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Effect of InAlAs Window Layer on Efficiency of Indium Phosphide Solar Cells

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SUMMARY

Indium phosphide (InP) solar cell efficiencies are limited by surface recombination. The effect of a wide-bandgap, lattice-matched indium aluminum arsenide ($In_{0.52}Al_{0.48}As$) window layer on the performance of InP solar cells was investigated by using the numerical code PC–1D. The p^+n InP solar cell performance improved significantly with the use of the window layer. No improvement was seen for n^+p InP cells. The cell results were explained by the band diagram of the heterostructure and the conduction band energy discontinuity. The calculated current-voltage and internal quantum efficiency results clearly demonstrated that $In_{0.52}Al_{0.48}As$ is a very promising candidate as a window layer material for p^+n InP solar cells.

INTRODUCTION

Indium phosphide (InP) solar cells have demonstrated great potential for space power because their resistance against electron (ref. 1), γ-ray (ref. 2), and proton (ref. 3) irradiations is superior to that of cells fabricated on gallium arsenide (GaAs) or silicon (Si). InP solar cells of large area (4 cm^2) and n-on-p type that are grown by metal-organic chemical vapor deposition (MOCVD) homoepitaxy with over 19-percent air-mass-zero (AM0) efficiency have been fabricated. These are the highest efficiency cells made to date (ref. 4). One of the ways to make the InP cell technology competitive for space power is to further increase the cell efficiency. However, the experimental cell efficiencies are limited by high surface recombination velocities (refs. 4 and 5). Depositing suitable passivation layers may improve the surface recombination, but unlike silicon, processing III–V compound semiconductors at high temperatures poses several problems. Using wide-bandgap window layers on GaAs (ref. 6) and Si (ref. 7) solar cells has been successful.

In this investigation we considered the effect of a wide-bandgap, lattice-matched indium aluminum arsenide ($In_{0.52}Al_{0.48}As$) window layer on the performance of InP solar cells by using the numerical code PC–1D (ref. 8). Recently InAlAs has been successfully used in several electronic and optoelectronic device structures made from InP and related materials. $In_{0.52}Al_{0.48}As$ is lattice matched to InP and has a bandgap of about 1.465 eV. We found that using $In_{0.52}Al_{0.48}As$ as a window layer significantly enhanced the p^+n InP cell efficiency. No improvement was seen in n^+p InP cells. The improvement in the p^+n cell was accounted for by the

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energy discontinuity at the heterojunction. The effect of the window layer on the p^+n InP cell's internal quantum efficiency was also studied.

THEORETICAL APPROACH

The p^+n InP cell structure with the InAlAs window layer that was considered in this work is shown in figure 1. Figure 2 depicts the calculated energy band structure of the InAlAs/InP heterostructure.

The p^+n InP cell had an emitter thickness of 0.15 μm with a doping concentration of 10^{18} cm^{-3} and a base thickness of 5 μm with a doping concentration of 10^{17} cm^{-3}. The doping concentration of the p^+ InAlAs window layer was 10^{18} cm^{-3}, and the thickness was varied from 10 to 100 nm. Moderate doping levels were considered in the window layer and the cell emitter to avoid bandgap-narrowing effects caused by heavy doping. A two-layer zinc sulfide/ magnesium fluoride (ZnS/MgF_2) antireflection coating and a 5-percent grid coverage were assumed. Minority carrier diffusion lengths of 0.5, 0.5, and 2 μm were assumed in the window, emitter, and base layers of the InP cell. Front- and back-surface recombination velocities of 10^7 cm/sec were assumed in the calculations. The InAlAs material parameters available in the literature were used where available. Other InAlAs parameters were extrapolated from values appropriate to InP. In the literature (ref. 9) a bandgap of 1.46 to 1.47 eV has been reported for $In_{0.52}Al_{0.48}As$. The value of 1.465 eV was used in this work. The discontinuity in conduction band energy ΔE_c at the heterojunction was 0.294 eV. Slightly higher values have been reported in earlier work (ref. 10); use of a higher value of ΔE_c would increase the barrier for minority carriers and hence improve cell efficiency yet further. The intrinsic carrier concentration n_i for InAlAs was scaled from the value for InP by using the relation

$$n_i(\text{InAlAs}) = n_i(\text{InP}) \exp\left(\frac{\Delta E_g}{2kT}\right) \tag{1}$$

where ΔE_g is the bandgap difference of the two materials. The value of n_i for InP used was 8×10^6 cm^{-3} (ref. 11). The optical absorption coefficient of the InAlAs was assumed to be the same as that for InP but shifted in wavelength by the bandgap ratio (1.35/1.465). The numerical code PC-1D (ref. 8) was used to solve the transport equations for the InAlAs/InP solar cell device and to calculate the cell and quantum efficiencies. More details about InP cell modeling are given in reference 12.

RESULTS AND DISCUSSION

Figure 3 shows the calculated current-voltage (I–V) characteristics (at AM0, 137.2 mW/cm^2, and 25 °C) for the p^+n InP solar cells with and without the InAlAs layer. The I–V curve for the cell without the InAlAs layer had a short-circuit current density of 26.9 mA/cm^2, an open-circuit voltage of 892.7 mV, and an efficiency of 14.37 percent (AM0). These values are comparable to values measured on existing p^+n solar cells (ref. 13).

The cell I–V curves with InAlAs window layers are for two typical thicknesses of 20 and 10 nm. The calculated AM0 efficiencies for these two thicknesses were 18.74 and 19.98 percent.

These values represent improvements in cell efficiency over the baseline cell efficiency of 14.37 percent. From figure 3 it is clear that using an InAlAs layer improved the short-circuit current density as well as the open-circuit voltage, resulting in a significant improvement in cell efficiency. As shown in figure 4 the cell efficiency was highest for the thinnest InAlAs layers, where the minimum amount of light was absorbed in the window layer. The cell efficiency improvement disappeared for window layers thicker than 100 nm, where the losses due to light absorbed by the InAlAs layer outweighed the increases due to the lower effective surface recombination velocity.

The efficiency of an InAlAs window layer on n^+p InP solar cells was also modeled, and no appreciable performance improvement was found for the range of parameters investigated. It could be understood by the theoretical and experimental studies that the InAlAs/InP heterojunction forms a *stagger* alignment, with the discontinuity in conduction band energy greater than the difference in bandgaps (ref. 10). Therefore the InAlAs will form a barrier to electrons but a sink for holes. Hence we expect that InAlAs will be effective in reducing the surface recombination velocity on p-type InP but not on n-type.

Figure 5 shows the calculated internal quantum efficiency of the p^+n InP solar cell with a 10- and a 50-nm window layer and without a window layer. The cell short wavelength improved significantly. The 10-nm window layer cell had an internal quantum efficiency of more than 80 percent in the 435- to 880-nm wavelength range, with a maximum internal quantum efficiency of 90.34 percent around 700-nm wavelength.

From the results of figures 4 and 5 it is clear that $In_{0.52}Al_{0.48}As$ is a very promising candidate as a window layer material for p^+n InP solar cells.

CONCLUSIONS

Using a wide-bandgap, lattice-matched indium aluminum arsenide ($In_{0.52}Al_{0.48}As$) window layer effectively reduced the surface recombination velocity in p^+n indium phosphide (InP) cells. Calculated p^+n InP cell efficiency and internal quantum efficiency significantly improved with the window layer.

No improvement in n^+p InP cells with an InAlAs window layer has been seen. The InP cell results were explained by the band structure and energy discontinuity at the InAlAs/InP heterojunction resulting in minority carrier confinement.

The calculated results demonstrated that $In_{0.52}Al_{0.48}As$ is a very promising candidate as a window layer material for p^+n InP solar cells.

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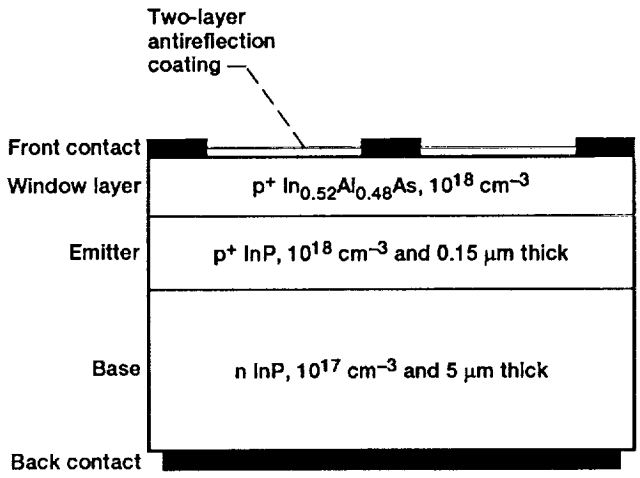

Figure 1.—Structure of a p+n indium phosphide solar cell with wide-bandgap, lattice-matched $In_{0.52}Al_{0.48}As$ window layer.

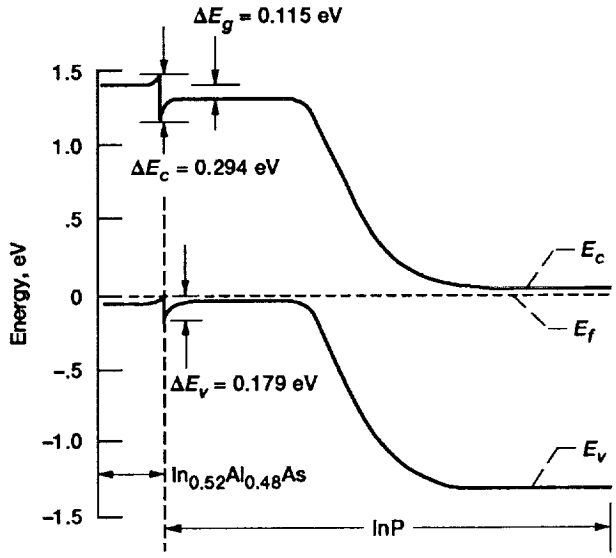

Figure 2.—Energy band structure of a p+ $In_{0.52}Al_{0.48}As$/p+ InP/n InP solar cell, where ΔE_g is bandgap difference of the two materials, ΔE_c is discontinuity in conduction band energy, ΔE_v is discontinuity in valence band energy, and E_f is Fermi level.

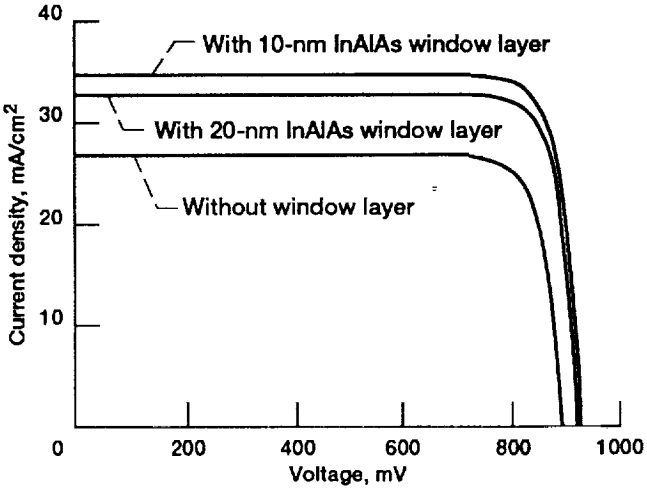

Figure 3.—Calculated I–V characteristics of a p+n indium phosphide solar cell with a 20- and a 10-nm $In_{0.52}Al_{0.48}As$ window layer and without a window layer. p+n InP AM0 cell efficiency: 14.73 percent (without window layer),18.74 percent (with 20-nm window layer), and 19.98 percent (with 10-nm window layer); air mass zero; intensity of sunlight outside Earth's atmosphere, 137.2 mW/cm^2; temperature, 25 °C.

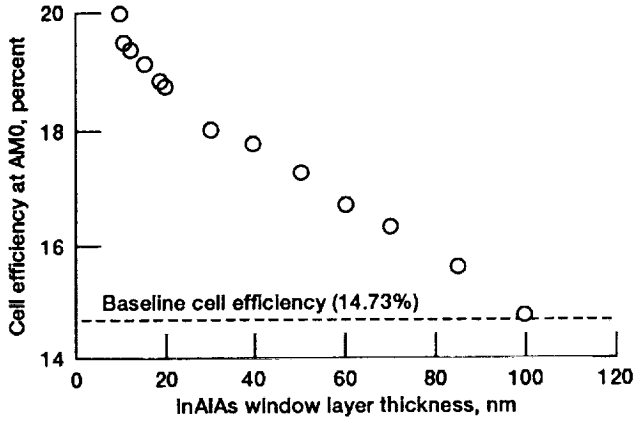

Figure 4.—Calculated efficiency of a p+n InP solar cell as a function of $In_{0.52}Al_{0.48}As$ window layer thickness. Air mass zero; intensity of sunlight outside Earth's atmosphere, 137.2 mW/cm^2; temperature, 25 °C. Dashed line shows the conversion efficiency of the baseline cell with no window layer.

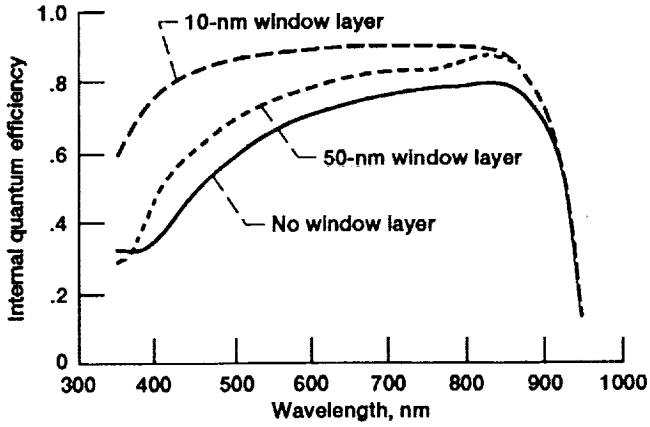

Figure 5.—Calculated internal quantum efficiency of a p^+n indium phosphide solar cell with a 50- and a 10-nm $In_{0.52}Al_{0.48}As$ window layer and without a window layer.

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

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