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SUMMARY

Performance data for NASA Lewis Research Center indium phosphide n^+p homojunction solar cell module on the LIPS III Flight Experiment is presented. The objective of the experiment is to measure the performance of the InP cells in the natural radiation environment of the 1100 km altitude, 60+° inclination orbit. Analysis of flight data indicates that the performance of the four cells throughout the first year is near expected values. No degradation in short-circuit current was seen, as was expected from radiation tolerance studies of similar cells. Details of the cell structure and flight module design are discussed. The results of the temperature dependency and radiation tolerance studies necessary for normalization and analysis of the data are included.

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INTRODUCTION

Indium phosphide (InP) solar cells are excellent candidates for space power generation because their potential for high efficiency is coupled with an inherent radiation resistance and low temperature annealability. A development program, underway since 1984, has the goal of maximizing the end-of-life efficiency of InP space solar cells 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 percent Air Mass Zero (AMO) achieved. An extensive investigation of radiation tolerance and temperature effects has also been initiated and continues as part of this ongoing development program. However, limited opportunities for space flight and its recency as a space photovoltaic material had prevented actual space flight testing of InP solar cells. The decision of the Naval Research Laboratory to build and launch the third Living Plume Shield (LIPS III) satellite provided the first opportunity to obtain invaluable flight data on InP solar cells. In this paper we report on the module design and early on-orbit performance of InP n^+p homojunction solar cells on the LIPS III spacecraft.

InP MODULE DESIGN

InP Solar Cell Characterization

The indium phosphide solar cells used in this experiment were made at Rensselaer Polytechnic Institute by the open tube diffusion of sulfur into p-type InP substrates (ref. 1). The substrates were LEC grown, <100> oriented wafers doped with zinc to a concentration of 5×10^{16} cm^{-3}. After vacuum evaporation of a Ga_2S_3 film, which in turn was encapsulated with silicon dioxide, the emitter was formed by open tube diffusion in a nitrogen ambient at 670 °C for 25 min. Cell fabrication was completed with deposition of Au and Au-5% Zn for emitter and base ohmic contacts and a single layer antireflection coating of SiO. A total cell area of 0.313 cm^2 was defined by mesa etching, with front contact obscuration of 15 percent. Details of the cell structure are seen in figure 1.

Fifteen cells, with AMO efficiencies ranging from 11.36 to 14.31 percent, were received. The two highest efficiency cells were reserved for use as standards; the remainder were used for fabrication of two flight modules of four cells each, a prime flight module and one back-up module. Table I lists the total area, AMO (25 °C) performance as received from RPI of the four cells selected for the prime flight module.

The operating temperature of a solar cell for a given orbit is, to a large extent, a function of array design. Since no previous flight experience exists for InP and the module design was new, it is necessary to know the temperature dependence of open tube diffused InP cells to enable normalization of flight data. The temperature dependence of maximum power, open-circuit voltage, short-circuit current and fill factor for these cells was previously determined as part of the Lewis Research Center's InP cell development program (refs. 2 and 3). Table II summarizes the values used in normalizing the flight data to a standard temperature of 25 °C.

The prime objective of the InP flight experiment is to measure the degree of performance degradation in the natural radiation environment of the LIPS spacecraft orbit. As a consequence of early research which showed indium phosphide superior to both gallium arsenide and silicon in a laboratory radiation environment, extensive radiation tolerance studies of open tube diffused n^+p InP solar cells have been performed (ref. 3). The cells were irradiated with 1 MeV electrons in a Van de Graaf generator to a maximum fluence of $3x10^{15}$ e^-/cm^2. The dependency of short-circuit current, open-circuit voltage and efficiency on electron fluence is shown in figures 2, 3 and 4. No damage equivalents exist for InP solar cells due to the immaturity of InP as a space cell material and the as yet lack of standardization of cell type and configuration. For this reason, Si equivalent fluences were used for analysis purposes; $6.49x10^{11}$/yr equivalent 1 MeV e^-/cm^2 for electrons and $2.28x10^{13}$/yr equivalent 1 MeV e^-/cm^2 for protons (ref. 4). It has been demonstrated that light illumination of InP cells while they are undergoing electron irradiation significantly reduces performance degradation (ref. 5). This effect will also be considered in the analysis of the InP module flight data.

Flight Module Fabrication

The InP flight module on LIPS III, shown in figure 5, was fabricated by Spectrolab, Inc. under contract to Lewis Research Center. The module substrate is a 1.6 mm thick aluminum sheet (alloy 6061-T6), 5 cm square. Electrical insulation was provided by 3 mil mica ply bonded to the Al substrate with DC93-500 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 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 one mil 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 1 mil Kapton sheet bonded with DC93-500.

Each cell was individually covered with 12 mil CMX fused silica microsheet, bonded with DC93-500. 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, 26 AWG 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 (see fig. 5). 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 5 mil, silver-coated, Teflon second surface mirror.

After fabrication was completed, the current-voltage characteristics of the flight module was measured in our X-25L solar simulator. This provided a reference for analysis of flight data as well as measure of cell degradation due to module assembly processes and cell glassing. Table III tabulates the results of this measurement. It should be noted that there is no correlation between tables I and III with regards to the ordering of cells. Based on the average value, the largest change was in fill factor, a decrease of 3.1 percent.

FLIGHT EXPERIMENT RESULTS

The LIPS III satellite is in a nearly circular orbit of 1100 km altitude with an inclination of 60+°. Details of the LIPS III satellite design, the data acquisition system and the experiments have been published by the satellite's builders at the Naval Research Laboratory (refs. 6 and 7). To date, data through the first 383 days of flight has been received, which corresponds to 5131 revolutions about the earth.

Each of the four cells on the InP module survived the launch environment and continue to provide meaningful data. Module temperature has ranged between 1 and 34 °C. The current-voltage characteristics of cell number 4 for three orbits is shown in figure 6. Also plotted is the preflight data measured in NASA Lewis' solar simulator prior to delivery of the module to the Naval Research Laboratory for satellite integration. This curve is designated

Day 0. The flight data has been normalized with respect to solar intensity and temperature (to a standard of 25 °C). The current at voltages below the maximum power point is uniformly low with respect to the preflight simulator data, a decrease of approximately 4 percent. Significant variation in the data occurs near the maximum power point. Further analysis of the flight data is necessary to determine if this variation is caused by the data acquisition system or is inherent to the cells. Unfortunately, open-circuit voltage is never reached in the flight data, the three curves shown in figure 6 being representative of data from all four cells. More extensive analysis may yield the open-circuit voltage.

An anomalous drop in current has been observed for all cells in much of the data. This decrease, at most 10 percent in magnitude, generally occurs between 0.3 and 0.7 V. In all cases, the current returned to expected values as the voltage increased to the maximum power point. The drop also occurred in preflight data taken through the LIPS data acquisition system. The effect has occasionally disappeared during the first year on-orbit, including the most recent 2 months. The drop seems to be a condition of only the small current experiments, and no explanation of the effect is apparent at this time (ref. 8).

A plot of short-circuit current as a function of time on orbit is shown in figure 7 for 2 of the 4 cells. All data has been normalized with respect to temperature and solar intensity. The variation in I_{SC} is ± 2 percent with the average value remaining constant during the first year on-orbit. This result is as expected based on laboratory radiation studies (fig. 2) and the equivalent electron and proton fluences in this orbit.

CONCLUSION

A module of four n^+p, homojunction InP solar cells has been designed and fabricated and was launched on the LIPS III Flight Experiment. Preliminary analysis of flight data from the first year reveals that short-circuit current has not decreased, in agreement with laboratory radiation tolerance studies. Anomalous drops in current at voltages between 0.3 and 0.7 V were seen in much of the data; however, the drop did not effect short-circuit current and maximum power determination. This drop also occurred in preflight data taken through the LIPS data acquisition system. More extensive analysis of the flight data continues, and only more time on-orbit will confirm the superior radiation tolerance of InP solar cells to the natural radiation environment of space.

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TABLE I. - 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 II. - 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

TABLE III. - 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

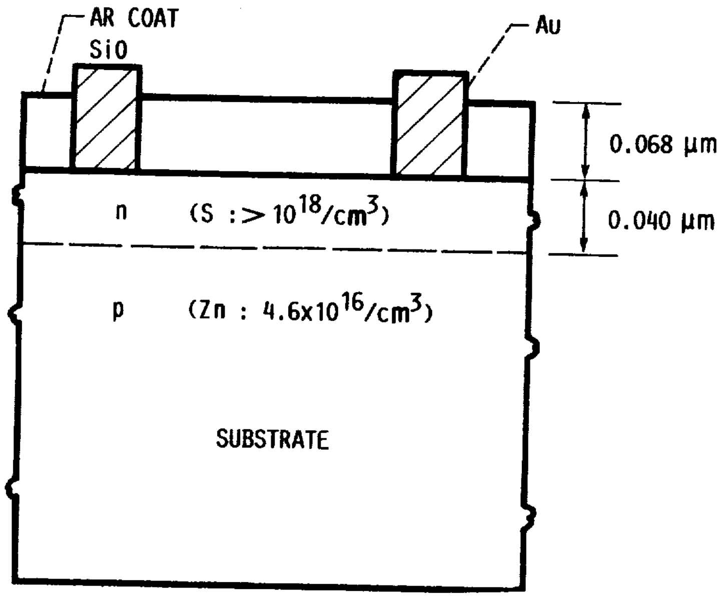

FIGURE 1. - n^+p InP CELL STRUCTURE.

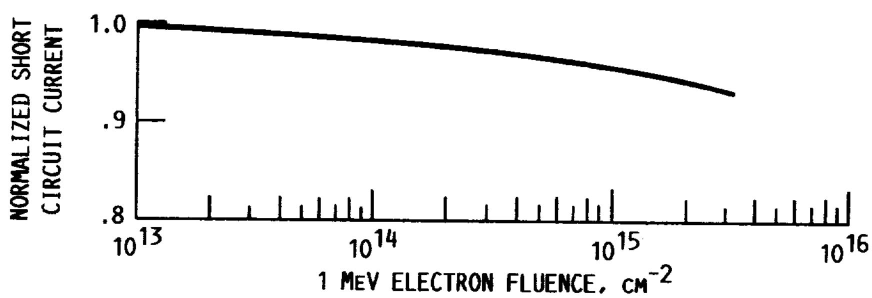

FIGURE 2. - NORMALIZED SHORT-CIRCUIT CURRENT VERSUS 1 MEV ELECTRON FLUENCE.

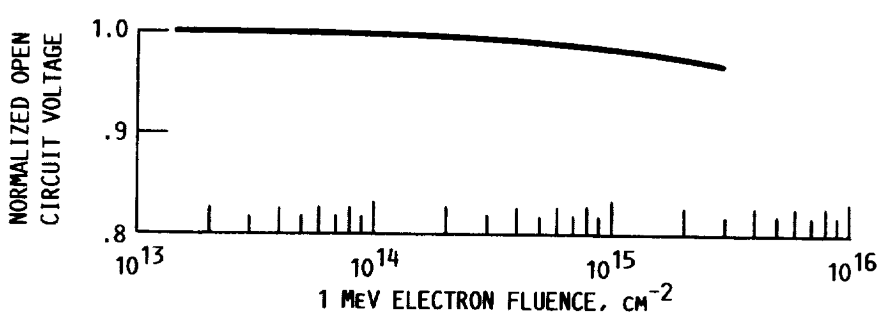

FIGURE 3. - NORMALIZED OPEN-CIRCUIT VOLTAGE VERSUS 1 MEV ELECTRON FLUENCE.

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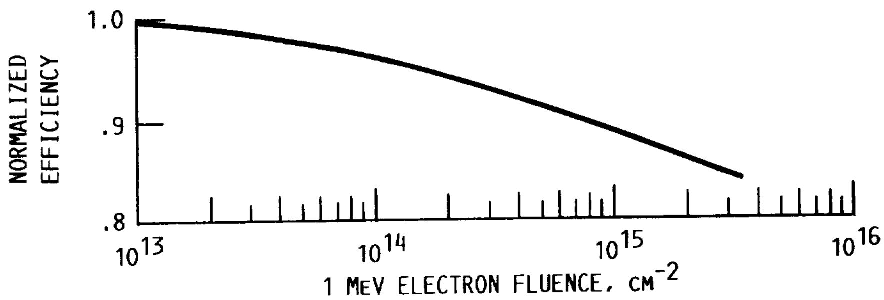

FIGURE 4. - NORMALIZED EFFICIENCY VERSUS 1 MeV ELECTRON FLUENCE.

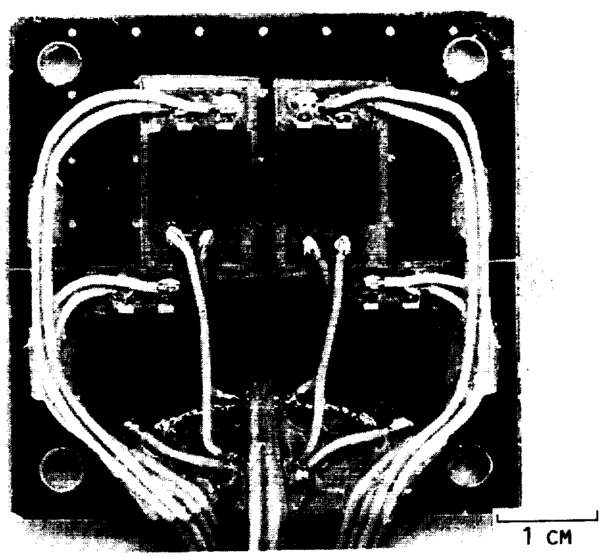

FIGURE 5. - InP FLIGHT MODULE.

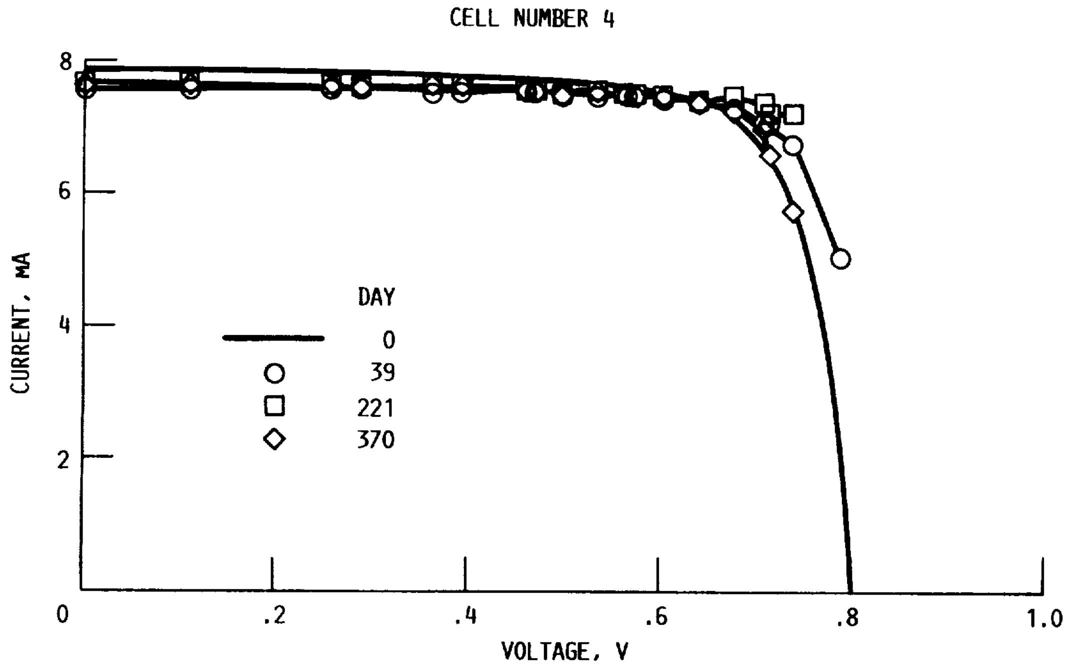

FIGURE 6. - FLIGHT I-V CURVES OF InP CELL NUMBER 4 (DAY 0 IS PRE-FLIGHT SOLAR SIMULATOR DATA).

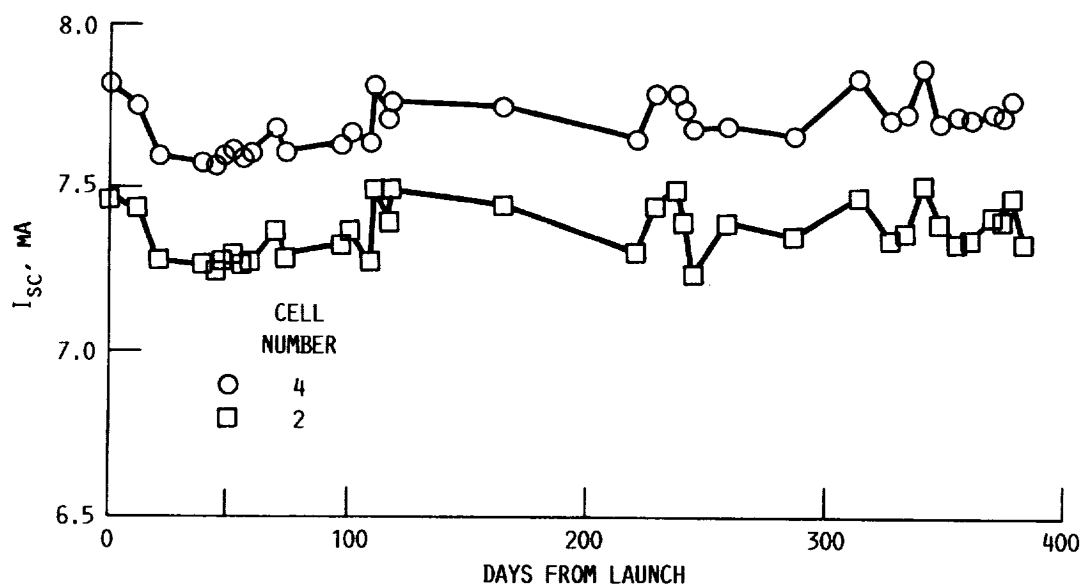

FIGURE 7. - I_{SC} VERSUS DAYS FROM LAUNCH (TEMPERATURE AND SOLAR INTENSITY CORRECTED).

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15. Supplementary Notes

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16. Abstract

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