N94-11389

SURFACE PASSIVATION OF InP SOLAR CELLS WITH InAlAs LAYERS

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The efficiency of indium phosphide solar cells is limited by high values of surface recombination. This work investigates the effect of a lattice-matched $In_{0.52}Al_{0.48}As$ window layer material for InP solar cells, using the numerical code PC-1D. We have found that the use of InAlAs layer significantly enhances the p^+n cell efficiency, while no appreciable improvement is seen for n^+p cells. The conduction band energy discontinuity at the heterojunction helps in improving the surface recombination. An optimally designed InP cell efficiency improves from 15.4% to 23% AM0 for a 10 nm thick InAlAs layer. The efficiency improvement reduces with increase in InAlAs layer thickness, due to light absorption in the window layer.

INTRODUCTION

Indium phosphide solar cells have great potential for space photovoltaic power applications due to their superior radiation resistance (refs. 1,2). However, experimental cell efficiencies are limited by high surface recombination (refs. 3,4). This work investigates the effect of a wide-bandgap lattice-matched $In_{0.52}Al_{0.48}As$ window layer on InP solar cells, using a numerical code PC-1D (ref. 5). PC-1D is a quasi-one-dimensional program operated on a personal computer for investigating the transport of electrons and holes in semiconductor devices. The semiconductor device transport equations are solved by a finite-element approach. We have found that the use of InAlAs as a window layer significantly enhances the p^+n InP cell efficiency, while no appreciable improvement is seen for n^+p cells. The performance enhancement in p^+n cells is due to the energy discontinuity at the heterojunction, as shown in Fig. 1. The InAlAs window layer acts as a minority carrier mirror and confines the minority carrier electrons in the cell emitter region.

Preliminary calculations on the effect of the window layer on performance of a baseline (unoptimized) p^+n cell are available elsewhere (ref. 6). This paper discusses the effects of the window layer on an optimally designed p^+n InP cell.

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[1]This work was done while the author held a National Research Council - NASA Lewis Research Center Associateship.

NUMERICAL APPROACH AND RESULTS

The previously presented results ("baseline cell") used materials parameters estimated to be of typical of solar cells currently fabricated. In this work we use parameters which we believe are achievable in InP. This is referred to as the "optimized" cell. The minority carrier lifetimes, diffusion lengths, and mobilities are shown in Table I. As can be seen, an improvement of 2 - 5 times in minority carrier diffusion length from the "baseline" to the "optimized" cell is required. The optimized p^+n InP cell model has been reported elsewhere (refs. 4,7). The InP solar cell structure is shown in Fig. 2. The front surface recombination velocity (SRV) has been assumed equal to 10^7 cm/s. Using PC-1D, we obtain an efficiency for the p^+n optimized InP cell with no window layer of 15.4% AM0. This cell efficiency is limited by front SRV, and could be increased to over 24% if the SRV could be reduced from 10^7 to 10^4 cm/s (ref. 4). The reduction in SRV could be effectively accomplished by the use of window layer, similar to improved results obtained on gallium arsenide (ref. 8) and silicon (ref. 9) solar cells.

Data on minority carrier lifetime in p^+ InP is sparse. Lifetime at concentrations up to $4x10^{17}$ cm^{-3} were measured (ref. 10). At $4x10^{17}$ cm^{-3}, the lifetime was slightly greater than 1 nS. Since the curve shows that the lifetime decreases with concentration, a lifetime under 1 nS is expected for concentration of 10^{18} cm^{-3}. A recent paper (ref. 11) however, indicates a lifetime over 3 nS at 10^{18} cm^{-3}. This work also suggests that in the range of 10^{15} cm^{-3} to 10^{17} cm^{-3}, minority carrier lifetime in p-type InP increases as doping increases, which is unexpected behavior. Until better lifetime data is available, the assumed value of 0.73 nS at 10^{18} cm^{-3} is a reasonable estimate lying between the two measured values.

In the present work we have considered the use of wide-bandgap lattice-matched $In_{0.52}Al_{0.48}As$ as a window layer. The p^+n InP solar cell structure with InAlAs window layer is shown in Fig. 2. An InAlAs doping of 10^{18} cm^{-3} was assumed, equal to the emitter doping. Moderate doping levels were considered to avoid heavy doping effects such as band gap narrowing. The minority carrier diffusion length was assumed to be 2 μm in the window layer. The InAlAs window layer thickness was varied from 10 nm to 200 nm. The InAlAs material parameters available in the literature were used and others (n_i, α) were extrapolated from values appropriate to InP as described in reference 6.

Figure 3 shows the calculated I-V characteristics of the p^+n InP cell with no window layer, and with window layer thicknesses of 10, 50, 100, and 150 nm. All results are calculated under AM0 illumination at 137.2 mW/cm^2 and 25 °C. The optimized InP cell efficiency without InAlAs layer is 15.4% AM0. Efficiency is significantly enhanced by the window layer. For a 10 nm thick window layer the calculated efficiency improves to 23% AM0. Efficiency decreases as the InAlAs layer thickness increases, due to increased light absorption in the window layer. Figure 4 shows the calculated p^+n InP cell efficiency as a function of window layer thickness. The optimized InP cell has a higher minority carrier diffusion lengths than the baseline cell, and the cell efficiency improvement due to the window layer is higher because the effect of surface recombination is more important as the other recombination is decreased. For comparison, calculated results for the baseline cell are also plotted. Compared to n^+p cells, p^+n cells have relatively thicker emitters and are more sensitive to surface recombination than n^+p structures [see calculated results (ref. 12), shown in Fig. 5]. The window layer improves the short circuit current as well as the open circuit voltage as seen in Fig. 3. The open circuit voltage changes little (975 to 970 mV) with the increase in window layer thickness from 10 nm to 150 nm. The short circuit current decreases with window layer thickness, and for a 150 nm thick window layer, the current is even lower than that of the optimized cell without a window layer (27.8 mA/cm^2).

The previous calculations have assumed that the doping of the window layer is identical to that of the emitter, 10^{18} cm^{-3}. As seen in Fig. 1, there is a discontinuity ΔE_c of about 179 mV in the valence band edge. The requirement that the Fermi level must be constant across the heterojunction forces the bands to bend, forming a positive energy spike (i.e., hole accumulation) in the valence band on the InAlAs side of the heterojunction, and a corresponding negative energy dip (i.e., hole depletion) on the InP side of the heterojunction. Correspondingly, the spike and dip result in electron depletion and accumulation on the InAlAs and InP sides of the heterojunction respectively.

If the doping is increased by a factor of $\exp(\Delta E_c/kT) = 10^3$ from the InP to the InAlAs, the spike and dip in the energy bands will vanish. This would require the doping of the p^+ emitter to be reduced to 10^{15} cm^{-3} if the window layer doping is held constant at 10^{18} cm^{-3}, or increasing the window doping to 10^{21} cm^{-3} if the emitter doping is held constant at 10^{18} cm^{-3}.

Reducing the emitter doping would decrease the cell voltage and increase the emitter sheet resistance. Because of the high sheet resistance of the emitter in p/n cells, this is not practical.

While increasing the window layer doping would be advantageous, there are two difficulties: (1) there is little or no information about the growth and properties of heavily doped p-type InAlAs, (2) doping above 10^{18} cm^{-3} will require heavy-doping corrections (particularly bandgap narrowing) to the InAlAs parameters, which will reduce the performance. Experimental information on heavy doping effects in p-type InAlAs is to date lacking.

Figure 6 shows the effect of the window layer doping on cell performance, where heavy doping effects have not been included. This curve shows that higher doping levels in the window layer result in increased performance. However, heavy doping effects will cause this curve to turn down at the high doping side of the scale.

The enhanced cell performance clearly demonstrate that the wide-bandgap lattice matched $In_{0.52}Al_{0.48}As$ is effectively reducing the surface recombination. The conduction band discontinuity at the heterojunction (InAlAs/InP), shown in Fig. 1, helps in confining the electrons in the cell emitter region, resulting in lower recombination.

The effect of an InAlAs window layer on an n^+p InP cell was also modeled, but resulted in no appreciable improvements in efficiency. Table II describes the calculated efficiency results for no window layer, 10nm and 50 nm InAlAs layers for n^+p baseline and optimized InP cells. Table I also describes the assumed n^+p indium phosphide solar cell parameters. The baseline cell represents approximately the current state-of-art technology (ref. 3). Figure 7 shows the calculated current-voltage characteristics of an n^+p baseline solar cell (ref. 13). A 10 nm window layer offers a slight improvement in efficiency but calculated cell efficiency reduces for thicker window layers. For all calculations a front SRV of 10^7 cm/s was assumed. The use of InAlAs on optimized n^+p InP cell offers slightly better improvement for 10 nm thick window layer, but still not significant. We were not able to calculate cell performance for window layers less than 10 nm thick using PC-1D. It may be possible to achieve improved results for window layers thinner than 10 nm. Quantum well structures with $In_{0.52}Al_{0.48}As$ layers around 5 nm thick have been fabricated successfully. To understand the performance of very-thin windows on solar cells will require a better understanding of the effects of the interface and surface and their interactions.

CONCLUSIONS

In summary, calculations have shown that significant efficiency improvements could be achieved by using $In_{0.52}Al_{0.48}As$ as a window layer material in p^+n indium phosphide solar cells. Cell efficiencies as high as 23% could be achieved with a 10 nm thick window layer. No appreciable improvement on n^+p InP cells has been seen with InAlAs window layer. The performance improvement is caused by the effective reduction in the surface recombination velocity due to minority carrier confinement by the conduction band energy discontinuity. The hetero-interface acts as a minority carrier mirror.

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TABLE I. Assumed baseline and optimized p^+n and n^+p indium phosphide solar cell parameters.

	EMITTER				BASE			
InP Solar Cell	Doping (cm^{-3})	Lifetime (nS)	Mobility (cm^2/V-S)	Diff.Length (μm)	Doping (cm^{-3})	Lifetime (nS)	Mobility (cm^2/V-S)	Diff. Length (μm)
Baseline	10^{18} p	0.046	2100	0.5	10^{17} n	25	65	2
Optimized	10^{18} p	0.733	2100	2	10^{17} n	151	65	5
Baseline	10^{18} n	0.025	40	0.05	10^{17} p	3.5	2800	5
Optimized	10^{18} n	0.1	40	0.1	10^{17} p	56	2800	20

TABLE II. Effect of InAlAs window layer on the performance of n^+p InP solar cell.

InAlAs Window Layer Thickness, nm	**Baseline n^+p InP Cell Efficiency, %**	**Optimized n^+p InP Cell Efficiency, %**
no window layer	19.5	21.5
10	19.6	22.6
50	16.3	19.8

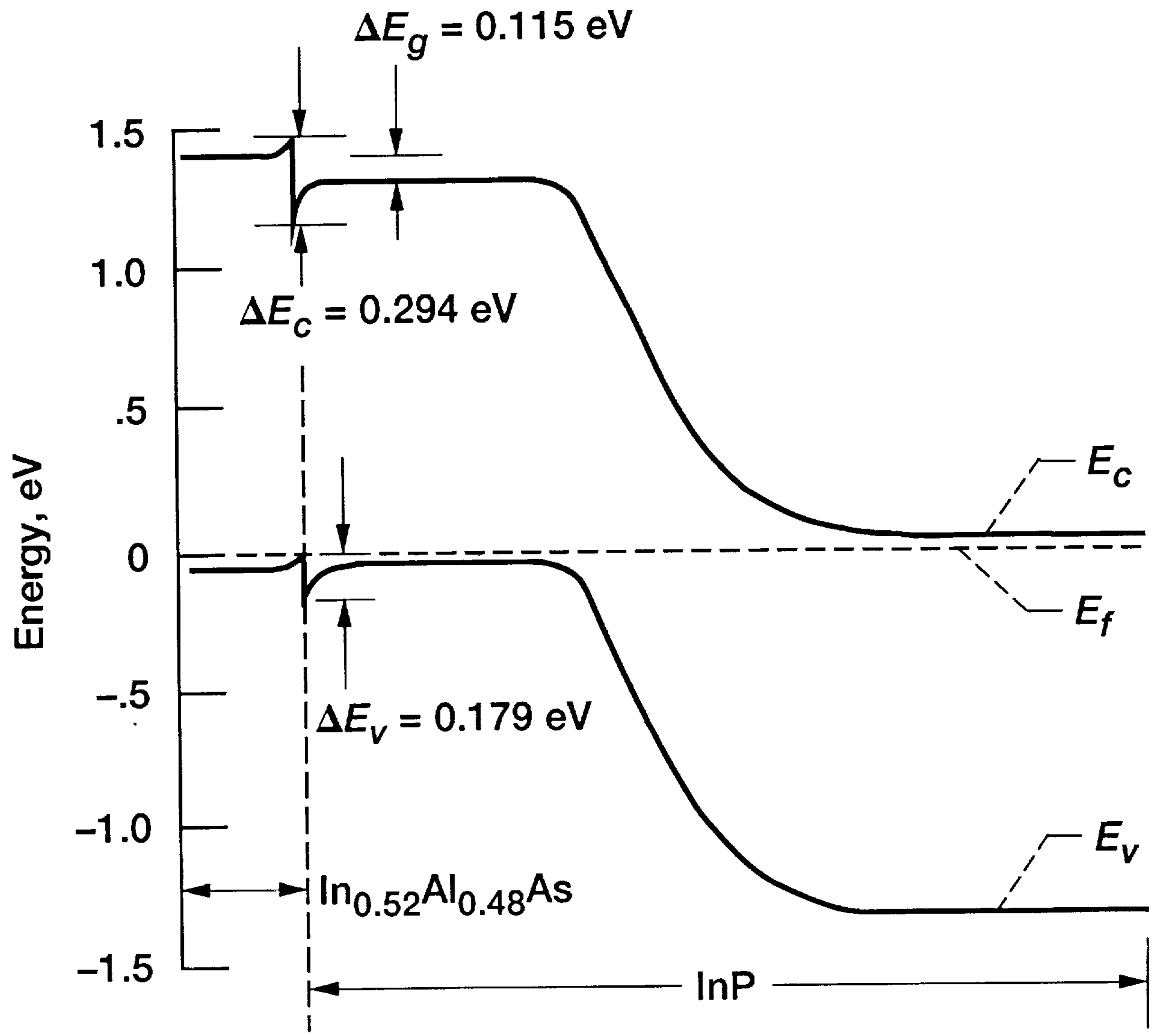

Fig. 1 Energy band diagram of a p+ InAlAs/p+ InP/n InP solar cell.

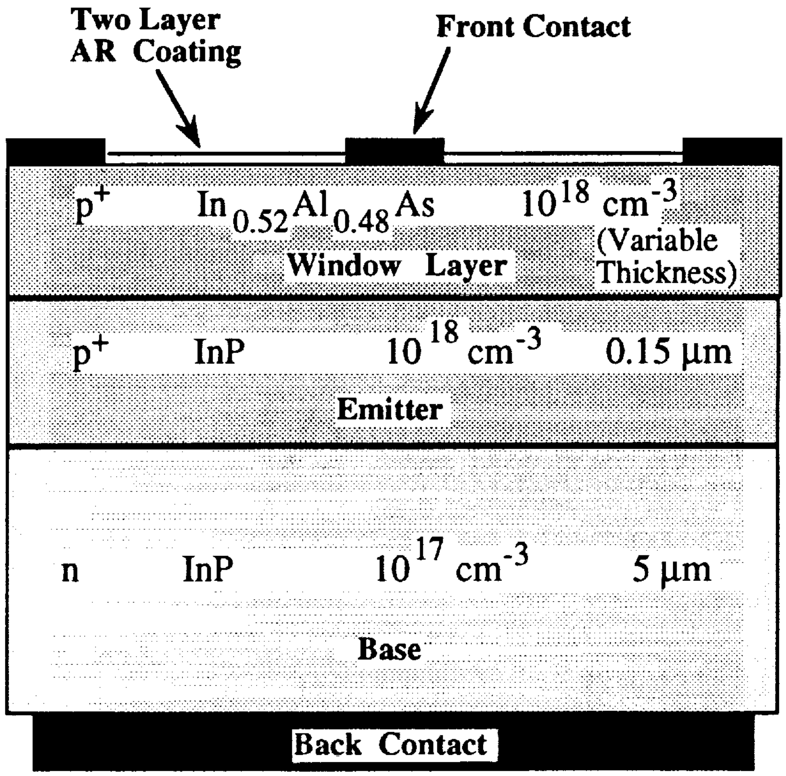

Fig. 2 Structure of a p^+n InP solar cell with an InAlAs window layer.

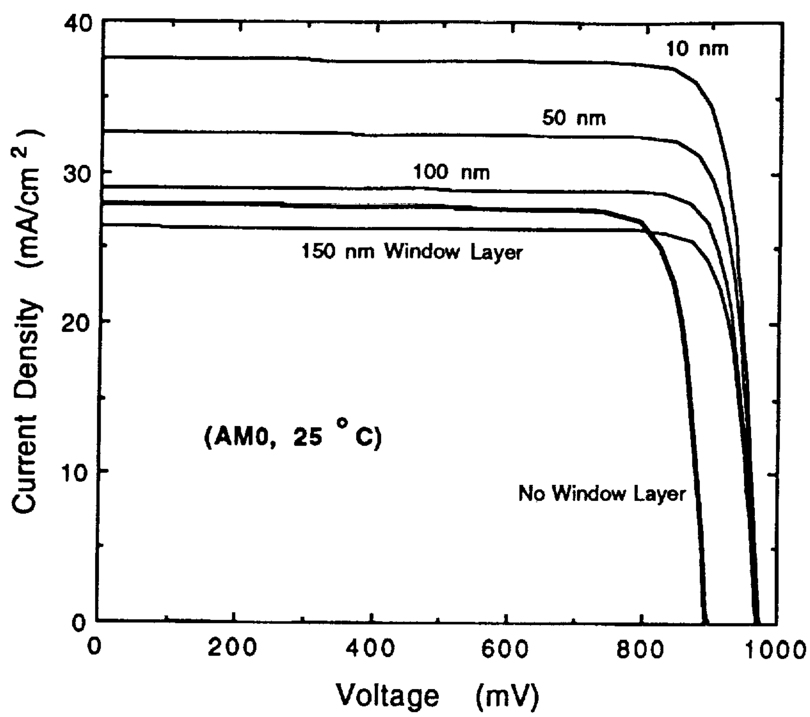

Fig. 3 Calculated I-V characteristics of a p^+n InP solar cell with and without InAlAs window layer.

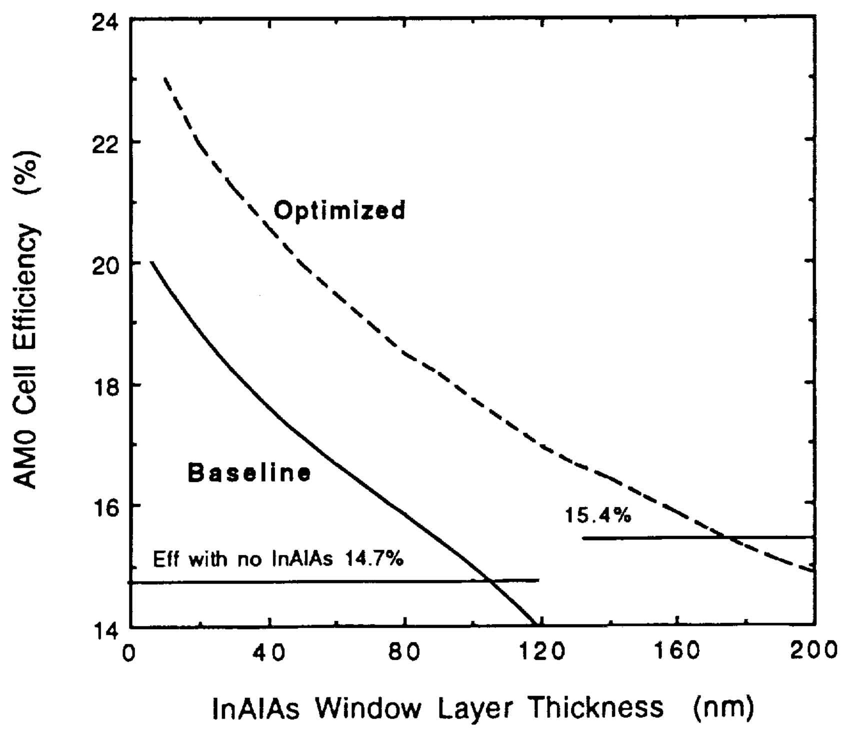

Fig. 4 Variation of p^+n InP solar cell efficiency with InAlAs window layer thickness.

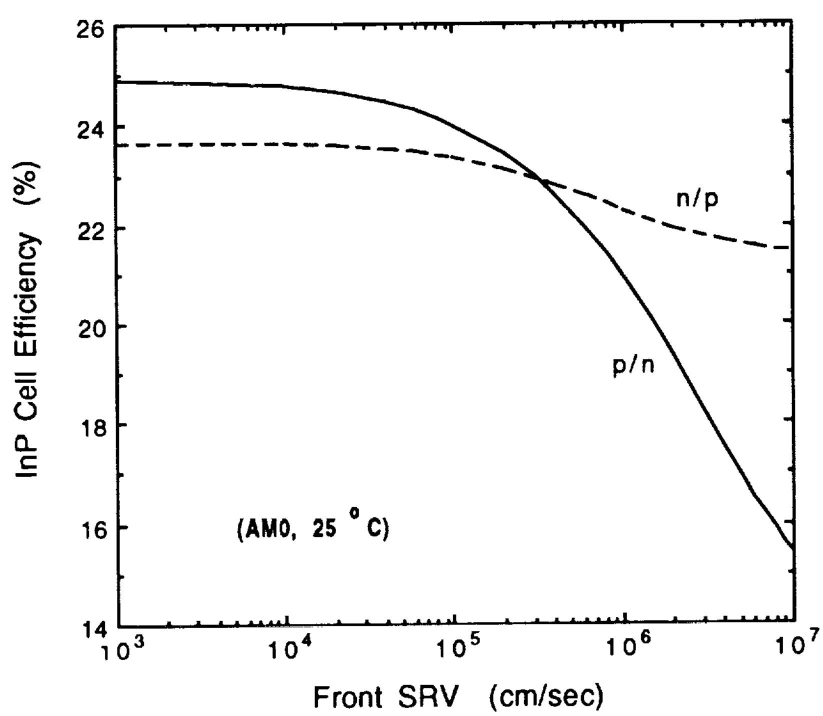

Fig. 5 Effect of the front surface recombination velocity on the calculated efficiency of the optimized n^+p and p^+n InP solar cells (ref. 12).

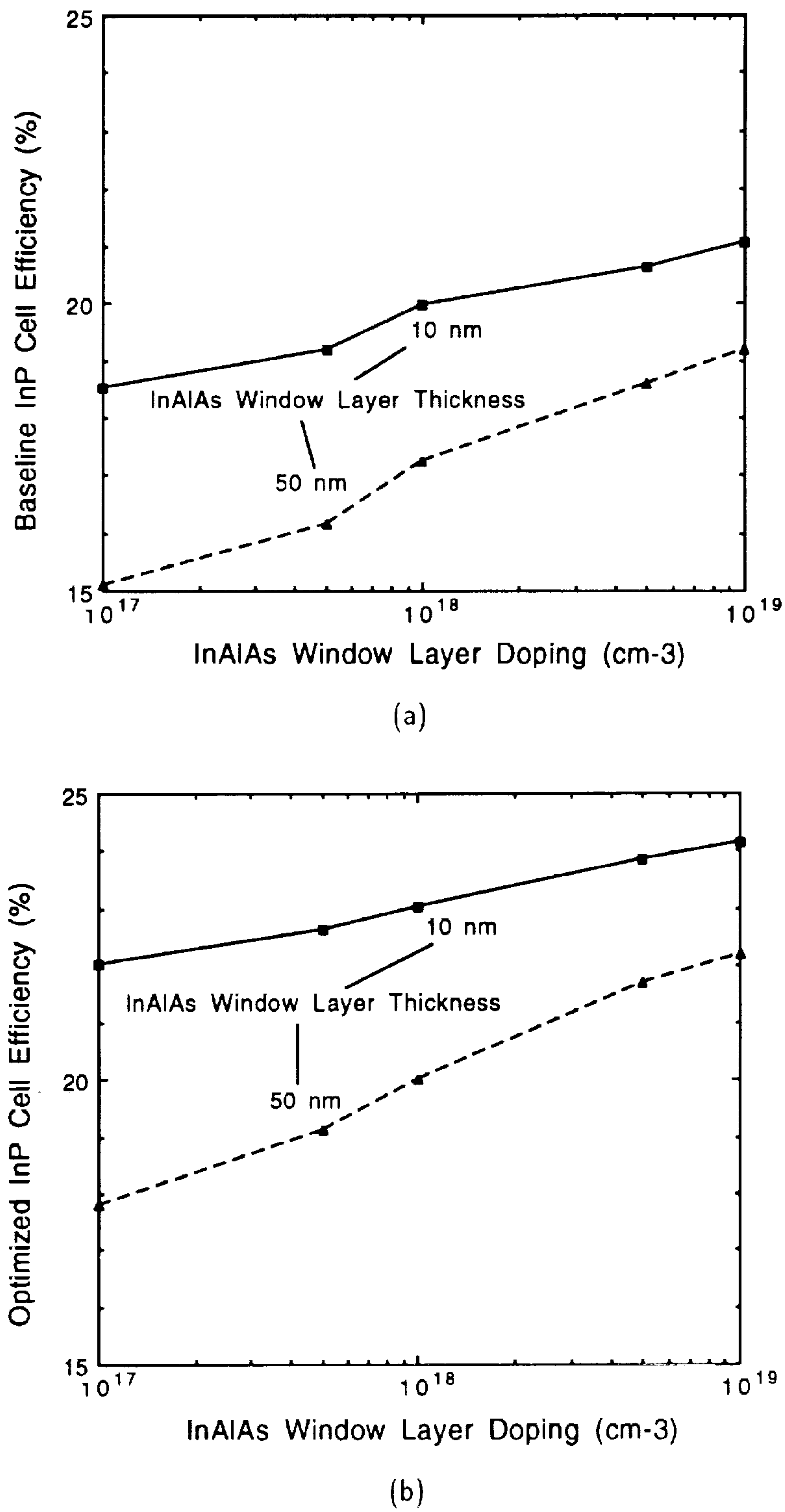

Fig. 6 Variation of p^+n InP solar cell efficiency with InAlAs window layer doping.

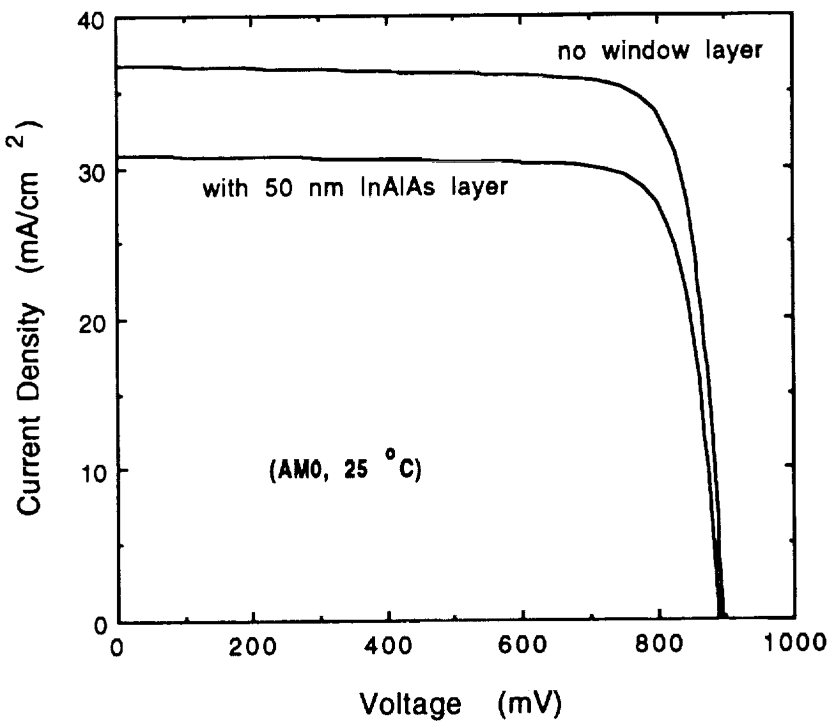

Fig. 7 Calculated I-V characteristics of an n^+p InP baseline solar cell with and without InAlAs.