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ABSTRACT

The flight performance of NASA-LeRC's indium phosphide homojunction solar cell module on the LIPS III satellite is presented. A module of four n^+p cells was fabricated and has been on-orbit on the LIPS III spacecraft since 1987. The experimental objective is the measurement of InP cell performance in the natural radiation environment of the 1100 kilometer altitude, 60° inclination, circular orbit. Flight data from the first year is near expected values, with no degradation in short-circuit current. Included in the paper is the temperature dependence of current-voltage parameters and the laboratory radiation tolerance studies necessary for normalization and analysis of the data. Details of the cell structure and flight module design are also discussed.

Keywords: Indium Phosphide, Solar Cells, Flight Experiment, LIPS III Spacecraft

1. INTRODUCTION

Upon recognizing its potential for space power generation, the Lewis Research Center embarked, in 1984, on a program to develop indium phosphide solar cells. The program has the goal of maximizing end-of-life power through the optimization of conversion efficiency and radiation tolerance. Cells of both the n^+p and p^+n configurations have been developed with an efficiency of 18.8% Air Mass Zero (AM0) achieved. An extensive laboratory investigation of radiation tolerance has also been undertaken, with radiation tolerance superior to both silicon and gallium arsenide clearly demonstrated (Refs. 1, 2). However, limited opportunities for space flight had prevented actual testing of InP in a natural radiation environment. The decision by the Naval Research Laboratory to launch the third Living Plume Shield (LIPS III) satellite provided the first opportunity to obtain flight data on InP solar cells. This paper will present the on-orbit performance of n^+p InP homojunction solar cells on the LIPS III flight experiment, and compare it with expected results based on laboratory testing. Details of solar cell and module design and fabrication will be discussed as well.

2. EXPERIMENT DESIGN

The flight module developed for the LIPS III satellite contains four n^+p homojunction indium phosphide solar cells along with a temperature sensor. The module is pictured in Figure 1. The cells were made at Rensselaer Polytechnic Institute by the open tube diffusion of sulfur into single crystal p-InP substrates (Ref. 3). The substrates used were Czochralski grown, <100> oriented wafers doped with zinc to a concentration of 5×10^{16} cm^{-3}. The source of sulfur for emitter formation was a vacuum evaporated thin film of Ga_2S_3 which in turn was encapsulated with silicon dioxide. Open tube diffusion in a nitrogen atmosphere at 670 °C for 25 minutes created the junction. Au and Au-5%Zn were used for front and rear ohmic contacts respectively with a single layer antireflection coating of silicon monoxide. A total cell area of 0.313 cm^2 was defined by mesa etching, with front contact obscuration of 15%. Details of the cell structure are seen in Figure 2.

Fifteen cells, with AM0 efficiencies ranging from 11.4 to 14.3 percent were obtained for fabrication into two modules of four cells each, a prime flight module and one reserve module. The two highest efficiency cells of the lot were retained to serve as secondary standards. The total area, AM0 (25 °C) current-voltage parameters of the four cells used in the prime flight module are listed in Table 1. The I-V curves, taken before incorporation into the module, were measured using a zenon arc lamp solar simulator in our laboratory.

The flight modules, prime and reserve, were fabricated by Spectrolab, Inc. of Sylmar, California, USA under contract to the Lewis Research Center. The module substrate is a 1.6 mm thick aluminum sheet (alloy 6061-T6), 5 cm square. Electrical insulation from the substrate and consequently the spacecraft was provided by a 75 micrometer thick sheet of mica ply bonded to the aluminum substrate with DC93-500 silicone adhesive. After rear contact was made by soldering a silver-plated Kovar interconnect to each cell, the cells were bonded to the substrate with CV2568 adhesive. Gold-plated Kovar termination tabs were bonded to the insulated substrate adjacent to each cell, two per cell for front and rear contact. The rear contact circuit was completed by soldering the silver-plated Kovar interconnects to this termination tab. The front contact circuit was completed by ultrasonically ball bonding 25 micrometer diameter gold wire to the cell busbar and the adjacent termination pad. For redundancy, six wires were used for each cell. Because cell area was delineated by mesa etching, it was necessary to insulate the wires from the p-InP substrate. This was accomplished with 25 micrometer Kapton sheet bonded with DC93-500 to the InP substrate adjacent to the mesa.

A 300 micrometer fused silica coverglass was bonded with DC93-500 adhesive to each cell. The coverglass adhesive also served to encapsulate the gold front contact wires and provide some added degree of mechanical strength. Two additional gold-plated Kovar termination strips were bonded to the substrate to serve as common negative current and voltage bus strips. Negative leads were then routed from each cell to the bus strips and soldered. Redundant leads from the bus strips were provided for the module pigtail. Redundant positive leads for the module pigtail were connected directly to the termination tabs for each cell, providing a four-wire, independent connection for each cell. Kapton insulated, multi-stranded wire was used for all connections.

Module temperature measurement capability was provided using a ceramic-based, platinum resistance thermal detector (RTD). The RTD was bonded with DC93-500 adhesive to the rear of a fifth InP cell. A U-shaped piece of mica ply was tailored to fit around the RTD and the gap filled with DC93-500 to provide a flat surface for mounting on the substrate. The RTD/cell assembly was then bonded to the center of the module between the four active cells (Figure 1). Kapton insulated wire was then spliced to the RTD leads and added to the module pigtail. Module fabrication was completed with the covering of all exposed areas of the substrate with a 125 micrometer thick, silver-coated, Teflon second surface mirror.

The current-voltage characteristics of the four cells on the completed prime flight module were again measured in our solar simulator immediately prior to delivery to the Naval Research Laboratory for integration on the spacecraft. This data (Table 2) provided a reference for analysis of flight data as well as measure of cell degradation due to module assembly processes and cell glassing. It should be noted that there is no correlation between Tables 1 and 2 with regards to the ordering of the cells.

3. FLIGHT PERFORMANCE

The Living Plume Shield III satellite was launched in the Spring of 1987 into a nearly circular orbit of 1100 kilometers altitude with an inclination of 60°. To date, data from the first thirteen months of flight has been received, corresponding to approximately 5200 revolutions of the earth. Each of the four cells in the experiment are providing meaningful data. (Details of the satellite's design, the data acquisition system and the experiments onboard have been published in References 4 and 5.)

The current-voltage characteristics of cell number 4 for three orbits throughout the first year is shown in Figure 3. Also plotted is the pre-flight data measured in our solar simulator prior to delivery to the Naval Research Laboratory. This curve is designated Day 0. Since module temperature ranged from between 1 and 34 °C, this data has been normalized to a standard temperature of 25 °C. Since the module design was new, knowledge of the temperature dependence of open tube diffused InP cells was necessary for normalization. As part of the Lewis Research Center's InP cell development program the temperature dependence of maximum power, open-circuit voltage, short-circuit current and fill factor had been previously determined for this type of cells (Ref. 6, 7). The values used in normalizing the flight data to a standard of 25 °C is summarized in Table 3. All data has also been normalized with respect to solar intensity.

Short-circuit current as a function of time on-orbit is plotted in Figure 4 for cell numbers 2 and 4. Again, all data has been normalized with respect to temperature and solar intensity. The data shown for these cells is representative of all four cells on the module. The variation in I_{sc} is ±2% with the average value remaining constant.

4. DISCUSSION

The currents at voltages below the maximum power point (Figure 3) are uniformly low with respect to the pre-flight solar simulator data, a decrease of about 4%. This may likely be due to dust contamination problems which occurred on the launch pad (Ref. 4). Significant variation in the data at the "knee" or maximum power point occurs for all cells. Whether this variation is inherent to the cells or is caused by the LIPS data system has not been determined as yet and will require the acquisition of flight data from subsequent orbits. Regrettably, the open-circuit voltage is never reached in any of the data, and analysis has been unable to reliably determine it.

In much of the data received from the first year on-orbit, an anomalous drop in current has been observed for all cells. This decrease, at most 10% in magnitude occurs between 0.3 and 0.7 volts. In all cases, the current returned to expected values as the voltage returned to the maximum power point. The decrease also occurred in the pre-flight data taken through the LIPS data acquisition system. The effect has occasionally disappeared during the first year, including the two most recent months. This anomalous behavior seems to be a condition of the those experiments with small short-circuit currents, with no explanation of the effect apparent at this time.

The principal objective of the experiment is to measure the degree of performance degradation of InP homojunction cells in the natural radiation environment of the LIPS III spacecraft. A secondary motivation is the comparison of actual flight data with laboratory radiation tolerance studies. This is of importance because damage equivalences do not exist for InP because of its recency as a space cell material and the as yet lack of standardization of cell type and configuration. Extensive radiation tolerance studies of InP n^+p open tube diffused cells have been conducted as a consequence of early research which showed indium phosphide superior to both silicon and gallium arsenide in a laboratory radiation environment (Ref. 8). Open tube diffused n^+p cells identical to the flight cells were irradiated with 1 MeV electrons to a fluence of 3×10^{15} e^-/cm^2 (Ref. 7). The dependency of efficiency, open-circuit voltage and short-circuit current on electron fluence is shown in Figures 5, 6 and 7.

Silicon equivalent fluences were used for flight data analysis in lieu of InP equivalences; 6.49×10^{11}/yr equivalent 1 MeV e^-/cm^2 for electrons and 2.28×10^{13}/yr equivalent 1 MeV e^-/cm^2 for protons (Ref. 9). From Figure 7 and the silicon equivalent fluences, little decrease in short-circuit current is expected during the first year. This is confirmed by Figure 4, the plot of short-circuit current as a function of days on-orbit.

A second effect of possible influence on the radiation performance of InP solar cells is the discovery that light illumination of InP cells during electron irradiation significantly reduces degradation (Ref. 10). Although data received thus far is insufficient to determine if this effect is active, it may take on increased significance as time on-orbit increases.

5. CONCLUSION

Four n^+p indium phosphide homojunction solar cells are currently on-orbit on the LIPS III spacecraft and returning meaningful data. Analysis of flight data from the first year reveals that all cells continue to operate at expected performance levels. Short-circuit current has not decreased, in agreement with laboratory radiation tolerance studies of similar open tube diffused junction cells and the known radiation flux of the orbit. Additional flight data is necessary to confirm the superior radiation tolerance of indium phosphide in the space radiation environment.

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TABLE 1 - AMO, 25 °C I-V PARAMETERS of InP CELLS PRIOR TO FABRICATION OF MODULE

Cell number	Voc, V	Isc, mA	FF, percent	EFF, percent
KK-125E	0.810	7.77	80.9	11.87
-126C	.811	7.78	81.2	11.94
-127A	.813	7.85	81.7	12.15
-128C	.813	7.95	81.5	12.27
Average	0.812	7.84	81.3	12.06

TABLE 2 - AMO, 25 °C I-V PARAMETERS OF FLIGHT MODULE IN SOLAR SIMULATOR

Cell number	V_{oc}, V	I_{sc}, mA	FF, percent	EFF, percent
1	0.800	7.86	78.2	11.45
2	.802	7.47	78.3	10.91
3	.805	7.63	80.2	11.47
4	.800	7.83	78.4	11.44
Average	0.802	7.70	78.8	11.32

TABLE 3 - TEMPERATURE DEPENDENCY TERMS - n^+p InP

Maximum power, mW/cm^2-K	-4.82×10^{-2}
Open-circuit voltage, mV/K	-2.37
Short-circuit current, mA/cm^2-K	+2.23x10-2
Fill factor, percent/K	-5.66x10-2

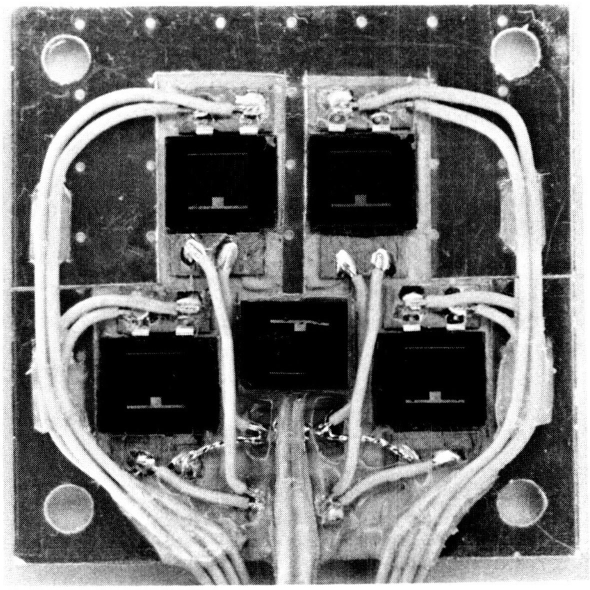

Figure 1. InP Homojunction cell flight module

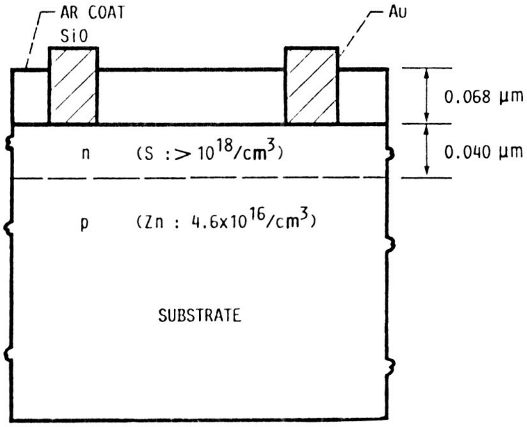

Figure 2. N^+P InP cell structure

CELL NUMBER 4

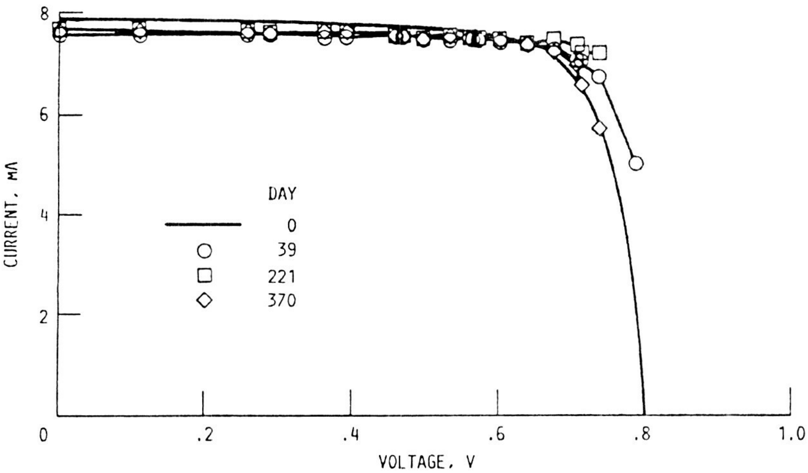

Figure 3. Flight I-V curves of cell number 4 (Day 0 is pre-flight simulator data)

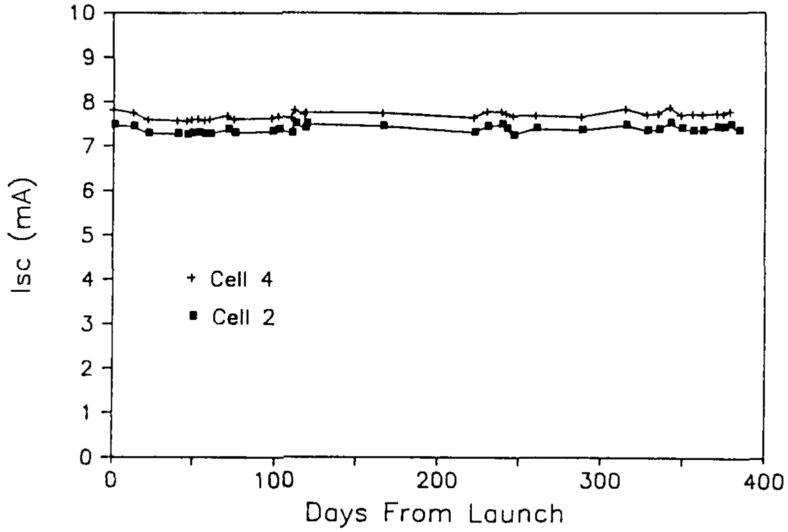

Figure 4. I_{sc} vs. days from launch

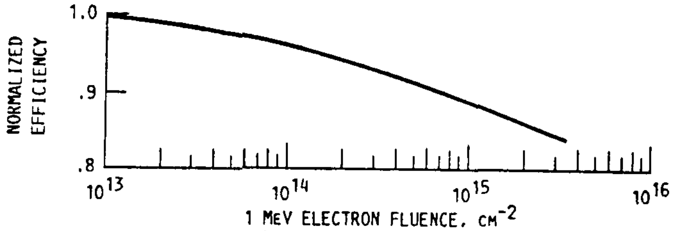

Figure 5. Normalized efficiency vs. 1 MeV electron fluence

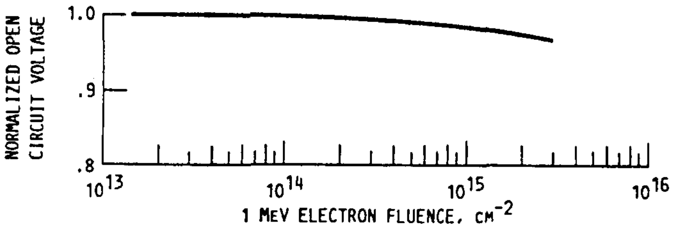

Figure 6. Normalized open-circuit voltage vs. 1 MeV electron fluence

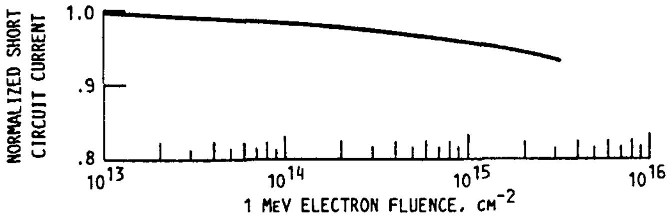

Figure 7. Normalized short-circuit current vs. 1 MeV electron fluence

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16. Abstract

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