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Extreme radiation hardness and light-weighted thin-film indium phosphide solar cell and its computer simulation

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Abstract

A very light-weighted and extreme radiation hardness high-doping n^+-i-p^+ InP solar cell is developed. The total thickness of its epitaxial layer is only 0.22 μm. It is more radiation hardened than many other structures so that it can provide the required output power for spacecraft even after a decade at 3200 km polar orbits. Its end of life efficiency is about 10% (AM0, 1Sun); its highest power/weight ratio is about 130 W/g (only the weight of epitaxial layers is considered). The surprising fact is that all of these are obtained from a very simple structure. © 2002 Published by Elsevier Science B.V.

Keywords: Extreme radiation hardness; InP solar cell; Computer simulation; Thin film; High power/weight ratio

1. Introduction

InP solar cells have long been demonstrated to degrade less under irradiation than GaAs and Si [1–4]. Preliminary studies on InP solar cells confirmed that room-temperature annealing and minority-carrier injection-enhanced annealing are responsible for the recovery of photovoltaic properties of degraded cells [3]. These hint that InP solar cells have broad prospects for space applications.

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In the past years, several structures of InP solar cells had been developed [5]. To further improve photovoltaic performance of InP solar cells with much higher radiation resistance, conversion efficiency and power/weight ratio, an n^+-i-p^+ structure InP solar cell is developed in this paper. For space applications, since the launching cost is very high, the power/weight ratio of solar cells is a very important factor to be considered. Moreover, higher end of life (EOL) efficiencies of solar cells are anticipated for space applications for it makes spacecraft have longer lifetimes. Many structures which are now being used in satellites, e.g. GaAs and Si solar cells, may have high begin of life (BOL) efficiencies, but their EOL efficiencies are too low. Current radiation-hard materials such as GaAs and InP exhibit significant degradation after only 10^{15} 1 MeV electrons/cm^2. While this exposure corresponds to about 10 years at a 700 km polar orbit, it is only a few days at a 3200 km polar orbit. The alternative approach is based upon a structure that permits the use of a material of much lower electrical quality while still attaining high-efficiency operation. This structure can then be optimized for the low-quality material expected after much radiation degradation. This means that the photovoltaic device efficiency will be relatively insensitive to radiation exposure until much more massive material degradation has occurred than has been previously possible. In addition, it can be expected to use the same structure to make a polycrystalline thin-film version at a very low cost. Furthermore, the same structure can be used with other materials as improved radiation-hardened materials are developed.

2. Structure of the cell

Fig. 1 shows the sketch of the cell. Both the n^+-InP and p^+-InP layers are 0.01 μm in thickness and the doping levels of these two layers are all as high as 10^{20} cm^{-3}. The superior radiation resistance of InP strongly depends upon the carrier concentration of the cell active layer. The InP cell with higher carrier concentration substrate is

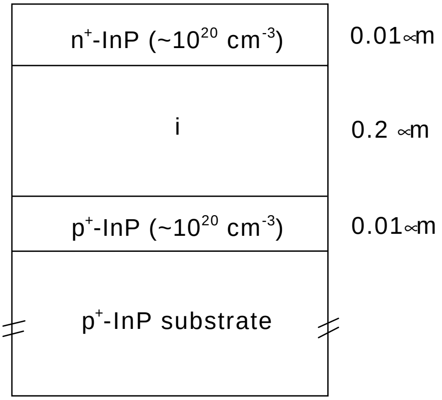

Fig. 1. Sketch of the n^+-i-p^+ InP solar cell.

more radiation resistant. The thickness of the i-layer decides the depletion width and there exists an optimum value at which the power/weight ratio of the cell is the highest. In this work, the thickness of the i-layer is taken from 0 to 1 μm for the calculation. The total thickness of the epitaxial layer is only 0.22 μm; the use of the i-layer is for obtaining a wider depletion region, so that a larger minority-carrier diffusion length can be obtained.

The change of short-circuit current density J_{sc} and open-circuit voltage V_{oc} of the cells as the diffusion length is in accordance with

$$J_{sc} = qgL, \tag{1}$$

$$V_{oc} = (nkt/q)\ln(J_{sc}/J_0 + 1), \tag{2}$$

where q is the electronic charge, g is the generation rate of the electron–hole pair due to the photon, L is the minority-carrier diffusion length, n is the diode ideality factor, k is the Boltzmann constant, and J_0 is the diode saturation current density. The efficiency of solar cells is

$$\eta = P_m/P_{in}, \tag{3}$$

where $P_m = ffV_{oc}I_{sc}$ is the maximum power output of the cell and P_{in} is the incident power. Increasing V_{oc} and I_{sc} will tremendously increase the conversion efficiencies.

3. Results and their comparison with some other systems

Solar cells used for spacecraft are required with as small a difference as possible between BOF efficiency and EOL efficiency. Fig. 2 shows the comparison of relative efficiencies of Si, GaAs and n^+-i-p^+ InP cells with the structure of Fig. 1. It is clear that the decline of n^+-i-p^+ InP structure with exposure to radiation is very slow.

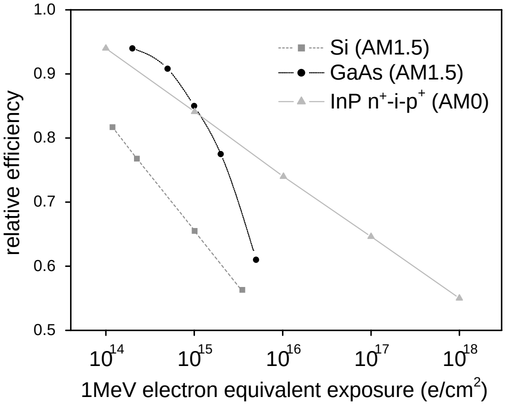

Fig. 2. Comparison of relative efficiency of Si, GaAs and n^+-i-p^+ InP solar cells.

Fig. 3 shows the comparison of this work with high-efficiency tandem solar cell [6], InP/Si structure [7] and normal InP solar cells. The slope of n^+-i-p^+ InP cell is always better even after exposures to radiation as high as 10^{18} 1 MeV electrons/cm^2.

Since the launch of spacecraft is very costly, the power/weight ratio is one of the most important factors of solar cells in space applications. Some solar cell systems have high conversion efficiency but do not have high power/weight ratio. Fig. 4 gives the comparison of power output between GaAs and normal InP cells [8]. It indicates that even for normal InP cells, they lose only 25% of their power output while GaAs cells loss 100%.

Fig. 5 is the computer simulation of AM0 efficiency of n^+-i-p^+ InP structure. It can be seen that with the increase of the thickness of the i-layer, the efficiency goes

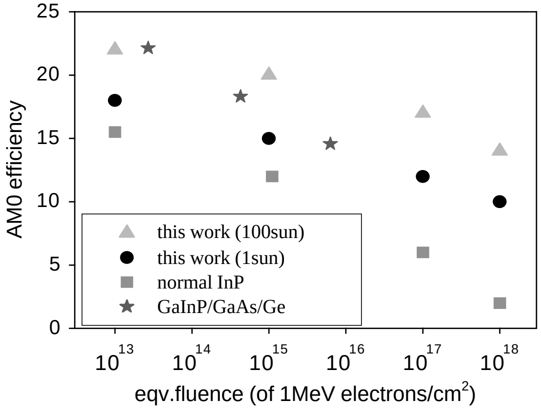

Fig. 3. Comparison of radiation hardness of several structures.

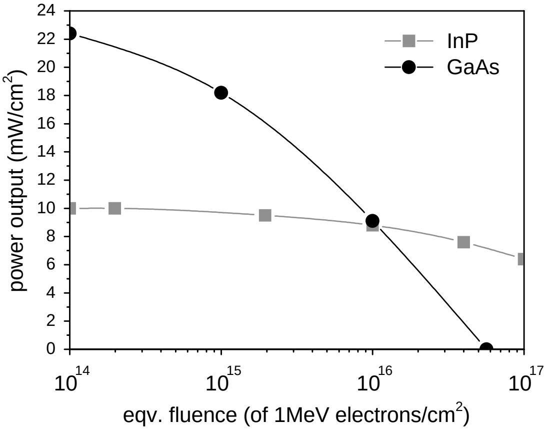

Fig. 4. Influence of radiation to power output of GaAs and normal InP solar cells.

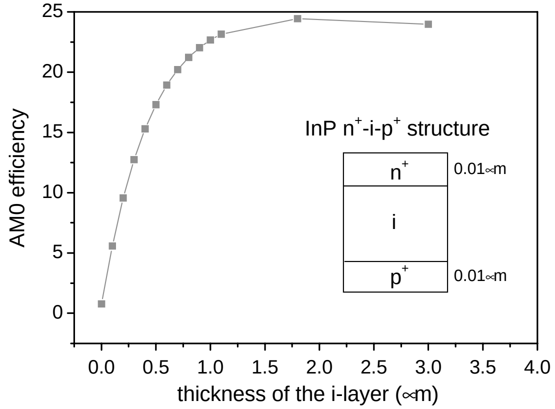

Fig. 5. Relationship between AM0 efficiency of n^+-i-p^+ InP solar cell and the thickness of the i-layer.

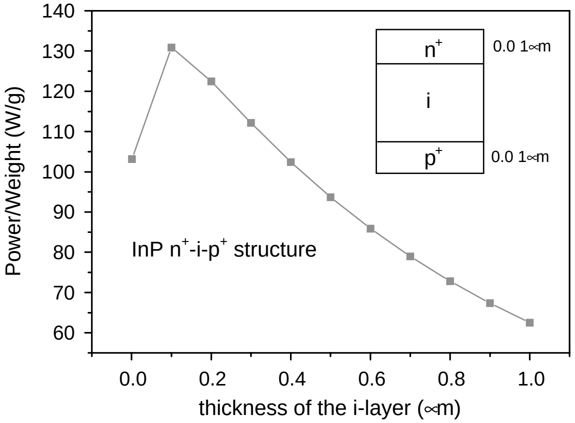

Fig. 6. Relationship between power/weight ratio of n^+-i-p^+ InP solar cell and the thickness of the i-layer.

up. This is due to the increase of the depletion width. The highest efficiency point is around 2 μm with an efficiency of 24.5%, and then the curve goes down slowly.

However, as shown in Fig. 6, the thickness of the i-layer with the highest power/weight ratio is between 0.1 and 0.2 μm and the ratio is as high as 130 W/g (only the epitaxial layers were considered when the weight was calculated).

4. Conclusions

It can be concluded from the discussion above that the n^+-i-p^+ InP structure has the character of extreme radiation hardness. A nearly 10% AM0 efficiency can be obtained even after exposure to radiation of 10^{18} 1 MeV electrons/cm^2. This results in a more flat efficiency–exposure curve, and it has a high power/weight ratio as 130 W/g (only the weight of epitaxial layers was considered). It is surprising that all of these are obtained with the very simple structure shown in Fig. 1.

References

[1] A. Yamamoto, M. Yamaguchi, C. Uemura, High conversion efficiency and higher radiation resistance InP homojunction solar cells, Appl. Phys. Lett. 44 (1984) 611–614.

[2] Y. Itoh, K. Ando, M. Yamaguchi, C. Uemura, High conversion efficiency and radiation resistant InP solar cells, IEDM Technical Digest, 1985, pp. 475–478.

[3] M. Yamaguchi, K. Ando, Mechanism for radiation resistance of InP solar cells, J. Appl. Phys. 63 (1988) 5555–5562.

[4] I. Weinberg, C.K. Swartz, R.E. Hart, R.L. Statler, Radiation and temperature effects in gallium arsenide, indium phosphide, and silicon solar cells, Proceedings of the 19th IEEE Photovoltaic Specialists Conference, New Orleans, USA, Institute of Electrical and Electronic Engineers, New York, May, 1987, pp. 548–551.

[5] R.W. Hoffman Jr., N.S. Fatemi, P.P. Jenkins, Development of high efficiency p^+/n InP solar cells for hetero-epitaxial applications, Proceedings of the 25th IEEE Photovoltaic Specialists Conference, Washington, DC, USA, Institute of Electrical and Electronic Engineers, New York, 13–17 May, 1996, pp. 171–174.

[6] M.R. Brown, et al., Characterization testing of dual junction $GaInP_2$/GaAs/Ge solar cell assemblies, Proceedings of the 26th IEEE Photovoltaic Specialists Conference, Anaheim, CA, USA, Institute of Electrical and Electronic Engineers, New York, 30 September–3 October, 1997, pp. 805–810.

[7] S. Wojtczuk, P. Colter, N.H. Karam, H.B. Serreze, Radiation-hard lightweight 12% AM0 BOL InP/Si solar cells, Proceedings of the 25th IEEE Photovoltaic Specialists Conference, Washington, DC, USA, Institute of Electrical and Electronic Engineers, New York, 13–17 May, 1996, pp. 151–155.

[8] S.J. Wojtczuk, N.H. Karam, P. Gouker, P. Colter, S.M. Vernon, Development of InP solar cells on inexpensive Si wafers, Proceedings of the First WCPEC, Hawaii, USA, 5–9 December, 1994, pp. 1705–1708.