/d

Figure A-13. Typical voltage, current and differential finger voltage waveforms for an ASEC cell under forward bias conditions. For currents of 200 to 400 A.

500 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 100 mV/d

550 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 100 mV/d

600 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 250 mV/d

Figure A-14. Typical voltage, current and differential finger voltage waveforms for an ASEC cell under forward bias conditions. For currents 500 to 600 A.

Figure A-15. 11 finger Solarex cell #3, reverse bias, left side, differential finger voltage versus current through the cell.

Figure A-16. 11 finger Solarex cell #3, forward bias, right side, differential finger voltage versus current through cell.

Figure A-17. 11 finger Solarex cell #18, reverse bias, right side, differential finger voltage versus current through the cell.

Figure A-18. 11 finger Solarex cell #18, forward bias, right side, differential finger voltage versus current through the cell.

Figure A-19. 11 finger Solarex cell #18, reverse bias, left side, differential finger voltage versus current through the cell.

Figure A-20. 11 FINGER SOLAREX CELL #18, FORWARD BIAS, LEFT SIDE, DIFFERENTIAL FINGER VOLTAGE VERSUS CURRENT THROUGH THE CELL.

600 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 250 mV/d

Figure A-21. Typical voltage, current and differential voltage waveforms for an 11 finger Solarex cell, under forward bias conditions.

600 A PULSE

Top Trace. Cell Voltage 20 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 500 mV/d

Figure A-22. Typical voltage, current, differential voltage waveforms for an 11 finger Solarex cell, under reverse bias conditions.

Figure A-23. 1/8 SECTION ASEC CELL #19B, DIFFERENTIAL FINGER VOLTAGE FOR FINGER #36 VERSUS CURRENT THROUGH THE CELL.

NOTE: Input Leads Reversed

Figure A-24. 1/8 SECTION ASEC CELL #19B, FORWARD BIAS, DIFFERENTIAL FINGER VOLTAGE FOR FINGER #36 VERSUS CURRENT THROUGH THE CELL.

Figure A-25. 1/8 SECTION ASEC CELL #19C, REVERSE BIAS, DIFFERENTIAL FINGER VOLTAGE FOR FINGER #36 VERSUS CURRENT THROUGH THE CELL.

Figure A-26. 1/8 SECTION ASEC CELL #19C, FORWARD BIAS, DIFFERENTIAL FINGER VOLTAGE FOR FINGER #36 VERSUS CURRENT THROUGH CELL.

25 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 10 A/d

Differential Finger
Voltage 100 mV/d

50 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 20 A/d
100 A PULSE

Differential Finger
Voltage 250 mV/d

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 50 A/d

Differential Finger
Voltage 250 mV/d

Figure A-27. Typical voltage, current, differential finger voltage for a 1/8 ASEC section under reverse bias conditions. For currents of 25 to 100 A.

150 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 50 A/d

Differential Finger
Voltage 500 mV/d

200 A PULSE

Top Trace. Cell Voltage 20 V/d
Bottom Trace. Cell Current 100 A/d

Differential Finger
Voltage 1000 mV/d

300 A PULSE

Top Trace. Cell Voltage 20 V/d
Bottom Trace. Cell Current 100 A/d

Differential Finger
Voltage 2500 mV/d

Figure A-28. Typical voltage, current, differential finger voltage for a 1/8 ASEC section under reverse bias conditions. For currents of 150 to 300 A.

400 A PULSE

Top Trace. Cell Voltage 20 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 2500 mV/d

500 A PULSE

Top Trace. Cell Voltage 20 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 2500 mV/d

Figure A-29. Typical voltage, current, differential finger voltage for a 1/8 ASEC section under reverse bias conditions. For current of 400 A.

400 A PULSE

Top Trace. Cell Voltage 10 V/d
Bottom Trace. Cell Current 200 A/d

Differential Finger
Voltage 500 mV/d

Figure A-30. Typical voltage, current, differential finger voltage for an 1/8 ASEC section under forward bias conditions for current of 400 A.

Figure A-31. 1/8 section ASEC cell differential finger voltage versus distance down the finger for a 200 amp, 100 μs square pulse.

Figure A-32. 1/8 section ASEC cell differential finger voltage versus distance down the finger for a 400 amp, $100 \mu\text{s}$ square pulse.

APPENDIX B

PHOTOMICROGRAPHS OF VISUAL DAMAGE

As discussed in Section 6.6, a detailed visual inspection of the cells was conducted after the overstress tests were completed. Composite diagrams showing the nature and location of the failures were presented. In this appendix, photomicrographs are presented which show typical visual damage for each of the cell types. Photomicrographs will only be presented for a few cells of each type. Damage is similar for the other cells under forward and reverse bias conditions. Each photomicrograph is accompanied by a description of the damage, damage type, cell type, test conditions, and the highest peak current to which the cell was subjected.

Figure B1

Cell: ASEC #13
Magnification: 275 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 7684 A
Damage Type: Finger Heating

This photo shows a finger which just began to melt and pull back. Note vertical filaments (Arrow)

Figure B2

Cell: ASEC #12
Magnification: 500 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 8271 A
Damage Type: Finger melt and open circuit.

This photo shows where a finger has melted and pulled back (arrows) resulting in an open circuit.

Figures B3, B4, B5

Cell: ASEC #14

Magnification: 500 x

Bias: Reverse

Pulser: Maxwell

Peak Current: 8588 A

Damage Type: Finger melt, open circuit and hole in Si.

Figure B3.

Figure B4.

Figure B5.

These photos show typical finger damage at the bus. Here the fingers have melted, pulled back and a hole has formed into the junction. The (=>) indicate the holes and the (—>) indicate where the finger has pulled back.

Figure B6.

Figure B7

Figure B6 and B7

Cell: ASEC #8

Magnification: 137.5 x

Bias: Reverse

Pulser: Maxwell

Peak Current: 4248 A

Damage type: Finger melt, open circuit and hole in Si.

These photos show severe damage to the finger and junction. Here a track has formed in the junction from the bus (—→) down the finger path.

Figure B8

Cell: ASEC #50

Magnification: 68.75 x

Bias: Reverse

Pulser: Maxwell

Peak Current: 6328 A

Damage Type: Hole in bus.

This photo shows a hole through the bus into the junction. Other failures of this type occurred on the outside edge of the bus under reverse bias conditions.

Figure B9, B10

Cell: ASEC #35

Magnification: 68.75 x, 137.5 x

Bias: Forward

Pulser: Maxwell

Peak Current: 15820 A

Damage Type: Finger melt, open circuit and hole in Si.

Figure B9.

Figure B10.

(Magnification of B9)

These photos show typical corner damage under forward bias conditions. The ($\Rightarrow$) indicate where a hole has formed into the junction. The ($\rightarrow$) indicate where the metal has pulled back.

Figure B11

Cell: SNL # 02
Magnification: 137.5 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 4113 A
Damage Type: None

This photo shows a discoloration of the surface next to the finger (arrows). This sometimes indicates heating has occurred in the area. This observation method was not used for reliable failure analysis as the discoloration can be due to processing.

Figure B12

Cell: SNL # 02
Magnification: 137.5 x
Bias: Reverse
Pulsar: Maxwell
Peak Current: 4113 A
Damage Type: Finger Melt

This photo shows a finger which has begun to melt.

Figure B13

Cell: SNL Ø4
Magnification: 500 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 5288 A
Damage Type: Finger melt and
open circuit.

This photo shows a finger where the Ag has melted and pulled back (→). However not all the tri-metal has melted (⇐). In the center the tri-metal has melted and pulled back, resulting in an open circuit.

Figure B14

Cell: SNL Ø3
Magnification: 500 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 5288 A
Damage Type: Finger melt, open circuit
and hole in Si.

This photo shows the same type of damage as described in Figure B13 except the finger has pulled back considerably further. In this case the tri-metal did not open circuit. However, a small hole did form through the tri-metal into the junction (→).

Figure B15

Cell: SNL Ø5
Magnification: 68.75 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 3887 A
Damage Type: Finger melt, open circuit.

This photo shows a finger which has been lifted from the surface of the cell.

Figure B16

Cell: SNL Ø2
Magnification: 137.5 x
Bias: Reverse
Pulse: Maxwell
Peak Current: 4113 A
Damage Type: Finger melt, open circuit and hole in Si.

This photo shows a finger which has melted and pulled back ($\Rightarrow$). Holes have also formed into the junction ($\rightarrow$).

Figure B17

Cell: SNL Ø2
Magnification: 137.5 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 4113 A
Damage Type: Finger melt, open circuit and hole in Si.

This photo shows the same type of damage as in Figure B17 except more severe. Here the metallization has pulled back into bubbles ($\square$). The ($\rightarrow$) indicate where a track has formed into the junction.

Figure B18

Cell: SNL Ø3
Magnification: 137.5 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 4610 A
Damage Type: Finger melt, open circuit and hole in Si.

This photo again shows the same type of damage as Figure B16 and B17. The ($\square$) indicate a hole into the junction. The ($\rightarrow$) indicates where the finger has pulled back.

Figure B19, B20

Cell: SNL 3

Magnification: 500 x

Bias: Reverse

Pulser: Maxwell

Peak Current: 3073 A

Damage Type: Finger melt and
hole in Si.

Figure B19.

These photos indicate a failure which occurred at a damaged finger. Figure B19 shows where a finger has been abraded and pushed over (→). Figure B20 shows where the metal has pulled back (→) and a hole has formed into the junction (⇔).

Figure B20.

Figure B21

Cell: SNL Ø1

Magnification: 6875 x

Bias: Reverse

Pulser: Maxwell

Peak Current: 3616 A

Damage Type: Finger melt, open circuit, hole in Si.

This photo shows damage which occurred in the corner of the cell. The (—) indicates finger melting. The (□) indicates a hole into the junction.

Figure B22

Cell: SOLAREX

Magnification: 68.75 x

This photo shows the textured surface of the SOLAREX cells.

Figure B23

Cell: SOLAREX #24

Magnification: 68.75 x

Many of the Solarex cells have damaged fingers such as shown in the photo. Here the finger has been torn off the surface of the cell. The dark spots (—→) indicate where there was good adhesion between the surface and the finger.

Figure B24

Cell: SOLAREX 25
Magnification: 137.5 x
Bias: Forward
Pulser: Maxwell
Peak Current: 20340 A
Damage Type: Finger melt

This photo shows a finger which has been melted (→). However the metal has not pulled back.

Figure B25

Cell: SOLAREX 25
Magnification: 137.5 x
Bias: Forward
Pulser: Maxwell
Peak Current: 20340 A
Damage Type: Finger melt.

This photo shows the same type of damage as finger B24 except more severe.

Figure B26

Cell: SOLAREX 17
Magnification: 137.5 x
Bias: Forward
Pulser: Maxwell
Peak Current: 26216 A
Damage Type: Finger Melt

This photo shows a finger where the Ag has melted and almost pulled back. In this photo the tri-metal pattern can be seen (—→).

Finger B27

Cell: SOLAREX 17
Magnification: 137.5 x
Bias: Forward
Pulser: Maxwell
Peak Current: 26216 A
Damage Type: Finger Melt

This photo shows a finger which has melted and the Ag has pulled back to the points indicated by the (—→). The tri-metal (—→) has not melted.

Figure B28

Cell: SOLAREX 23

Magnification: 500 x

Bias: Forward

Pulser: Maxwell

Peak Current: 22939 A

Damage Type: Finger Melt

This photo shows a finger which has melted and the Ag pulled back ($\Rightarrow$).
The ($\Rightarrow$) shows where the tri-metal has begun to melt.

Figures B29 and B30

Cell: SOLAREX 24

Magnification: 137.5 and 500 x

Bias: Forward

Pulser: Maxwell

Peak Current: 26668 A

Damage Type: Finger Melt and
open-circuit

These photos both show a finger which has melted and pulled back resulting in an open circuit. (Figure B30 is an enlargement of Figure B29). The (→) indicates where the metal has pulled back.

Figure B29.

Figure B30.

Figure B31

Cell: SOLAREX 25
Magnification: 137.5 x
Bias: Forward
Pulser: Maxwell
Peak Current: 2034 A
Damage Type: Finger Melt,
Open Circuit
and hole in Si

This photo shows a finger which has melted and pulled back to an open circuit. Here a hole has formed into the junction (→).

Figure B32

Cell: SOLAREX 23
Magnification: 137.5 x
Bias: Forward
Pulser: Maxwell
Peak Current: 22939 A
Damage Type: Finger Melt,
Open Circuit
and hole in Si

This photo shows the same type of damage as Figure B31 except the hole in the junction (→) is longer.

Finger B33

Cell: Solarex 27

Magnification: 68.75 x

Bias: Forward

Pulser: Maxwell

Peak Current: 21470 A

Damage Type: Damaged Cell

This photo shows a cell which had been damaged prior to overstress testing. The failure occurred at the remaining bus and finger contacts. The failure indicated by ($\Rightarrow$) is a finger melt resulting in an open circuit. The failure indicated by the ($\longrightarrow$) is a partial finger melt.

Figure B34

Cell: SOLAREX 22
Magnification: 137.5 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 23052 A
Damage Type: Finger Melt and
Open Circuit

This photo shows a finger which has melted and pulled back (—→) resulting in an open current.

Figure B35

Cell: SOLAREX 17
Magnification: 137.5 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 26216 A
Damage Type: Finger Melt and
Open Circuit

This photo shows a finger which has melted and lifted up from the surface. The lifted section is indicated by the (—→).

Figure B36

Cell: SOLAREX 17
Magnification: 137.5 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 26216 A
Damage Type: Finger melt,
Open Circuit and hole in Si.

This photo shows a finger which has melted and pulled back to the points indicated by the (→). A hole has also formed into the junction indicated by the (→).

Figure B37

Cell: Photowatt

Magnification: 68.75 x

This photo shows the textured surface of the Photowatt cell. The (—→) indicates the finger.

Figure B38

Cell: Photowatt

Magnification: 500 x

This photo shows the end of a Photowatt finger (undamaged).

Figure B39

Cell: Photowatt # 9
Magnification: 68.75 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 429 A
Damage Type: Bus melt

This photo shows bus damage. Here the bus has vaporized and alloyed into the surface of the Si.

Figure B40

Cell: Photowatt # 9
Magnification: 60.75 x
Bias: Reverse
Pulser: Maxwell
Peak Current: 429 A
Damage Type: Bus melt and hole in bus.

This photo is of the same cell as Figure B39. The damage area is closer to the current input point. Here the damage is much more severe and holes have formed in the junction (→).

Figure B41 and B42

Cells: Photowatt # 15

Magnification: 68.75 x

Bias: Reverse

Pulser: Maxwell

Peak Current: 452 A

Damage Type: Hole in bus edge

Both of these photos both show cell edge damage. The holes indicated by the (—→) go through to the back side of the cell.

Figure B41.

Figure B42.

Figure B43

Cell: Photowatt # 28
Magnification: 68.75
Bias: Reverse
Pulser: SPG-200 1.5 μ s
Peak Current: 560 A
Damage Type: Hole in bus edge.

This photo shows edge damage to a cell. The ($\longrightarrow$) indicate small holes into the junction and the ($\longleftarrow$) indicates large holes into the junction.

Figure B44

Cell: Photowatt 28
Magnification: 68.75
Bias: Reverse
Pulser: SPG-200 1.5 μ s
Peak Current: 560 A
Damage Type: Finger melt, open circuit and hole in Si.

This photo shows a finger next to the edge of the cell. The finger melted and a hole has formed into the junction ($\longrightarrow$).

Figure B45

Cell: Photowatt 30
Magnification: 68.75 x
Bias: Reverse
Pulser: SPG-200 1.5 μ s
Peak Current: 560 A
Damage Type: Damaged Cell

This photo shows a bus damaged prior to overstress testing and the resulting failure. The failure ($\longrightarrow$) is a bus melt.

Figure B46

Cell: Photowatt 27
Magnification: 137.5 x
Bias: Reverse
Pulser: Velonix 10 μ s
Peak Current: 11 A
Damage Type: Track from bus to edge.

This photo shows a track ($\longrightarrow$) into the junction from the bus to the edge of the cell.

Figure B47

Cell: Photowatt 26
Magnification: 68.75 x
Bias: Reverse
Pulser: Velonix 10 μ s
Peak Current: 25 A
Damage Type: Finger melt,
open circuit and hole in Si.

This photo shows severe damage to a finger. The end of the finger is just slightly out of view at the bottom of the photo. The shiny spots (1) are where the metal has pulled back into bubbles. The medium dark areas (2) indicate where there is an open circuit. The very dark areas (3) are where track/holes have formed into the junction.

Figure B48

Cell: Photowatt 36
Magnification: 68.75 x
Bias: Reverse
Pulser: Velonix 50 μ s
Peak Current: 15 A
Damage Type: Finger melt, open
circuit, hole in Si and track
from finger to edge.

This photo shows two types of damage. The primary damage to the finger is a track into the junctions indicated by the (→). There is also a track from the finger to the edge of the cell (⇌).

Figure B49

Cell: Photowatt 45
Magnification: 500 x
Bias: Reverse
Pulser: Velonix 100 μ s
Peak Current: 7 A
Damage Type: Finger Melt.

This photo shows the end of a finger which has melted, indicated by the light line in the photo (—→).

Figure B50

Cell: Photowatt 43
Magnification: 68.75 x
Bias: Reverse
Pulser: Velonix 100 μ s
Peak Current: 7 A
Damage Type: Damaged Cell

This photo shows cell damaged prior to overstress testing. The failure (—→) was the formation of a hole in the junction. After repeated pulses the failure cleared itself.

Figure B51

Cell: Photowatt 1
Magnification: 137.5 x
Bias: Forward
Pulser: MRC 100 μ s
Peak Current: 300 A
Damage Type: Finger Melt

This photo shows a finger which has melted but not pulled back ($\longrightarrow$). The bus is the dark area at the top of the photo.

Figure B52

Cell: Photowatt 1
Magnification: 500 x
Bias: Forward
Pulser: MRC 100 μ s
Peak Current: 300 A
Damage Type: Finger Melt

This photo is an enlargement of the damaged area indicated by the arrow in Figure B51.

Figure B53

Cell: Photowatt 1

Magnification: 137.5 x

Bias: Forward

Pulser: MRC 100 μ s

Peak Current: 300 A

Damage Type: Finger melt, open circuit and hole in Si.

This photo shows a finger which has melted and a hole formed in the junction ($\longrightarrow$).

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