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Recent Progress in InP Solar Cell Research

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RECENT PROGRESS IN InP SOLAR CELL RESEARCH

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ABSTRACT

Significant new developments in InP solar cell research are reviewed. Recent accomplishments include monolithic multibandgap two junction cells (3 and 2 terminal) using InP as the top cell and lattice matched GaInAs and GaInAsP as the bottom, low bandgap, component. Concentrator cells include the three terminal multibandgap cell and an n+p cell using an InP substrate. The review also includes small scale production of ITO/InP cells and results for n+p InP and ITO/InP cells in space on board the LIPS III satellite.

INTRODUCTION

The demonstration that InP solar cells were significantly more radiation resistant than either GaAs or Si under both proton and electron irradiations initiated a new direction in InP solar research [1,2]. Prior to this, the cell had been considered mainly for terrestrial applications. However, their demonstrated superior performance supplied the motivation for efforts in the USA, Japan and the United Kingdom aimed at developing InP cells for use in the space radiation environment [3]. Previously, the most notable achievement was the demonstration of AMO efficiencies over 19% in 4 cm^2 InP cells [4]. In addition, the cells have demonstrated excellent radiation resistance, in space, on board the LIPS III satellite [5]. In the present case, we review significant progress over the past year. This will include the latest developments in heteroepitaxial, homoepitaxial and ITO/InP cell research and a summary of results for InP cells on board the LIPS III satellite.

InP CELLS ON FOREIGN SUBSTRATES

The high cost of InP substrates has provided motivation for research efforts aimed at the processing of cells from thin InP layers epitaxially grown on cheaper substrates. Ideally, one would prefer silicon substrates. In addition to cost reduction, the added mechanical strength of silicon would greatly facilitate handling and substrate thinning. However, the high degree of lattice mismatch between InP and Si (7.5%) introduces dislocations which tend to reduce cell performance. The initial attempts, at the Spire corporation, to process InP cells using Si substrates, employed GaAs as an intermediate layer [6]. This resulted in cells whose efficiency was 7% [6]. The cells, epitaxially grown by OMVPE, were n+p. However, since silicon is an n-dopant in both InP and GaAs, counterdoping of the GaAs layer resulted in a reverse diode which, despite the introduction of a shorting path through the latter, resulted in low cell efficiencies. To circumvent this, and still retain the n+p configuration, the structure shown in fig.1 was developed [7]. Despite the fact that $In_{.53}Ga_{.47}As$ is lattice matched to InP, the cell dislocation density was high (10^8 cm^{-2}) and the best cell efficiency was 9.9% (table I). However, despite the relatively low efficiency this is the highest efficiency obtained to date using silicon as the starting substrate [7].

Although not as desirable as Si, the use of a GaAs substrate with its lower lattice constant mismatch (3.7%) should yield a lowered dislocation density and therefore higher efficiencies. AMO efficiencies as high as 13.7% have already been demonstrated, in previous years, for an n+p InP cell using a GaAs substrate with lattice matched GaInAs [8,9]. Although this cell does not represent recent progress, the cell parameters are shown for completeness in table I. The increased efficiency can be attributed to the lower dislocation densities ($3x10^7$ cm^{-2}) present in these cells. It is noted that contact metallization on these cells covered 8% of the front surface. Concentrator cells have been developed using similar structures but with 20% front surface contact coverage to reduce series resistance [10]. However, use of an ENTECH prismatic cover reduced front contact obscuration to a relatively low value [11]. A schematic representation of this cell is shown in fig. 2. Efficiencies achieved were 18.9% at 25°C and a concentration of 71.8X AMO and 15.7% at 80°C under 75.6X AMO concentration [10]. Cell parameters for operation at 25°C under concentration, are shown in table I. These latter values, although under concentration, are the highest reported to date for single junction heteroepitaxial InP cells. However, the present plastic ENTECH cover requires either protection or modification for operation in the space radiation environment.

Although dislocations reduce cell performance, it has been found that single junction heteroepitaxial InP cells exhibit radiation resistance

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which is superior to that of single junction homoepitaxial InP cells [12]. It was concluded that this was not intrinsic to InP, but was attributable to the effect of dislocations in reducing minority carrier diffusion lengths [12]. Dislocations in heteroepitaxial single junction InP cells were also found to affect temperature dependencies, photoluminescence spectral intensities and carrier removal under 10 MeV proton irradiations [13].

CELLS ON InP SUBSTRATES

Wanlass and his coworkers have produced a monolithic two junction cell, by OMVPE, using InP as the top cell (Eg=1.35 eV) and $Ga_{.47}In_{.53}As$ (Eg=0.73 eV) as the bottom cell. A schematic representation of this cell is shown in fig. 3. As seen from the figure, this monolithic cell is composed of back to back diodes. Hence, as shown,the device is not intended to operate with two terminals. Instead, a third, terminal, from the middle contact region, serves as the second contact for both the top and bottom cells. The I-V curves of both cells under a 50X AM1.5 spectrum at 25°C, are shown in fig. 4. Hence, the combined efficiency of these cells is 31.8% (SERI measurement) at 50X AM 1.5 concentration and 25°C.

The cell shown in fig. 3 exhibits the highest efficiency attained, albiet under concentration, for a multijunction device containing InP. A concentrator cell, which is essentially the top cell of fig. 3, has been processed by OMVPE on an InP substrate [14]. This cell with 20% front contact coverage and ENTECH prismatic cover has attained an efficiency of 21.4% under 106.5X AMO at 25°C and 19.1% efficiency under 125.6X AMO concentration and 80°C (SERI measurement). A schematic representation of this cell and associated I-V curves are shown in figures 5 and 6 respectively.

As mentioned previously, the device of fig. 3 requires three terminals and separate outputs from each cell. From a spacecraft circuit designers point of view, a two terminal monolithic tandem cell would be more convenient. In this connection, a two terminal monolithic device, with an InP top cell has been demonstrated by Shen and his coworkers (fig.7) [15]. The InGaAsP bottom cell (Eg=0.95 eV) is lattice matched to InP. Both cells are in the p+n rather than the n+p configuration used in the previously mentioned cells. In the present case the n regions of both cells were processed by LPE after which the p+ regions were formed by thermal diffusion of zinc. The intercell ohmic contact was provided by an n+p+ InGaAsP tunnel junction which covered 12.5% of the bottom cell's surface area. similarly, the metal contacts for the top cell covered 12.5% of the surface area. With Sb_2O_3 used as an antireflection coating, the best cell efficiency under AM1.5 global illumination was 14.8% with Voc=1-.363 volts, Isc=13.84 mA/cm2 and fill factor = 78.7% (SERI measurement). At present, we have no information concerning the cell's performance under an AMO one sun spectrum. Since only a few devices were processed one could anticipate improved performance with further research efforts [15].

Cells processed by sputtering indium tin oxide (ITO) onto p-type InP are of interest because of their relative simplicity in cell fabrication. Prior to the results to be described here, a small area (0.108 cm^2) ITO/InP cell produced by D.C. magnetron sputtering of ITO onto an epitaxially grown p-type InP layer, achieved an AMO efficiency of 17% (SERI measurement) [16]. This procedure, although detracting from the simplicity of the processing, served to illustrate the importance of good substrate quality in producing good ITO/InP cells. Most recently, Gessert et al have undertaken small scale production of these cells, 4 cm2 in area, processed by depositing ITO directly onto reasonably good substrates [17]. It was felt that recent advances in cell processing indicated that the fabrication technology for these cells was approaching the practical stage and that production of a relatively large number of cells would result in a better understanding of the effect of fabrication procedures on cell performance [7]. A histogram of efficiencies for 32 of these 4 cm^2 ITO/InP cells is shown in fig. 8. The average AMO efficiency of the 32 cells is 15.5%, with the highest efficiency being 16.1% (SERI measurement). For this latter cell Jsc=33.65 mA/cm2, Voc=786 mV and FF=83.1% [17]. The antireflection coating for these cells consisted of 55 nm of ITO topped by 75 nm of MgF_2. Rather than being heterojunctions, the ITO/InP cells were found to be n+p InP cells, the n+ region being formed during the sputtering process [9]. This being the case, their efficiencies are comparable to commercially available homojunction n+p InP cells processed in Japan by thermal diffusion and used to power a small lunar orbiting satellite on board the MUSES-A satellite [18]. The present results thus indicate the possibility of a U.S. supplier for these interim cells.

FLIGHT TESTING

Both homojunction n+p InP and ITO/InP solar cells are currently in space, in 4 cell test modules, on board LIPS III, a satellite launched in the late spring of 1987 into an 1100 KM orbit whose inclination was slightly in excess of 60°. Characteristics of both cell types flown can be found in references 5 and 19. Since Isc is the only reliable and reproducible parameter obtained from the spacecraft, over the mission duration, we restrict our comments to the behavior of this data element [5,19]. The behavior of short circuit current in the homojunction n+p cell during 971 days in orbit is shown in fig. 9 [5]. Currently we have received additional data, from the NASA Lewis module, which indicates no change from fig. 9 after 1223 days in orbit. As seen from the figure, Isc has increased slightly with time in orbit. At present we can give no satisfactory explanation for this upward trend. However, no decrease in Isc is indicated after more than 3 years in space. The ITO/InP cells do not show this upward trend for data reported after 892 days in space [19]. These latter cells produced at the Newcastle Polytechnic under the aegis of RAE, Farnborough UK, show no decrease in Isc over the reporting period.

Since no damage equivalence data exists for InP, we use the 1 MeV electron equivalent data for silicon to obtain a rough estimate of the expected degradation [20]. It should be noted that the homojunction cells have 12 mil glass covers while the ITO/InP covers are approximately 4 mils in thickness. This yields, using the data for silicon, a 1 MeV electron equivalent fluence of 7.8×10^{13} cm^{-2} for the n+p cells and 1.1x1014 cm-2 for the ITO/InP cells over their respective reporting periods. For this electron fluence our laboratory data for the homojunction n+p cell indicates a degradation of approximately 1% in Isc [21]. On this basis, little or no degradation is expected for the U.S. cells. With respect to the British ITO/InP cells, we have no readily available laboratory data for Isc after 1 MeV electron irradiation. We are thus unable to estimate the degradation in Isc expected for these latter cells. The fact remains however that neither cell shows degradation in Isc over their respective reporting necessity.

CONCLUSION

It is noted that no advances in 1 sun AMO efficiencies over the 19.1% previously accomplished for InP have been reported during the past year [4]. It is generally believed, based on computer modelling, that surface passivation is the key to obtaining efficiencies over 20%. Unfortunately, there has been little or no activity in this problem area. Nevertheless, there have been notable advances in the processing of heteroepitaxial and homoepitaxial cells particularly under concentration. These latter efforts tend to use the ENTECH prismatic cover in order to maximize efficiency. Radiation damage to these plastic covers presents a problem when used in the space radiation environment. Hence research directed toward either protecting the covers or replacing the presently used plastic material is a practical necessity. Efforts directed toward this goal are presently under way at ENTECH under a contract managed by NASA Lewis. The work on ITO/InP is interesting and may result in an interim supply of these cells manufactured in the United States. However, as presently constituted, it is doubtful that AMO efficiencies over 17% will be routinely produced in these cells. Our own preference tends toward heteroepitaxially grown InP cells using cheaper and more durable substrates. In addition, use of processes such as ClEFT and peeled film technology show promise of producing reduced substrate cost. On balance however, the field of InP solar cell research is still dynamic and creative inasmuch as significant results have been obtained over the past year using novel cell configurations.

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Table 1 AMO Performance of Heteroepitaxial InP Cells Using Si and GaAs Substrates

CELL	Jsc mA/cm^2	Voc mV	FF %	EFF, %	REFERENCE
InP/TJ[a]/GaInAs/Si[b]	28.07	682	70.6	9.9	7
InP/GaInAs/GaAs[c,d]	31.7	783	75.5	13.7	9
InP/GaInAs/GaAs[c,e]	2588	902	79.3	18.9	10

[a] Tunnel Junction (p^+ GaInAs/n^+InP)

[b] Spire Measurement

[c] SERI Measurement

[d] 8% Contact Coverage

[e] 20% Contact Coverage, ENTECH Cover Concentrator - 71.8X AMO, 25°C

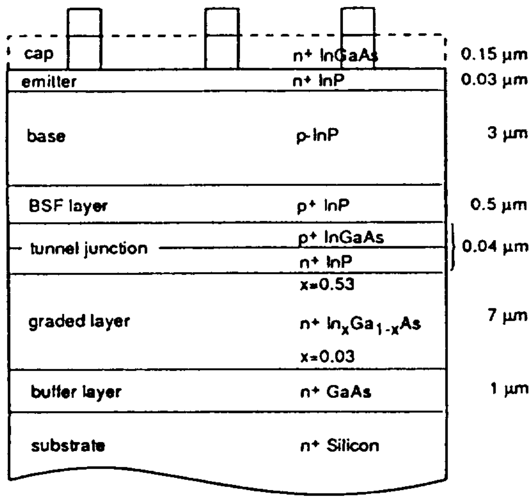

Fig. 1 Heteroepitaxial InP Cell with Tunnel Junction and Si Substrate.

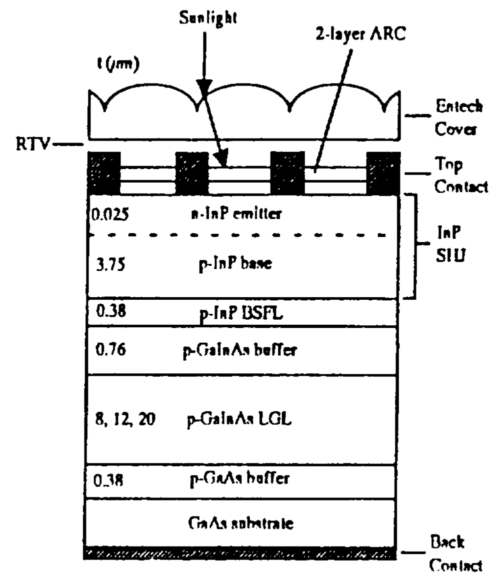

Fig. 2 Heteroepitaxial InP Concentrator Cell-GaAs Substrate.

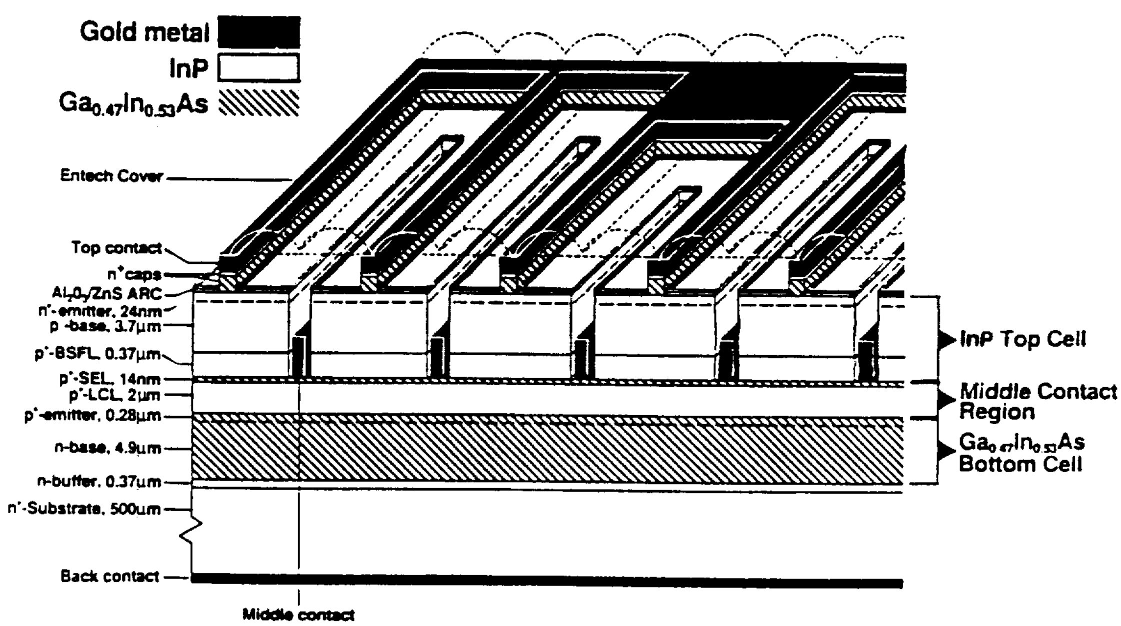

Fig. 3 Monolithic, 3 Terminal InP/Ga$_{.47}$In$_{.53}$As Concentrator Cell.

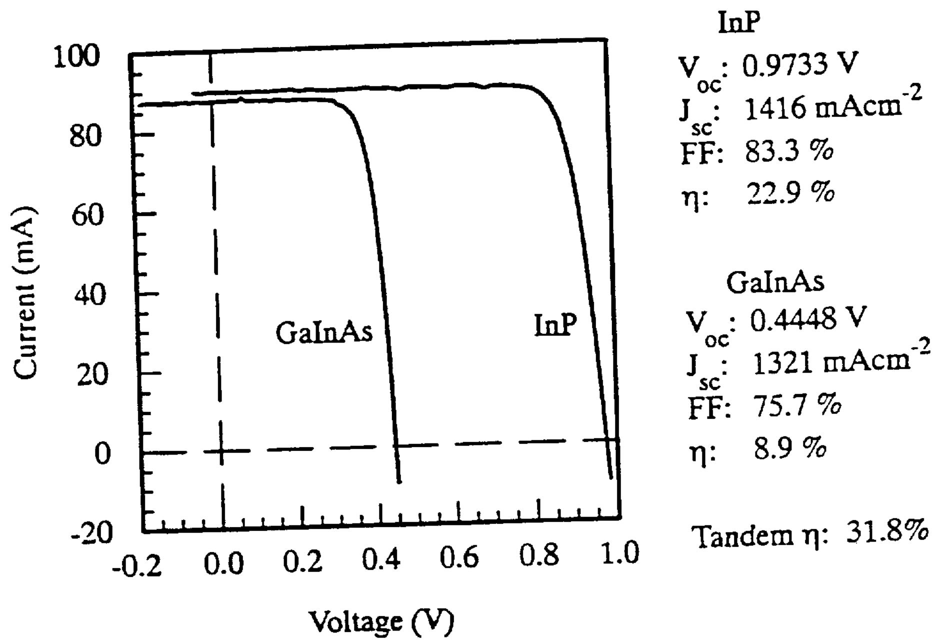

Fig. 4 I-V Curves of Monolithic Cell shown in Fig. 3.
AM1.5 Concentration = 50 suns, T = 25°C
(SERI Measurements)

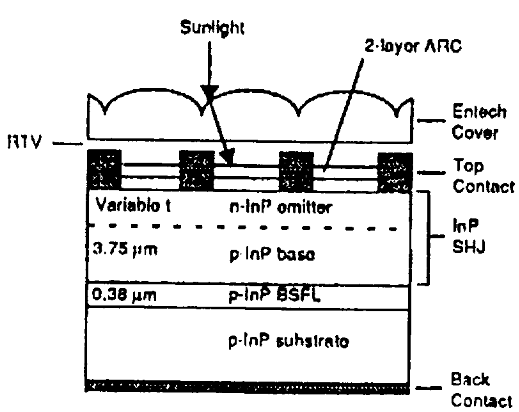

Fig. 5 Schematic Diagram of InP Shallow-Homojunction Concentrator Solar Cell.

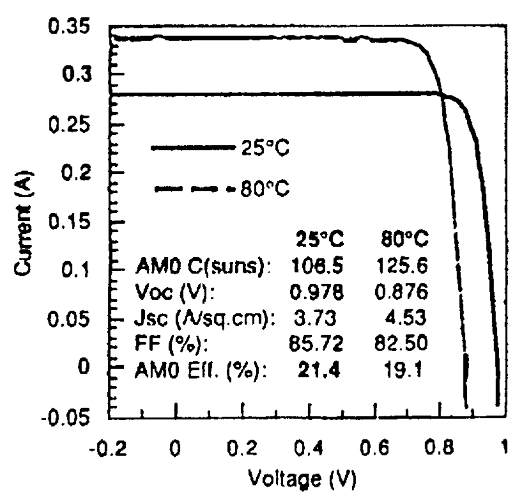

Fig. 6 I-V Data for Cell shown in Fig. 5.

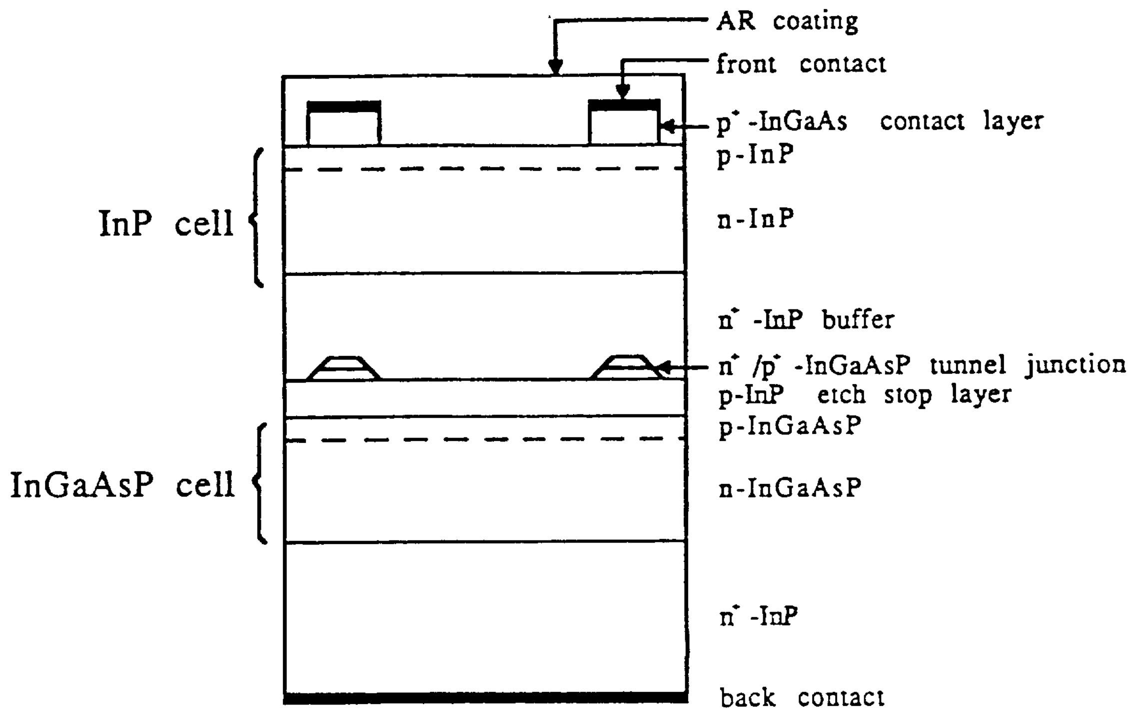

Fig. 7 Schematic Cross Section of a Two-Terminal, Monolithic InP/InGaAsP Tandem Cell.

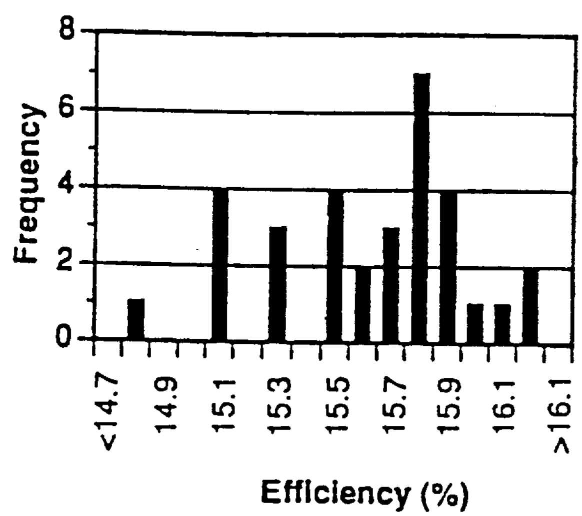

Fig. 8 Efficiency Histogram for Small Scale Production if ITO/InP Cells.

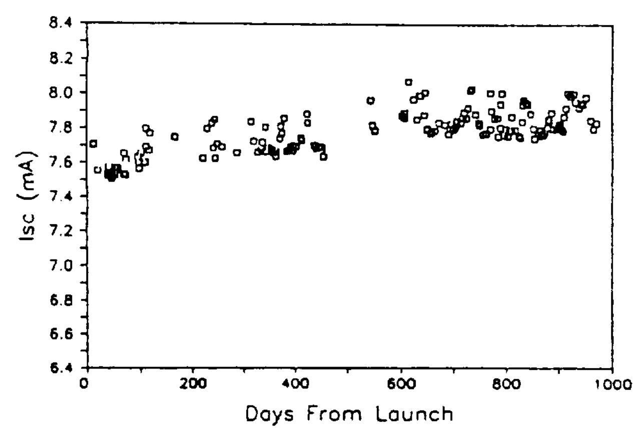

Fig. 9 Isc vs. Time on Orbit for Typical InP Cell.

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16. Abstract

Significant new developments in InP solar cell research are reviewed. Recent accomplishments include monolithic multibandgap two junction cells (3 and 2 terminal) using InP as the top cell and lattice matched GaInAs and GaInAsP as the bottom, low bandgap, component. Concentrator cells include the three terminal multibandgap cell and an n+p cell using an InP substrate. The review also includes small scale production of ITO/InP cells and results for n+p InP and ITO/InP cells in space on board the LIPS III satellite.

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