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# THERMAL STRESS CYCLING OF GaAs SOLAR CELLS

Bruce K. Janousek, Robert W. Francis, and Jerry P. Wendt[1]
The Aerospace Corporation
Los Angeles, California

## I. Introduction

A thermal cycling experiment is being performed on GaAs solar cells to establish the electrical and structural integrity of these cells under the temperature conditions of a simulated low-earth orbit of 3-year duration (15,000 cycles from -80°C to +80°C). Thirty single junction GaAs cells were obtained (ten each from Applied Solar Energy Corporation, Hughes Research Laboratories, and Varian Associates) and tests were performed to establish the beginning-of-life characteristics of these cells. These tests consisted of cell I-V power output curves, from which were obtained short-circuit current, open circuit voltage, fill factor, and cell efficiency, as well as optical micrographs, spectral response, and ion microprobe mass analysis (IMMA) depth profiles on both the front surfaces and the front metallic contacts of the cells. Following 5,000 thermal cycles, the performance of the cells was re-examined in addition to any factors which might contribute to performance degradation. The results presented here establish that, after 5,000 thermal cycles, the cells have retained their power output with no loss of structural integrity or change in physical appearance.

## II. Beginning of Life Cell Characteristics

The thirty GaAs solar cells obtained for this experiment were 2 x 2 cm, p-on-n, unglassed, single-junction cells with thicknesses of either 12 or 15 mils. To fully characterize these cells the following tests were carried out: 1) I-V measurements, 2) spectral response, 3) IMMA depth profiles, and 4) optical microscopy.

### A. Cell I-V Curves

The cell I-V curves were measured at the Jet Propulsion Laboratory (JPL) using a Spectrolab X-25 solar simulator in conjunction with a balloon-flown GaAs standard cell to establish beginning-of-life efficiency and to confirm the efficiencies reported by the vendors. All cells loaded into the temperature cycler had a beginning-of-life AM0 efficiency greater than 16% aside from one cell with a measured efficiency of 15.95%. The average efficiency of the combined thirty cells was 16.66% with a standard deviation of 0.53%.

B. Cell Spectral Response

Absolute spectral response measurements were obtained at JPL on two solar cells from each of the three vendors. These curves allow one to follow the factors which might contribute to loss in performance by determining which region of the cell is degrading. The beginning-of-life cell spectral response curves all show the classical behavior exhibited by GaAs solar cells - a sharp rise near the bandgap wavelength (~ 900 nm) to a maximum response of ~ 0.55 mA/mW followed by a gradual decrease in response at shorter wavelengths and a sharp drop at wavelengths less than 450 nm.

C. Ion Microprobe Mass Analysis

One of the possible degradation mechanisms in GaAs solar cells is the diffusion of the front contact metallization into the junction region of the cell with subsequent cell shorting. Thus, elemental depth profiles were obtained employing an ARL ion microprobe mass analyzer (IMMA) on the front of one each of the vendors' cells both on and between the grid lines. By obtaining IMMA depth profiles before and after temperature cycling, one can determine whether metal diffusion is occurring.

IMMA sputtering was carried out on the tip of a grid line furthest from the cell bus bar to minimize the possibility of degrading the cell output. The investigated cells demonstrated both well-behaved graded metallization profiles and semiconductor interface regions.

D. Optical Micrographs

Color photographs at a magnification of 4X were taken of all 30 cells in order to compare the cell surface morphology, optical properties, and possible grid line delamination before and after thermal cycling.

III. Temperature Cycling

Temperature cycling is being performed in The Aerospace Corporation's

Aerophysics Laboratory. The cycle period is 30 minutes, and the temperature extremes are -80°C and +80°C with a sinusoidal temperature vs. time relationship. During cycling, the cells are maintained at a pressure less than $10^{-6}$ Torr. The cycler includes fail safe features which prohibit the solar cell from experiencing temperatures above +100°C and below -100°C. In the event of a loss of vacuum, the cells are returned to room temperature.

During cycling, the solar cells sit in an aluminum "picture frame" which is bolted to the temperature-controlled cooling/heating block. The picture frame has 36-1.0 inch square openings to accommodate the cells. Three 2 x 2 cm silicon solar cells are included in the thermal cycling test to provide an internal standard for comparison to the GaAs thermal stress results. The remaining three openings are filled with electrically-inactive GaAs cells with thermocouples attached with conductive epoxy to allow temperature monitoring inside the cell block. In addition, three thermocouples are epoxied to the outside of the temperature block to provide control and monitoring of the temperature and thermal gradients. A cover plate over the solar cells encloses the cells while they are in thermal contact with the cooling/heating block such that no light reaches the cells during the temperature cycling.

Table 1 describes the monitored thermal data for the initial 497 thermal cycles; this data is indicative of the thermal environment for the subsequent 4,503 cycles. T6 and T8 are thermocouples affixed to the outside of the cooling/heating block on each end and T7 is attached to the outside middle of the block. The thermocouples attached to the GaAs blanks inside the block were not employed for temperature control or monitoring since the thermocouples became disconnected from the GaAs surface during cycling, resulting in anomalous temperature readings. Prior to this, however, it was established that the temperatures measured inside the block on the GaAs blanks were representative of the temperatures measured on the outside surface of the block. The maximum low temperature (-112.4°C) was achieved at T8 when a solenoid valve temporarily stuck open, allowing liquid nitrogen to enter the cooling/heating block from both sides.

## IV. Temperature Cycling Results

### A. Cell I-V Curves

Data comparing cell performance before and after the 5,000 thermal cycles are presented in Table 2. The solar cells are listed in descending order of beginning-of-life efficiency. Two cells, #9 and #19, were damaged during IMMA analysis, resulting in a performance degradation. Thus, the averages listed at the bottom of Table 2 reflect those taken on the beginning-of-life performance and the 5,000 thermal cycle performance excluding cells #9 and #19.

The data in Table 2 indicate that the performance change of the GaAs solar cells after 5,000 thermal stress cycles is very small and within the experimental error of the measurement (± 0.20%). The small decrease in efficiency observed (16.67% to 16.60%) was largely due to a decrease in average cell fill factor from 0.781 to 0.777. The small decrease in average $V_{oc}$ was almost identical, on a percentage basis, to the small increase in average $I_{sc}$. The average efficiency of the three Si cells included for comparison in the temperature cycling test increased from 13.44% to 13.50% after 5,000 cycles, an increase which is again within the experimental error of the efficiency measurement.

B. Cell Spectral Response

Absolute spectral response curves after 5,000 thermal cycles for the six cells on which spectral response measurements were obtained before cycling showed negligible changes due to the thermal stress.

C. Ion Microprobe Mass Analysis

Ion Microprobe Mass Analysis depth profiles obtained after the 5,000 thermal cycles between and on the metal grid lines on one each of the vendors' cells showed no interface redistribution or enhanced penetration of sintered metal contacts due to the thermal stress.

D. Optical Micrographs

Optical micrographs taken after 5,000 thermal cycles showed no change in the surface morphology or optical properties of the solar cells. The grid line of one cell peeled along a short section (~ 0.7 mm) furthest from the bus bar; this may have caused the fill factor decrease for this cell from 0.814 to 0.799.

## V. Summary/Conclusions

Temperature cycling of single junction GaAs solar cells to simulate the temperature conditions of a low-earth orbit of 3-year duration has been initiated. The change in cell electrical performance after 5,000 thermal stress cycles was found to be negligible. Furthermore, there were no observed changes in the cell spectral response, metallization and interface profiles, surface morphology, and optical characteristics. These results should enhance the overall confidence in GaAs solar cells for space applications since the cells tested in this experiment represent different crystal growth and metallization schemes. The cells are currently undergoing the second set of 5,000 thermal cycles, and performance will again be evaluated after 10,000 and 15,000 thermal cycles.

## VI. References

1. The authors gratefully acknowledge the cooperation of Applied Solar Energy Corporation, Hughes Research Laboratories, and Varian Associates for supplying solar cells for this experiment. We would also like to thank Bruce Anspaugh and Bob Weiss of the Jet Propulsion Laboratory for their assistance in carrying out the cell efficiency and spectral response measurements, Martin Lundquist and Tim Wall for the design and operation of the temperature cycler, and Nick Marquez for carrying out the Ion Microprobe Mass Analysis experiments.

Table 1. Temperature Cycling Data for the Initial 497 Thermal Cycles

Minimum Temperatures (°C)

| | T6 | T7 | T8 |
|---|---|---|---|
| Average | -87.1 | -87.6 | -93.5 |
| σ | 3.6 | 1.7 | 4.5 |
| Minimum Minimum | -69.1 | -85.0 | -82.1 |
| Maximum Minimum | -96.7 | -95.0 | -112.4 |

Maximum Temperatures (°C)

| | T6 | T7 | T8 |
|---|---|---|---|
| Average | 79.7 | 85.0 | 87.2 |
| σ | 2.4 | 2.4 | 3.9 |
| Minimum Maximum | 70.7 | 70.9 | 70.2 |
| Maximum Maximum | 90.9 | 95.3 | 99.4 |

Table 2. Comparison of Solar Cell Electrical Performance Before and After 5,000 Thermal Cycles

| Cell# | $V_{oc}(0)$ volts | $V_{oc}(5,000)$ volts | $I_{sc}(0)$ mA | $I_{sc}(5,000)$ mA | ff(0) | ff(5,000) | $\eta(0)$ % | $\eta(5,000)$ % |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.015 | 1.012 | 116.8 | 116.8 | 0.814 | 0.799 | 17.82 | 17.45 |
| 2 | 1.038 | 1.035 | 118.9 | 119.6 | 0.774 | 0.772 | 17.66 | 17.74 |
| 3 | 1.031 | 1.029 | 119.4 | 119.8 | 0.776 | 0.775 | 17.65 | 17.64 |
| 4 | 1.001 | 0.998 | 116.5 | 116.5 | 0.818 | 0.816 | 17.64 | 17.54 |
| 5 | 1.017 | 1.016 | 112.7 | 113.2 | 0.814 | 0.800 | 17.24 | 17.00 |
| 6 | 1.034 | 1.032 | 118.9 | 119.4 | 0.750 | 0.750 | 17.04 | 17.06 |
| 7 | 1.030 | 1.028 | 117.8 | 118.0 | 0.759 | 0.758 | 17.03 | 17.00 |
| 8 | 1.005 | 1.009 | 114.1 | 114.1 | 0.800 | 0.788 | 16.96 | 16.77 |
| 9* | 1.018 | 0.996 | 119.8 | 89.1 | 0.750 | 0.710 | 16.90 | 15.83 |
| 10 | 1.018 | 1.016 | 113.7 | 113.3 | 0.788 | 0.789 | 16.86 | 16.78 |
| 11 | 0.993 | 0.991 | 114.3 | 115.6 | 0.804 | 0.798 | 16.86 | 16.90 |
| 12 | 0.976 | 0.974 | 117.1 | 116.7 | 0.793 | 0.794 | 16.74 | 16.67 |
| 13 | 1.013 | 1.011 | 111.3 | 112.0 | 0.803 | 0.798 | 16.73 | 16.69 |
| 14 | 0.974 | 0.969 | 117.1 | 117.7 | 0.787 | 0.783 | 16.58 | 16.50 |
| 15 | 1.033 | 1.031 | 117.1 | 117.9 | 0.740 | 0.736 | 16.55 | 16.53 |

| Cell # | $V_{oc}(0)$ volts | $V_{oc}(5,000)$ volts | $I_{sc}(0)$ mA | $I_{sc}(5,000)$ mA | ff(0) | ff(5,000) | $\eta(0)$ % | $\eta(5,000)$ % |
|---|---|---|---|---|---|---|---|---|
| 16 | 0.952 | 0.950 | 117.4 | 117.7 | 0.800 | 0.794 | 16.52 | 16.41 |
| 17 | 1.018 | 1.015 | 118.0 | 118.6 | 0.743 | 0.738 | 16.50 | 16.40 |
| 18 | 1.021 | 1.018 | 112.0 | 112.4 | 0.778 | 0.772 | 16.44 | 16.33 |
| 19* | 0.950 | 0.961 | 115.2 | 115.3 | 0.808 | 0.676 | 16.34 | 13.84 |
| 20 | 1.024 | 1.021 | 119.1 | 119.8 | 0.725 | 0.719 | 16.33 | 16.25 |
| 21 | 0.987 | 0.984 | 111.6 | 111.7 | 0.802 | 0.798 | 16.32 | 16.20 |
| 22 | 0.968 | 0.966 | 115.0 | 115.7 | 0.793 | 0.792 | 16.31 | 16.37 |
| 23 | 1.005 | 1.003 | 110.6 | 110.8 | 0.793 | 0.781 | 16.29 | 16.03 |
| 24 | 1.006 | 1.004 | 115.6 | 115.3 | 0.752 | 0.757 | 16.16 | 16.19 |
| 25 | 1.009 | 1.006 | 113.0 | 113.5 | 0.766 | 0.761 | 16.14 | 16.05 |
| 26 | 0.982 | 0.979 | 114.5 | 115.0 | 0.777 | 0.776 | 16.14 | 16.14 |
| 27 | 1.006 | 1.004 | 111.2 | 111.1 | 0.780 | 0.776 | 16.11 | 16.00 |
| 28 | 1.000 | 0.998 | 109.1 | 109.3 | 0.798 | 0.792 | 16.08 | 15.97 |
| 29 | 0.989 | 0.986 | 113.7 | 113.6 | 0.773 | 0.778 | 16.07 | 16.09 |
| 30 | 1.012 | 1.009 | 111.4 | 111.2 | 0.766 | 0.772 | 15.95 | 15.99 |
| Averages | 1.006V | 1.003V | 114.9mA | 115.2mA | 0.781 | 0.777 | 16.67% $\sigma$= 0.54% | 16.60% $\sigma$= 0.53% |

* Cells damaged during IMMA analysis. Data on these cells not included in averages.