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David J. Brinker and Irving Weinberg
Lewis Research Center
Cleveland, Ohio

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RECENT DEVELOPMENTS IN INDIUM PHOSPHIDE SPACE SOLAR CELL RESEARCH

David J. Brinker and Irving Weinberg

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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SUMMARY

Recent developments and progress in indium phosphide solar cell research for space application are reviewed. Indium phosphide homojunction cells have been fabricated in both the n^+p and p^+n configurations with total area efficiencies of 17.9 and 15.9 percent (air mass 0 and 25 °C) respectively. Organometallic chemical vapor deposition, liquid phase epitaxy, ion implantation and diffusion techniques have been employed in InP cell fabrication. A theoretical model of a radiation tolerant, high efficiency homojunction cell has been developed. A realistically attainable AMO efficiency of 20.5 percent was calculated using this model with emitter and base doping of 6×10^{17} and 5×10^{16} cm^{-3} respectively. Cells of both configurations have been irradiated with 1 MeV electrons and 37 MeV protons. For both proton and electron irradiation, the n^+p cells are more radiation resistant at higher fluences than the p^+n cells. The first flight module of four InP cells has been assembled for the Living Plume Shield III satellite.

INTRODUCTION

Indium Phosphide (InP) homojunction solar cells hold great promise for space power generation because of their inherent radiation resistance and low temperature annealability as well as their potential for high efficiency. A development program, underway since 1984, has the goal of maximizing the end of life efficiency of InP space cells through the optimization of conversion efficiency and radiation tolerance. Advancement toward this goal is being made through the investigation of a number of fabrication techniques, proton and electron irradiation testing, aircraft flight cell calibration, and the development of a flight module for the Living Plume Shield (LIPS) III satellite. In this paper we report on the recent progress in InP cell development, emphasizing work in the this country and including results from abroad.

STATE-OF-THE-ART IN CELL PERFORMANCE

Significant progress has been made toward improving the conversion efficiency of InP space solar cells in both the n^+p and p^+n configurations. Previously reported results (ref. 1) of InP AMO efficiencies were restricted to the n^+p type. Furthermore, junction formation was limited to the diffusion of sulfur or selenium by either the open tube (ref. 2) or sealed ampoule (ref. 3) method. In the past year, however, high efficiencies have been measured in both configurations and cells have been fabricated by liquid phase epitaxy (LPE) and organometallic chemical vapor deposition (OMCVD) of the active layers as well as the diffusion technique.

The higher minority carrier diffusion length of electrons in p-InP (in comparison to the hole diffusion length in n-InP) makes the p-type material the logical choice for the base of the solar cell. At the same time, the higher electron mobility in n-InP can allow a shallower n-type emitter for a given doping level than a p-type emitter. For these reasons, the n^+p structure appears to be the configuration of choice and, consequently, most investigators have concentrated their efforts in this direction. Table I summarizes the results of AMO measurements of n^+p InP cells made by OMCVD, ion implantation and open tube diffusion. The highest AMO total area efficiency achieved to date is 17.9 percent in an n^+pp^+ cell made by the OMCVD junction formation technique (ref. 4). The cell was formed by the growth of three epilayers on a Zn-doped InP substrate (fig. 1). The p^+ layer (5×10^{18} Zn/cm^3) is 0.5 μm thick and serves as a buffer. The active base region is 3 μm thick and Zn-doped to 2×10^{16} cm^{-3}. The emitter layer as grown is about 0.1 μm thick and is doped with Si to a level of about 10^{18} cm^{-3}. Formation of the cell entirely in epitaxially grown material may eliminate performance degradation due to residual defects in the substrate caused by the slicing and polishing processes, as evidenced in ion implanted cells. The OMCVD cells had a reduced space charge region (SCR) recombination current, which leads to an increased fill factor. The OMCVD technique also allows precise control of emitter thickness and the possibility of further enhancement of performance through the use of graded dopant profiles.

Ion implanted junction cells were fabricated by the implantation of $^{28}Si^+$ into an InP substrate Zn-doped to 2×10^{16} cm^{-3}. Emitter thickness was 0.2 μm. The best results were obtained using capless annealing in flowing PH_3. The lower fill factor is due to increased SCR recombination and series resistance. The increased series resistance results from difficulties in contacting the moderately doped substrates used.

Open tube diffusion of sulfur was also used to fabricate n^+p cells. The cell structure is shown in figure 2 and cell performance is summarized in table I. The source of sulfur was a vacuum evaporated film of Ga_2S_3 which was encapsulated with SiO_2 to prevent degradation of the InP surface (ref. 5). After deposition of the SiO_2 layer in a CVD reactor by the pyrolysis of silane and oxygen, diffusion of the sulfur was carried out at 670 °C in flowing nitrogen for 25 min. This technique resulted in junction depths of approximately 0.06 μm with a carrier concentration of 6×10^{18} cm^{-3}. This technique holds promise as a low cost fabrication method and was used in the fabrication of the InP cells used in the radiation studies and on the LIPS III flight experiment.

P^+NN^+ InP solar cells have been fabricated using both OMCVD and LPE (ref. 6). A novel feature of these cells (fig. 3) is the incorporation of a heavily doped p-$In_{0.53}Ga_{0.47}As$ contacting layer on the front surface of the cells. The layer is perfectly lattice matched to InP and has allowed for fabrication of contacts an order of magnitude lower in specific contact resistance than those obtained by directly contacting the InP p-layer. This layer also eliminates the possibility of contact metal spikes shorting the extremely thin emitter. For the LPE cells, the three epitaxial layers were grown successively in a conventional horizontal growth system. The OMCVD cells were grown in horizontal atmospheric system using a fast switching run-vent manifold. Performance results are listed in table I.

Table II summarizes the results of both homojunction InP cells and ITO/p-InP cells measured under terrestrial conditions. The n^+pp^+, p^+n (ref. 7) and

p^+n (ref. 8) cells were made using OMCVD, with the performance measured using active areas. The ITO/p-InP cell was made by the vacuum deposition of indium tin oxide (ITO) (ref. 9). Evidence suggests that the cell is indeed a true n-p homojunction, with the indiffusion of tin from the ITO forming the n-type emitter. Its performance was measured using the total area.

InP solar cells on silicon substrates hold the promise for high efficiency and radiation hardness coupled with low cost and light weight. Single crystal InP thin films have been successfully grown on Si using the OMCVD technique (refs. 10 and 11). The major obstacles encountered in this approach are the high density of dislocations in the InP layer due to the large lattice mismatch and the development of cracks due to the difference in coefficients of thermal expansion. The first reported results of solar cells efficiencies in InP on Si are about 3 percent (AM1.5)(ref. 11). Reduction of the InP film defect density is necessary before efficiencies approaching those achieved in conventional cells are achieved.

THEORETICAL STUDIES

To ensure continued advances in cell performance in terms of both efficiency and radiation hardness and a better understanding of the mechanisms leading to InP radiation tolerance, a one-dimensional model of the InP shallow homojunction was developed (ref. 12). The goal of the study was to determine the maximum realistically attainable AM0 efficiency and the design parameters which would yield this performance. The model is a low-injection, closed-form solution model which includes such considerations as: position- and wavelength-dependent optical generation in the emitter, base, space-charge and substrate regions; metal contact area and front SRV; series resistance dependence on grid geometry; and doping dependent mobilities and diffusivities. The effect of 1 MeV electron irradiation was factored into the model by decreasing the indirect lifetimes in the emitter and base and the minority mobility in the base. End-of-life was chosen arbitrarily to be an electron irradiation fluence of 1.0×10^{15} cm^{-2}.

The design parameters for a near-optimum n^+pp^+ InP homojunction cell are shown in table III. The key features of the design are the very shallow emitter, doped to mid 10^{17} cm^{-3} range, the presence of a heavily doped back surface field/buffer layer and a front surface recombination velocity of less than 1×10^5 cm/s. The total area, AM0, 25 °C performance of this design is shown in table IV. The maximum achievable efficiency is about 20.5 percent with roughly 10 percent degradation after a fluence of 1×10^{15} 1 MeV e^-/cm^2. This performance level is based on the optical and electronic materials parameters available in a low defect density, epitaxially grown InP cell utilizing a buffer layer grown on a good quality substrate. The results of this model are in fair agreement with predictions based on Loferski's calculations of efficiency as a function of bandgap (ref. 13). It also indicated that, although impressive results have been achieved in the past year, there is still room for realistic improvement in InP space solar cells performance.

RADIATION EFFECTS

The effect of radiation on performance for n^+p and p^+n InP solar cells was determined (ref. 14). The n^+p cells were made by the open tube diffusion method described earlier, while the p^+n cells were fabricated using OMCVD. Preirradiation performance data is given in table V. The cells were irradiated with 1 MeV electrons in the Naval Research Laboratories Van de Graaf generator. Solar cell measurements were carried out at NASA Lewis Research Center, using an AMO xenon arc simulator. Performance data is based on total area, including that covered by the front contacts. The n^+p cells exhibit greater radiation resistance, as seen in the normalized efficiency plot (fig. 4). The behavior of the remaining parameters at constant high fluence is summarized in table VI.

The change in fill factor, after irradiation, is relatively small and approximately the same for both configurations. Hence relative small changes in shunt and series resistances are not significant factors in comparing the two configurations. Similarly, the percentage change in V_{OC} is approximately the same for both cell types. However, the percentage loss in I_{SC} is slightly, but definitely, larger for the p^+n cell. For further investigation of the loss in I_{SC} we examined the normalized spectral response shown in figures 5 and 6. In the figures, $(I_{SC}(\lambda))_\phi$ is short circuit current at wavelength λ and 1 MeV electron fluence ϕ, while $(I_{SC}(\lambda))_0$ is short circuit current in the unirradiated cell at the same wavelength. The position of the p-n junction is computed from the optical path length $1/\alpha(\lambda)$ where $\alpha(\lambda)$ is the absorption coefficient at wavelength λ (ref. 15). From the figures is it seen that most of the current loss occurs in the emitter of the p^+n cell and in the base of the n^+p cell. From previous results, it has been demonstrated that for n^+p InP cells, radiation resistance increases as p-dopant concentration increases (ref. 16). Since the zinc p-dopant concentration in the p^+n cell is at least an order of magnitude greater than that present in the n^+p cell and since most of the damage occurs in the p-regions of both cells, one would a priori expect comparatively less radiation resistance in the n^+p cell. Since this is not the case for the present cells, the current results are considered to be anomalous. In any event, it is concluded that the relatively decreased radiation resistance of the p^+n cell is due to comparatively greater losses in the heavily doped emitter region.

InP cells were also irradiated using 37 MeV protons to a total fluence of 2.6×10^{12} cm^2. The n^+p cells were, as in the electron study, made by the open tube diffusion technique. The p^+n cells were fabricated using OMCVD. At the same time high efficiency GaAs cells of both configurations were irradiated. The results are shown in figure 7. As in the electron case, the n^+p configuration is more radiation tolerant than the p^+n cells. As is also seen in electron radiation studies, InP is more radiation tolerant than GaAs.

LIPS III FLIGHT EXPERIMENT

The decision of the Naval Research Laboratory to fly the third Living Plume Shield (LIPS III) satellite in 1987 has provided the first opportunity to obtain flight data, including radiation exposure, of InP solar cells. We have assembled a module of four n^+p InP homojunction cells on a 5 cm^2 aluminum substrate. The InP solar cells were made by the open tube diffusion technique described earlier. Fifteen cells were obtained for the flight experiment with the best efficiency of the lot the 14.3 percent described in table I.

A silver plated Kovar interconnect was soldered to the back of each cell. Front contact consists of six 1.0 mil gold wires ultrasonically bonded to the front contact pad and a gold-plated Kovar bus tab. The design was simple, yet rugged enough to survive all preflight testing. The cells were glassed using 12 mil CMX coverglass and the module was assembled using standard silicone space qualified adhesives and Kapton insulation. Each cell was independently wired using a four wire connection, thus allowing for redundancy in case of the failure of any single cell as well as the performance measurement of any single cell. A thin film platinum resistance temperature detector was mounted under a fifth, nonoperative cell located in the center of the module.

The AMO total area efficiencies of the four flight cells ranged from 11.9 to 12.3 percent before assembly into the module. After assembly, they decreased about one percentage point, ranging from 10.9 to 11.5 percent. This drop can be attributed to light attenuation through the coverglass and adhesive and the effect of the interconnect welding and soldering procedures.

SUMMARY OF RESULTS

Significant gains in efficiency for InP space cells has been made in both the $n^{+}p$ and $p^{+}n$ configurations with 17.9 and 15.9 percent, respectively, the best to date. Cells have been made with a variety of techniques amenable to mass production, including OMCVD, LPE and diffusion. Theoretical studies indicate that 20.5 percent is possible with realistic materials properties and cell design. The superiority of InP over GaAs when subjected to 1 MeV electron and 10 and 37 MeV proton fluences has been demonstrated by radiation testing. A flight module of four $n^{+}p$ cells has been prepared for the LIPS III experiment and will yield the first flight data for InP.

In conclusion, the development of InP solar cells for space application is continuing at a rapid pace. There appears to be no major impediment for further improvements in performance and utilization for space power generation.

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TABLE I. - AIR MASS ZERO CELL PARAMETERS OF InP HOMOJUNCTION SOLAR CELLS

Cell type	Growth technique	Efficiency,[a] percent	J_{sc}, mA/cm^2	V_{oc}, mV	FF, percent	Reference
n^+pp^+	OMCVD	17.9	33.9	868	83.7	4
n^+p	ion implant.	14.0	31.8	801	75.3	4
n^+p	diffused	14.3	30.6	814	78.8	5
p^+nn^+	OMCVD	15.9	32.8	864	76.7	6
p^+nn^+	LPE	15.0	29.3	866	81.0	6

[a]Measurements performed at NASA Lewis Research Center; total area, 137.2 mW/cm^2; 25 °C.

TABLE II. - InP CELL PARAMETERS AT OTHER THAN AIR MASS ZERO

Cell type	Air mass	Efficiency, percent	J_{sc}, mA/cm^2	V_{oc}, mV	FF, percent	Reference
n^+pp^+	1.5	[a]20.0	30.0	830	80.0	7
p^+n	↓	[a]18.1	28.2	835	78.8	8
p^+in	↓	[a]22.0	35.8	811	76.0	8
ITO/p-InP	↓	[b]16.5	27.9	790	74.8	9

[a]Active area, 100 mW/cm^2; 20 °C.
[b]Total area, 100 mW/cm^2; 25 °C.

TABLE III. - DESIGN PARAMETERS FOR n^+pp^+ InP HOMOJUNCTION SOLAR CELL

Junction area, cm^2	1.00
Grid coverage, percent	6.00
Specific contact resistance, Ω-cm	1.0×10^{-3}
Intrinsic carrier conc., cm^{-3}	1.65×10^7
Front SRV, cm/sec	1×10^5
N^+ emitter width, Å	400
N^+ emitter doping, cm^{-3}	6.0×10^{17}
P base width, μm	1.50
P base doping, cm^{-3}	5.0×10^{16}
P^+ BSF/buffer width, μm	250
P^+ BSF/buffer doping, cm^{-3}	5.0×10^{18}

TABLE IV. - THEORETICAL AMO PERFORMANCE OF $n^{+}pp^{+}$ InP HOMOJUNCTION SOLAR CELL

	BOL	EOL	EOL/BOL
J_{sc}, mA/cm^2	36.53	36.09	0.988
V_{oc}, mV	901.6	839.9	.932
FF, percent	84.79	82.34	.971
Efficiency, percent	20.34	18.18	.894

TABLE V. - InP PREIRRADIATION PERFORMANCE PARAMETERS

Cell	Efficiency, percent	V_{oc}, V	J_{sc}, mA/cm^2	FF, percent
$n^{+}p$	12.9	0.815	26.3	82.6
	12.7	.814	26	82.3
$p^{+}n$	13.9	0.843	32.4	70
	14.7	.858	33	71

TABLE VI. - NORMALIZED InP CELL PARAMETERS AT CONSTANT HIGH FLUENCE

[InP: $N^{+}p$ and $p^{+}n$. d = 1 MeV electron fluence = 3×10^{15}/cm^2.]

Cell		$\epsilon\phi/\epsilon_o$	$(I_{sc})_\phi/(I_{sc})_o$	$(V_{oc})_\phi/(V_{oc})_o$	$(FF)_\phi/(FF)_o$
InP	$p^{+}n$	0.85	0.96	0.93	0.94
	$n^{+}p$	.82	.93	.92	.95

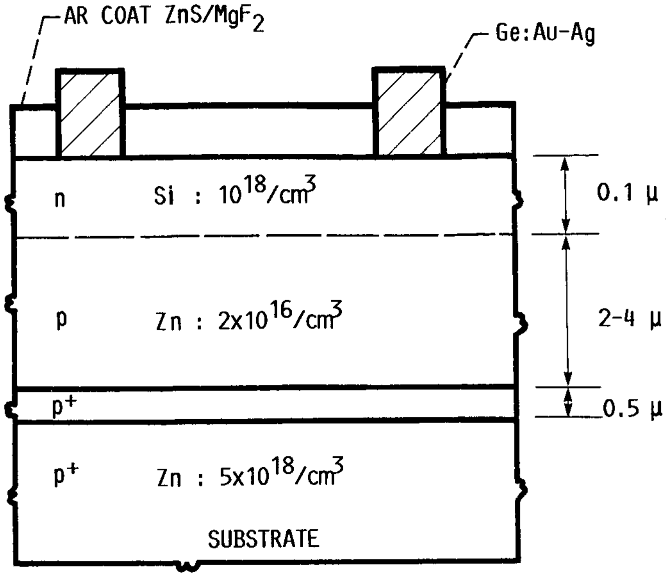

FIGURE 1. - N^+PP^+ InP CELL STRUCTURE - OMCVD.

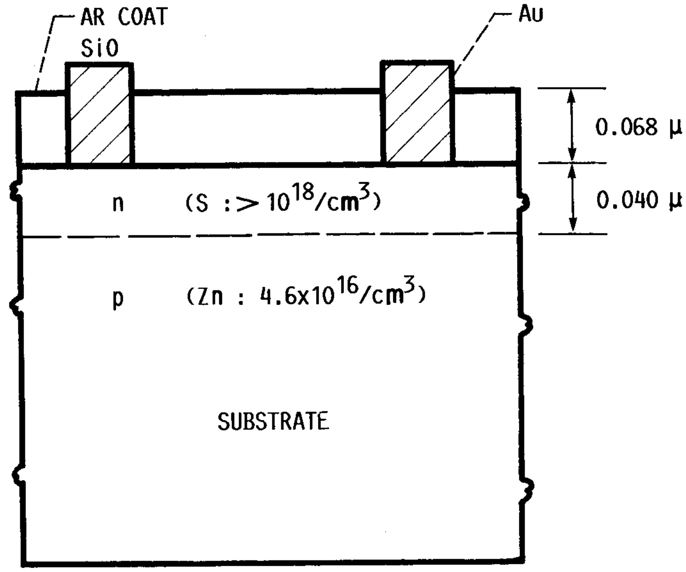

FIGURE 2. - N^+P InP CELL STRUCTURE - OPEN-TUBE DIFFUSION.

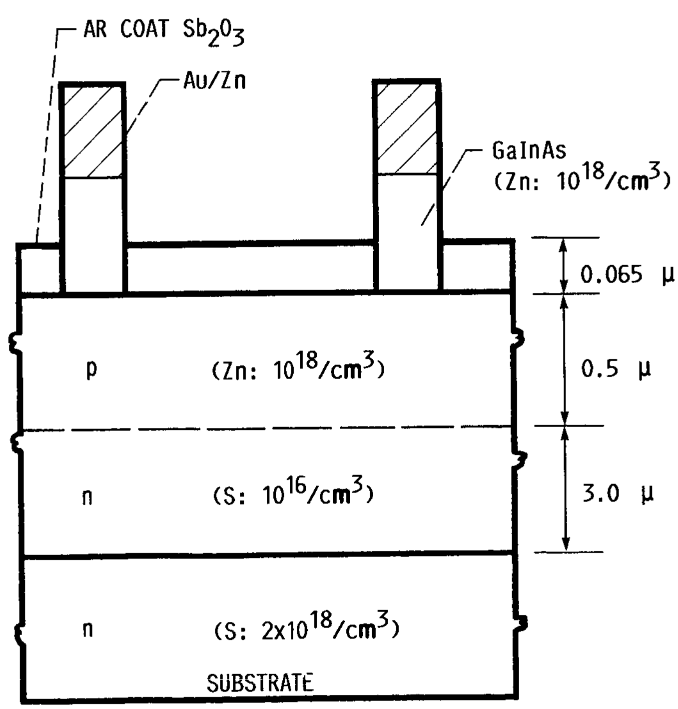

FIGURE 3. - P^+NN^+ InP CELL STRUCTURE - OMCVD AND LPE.

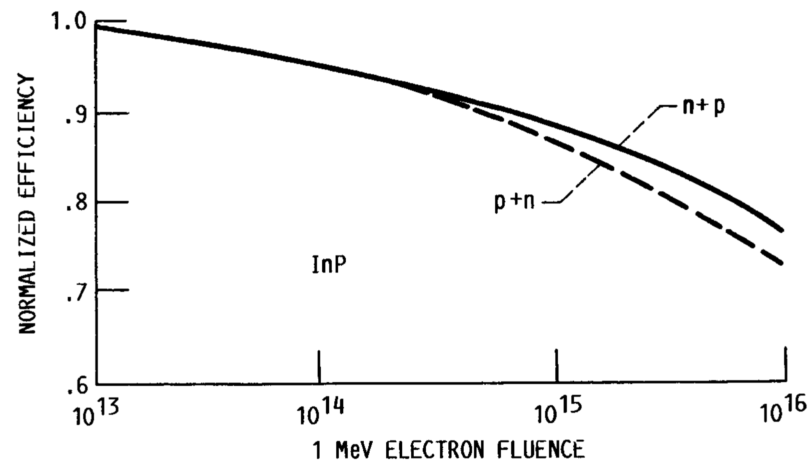

FIGURE 4. - NORMALIZED EFFICIENCY AFTER 1 MeV ELECTRON IRRADIATION.

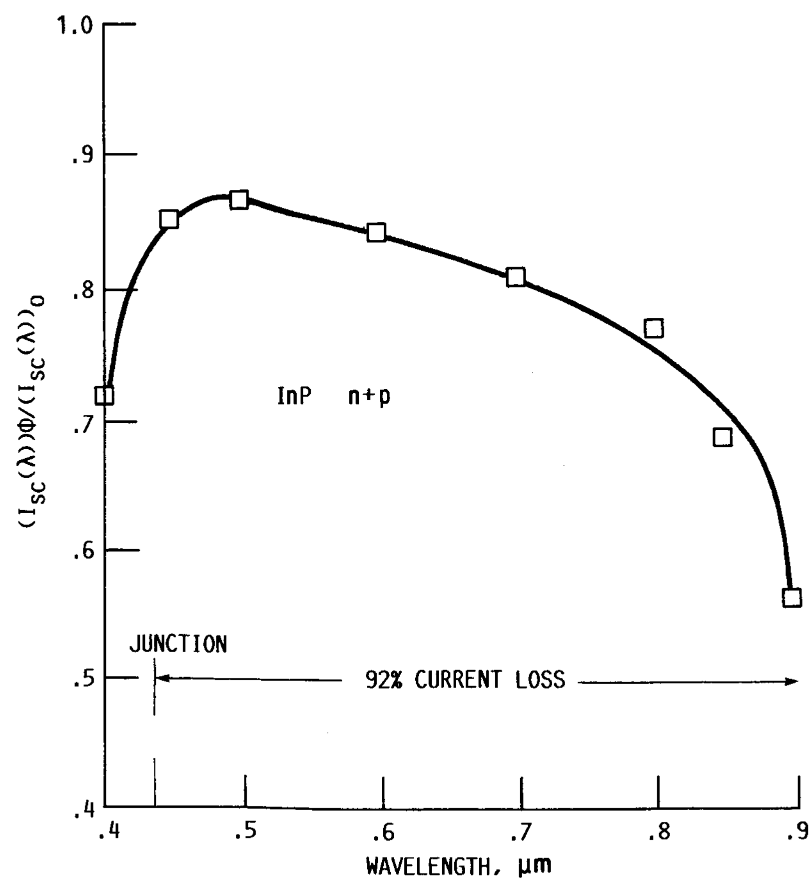

FIGURE 5.- NORMALIZED SPECTRAL RESPONSE OF n^+p InP CELL 1 MeV ELECTRON FLUENCE = 3×10^{15} cm^{-2}.

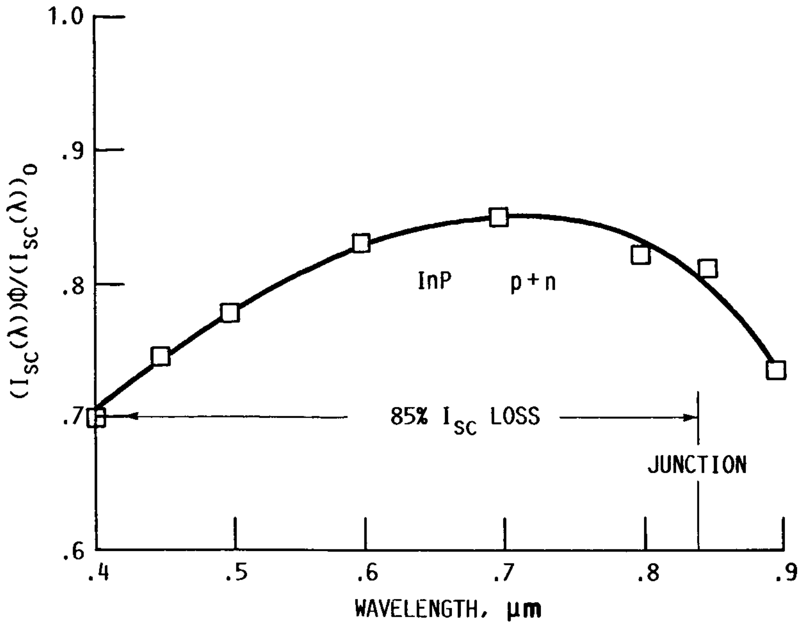

FIGURE 6. - NORMALIZED SPECTRAL RESPONSE OF n^+p InP CELL. 1 MeV ELECTRON FLUENCE = $3x10^{15}/cm^2$.

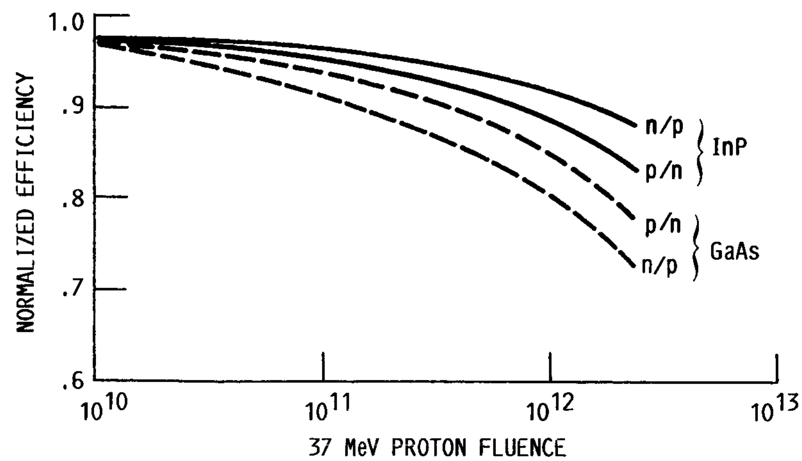

FIGURE 7.- NORMALIZED EFFICIENCY AFTER 37 MeV PROTON IRRADIATION.

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16. Abstract

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