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Status and Future Directions of InP Solar Cell Research

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STATUS AND FUTURE DIRECTIONS OF InP SOLAR CELL RESEARCH

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Indium phosphide is a strong contender for many photovoltaic-powered space applications because of its excellent radiation hardness and its potential for high efficiency. This paper provides an overview of the current status and future directions of indium phosphide space solar cell research.

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1. INTRODUCTION

The superior performance of indium phosphide (InP) solar cells compared to that of gallium arsenide (GaAs) and silicon (Si) cells under electron [1] and proton [2] irradiations gives new direction to the study of photovoltaic power for space missions. A recent review paper [3] describes in detail the effects of radiation damage on InP solar cells. Computer modeling work [4] has predicted high-efficiency InP solar cells, and experimental cells developed by various designs and processes show very encouraging performance results [5-8] under AM0 spectrum. However, high wafer cost, low thermal conductivity, and high fragility of InP are major obstacles to widespread use, even for space applications. To achieve cost effectiveness, extensive research and development is under way to boost cell efficiency through novel designs and processes and to develop multijunction tandem cells. Another promising approach under investigation is to develop heteroepitaxial InP films on cheaper substrates such as Si to reduce the cell cost. Efforts are also under way to develop CLEFT (cleaved lateral epitaxial films for transfer) and peeled-film (by chemical lift-off) InP layers, similar to the successful development of GaAs films.

This paper provides an overview of the current status and future directions of InP space solar cell research. The scope of the paper does not allow us to discuss other recent major developments in InP cell modeling, contacts, and characterization, or developments in other solar cell materials. Solar cells made from InP and related materials are not expected to be used in the near future for terrestrial applications, but significant AM1.5 cell efficiencies are given for comparison. This paper deals with the developments in single-junction cells, multijunction tandem cells, and space flight testing, including radiation effects. Concentrator InP solar cells are also discussed, since they offer the possibility of simultaneous thermal and current injection annealing. These cells also promise cost effectiveness and the concentrator elements may provide cells with extra protection from space radiation. The concluding section addresses the steps to be taken in the future and provides guidelines for further research and development.

2. SINGLE-JUNCTION CELLS

This section describes the significant latest developments in single-junction InP cells. Multijunction tandem cells are discussed in section 3.

2.1 Homoepitaxial InP Solar Cells

Low-temperature epitaxially grown active layers on single-crystal InP wafers provide better cell efficiencies than conventional thermally diffused cells. Large-area (4 cm^2) homoepitaxial n^+p InP solar cells made by metalorganic chemical vapor deposition (MOCVD) have exhibited 19.1% AM0 efficiency at 25°C [5], the highest to date. Figure 1 shows the current - voltage (I-V) characteristics measured by NASA Lewis. These cell efficiencies are limited by the lack of effective surface passivation, effects of bandgap narrowing and series resistance.

There has been very limited effort in the development of p^+n type InP cells to date. The best cell efficiency, 15.9% AM0 (25°C), has been reported for the

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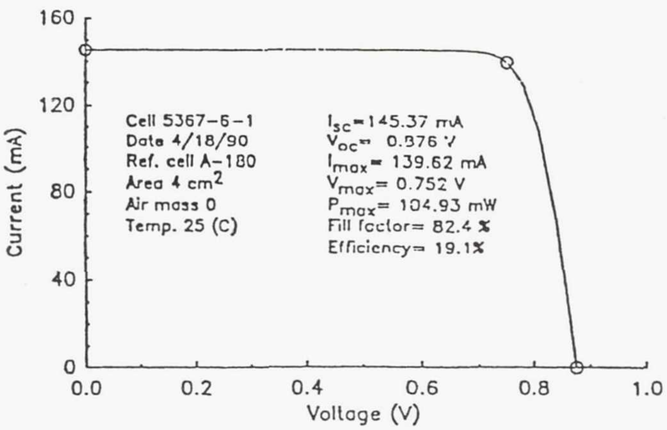

Fig. 1 I-V curve of the high efficiency homoepitaxial InP cell.

MOCVD grown cells [9]. A systematic optimal design study [10] of the comparison of n^+p and p^+n InP solar cells has shown possibly better performance of p^+n structures compared to n^+p because of higher open circuit voltage. This research urgently requires further attention.

The n^+p InP shallow homojunction concentrator solar cells [6] made by atmospheric-pressure metalorganic vapor phase epitaxy (APMOVPE) have achieved record efficiency of 21.4% AM0, 106.5 suns at 25°C, which reduces to 19.1% at 80°C (see Fig. 2). The study of solar cell performance at high temperatures (up to 100°C) is quite important because some of the space missions will be exposed to such high temperatures.

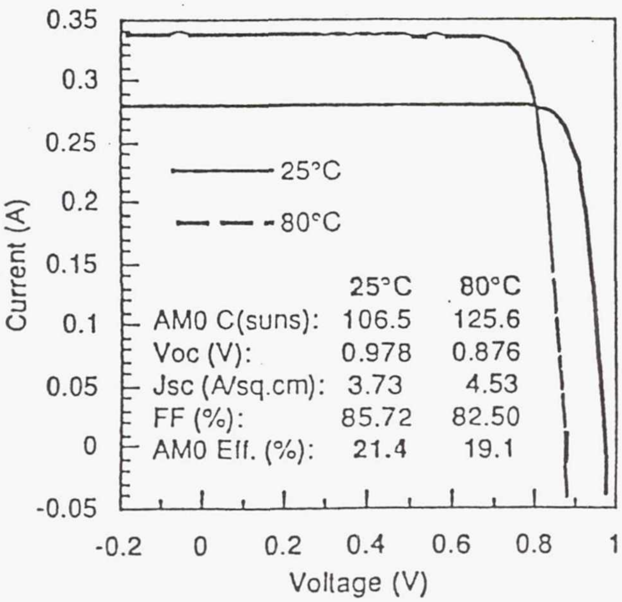

Fig. 2 I-V characteristics of the shallow homojunction InP cell at peak AM0 efficiency under concentration at 25°C and 80°C.

2.2 Heteroepitaxial InP Solar Cells

Heteroepitaxial (HE) growth of thin-film InP layers on foreign substrates (GaAs, Ge, Si) offers great potential for cost reduction, especially on single-crystal silicon. This approach would also meet other requirements for space worthiness, such as lighter weight (InP is denser than Si), higher mechanical strength (InP is very fragile), higher thermal conductivity, and large growth area (availability of large-diameter Si wafers); leading to high power-to-weight and power-to-area ratios. Initial efforts in the development of MOCVD grown InP cells on Si (with GaAs buffer) and GaAs substrates have resulted in relatively low cell efficiencies [11]. The misfit dislocations ($>10^8$ cm^{-2}) generated because of large lattice constant and thermal expansion mismatch between InP and the starting substrates are responsible for these low cell efficiencies. A recent study [12] report in detail the effects of the dislocations on heteroepitaxial InP solar cell performance and found that cell efficiencies over 20% AM0 could be achieved by reducing the number of dislocations below 10^5 cm^{-2}. Several approaches, such as the use of intermediate buffer layers, thermal cycle growth, post thermal annealing, and strained layer superlattices, have been tried to grow heteroepitaxial InP layers with minimal defects. In this paper we will describe the latest HE InP cell developments using lattice-matched GaInAs as intermediate buffer layers.

Heteroepitaxial InP cells on GaAs substrates have been developed (by APMOVPE) using GaInAs intermediate layers [7], as shown in Fig. 3. The structure

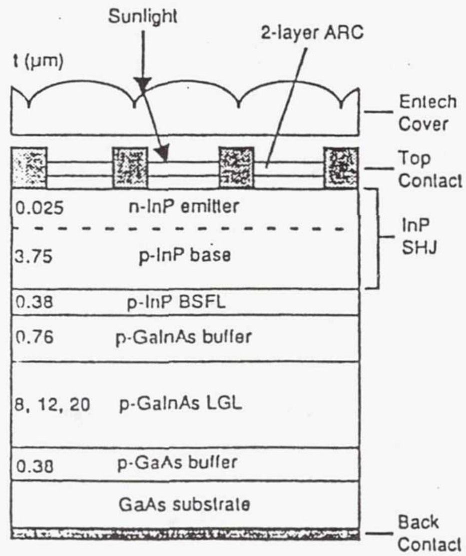

Fig. 3 Structure of the heteroepitaxial InP solar cell on a GaAs substrate with GaInAs buffer layer.

is initiated with a linearly graded (GaInAs) layer, which is followed by $Ga_{0.47}In_{0.53}As$ lattice matched to InP. Such cells have shown AM0 efficiencies (25°C) of 13.7% and 18.9% at 1 sun and 71.8 suns, respectively. The HE InP cell efficiency reduces to 15.7% AM0, 75.6 suns at 80°C. Figure 4 shows the HE InP solar cell I-V data at AM0, 71.8 suns, 25°C.

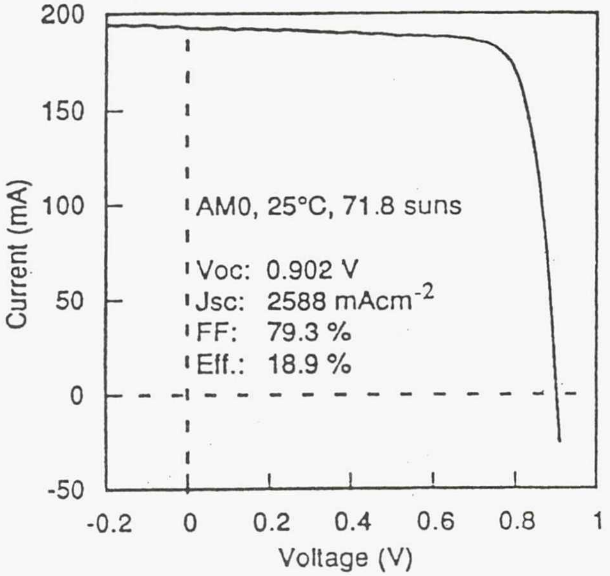

Fig. 4 I-V curve for the heteroepitaxial InP concentrator cell at peak efficiency.

Efforts have been also made to develop HE InP solar cells on silicon substrates by MOCVD [13]. These n-on-p cells have GaInAs layers of graded composition and a tunnel junction to provide an ohmic back contact as shown in Fig. 5. AM0 cell efficiencies of 9.9% at 25°C, 1 sun have been measured. The HE

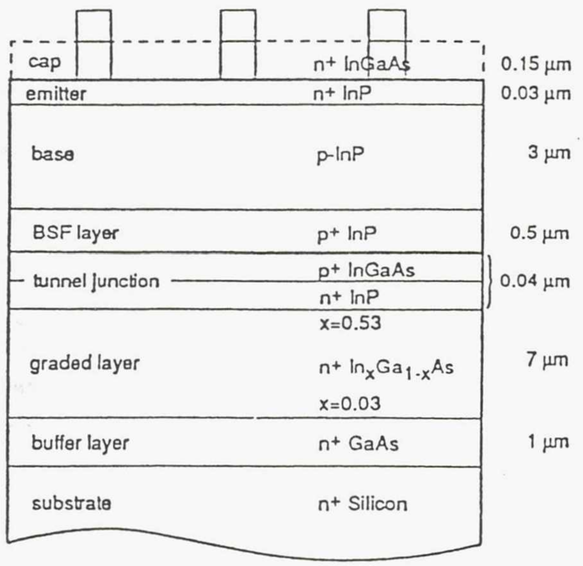

Fig. 5 Structure of the HE InP solar cell on a Si substrate with GaAs buffer and tunnel junction.

InP cells on Si or GaAs substrates [7,13] with GaInAs layers still have a large number of dislocations (10^7 to 10^8 cm^{-2}), which need to be controlled to improve efficiencies further.

Recently, indium tin oxide (ITO) InP space solar cells have also shown good progress. These 4 cm^2 ITO InP cells [14] have achieved the highest efficiency of 16.2% AM0 (1 sun, 25°C), which is comparable to cells [15] produced by closed ampule diffusion (4 cm^2, 16.6% AM0, 1 sun, 25°C).

3. MULTIJUNCTION TANDEM CELLS

The concept of multibandgap, multijunction tandem cells is very attractive for achieving high cell efficiencies and cost effectiveness by utilizing a larger portion of the solar spectrum. An InP bandgap energy of 1.35 eV makes it very suitable as a top cell or middle cell, respectively, in a two- or three-cell tandem structure (monolithic or mechanically stacked). Tandem cells under concentrated light have a potential for achieving efficiencies in excess of 30% [8].

Monolithic, three-terminal $InP/Ga_{0.47}In_{0.53}As$ tandem solar cells have been designed [8]. Figure 6

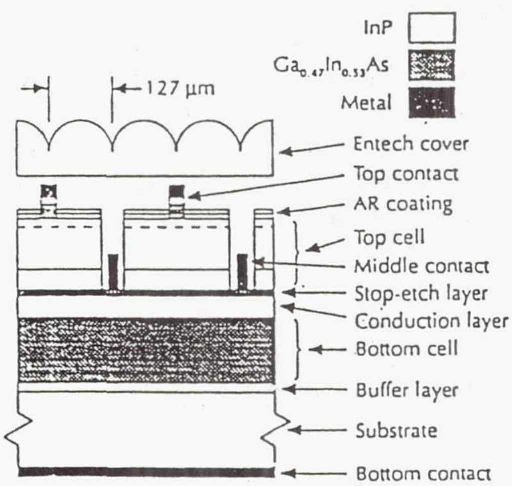

Fig. 6 Structure of the InP/GaInAs monolithic, three-terminal tandem solar cell.

shows the structure of such a cell grown by APMOVPE. Lattice-matched $Ga_{0.47}In_{0.53}As$ (bandgap energy, 0.75 eV) forms the bottom p^+n cell in the two-bandgap material structure. A middle contact is common to both cells, and an Entech prismatic cover is used to reduce the grid shadowing losses. Figure 7 demonstrates the AM0 efficiency versus sun concentration at 25°C for the tandem cell. The tandem cell (top + bottom) efficiency improves from 23.9% (1 sun) to a maximum of 28.8% (40.3

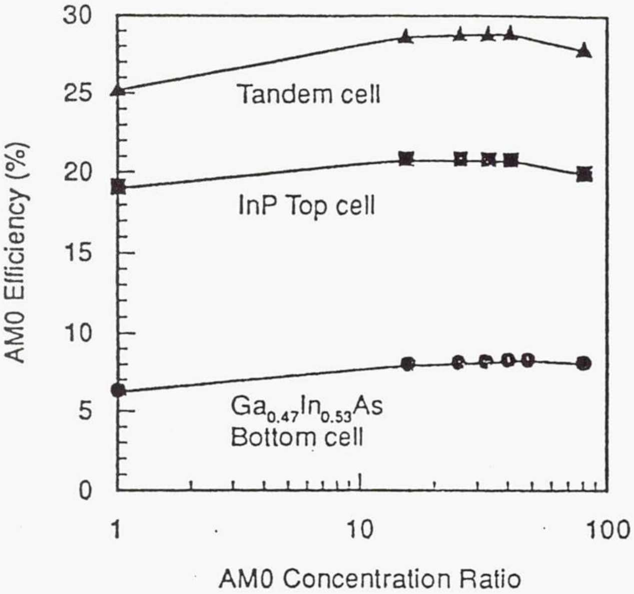

Fig. 7 Efficiency vs. concentration ratio results of the tandem cell shown in Fig. 6 at 25°C.

suns) and afterwards decreases because of series resistance effects of the top n^+p InP cell. These cells have exhibited a record tandem efficiency [16] of 31.8% (direct spectrum AM1.5, 50 suns, 25°C).

Recently, a monolithic, two-terminal InP/InGaAsP (0.95 eV) tandem structure [17] has been proposed (see Fig. 8). This cell has been fabricated by liquid phase epitaxy (LPE). The two cells are of p-on-n type. The tandem cell efficiency of 14.8% under AM1.5 global spectrum at 1 sun and 25°C has been achieved. The cell efficiency is limited by the low current output of the bottom InGaAsP cell, which results in current mismatch. A monolithic, two-terminal, three-cell structure has also been proposed, consisting of $GaInP_2$/InP/InGaAsP in a p-on-n series connected configuration. Although $GaInP_2$ is not perfectly lattice matched to InP, efficiencies in excess of 30% are predicted for the three-cell tandem structure.

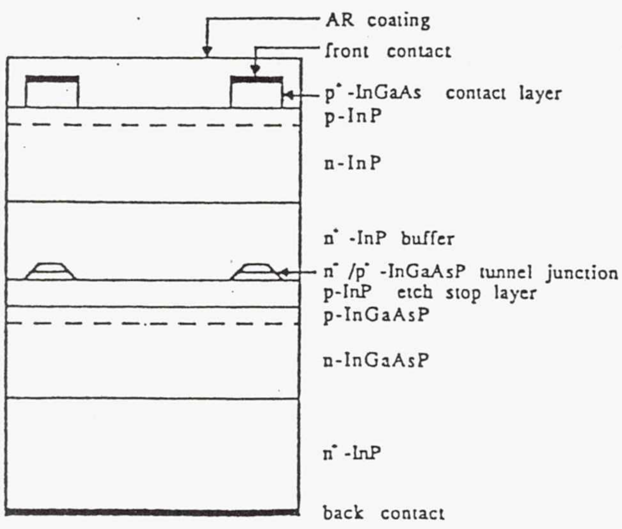

Fig. 8 Structure of the monolithic, two terminal InP/InGaAsP tandem solar cell.

4. SPACE FLIGHT EXPERIMENTS

From the early work [1,2] to the recently reported results [18-20] on various types of newly developed cells, InP cells have performed well under electron and proton irradiations and offer the best chance of achieving a high end-of-life (EOL) efficiency. It is important to verify this promise by testing in space.

The first InP solar cells were tested in space aboard the Living Plume Shield (LIPS-III) satellite, which was launched in the late spring of 1987 (1100 km circular orbit of 60+° inclination, 3 to 5 years mission life) by the Naval Research Laboratory. Among the 30 solar cell experiments of different materials and designs, two panels (each of four cells) of InP experiments were provided by NASA Lewis and the Royal Aerospace Establishment, United Kingdom. The telemetry data received from the spacecraft shows no degradation in the short circuit current of InP cells [21] after more than 4 years on orbit.

Recently NASA Lewis placed two types (homoepitaxial InP and ITO InP) of InP cells of large area (4 cm^2) on a UoSAT-5 microsatellite. The UoSAT-5, designed and constructed by the University of Surrey, United Kingdom, was launched from an Ariane rocket on July 17, 1991 (775-km polar, sun-synchronous Earth orbit). Figure 9 shows the UoSAT-5 spacecraft with the solar cell technology experiment and other communications, radiation, and Earth imaging experiments. The UoSAT-5 has been commissioned and stabilized. All the on-board systems and payloads are performing well. The InP cell space experiment (together with GaAs and Si solar cells) will telemeter useful information about the effects of space radiation in orbit on long-term electrical performance.

Another major space flight testing of high-efficiency InP solar cells, together with 10 other types of cells GaAs/GaSb, GaAs, $GaAs/CuInSe_2$, AlGaAs/GaAs, GaAs/Ge, and Si) is planned for a Pegastar satellite, which is scheduled for launch by Pegasus booster in November 1992 (elliptical orbit, 350 by 1850 km, near-polar, 70° inclination). This experiment has been named Photovoltaic Array Space Power Plus Diagnostics (PASP Plus), which is a part of the

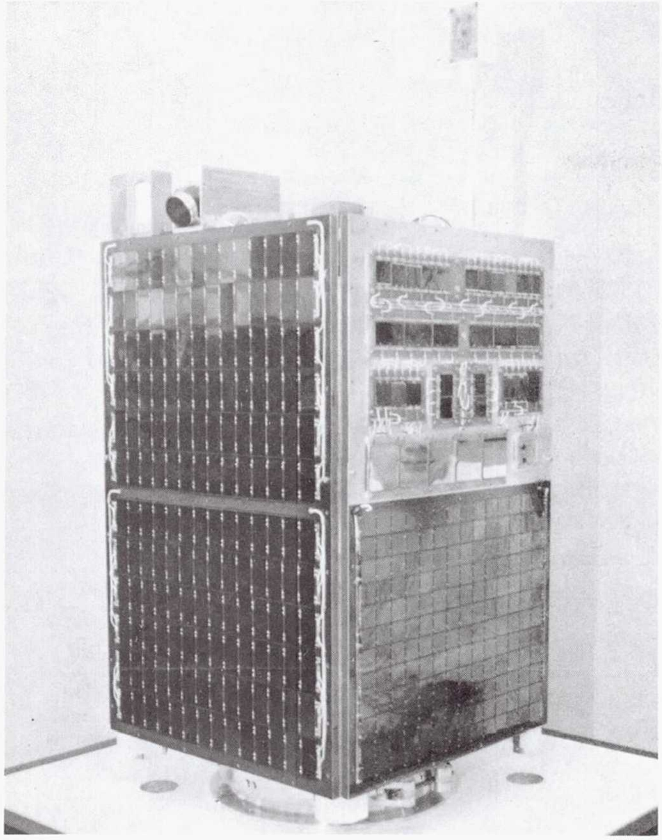

Fig. 9 Photo of the UoSAT-5 microsatellite launched on July 17,1991 with InP solar cell experiment (courtesy of M. F. Piszczor of NASA Lewis).

APEX (Advanced Photovoltaic and Electronics Experiment) mission sponsored by the U.S. Air Force's Space Test Program. It is hoped that this flight testing will generate valuable data on the effects of space environment on solar cells. Figure 10 shows an InP panel fabricated by the Spire Corporation for space experiments on PASP Plus using the highest efficiency homoepitaxial (2 cm by 2 cm) MOCVD cells [5].

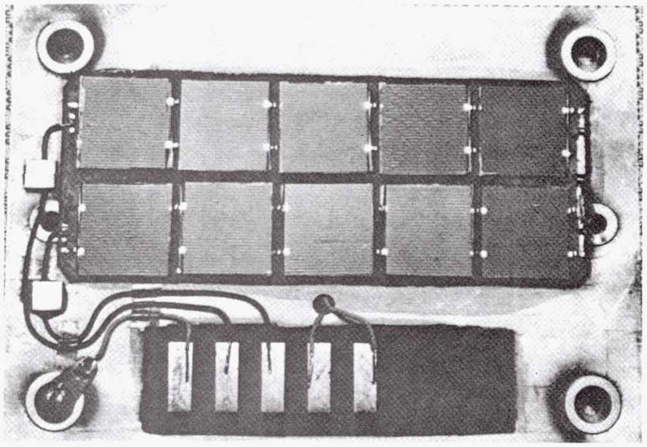

Fig. 10 Photo of the PASP Plus InP cell panel (courtesy of M. J. Nowlan of Spire Corp).

5. CONCLUSIONS

Extensive development work in the United States, Japan, and the United Kingdom has been very encouraging, but more research and development is required to increase InP solar cell efficiency and reduce cost to make this technology suitable for space applications.

Current InP cell efficiencies are limited by surface recombination, which is due to the absence of suitable passivation layers. Cell efficiencies in excess of 20% will not be realized without surface passivation. Recently, calculations [22] have shown that the use of wide-bandgap lattice-matched $In_{0.52}Al_{0.48}As$ as a window layer in p^+n InP structure may result in significant improvement (see Fig. 11) in cell efficiency. Bandgap narrowing effects due to heavy doping in the cell emitter and BSF (back surface field) regions should be reduced by using modest doping levels or be properly accounted for in the modeling calculations. Advanced design concepts using light trapping, texturized surfaces, and prismatic covers, for example, should be fully exploited to enhance cell efficiency. Low loss ohmic contact technology requires proper attention, especially front contact in p^+n type InP cells.

Heteroepitaxial InP cells on cheaper substrates seem to be the ultimate choice to meet space power requirements. To date, the major obstacle is the generation of misfit dislocations, which keeps cell efficiencies low. Current and new material growth and cell processing techniques should be investigated to control the

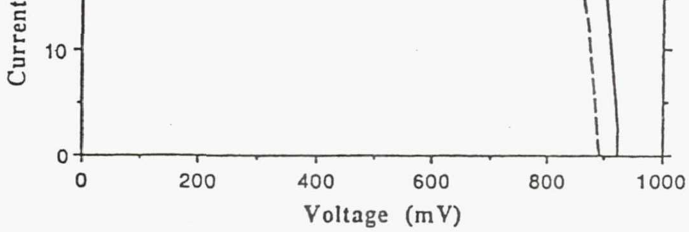

Fig. 11 Calculated I-V characteristics of the p^+n InP solar cell with 20 nm (solid curve) and without (dashed curve) $In_{0.52}Al_{0.48}As$ window layer (AM0, 1 sun, 25°C).

density of threading dislocations. Work with CLEFT and peeled film for InP cells is in the beginning stages and should be pursued very seriously. This technology has a great potential for high-specific-power (W/kg) solar arrays.

Use of concentrated light, especially in tandem cells, has been very successful in achieving high cell efficiencies. Improved concentrator element development, together with existing and new combinations of two- or three-bandgap material tandem cells, would lead to AM0 efficiencies over 40%. Spacecraft solar array designers and manufacturers would prefer two-terminal monolithic compared to multiterminal mechanically stacked tandem cells. Tandem-junction cell testing under AM0 spectrum requires proper solar simulators as well as calibrated reference cells. NASA Lewis has been providing reference cells of new materials and designs using its high-altitude Learjet facility and has also been monitoring the development of glass prismatic covers and mini-dome Fresnel lens under a contract to Entech.

More space flight experiments are needed in high radiation zones to evaluate the degradation in the InP cell performance and determine the EOL efficiencies. This would also help build confidence in the use of advanced photovoltaic technology by satellite manufacturers and aerospace industries. Existing and planned testing aboard various satellites will yield important information. More electron and especially proton irradiation data are required, particularly on newer types of cells. The change in radiation degradation of different subcells in a tandem cell poses a very interesting challenge. Damage coefficients for InP need to be determined.

The United States has a very ambitious space exploration program, from putting Space Station Freedom into low earth orbit, to setting up permanent bases on the Moon, to sending manned missons to Mars. Advancements made in InP space solar cell research will certainly benefit this program.

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References

1. M. Yamaguchi, C. Uemura and A. Yamamoto, J. Appl. Phys., 55, pp. 1429, 1984.
2. I. Weinberg, C. K. Swartz and R. E. Hart, Conf. Record 18th IEEE PVSC, pp. 1722, 1985.
3. I. Weinberg, Solar Cells, 31, 331, 1991.
4. R. K. Jain, I. Weinberg and D. J. Flood, Proc. 11th SPRAT Conf., pp. 29-1, 1991.
5. C. J. Keavney, V. E. Haven and S. M. Vernon, Proc. 2nd Int'l Conf. on Indium Phosphide and Related Materials, pp. 435, 1990.
6. J. S. Ward et al., Proc. 11th SPRAT Conf., pp. 28-1, 1991.
7. M. W. Wanlass et al., Proc. 11th SPRAT Conf., pp. 27-1, 1991.
8. M. W. Wanlass et al., Proc. 11th SPRAT Conf., pp. 16-1, 1991.
9. K. Y. Choi, C. C. Shen and B. I. Miller, Conf. Record 19th IEEE PVSC, pp. 255, 1987.
10. R. K. Jain, I. Weinberg and D. J. Flood, Proc. 3rd Int'l Conf. on Indium Phosphide and Related Materials, pp. 168, 1991.
11. C. J. Keavney et al., Appl. Phys. Lett. 54, 1139, 1989.
12. R. K. Jain and D. J. Flood, Conf. Record 22nd IEEE PVSC, 1991 (to be published).
13. C. J. Keavney, S. M. Vernon and V. Haven, Proc. 11th SPRAT Conf., pp. 1-1, 1991.
14. T. A. Gessert et al., Conf. Record 22nd IEEE PVSC, 1991 (to be published).
15. M. Yamaguchi et al., Conf. Record 21st IEEE PVSC, pp. 1198, 1990.
16. M. W. Wanlass et al., Conf. Record 22nd IEEE PVSC, 1991 (to be published).
17. C. C. Shen, P. T. Chang and K. A. Emery, Conf. Record 22nd IEEE PVSC, 1991 (to be published).
18. I. Weinberg et al., Conf. Record 22nd IEEE PVSC, 1991 (to be published).
19. R. J. Walters et al., Conf. Record 22nd IEEE PVSC, 1991 (to be published).
20. N. M. Pearsall et al., Conf. Record 22nd IEEE PVSC, 1991 (to be published).
21. D. J. Brinker and I. Weinberg, Conf. Record 21st IEEE PVSC, pp. 1167, 1990.
22. R. K. Jain and G. A. Landis, Appl. Phys. Lett., 59, 2555, 1991.

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13. ABSTRACT ***(Maximum 200 words)***

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