

# Indium (In) Effects to The Efficiency Performance of $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$ Based Solar Cell Using Silvaco Software Modelling & Simulation

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**Abstract.**  $\text{Ga}_{1-x}\text{In}_x\text{P}$  composition has been applied to the top cell of multi-junction  $\text{GaInP}/\text{GaAs}$  based solar cell and currently have achieving a conversion efficiency of more than 46%, however its capability is unclear. We performed an analysis using Silvaco simulation method to evaluate the effect of In and the substitution was made to the  $\text{Ga}_{1-x}\text{In}_x\text{P}$  for the range of  $x$  from 0 to 1. We found that the highest efficiency recorded was 17.66% when the composition of Indium was  $x=1$ . The efficiency has been increasing about 11.71% from  $x=0$  to  $x=1$  In content. As the composition of In raised, the value of efficiency and short circuit current density,  $J_{sc}$  also become higher ( $13.60 \text{ mA/cm}^2$ ) by having a greater photon absorption in a wider band gap energy. In addition to that,  $V_{oc}$ ,  $P_{max}$ ,  $V_{max}$ ,  $I_{max}$  and fill factor was measured to be 2.15 V,  $2.44 \text{ mW/cm}^2$ , 2.0 V,  $1.22 \text{ mA/cm}^2$  and 83.34 respectively. In conclusion, this study confirms that the existence of In in  $\text{Ga}_{1-x}\text{In}_x\text{P}$  improves the solar cell efficiency by gaining a higher energy gap and producing more electrons for best achievement in multilayer solar cell applications.

## 1. Introduction

Multi-junction solar cells is a natural extension of single-junction cells and has been one of the most promising choices to capably convert the light into electrical energy [1–4]. GaAs based compound multi-junction devices are low band gap components of the most efficient solar cells [5]. It is required to limit the losses and improve the efficiency of photovoltaic (PV) cells in order to obtain a high performance PV cell [6,7]. In order to control the amount of current produced at a time, the selection of materials with certain energy gap for each layer is very important [8].

Recent papers have reported that the efficiency around 30% for GaInP on a Ge substrate have been obtained [9]. After that, Si-based has replaced Ge-based bottom cells because it is cheaper than other material and most widely used in semiconductor device and solar cell industry [10]. The growth of



compound semiconductor-based cells on Si-based bottom cell has been reported [11]. It is difficult to develop a multilayer cell with a large number of subcells on Si substrates because of a different thermal coefficients and lattice constant of semiconductor materials for the respective subcells. Hence, to prevent a lattice mismatch among materials, a two-layer cells or tandem cell is preferable to be investigated. GaInP/Si solar cell previously reported to achieve the experimental efficiency about 9.9–10.4% [12] and our previous research reported that the simulation efficiency of  $\text{Ga}_{0.5-x}\text{In}_{0.5}\text{P}/\text{Si}$  with the contribution of  $x=0.5$  In content was only 10.12% [13]. Presently, compound semiconductor using GaAs has been developed and used as a space solar cell material because of more superior radiation resistance and high conversion compared to Si cells [14].

National Renewable Energy Laboratory (NREL) has demonstrated a high efficiency (~27% terrestrial) GaInP/GaAs n-on-p tandems [15]. GaInP/GaAs solar cells have the potential for achieving a conversion efficiency of more than 30% and 35%, respectively, and monolithic tandem cell with an efficiency of 29.5% has already been reported from previous research [10]. The wider gap of 1.9 eV top cell design is an intermediate step towards developing a 2.0 eV  $\text{In}_{0.5}\text{Al}_{0.1}\text{Ga}_{0.5}\text{P}$  top cell which also gives better current matching to the GaAs substrate. AlGaAs can also be an alternative to GaInP. However, due to its high sensitivity to water and oxygen contamination has made it undesirable choice [16]. Therefore, In ( $\geq 0.5$ ) is found to be promising material composition of solar cell [17]. GaInP material is a wide range of band gap semiconductor nearly 1.9 eV that can be grown lattice-matched to Ge and GaAs and was selected as a proper material to be used as a top cell for multi-band gap tandem solar cells [18–20].

The objective of this research work is to study and to explore the effect of In contribution in tandem cell  $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$  substrate using simulation model.  $\text{Ga}_{1-x}\text{In}_x\text{P}$  cell within the range of  $x$  from 0 to 1 was expected to absorb the photon energy differently since their energy gap will be changed accordingly depending on the In content. Introducing In into the GaP was expected to increase the efficiency of solar cell to gain high power density. In this work, Silvaco TCAD tools were selected to accomplish this research objective. The Atlas simulator from Silvaco International has the feature to model a wide variety of physical device characteristics. This model generates the electrical characteristics of a solar cell based on the virtual fabrication of its physical structure, allowing for direct manipulation of materials, doping, and dimensions. The usage of Atlas is already investigated for solar cell application in previous research. This ability shows remarkable promise towards the multilayer solar cell design [21–23].

## 2. Details of The Simulated Solar Cell

The experiment was conducted by using a simulation software application, Silvaco Atlas by having the composition of  $x$  in the  $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$ . Silvaco TCAD was chosen as a tool because of its feature to make the structure of semiconductor devices process physically and able to generate the electrical characteristics for solar cell simulation. Figure 1 shows the modelling design of  $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$  for ( $0 \leq x \leq 1$ ) layer using Silvaco.



**Figure 1.**  $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$  Solar Cell layer.

The simulation was done by changing the  $x$  composition for the  $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$  tandem cell within the range of  $x$  from 0 to 1. In this simulation, efficiency and material electrical properties were

calculated. The current matching condition was determined by n-type of  $0.05 \mu\text{m}$  thickness with  $2 \times 10^{18} \text{ cm}^{-3}$  of doping concentration while for p-type,  $0.55 \mu\text{m}$  thickness with  $7 \times 10^{16} \text{ cm}^{-3}$  concentration was used. The composition of Indium (In) was varied to determine the effectiveness and improve the cell structure. The range of  $0 \leq x \leq 1$  for In was used and has been analysed in terms of its performance.

### 3. Results and discussions

Table 1 shows the output of the simulation which is the short current density ( $J_{sc}$ ), open circuit voltage ( $V_{oc}$ ), maximum power ( $P_{max}$ ), maximum current ( $I_{max}$ ), maximum voltage ( $V_{max}$ ), fill factor (FF) and efficiency.

Based on table 1,  $J_{sc}$  was only  $11.23 \text{ mA/cm}^2$  without the content of In.  $J_{sc}$  is the current through the solar cell due to the generation and collection of light-generated carriers, which is the involvement of electron and hole in the cell. It is the largest current from the solar cell and depends on the area, the number of photons, the spectrum of the incident light and optical properties. When the composition of In increase, the area of cell also increase and the energy gap become wider so that, it can capture more photons at the area. This is one of the reasons of thin layer should be made thinner than a bottom layer cell as we had discussed formerly. At  $x=1.0$ , the  $J_{sc}$  reaches  $13.60 \text{ mA/cm}^2$ , which is the highest value of  $J_{sc}$ .

The energy gap also enlarges in this work, proves by the increment number of open circuit voltage,  $V_{oc}$ . This occurs as the recombination current falls on the solar cell. At a certain case, there is a drop off to  $V_{oc}$  at a very high band gap due to the very low short circuit current,  $I_{sc}$ .

**Table 1.**  $\text{Ga}_{1-x}\text{In}_x\text{P}$  /GaAs solar cell efficiency.

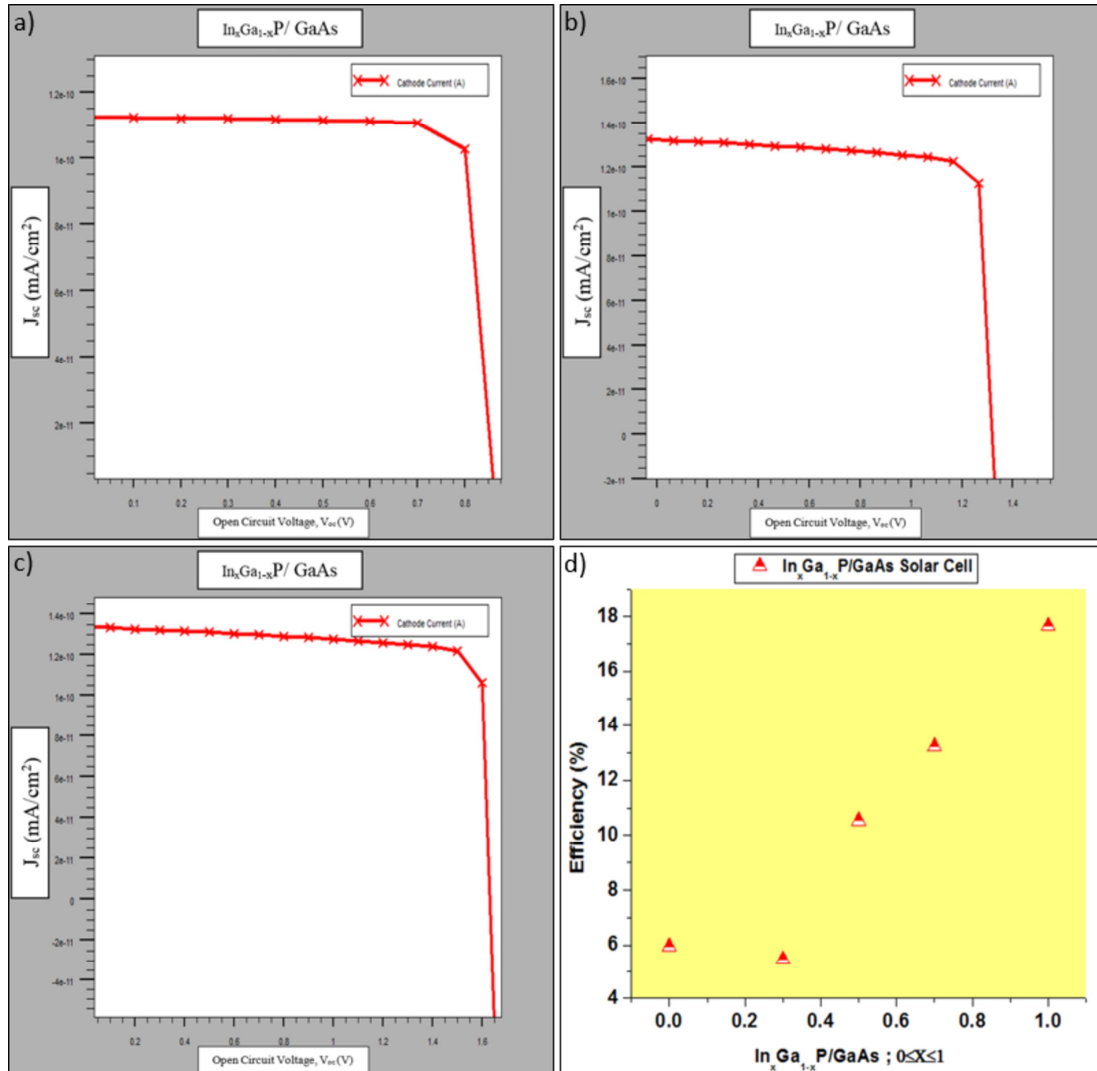
Range ( $0 \leq x \leq 1$ )	Short Circuit Current Density, $J_{sc}$ ( $\text{mA/cm}^2$ )	Open Circuit Voltage, $V_{oc}$ (V)	Maximum Power, $P_{max}$ ( $\text{mW/cm}^2$ )	Maximum Voltage, $V_{max}$ (V)	Maximum Current, $I_{max}$ ( $\text{mA/cm}^2$ )	Fill Factor, FF	Efficiency (%)
0	11.23	0.86	8.23	0.8	1.03	84.86	5.95
0.3	13.17	0.25	2.64	0.20	1.30	79.38	7.47
0.5	13.24	1.31	1.46	1.20	1.21	83.66	10.54
0.7	13.37	1.63	1.87	1.50	1.21	83.75	13.23
1.0	13.60	2.15	2.44	2.00	1.22	83.34	17.66

Maximum power,  $P_{max}$  can be calculated by having  $P_{max} = V_{oc} I_{sc} FF$ , which is the product of short-circuit current ( $I_{sc}$ ), open-circuit voltage ( $V_{oc}$ ) and fill factor (FF). The  $P_{max}$  irregularly fluctuate as the In content enlarges in the region between 0.1 to 0.5.

The current-voltage (I-V) characteristic shifts as the cell begins to produce power when the light hit on the cell. The amount of the shifts in term of the I-V curve becomes greater as the light intensity increase. Identically, the input of the photo-current to the total current through the solar cell becomes less significant when the voltage is increased after the maximum point is reached and the total current changes sign, is said to be drop off because of the very low  $I_{sc}$ .  $P_{max}$  was displayed to be slightly differ from the range of x from 0 to 0.5 depends on the material properties.

By introducing GaInP as a top cell on GaAs substrate, the GaInP itself must be able to absorb the amount of light with maximum conversion efficiency. To attain this necessity, the technique is by thinning the top cell layer. Figure 2 (a, b, c) shows the current-voltage (I-V) curve and (d) the efficiency graph respectively.

At the beginning of the simulation, the efficiency was about 5.95% without In content ( $\text{In}_x$ ; where  $x=0$ ) known as GaP/GaAs. The trend increase to 7.47 % ( $x=0.3$ ), gaining about 1.52%.



**Figure 2.** Current-voltage (I-V) curve  $Ga_{1-x}In_xP/GaAs$  when a)  $x=0$ , b)  $x=0.5$  c)  $x=0.7$ , and d) efficiency graph from the range of  $(0 \leq x \leq 1)$ .

The efficiency resumes to rise up to 10.54% to 13.23% ( $x=0.5 \sim 0.7$ ). Finally, with the In content of  $x=1$ , the efficiency was of the highest value, which is 17.66% after having about 7.12% increment from In content ( $x \geq 0.5$ ).

**Table 2.** Material Properties of GaAs, GaP, InP and GaInP.

Material	Band gap, $E_g$	Lattice Constant, Å	Electron Mobility, $\mu_n$ ( $cm^2 V^{-1} s^{-1}$ )	Hole Mobility, $\mu_p$ ( $cm^2 V^{-1} s^{-1}$ )
GaAs	1.43	5.65	8500	400
GaP	2.26	5.45	250	150
InP	1.27	5.86	4600	150
InGaP	1.90	5.65	1945	141

Table 2 shows the III-V compound semiconductor material properties consist of the band gap, lattice constant, electron mobility and hole mobility. These properties can be related to the simulation output in Table 1. Without the substitution of In composition,  $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$  ( $x=0$ ), the cell is known as GaP/GaAs. The GaP material took part in the elementary simulation with a high band gap (2.26 eV) and if the photon has lower energy than band gap material ( $eV \leq E_g$ ), the loss mechanism occurs when the solar cell is unable to extract power in the photon. This case refers to the fluctuation of the maximum power,  $P_{\max}$  and also the maximum of current and voltage ( $I_{\max}$ ,  $V_{\max}$ ) in table 1 above. The lower electron mobility for GaP which is  $250 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  also affects the solar cell system when it slows down the movement of electron and hole to be paired off. As a movement of carrier becomes slow, the recombination took place. This is another loss mechanism in solar cell where the electron holes left behind by previous excitations meet the electrons created by the photoelectric effect.

It is important to stack the layer using suitable material, having a greater mobility such as GaAs material. When the photon absorbed to the bottom layer of solar cell, the electron in GaAs material with high mobility promotes the acceleration of electron-hole in the conduction band area so that the electron is quickly getting excited. This excitation will then produce current and voltage. Stacking more layers which consists of different material can eliminate the loss, but the selection of material must have almost equal lattice constant. The lattice constants are prescribed as physical dimensions of unit cells in the crystal lattice. Choosing the proportionate value or in the other words, matching the lattice structures between two different semiconductor materials, allows a region of band gap change to be formed in a material without introducing a change in crystal structure. Recombination centres can occur when there are mismatched in the crystal lattice constants which creates defects or dislocation in the lattice.

#### 4. Conclusions

This work demonstrates the existence of In in  $\text{Ga}_{1-x}\text{In}_x\text{P}/\text{GaAs}$  based solar cell which improves the solar cell efficiency by gaining a higher energy gap and producing more electrons for best achievement in multilayer solar cell applications. In contribution with  $x=1$ , lead to a higher efficiency linearly from the range of  $x$  from 0 to 1. GaP structure was tuned to gain higher energy gap which led to high absorption of photon energy and enhanced the number of electrons released by increasing the In content. Greater efficiency was obtained by eliminating loss mechanisms such as recombination in a cell and power losses which due to the photon energy gap less than the energy gap of the material chosen ( $E_v \leq E_g$ ). Nominating multilayer structure using III-V compound semiconductor also improves the solar cell applications instead of varying the composition of metal into a top layer of multilayer structure.

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