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Diffusion Length Variation in 0.5- and 3-MeV-Proton-Irradiated, Heteroepitaxial Indium Phosphide Solar Cells

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DIFFUSION LENGTH VARIATION IN 0.5- AND 3-MeV-PROTON-IRRADIATED, HETEROEPITAXIAL INDIUM PHOSPHIDE SOLAR CELLS

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SUMMARY

Indium phosphide (InP) solar cells are more radiation resistant than gallium arsenide and silicon solar cells, and their growth by heteroepitaxy offers additional advantages leading to the development of lighter, mechanically strong, and cost-effective cells. Changes in heteroepitaxial InP cell efficiency under 0.5- and 3-MeV proton irradiations have been explained by the variation in the minority-carrier diffusion length. The base diffusion length versus proton fluence has been calculated by simulating the cell performance. The diffusion length damage coefficient K_L has also been plotted as a function of proton fluence.

INTRODUCTION

Indium phosphide (InP) solar cells have demonstrated better radiation resistance than gallium arsenide (GaAs) and silicon (Si) cells (refs. 1 and 2), but the high cost of InP wafers inhibits their use for large space power applications. The cost could be reduced by developing high-efficiency heteroepitaxial InP solar cells on lower cost substrates. Heteroepitaxy may also lead to the development of lighter and mechanically strong cells, which would offer additional advantages for their use in space.

InP cells have been grown on Si and GaAs substrates (refs. 3 to 5), but their efficiencies have to be increased in order for them to be viable for space use. Calculations have shown that misfit dislocations, caused by lattice mismatch and differential thermal expansion, greatly influence the heteroepitaxial InP solar cell performance (ref. 6). Transmission electron microscopy of heteroepitaxial InP cell structures has shown (refs. 7 and 8) a high density of threading dislocations and other defects.

We have been studying the effect of proton and electron (refs. 9 and 10) irradiations on heteroepitaxial InP cells. This work reports on the effect of 0.5- and 3.0-MeV proton (fluence, 10^{11} to 10^{13} cm^{-2}) irradiations on the base diffusion length of InP cells grown on GaAs substrates with $In_xGa_{1-x}As$ graded intermediate layers. The diffusion length damage coefficient K_L has also been calculated.

EXPERIMENTAL PROCEDURE

The cells were fabricated at the Spire Corporation under a contract to NASA Lewis Research Center. The cells were grown by metalorganic chemical vapor deposition on GaAs substrates with graded InGaAs intermediate layers. The composition of the last layer was $In_{0.53}Ga_{0.47}As$; this lattice match to InP helped to reduce the threading dislocations. These n^+p cells had a 30-nm-thick emitter with an area of 1 cm^2. The emitter and base doping concentrations were 2×10^{18} cm^{-3} and 3×10^{16} cm^{-3}, respectively. Figure 1 shows the heteroepitaxial

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InP cell structure. Cells were measured before and after proton irradiations at NASA Lewis under air-mass-zero (AM0) spectrum conditions at 25 °C. Four cells were radiated for studying the effects of 0.5- and 3-MeV protons.

APPROACH, RESULTS, AND DISCUSSION

Computer simulations using the PC–1D numerical code (ref. 11) were performed to calculate the effect of proton irradiations on cell performance. PC–1D is a quasi-one-dimensional program, based on a finite-element approach, for solving the semiconductor device transport equations.

Available heteroepitaxial InP cell process and material parameters were used. Calculated current-voltage (I-V) characteristics were fitted to the measured average results of the four cells under AM0 spectrum before proton irradiations. Minority-carrier diffusion lengths and series resistance were varied to achieve a match with the measured cell parameters. Surface recombination velocities of 10^7 cm/sec were assumed. A value of 8×10^6 cm^{-3} for intrinsic carrier concentration was used in this work. Figure 2 shows the calculated I-V characteristics of the unirradiated cell and the measured data points. From this figure it is clear that the agreement between theoretical and experimental results was quite good and formed the baseline for further cell simulations. A 0.5-μm base diffusion length was required to achieve the results shown in figure 2.

Figure 3 shows the effect of fluence on cell efficiency for 0.5- and 3-MeV protons. The 0.5-MeV protons appear to produce more damage than the 3-MeV protons as indicated by the decrease in efficiency. The proton ranges of 4.8 and 69 μm, respectively, for the energies of 0.5 and 3 MeV suggest that most of the damage occurred in the base region and beyond. It was assumed that the shallow (30 nm) emitter region of the heteroepitaxial InP cell was unaffected by the protons considered in this work.

The computer simulations suggest that the decrease in cell performance with proton fluence (see fig. 3) was primarily due to the decrease in the base diffusion length. The simulations were made to fit the cell efficiency at various fluences for 0.5- and 3-MeV protons by varying the base diffusion length. Figure 4 shows the base diffusion length as a function of proton fluence. The effects of carrier removal in the base have been included. The base doping concentration was accordingly modified in the calculations, on the basis of the measured number of carriers removed in the cells considered in this work at the various 0.5- and 3-MeV proton fluences (ref. 10). Figure 4 demonstrates that 0.5-MeV protons damaged the InP cell base region more than 3-MeV protons. The heteroepitaxial InP cell efficiencies under 0.5- and 3-MeV proton irradiations have been explained by the variation in the base diffusion length.

The damage caused by the electron and proton irradiations of a semiconductor device is characterized by a damage coefficient. The diffusion length damage coefficient K_L is defined as (ref. 12)

$$1/L_\phi^2 - 1/L_0^2 = \left\{\sum_j (N_{Tj}/\phi D)\sigma_j v\right\}\phi \qquad (1)$$

or

$$1/L_\phi^2 - 1/L_0^2 = K_L\phi \qquad (2)$$

where L_0 and L_ϕ are, respectively, the minority-carrier diffusion lengths before and after irradiation, N_{Tj} and σ_j are the concentration and capture cross section, respectively, of the jth defect, D is the minority-carrier diffusivity, v is the thermal velocity, and ϕ is the fluence.

Figure 5 shows the calculated K_L as a function of fluence for 0.5- and 3-MeV protons. The diffusion length damage coefficient is almost constant with proton fluence, 3×10^{-4} (at 0.5 MeV) and 3×10^{-5} (at 3 MeV). These are the first reported calculations of K_L under proton irradiations of InP solar cells. Using a similar relation (eq. (2)), Yamaguchi and Ando (ref. 13) have obtained the diffusion length damage coefficient K_L for 1-MeV electron irradiation as a function of impurity concentration.

SUMMARY OF RESULTS

Heteroepitaxial indium phosphide (InP) solar cells offer a great potential for space power applications. The cell efficiency changes due to 0.5- and 3-MeV proton irradiations have been explained by the variation of the base diffusion length. The 0.5-MeV protons influence the cell performance more strongly than the 3-MeV protons. Computer simulations were used to determine the variation of the base diffusion length with proton fluence for both the energies. The diffusion length damage coefficient K_L has been calculated for the first time and is constant with fluence. The damage coefficient for 0.5-MeV protons is an order of magnitude higher than that for 3-MeV protons. The effect of carrier removal has been considered in the calculations.

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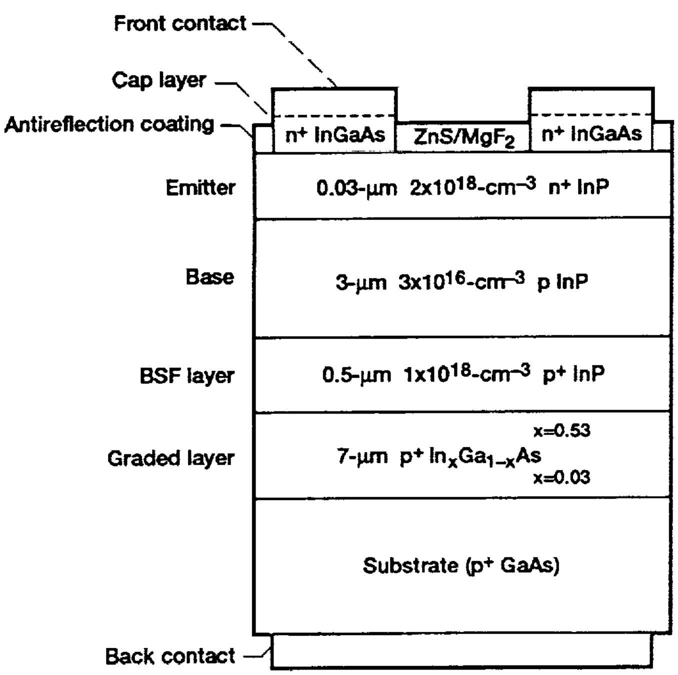

Figure 1.—Structure of metalorganic, chemical-vapor-deposited $n^+ pp^+$ $InP/In_xGa_{1-x}As/GaAs$ solar cell.

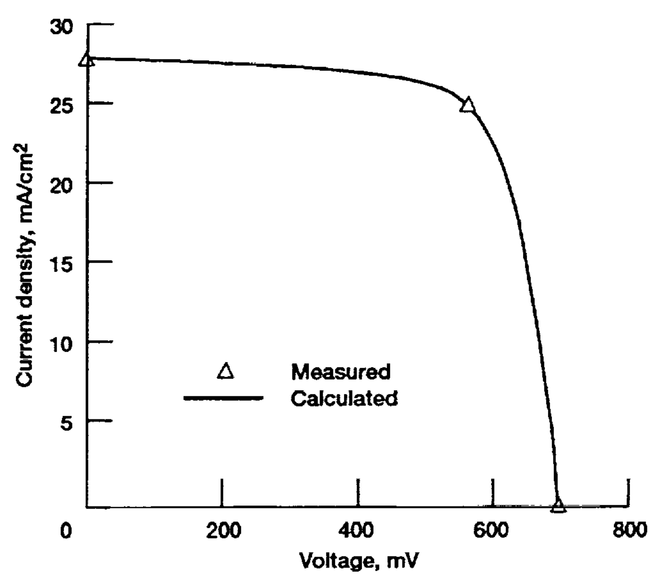

Figure 2.—Comparison of calculated current-voltage characteristics with measured (average) parameters of unirradiated heteroepitaxial InP solar cells

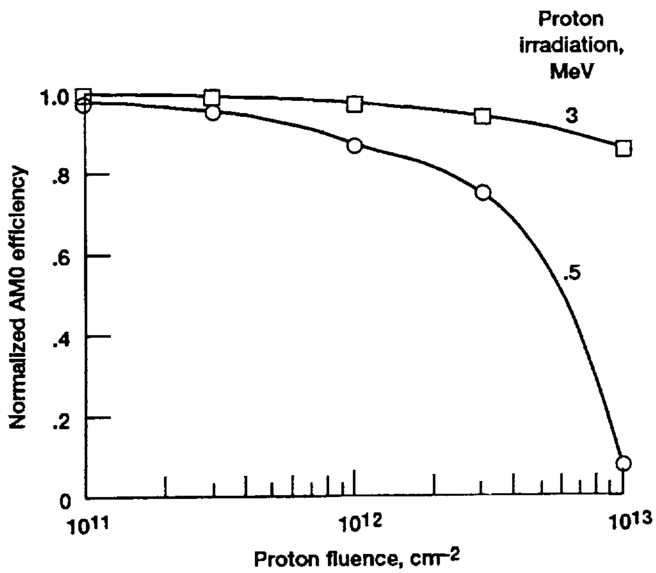

Figure 3.—Changes in AM0 conversion efficiency of heteroepitaxial InP solar cells with fluence for 0.5- and 3-MeV proton irradiations.

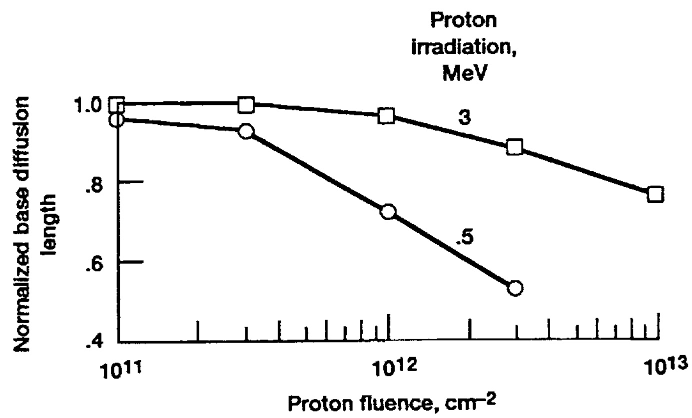

Figure 4.—Variation of base diffusion length with fluence in heteroepitaxial InP solar cells after 0.5- and 3-MeV proton irradiations.

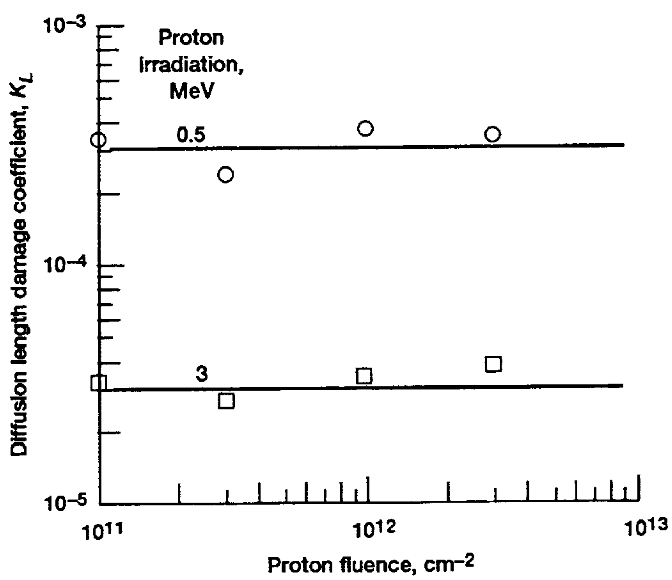

Figure 5.—Dependence of diffusion length damage coefficient on fluence in heteroepitaxial InP solar cells after 0.5- and 3-MeV proton irradiations.

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

Indium phosphide (InP) solar cells are more radiation resistant than gallium arsenide and silicon solar cells, and their growth by heteroepitaxy offers additional advantages leading to the development of lighter, mechanically strong, and cost-effective cells. Changes in heteroepitaxial InP cell efficiency under 0.5- and 3-MeV proton irradiations have been explained by the variation in the minority-carrier diffusion length. The base diffusion length versus proton fluence has been calculated by simulating the cell performance. The diffusion length damage coefficient K_L has also been plotted as a function of proton fluence.

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