

## INDIUM PHOSPHIDE WINDOW LAYERS FOR INDIUM GALLIUM ARSENIDE SOLAR CELLS

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Window layers help in reducing the surface recombination at the emitter surface of the solar cells resulting in significant improvement in energy conversion efficiency. Indium gallium arsenide ( $\text{In}_x\text{Ga}_{1-x}\text{As}$ ) and related materials based solar cells are quite promising for photovoltaic and thermophotovoltaic applications. The flexibility of the change in the bandgap energy and the growth of InGaAs on different substrates make this material very attractive for multi-bandgap energy, multi-junction solar cell approaches. The high efficiency and better radiation performance of the solar cell structures based on InGaAs make them suitable for space power applications. This work investigates the suitability of indium phosphide (InP) window layers for lattice-matched  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  (bandgap energy 0.74 eV) solar cells. We present the first data on the effects of the p-type InP window layer on p-on-n lattice-matched InGaAs solar cells. The modeled quantum efficiency results show a significant improvement in the blue region with the InP window. The bare InGaAs solar cell performance suffers due to high surface recombination velocity ( $10^7$  cm/s). The large band discontinuity at the InP/InGaAs heterojunction offers a great potential barrier to minority carriers. The calculated results demonstrate that the InP window layer effectively passivates the solar cell front surface, hence resulting in reduced surface recombination and therefore, significantly improving the performance of the InGaAs solar cell.

### INTRODUCTION

Window layers are quite important in improving the solar cell energy conversion efficiency. They help in effectively reducing the surface recombination at the emitter surface of the solar cell without absorbing the useful light required for the device. Unlike silicon, solar cells based on III-V compound semiconductors and related materials suffer from the lack of native passivating oxides and/or wide choice of suitable large bandgap energy window materials. Various window layer materials have been investigated for III-V compound semiconductor based solar cells [1]. Further optimization work on the existing choices of windows and more development work on new window materials are required. It is also important to understand the physics of the window-emitter hetero-interface as well as growth related issues.

Indium gallium arsenide ( $\text{In}_x\text{Ga}_{1-x}\text{As}$ ) material has been used widely in several state-of-the-art electronic and optoelectronic devices.  $\text{In}_x\text{Ga}_{1-x}\text{As}$  and related materials based solar cells are quite promising for photovoltaic (PV) [2] and thermophotovoltaic (TPV) applications [3].  $\text{In}_x\text{Ga}_{1-x}\text{As}$  is a ternary semiconductor whose bandgap energy can be varied between 1.42 eV (of GaAs) and 0.36 eV (of InAs) by changing the In/Ga ratio (see Fig. 1). The flexibility of the change in the bandgap energy and the growth of InGaAs on different substrates (Si, Ge, GaAs, InP, InAs) make this material very attractive for various devices. InGaAs solar cells grown on gallium arsenide (GaAs) substrates were developed twenty years ago [4]. The 1.15 eV and 1.35 eV bandgap energy InGaAs on GaAs cells

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demonstrated efficiencies in excess of 24% at 400-sun concentration [5]. These developments were intended for the use of InGaAs cells in multi-bandgap energy, multi-junction solar cell approaches. Two-junction monolithic InP/InGaAs tandem cells grown on InP substrates have demonstrated AM0 1-sun efficiencies over 22% [6].

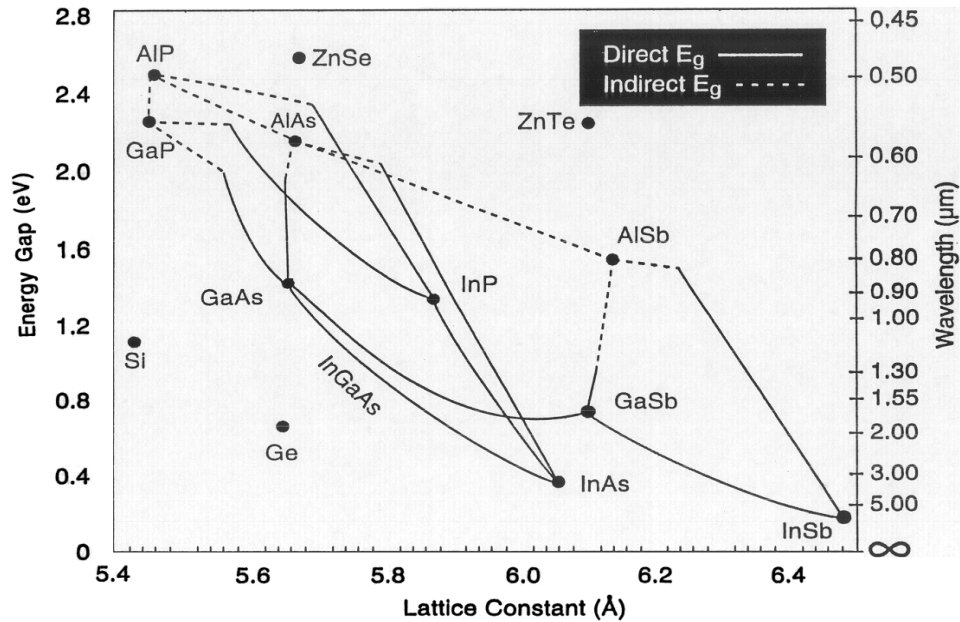


Figure 1. Bandgap energy of indium gallium arsenide and related materials as a function of lattice constant.

Record efficiency n-on-p and p-on-n lattice-matched InGaAs (0.74 eV bandgap energy) solar cells grown on InP were reported [7,8]. Lower bandgap energy (0.74 eV and below) InGaAs cells grown on InP substrates offer high efficiencies [9] for thermophotovoltaic applications and have been developed [8]. InGaAs based solar cells also find use in quantum well, operation under monochromatic light, and related applications. The demonstration of high PV and TPV efficiencies and better radiation performance [10] of the solar cell structures based on InGaAs solar cells make them attractive for space power applications. InGaAs and related materials based solar cells grown on GaAs substrates for applications in tandem cells are getting renewed interest and are under investigation. The InGaAs based cell technologies on GaAs substrates could easily be adopted later on germanium (Ge) substrates [2], similar to high efficiency GaInP/GaAs/Ge dual or triple-junction cells grown on Ge substrates.

InGaAs solar cells have been fabricated with or without window layers but no quantitative theoretical or experimental data on the effects of window materials are available in the literature. This work investigates the suitability of indium phosphide (InP) window layers for lattice-matched  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  (bandgap energy 0.74 eV) solar cells. We present the data on the effects of the p-type InP window layer on p-on-n lattice-matched InGaAs solar cells. p-on-n structure was selected for further investigation and development as it offered better optical and electrical properties than n-on-p structure. The calculated quantum efficiency results demonstrate the suitability of the InP window in effectively reducing the surface recombination at the front surface of the InGaAs cell resulting in significant improvements in the blue response. The large band discontinuities at the heterojunction provide a great potential barrier for the minority carriers. PC1D computer code [11] was used in performing the numerical calculations.

## MODELING APPROACH

### InGaAs Material Parameters

The InGaAs solar cell modeling requires an accurate knowledge about the various physical parameters. Little or no experimental information is available about the various physical parameters of lattice-matched or mismatched InGaAs material. The optical absorption coefficient and the intrinsic carrier concentration are very important parameters, which greatly influence the solar cell current and voltage respectively. Jain et al. [12,9] provided the first estimated and calculated data on these two important parameters based on available information. Figure 2 shows the optical absorption coefficient versus wavelength for the lattice-matched 0.74 eV bandgap energy InGaAs at 300 K.

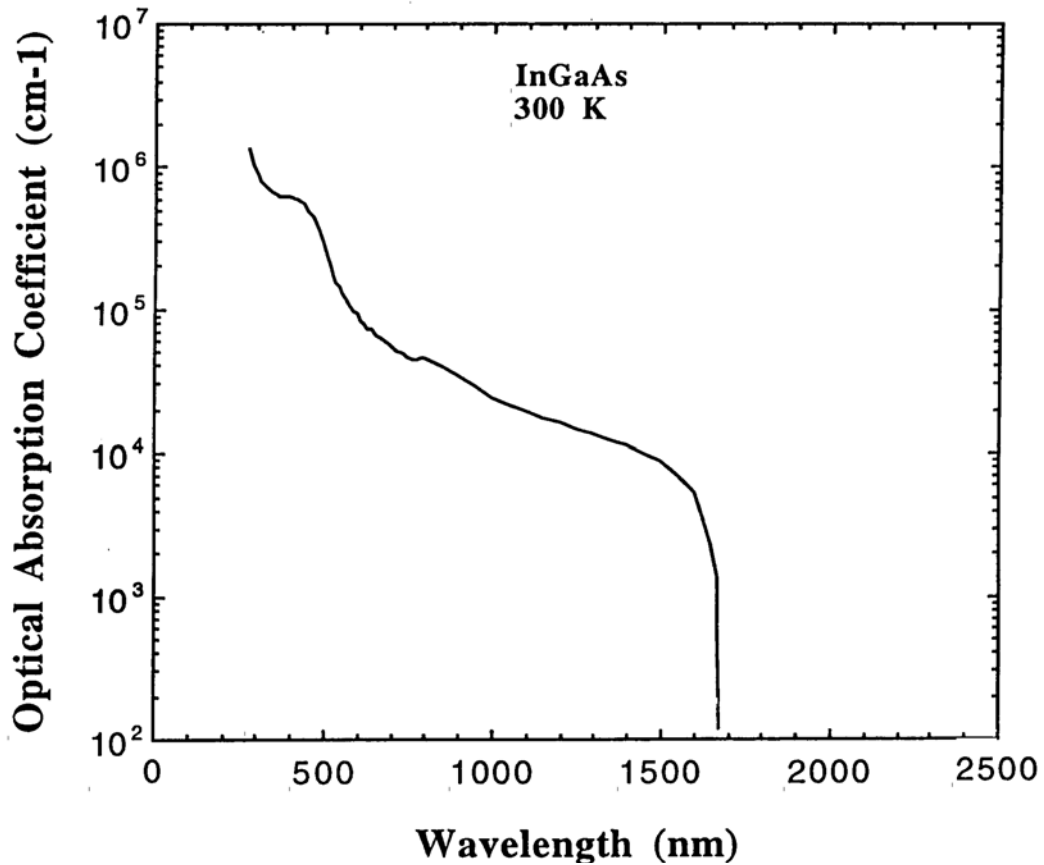


Figure 2. Optical absorption coefficient of lattice-matched InGaAs (0.74 eV bandgap energy) versus wavelength at 300 K.

The intrinsic carrier concentration,  $n_i$  for InGaAs was calculated by using the scaling relation described by Jain et al. [12],

$$n_i(\text{InGaAs}) = n_i(\text{GaAs}) \exp\{-\bullet E_g/(2kT)\} \quad (1)$$

where  $\bullet E_g$  is the bandgap difference,  $k$  is the Boltzman's constant, and  $T$  is the temperature in K. Figure 3 shows the plot of the intrinsic carrier concentration vs. InGaAs bandgap energy at 300 K. An  $n_i$  value of  $2.59 \times 10^6 \text{ cm}^{-3}$  for GaAs at 300 K was used. As the bandgap energy of InGaAs decreases (with increase in In/Ga ratio), the  $n_i$  value increases and correspondingly the open-circuit voltage of the InGaAs solar cell decreases. The absorption coefficient versus wavelength values (Fig. 2) and the  $n_i$  value at 0.74 eV (Fig. 3) were used in modeling the performance of the lattice-matched InGaAs solar cell. Similarly, the various physical parameters for the InP window material were used from the literature.

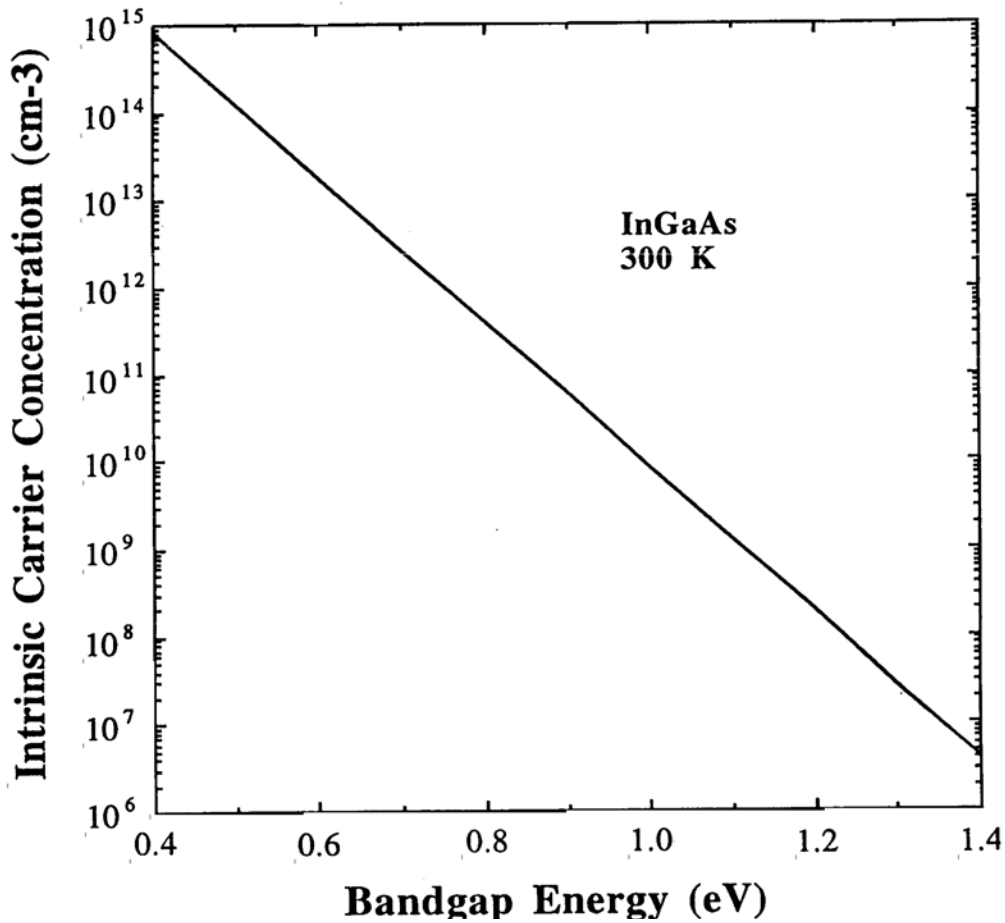


Figure 3. Plot of the intrinsic carrier concentration versus InGaAs bandgap energy at 300 K.

#### InP/InGaAs Interface Band Structure

InP forms a heterojunction with InGaAs and the InP/InGaAs interface plays an important role in controlling the performance of the devices based on these materials. The bandgap energy difference between the two materials causes the mis-alignment of the conduction and valence bands resulting into band discontinuities. The band offsets in InP/InGaAs heterojunction structures have been studied experimentally and theoretically. Reference 13 describes the various values for the conduction band and the valence band discontinuities ( $\bullet E_c$  and  $\bullet E_v$ ) measured and calculated by several research groups.

We have used average experimental values of 0.23 eV and 0.37 eV for  $\Delta E_C$  and  $\Delta E_V$  respectively in this work. Figure 4 shows our calculated band structure diagram for the p-InP/p-InGaAs heterojunction. These results have been discussed in detail in the next section.

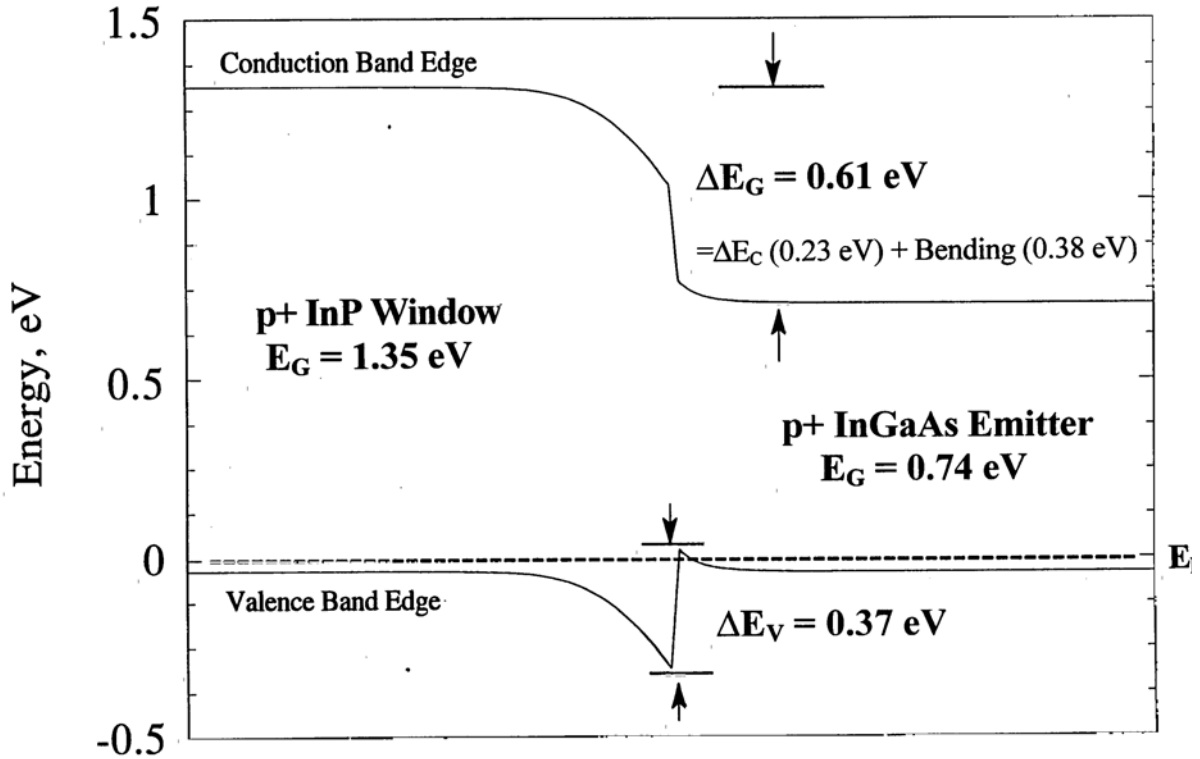


Figure 4. Band structure diagram of p-InP/p-In<sub>0.53</sub>Ga<sub>0.47</sub>As (window/emitter) heterojunction interface.

## RESULTS AND DISCUSSION

For the past several years, we have been using a numerical code PC1D for silicon and III-V compound semiconductor based (GaAs, InP, InGaAs, GaInP, etc.) solar cell modeling and simulation of the measured cell performance to understand and provide feedback for further improvements to produce state-of-the-art devices. This work has resulted in several publications and a US patent [14]. NASA Lewis (now Glenn) Research Center has been continuing the pioneering work on the development of InGaAs based solar cells [15-17] and has reported record cell efficiencies [7,8].

In this work we have considered a p-on-n lattice-matched InGaAs solar cell grown on InP substrate. Figure 5 shows the cell structure considered. The emitter and base thickness and doping concentration were 0.3  $\mu\text{m}$ ,  $2 \times 10^{18} \text{ cm}^{-3}$  and 4  $\mu\text{m}$ ,  $1 \times 10^{17} \text{ cm}^{-3}$  respectively. The p InP window layer doping concentration was  $2 \times 10^{18} \text{ cm}^{-3}$ , same as in the emitter. No antireflection coatings were considered to separate the effects of the window layer on the performance of the InGaAs solar cell. Minority carrier diffusion lengths of 0.5, 1, and 4  $\mu\text{m}$  have been assumed in the window, emitter and base layers. The front, interface and the back surface recombination velocities were assumed to be  $10^7$ ,  $10^7$ , and  $10^4 \text{ cm/s}$ . These values are typical of the current state-of-the art in p-on-n InGaAs solar cells. The heterojunction band structure parameters were used in modeling calculations.

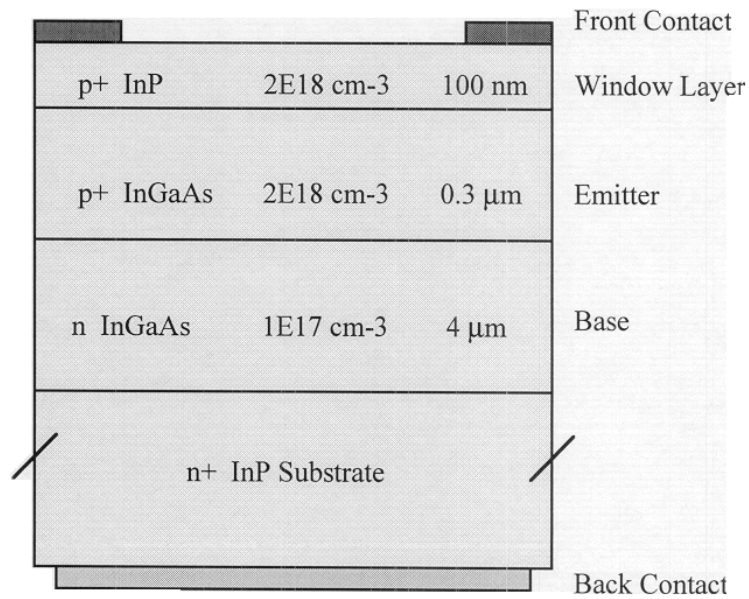


Figure 5. Structure of an InP/In<sub>0.53</sub>Ga<sub>0.47</sub>As p-on-n solar cell.

Figure 6 shows the calculated internal quantum efficiency response for the InGaAs solar cell with and without InP window layer. A 100 nm thick window layer was considered. Calculations were

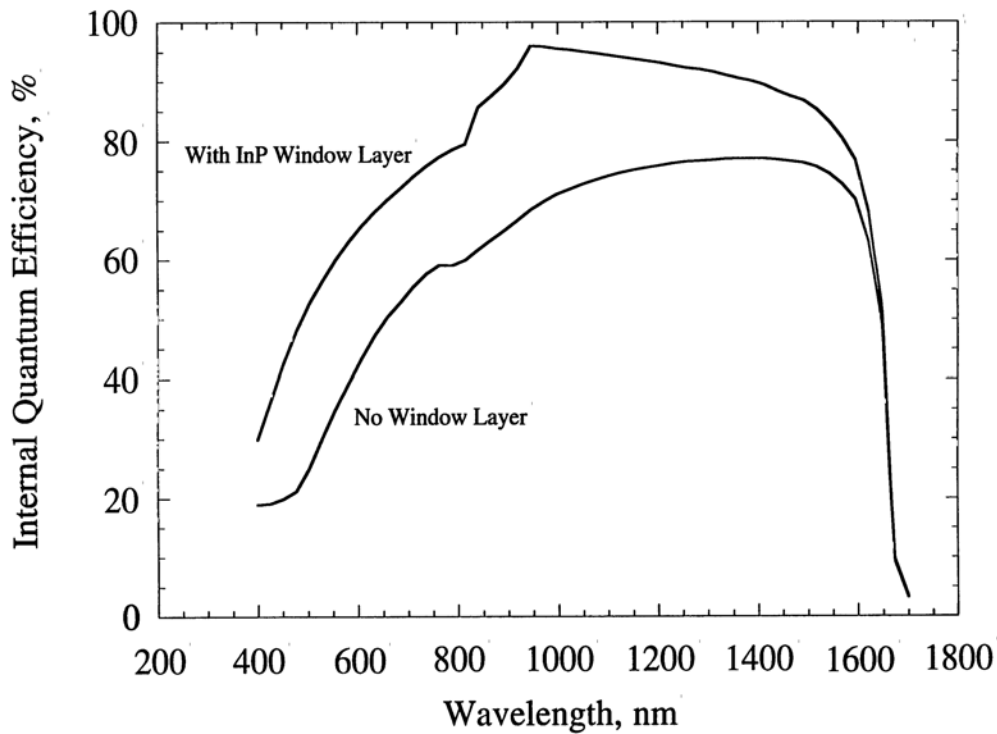


Figure 6. Plot of the internal quantum efficiency versus wavelength of p-on-n InGaAs solar cell with and without InP window layer.

performed by varying the window layer thickness and no significant difference in results was observed. This suggests that the wide-bandgap 1.35 eV InP window layer material does not absorb the light useful to InGaAs solar cell. There is a significant improvement in internal quantum efficiency, especially in the blue region, with window layer as shown in Figure 6. These results can be explained by the large conduction band discontinuity as shown in Figure 4. This discontinuity of 0.61 eV  $\{= \bullet E_c (0.23 \text{ eV}) + \text{Band bending } (0.38 \text{ eV})\}$  acts as an effective potential barrier for the minority carriers (electrons) of the p-on-n InGaAs cell, thereby stopping them from recombining at the surface. We have also calculated the effect of InP as a back surface passivation layer for InGaAs solar cells and found that the red response increases significantly. Detailed results will be published elsewhere.

## CONCLUSIONS

The modeling results demonstrate the suitability of InP window layer material for lattice-matched InGaAs p-on-n solar cells. The internal quantum efficiency response significantly improves with window layer. These results can be explained by the large conduction band offset which acts as a potential barrier to minority carriers. Hence, InP reduces the surface recombination and effectively passivates the InGaAs surface. InGaAs based solar cells have been developed in single and multijunction structures for space photovoltaic and thermophotovoltaic applications. The current work and future developments should benefit from the results reported in this paper.

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