

Modeling of InGaN p - n junction solar cells

Shih-Wei Feng,^{1,*} Chih-Ming Lai,² Chin-Yi Tsai,¹ Yu-Ru Su,¹ and Li-Wei Tu³

¹Department of Applied Physics, National University of Kaohsiung, 700, Kaohsiung University Rd., Nanzih District, Kaohsiung 81148, Taiwan

²Department of Electronic Engineering, Ming Chuan University, Taoyuan, Taiwan

³Department of Physics and Center for Nanoscience and Nanotechnology, National Sun Yat-Sen University, Kaohsiung, Taiwan

*swfeng@nuk.edu.tw

Abstract: InGaN p - n junction solar cells with various indium composition and thickness of upper p -InGaN and lower n -InGaN junctions are investigated theoretically. The physical properties of InGaN p - n junction solar cells, such as the short circuit current density (J_{SC}), open circuit voltage (V_{oc}), fill factor (FF), and conversion efficiency (η), are theoretically calculated and simulated by varying the device structures, position of the depletion region, indium content, and photon penetration depth. The results indicate that an $\text{In}_{0.6}\text{Ga}_{0.4}\text{N}$ solar cell, with optimal device parameters, can have a $J_{SC} \sim 31.8 \text{ mA/cm}^2$, $V_{oc} \sim 0.874 \text{ volt}$, $FF \sim 0.775$, and $\eta \sim 21.5\%$. It clearly demonstrates that medium-indium-content InGaN materials have the potential to realize high efficiency solar cells. Furthermore, the simulation results, with various thicknesses of the p -InGaN junction but a fixed thickness of the n -InGaN junction, shows that the performance of InGaN solar cells is determined by the upper p -InGaN junction rather than the n -InGaN substrate. This is attributed to the different amount of light absorption in the depletion region and the variation of the collection efficiency of minority carriers.

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OCIS codes: (040.5350) Photovoltaic; (350.6050) Solar energy.

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1. Introduction

The bandgap of InGaN wide-bandgap semiconductors, ranging from 0.7 to 3.4 eV, can fit the full solar spectrum [1]. This provides InGaN with a great potential for photovoltaic applications; especially, when they are used in multi-junction tandem solar cells in which a bandgap between 0.7 and 2.5 eV can be selected, by changing their compositions, to optimize the devices’ efficiency and performance [2]. Although InGaN solar cells are still not fully developed, various theoretical models and numerical simulations have been conducted to investigate the performance of single- and multiple-junction InGaN solar cells [3–6]. Our previous simulation results show that the performance of InGaN *p-i-n* solar cells critically depends on the indium content, thickness, and defect density of the *i*-layer [3] and a high-quality $\text{In}_{0.75}\text{Ga}_{0.25}\text{N}$ solar cell with a 4 μm *i*-layer thickness can exhibit 23% conversion efficiency. Other works have shown that an $\text{In}_{0.65}\text{Ga}_{0.35}\text{N}$ *p-n* junction solar cell with optimized doping concentration and thickness can have 20% conversion efficiency [4]. It also has been shown that a high quality InGaN/Si tandem solar cell with optimized InGaN bandgap and Si thickness was estimated to have 30–32% conversion efficiency [5]. Single-, double-, and triple-junction InGaN solar cells were calculated to exhibit 24.95, 34.44, and 41.76% conversion efficiencies, respectively [6].

On the other hand, device fabrications of various InGaN solar cells have been conducted with some interesting and promising results. For example, *p*-GaN/*i*-InGaN/*n*-GaN heterojunction [7–9], *p*-InGaN/*i*-InGaN/*n*-InGaN homojunction [10], *p*-InGaN/*n*-InGaN homojunction [11], and InGaN/GaN multiple quantum well [12,13] solar cells have been demonstrated to show good photovoltaic effects. However, due to high densities of threading dislocations, stacking faults, and V-shaped defects, the conversion efficiencies of those solar cells are lower than 2% [7–13]. Piezoelectric polarization effects can also reduce the efficiencies of InGaN/GaN solar cells [14,15]. Possible solutions to the challenges in InGaN solar cells have been proposed: conductive and transparent substrates, high quality film growth, *p*-type doping, and cell design [2]. Although the experimental efforts on InGaN solar cells are still in the initial stages, theoretical studies could provide useful insight and possible guidelines to optimize their performance. For example, the influences of various device structures and the indium composition on the performance of InGaN *p-n* junction solar cells InGaN solar cells deserve careful investigations. Although, previous theoretical works have

been conducted and some interesting results have been obtained, several important factors are still not fully investigated, such as the position of the junction. Therefore, in this study, the physical properties of InGaN p - n junction solar cells, such as the short circuit current density, open circuit voltage, fill factor, and conversion efficiency, are theoretically calculated and simulated by varying the device structures, position of the depletion region, indium content, and photon penetration depth.

This paper is organized as follows: In section 2, theoretical modelling is described. In section 3, simulation results of the performance of InGaN p - n junction solar cells are discussed. Finally, conclusions are drawn in section 4.

2. Theoretical modelling of short circuit current density, open circuit voltage, fill factor, and conversion efficiency of InGaN p - n junction solar cells

Figure 1 shows the structure of InGaN p - n junction solar cells used for the theoretical simulation. w_p and w_n are the widths of the p - and n -InGaN junctions, respectively. d_p and d_n are the widths of the depletion region in the p - and n -InGaN junctions, respectively. The solar cells are under solar radiation AM 1.5G illumination (100 mW/cm^2). Photons are assumed to be incident from the p -InGaN side of the InGaN solar cells.

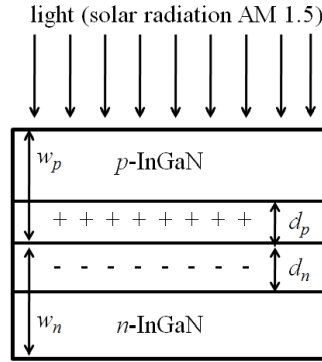


Fig. 1. The structure of InGaN p - n junction solar cells used for theoretical simulation. Light is incident from the p -InGaN side. w_p and w_n are the widths of the p - and n -InGaN junctions, respectively. d_p and d_n are the widths of the depletion region in the p - and n -InGaN junctions, respectively.

In the numerical simulations, the theoretical model is used to design the structures of InGaN p - n junction solar cells with various widths and indium compositions. The first-principles-continuity and Poisson's equations are combined to analyze the transport behavior of the solar cells [16]. The photovoltaic function of an InGaN p - n junction can be analyzed by solving a set of coupled differential equations for the electron density, hole density, and electrostatic potential [16]. Carrier and current densities can be analytically obtained to determine the current-voltage (J - V) curve of the InGaN p - n junction solar cells. The total current density, J , in the InGaN p - n junction solar cells can be expressed as [16]:

$$J = J_{SCP} + J_{SCN} + J_{G,D} - (J_{DP} + J_{DN})(e^{qV_a/kT} - 1) - J_{DD}(e^{qV_a/2kT} - 1) \quad (1)$$

where J_{SCP} is the hole diffusion current density in the p -InGaN junction, J_{SCN} is the electron diffusion current density in the n -InGaN junction, and $J_{G,D}$ is the drift current density in the depletion region. J_{DP} , J_{DN} , and J_{DD} are the dark current densities in the p -InGaN junction, n -InGaN junction, and depletion region, respectively. V_a is the built-in potential. Each term of J_{SCP} , J_{SCN} , $J_{G,D}$, J_{DP} , J_{DN} , and J_{DD} in Eq. (1) can be obtained in Reference [16]. From Eq. (1), J can be expressed as:

$$J = J_{sc} - J_{s1}(e^{qV_a/kT} - 1) - J_{s2}(e^{qV_a/2kT} - 1) \quad (2)$$

$$J_{SC} \equiv J_{SCP} + J_{SCN} + J_{G,D} \quad (3)$$

$$J_{s1} \equiv J_{DP} + J_{DN} \quad (4)$$

$$J_{s2} \equiv J_{DD} \quad (5)$$

where J_{SC} is the photocurrent, $J_{s1}(e^{qV_a/kT} - 1)$ is the dark current in the neutral region, and $J_{s2}(e^{qV_a/2kT} - 1)$ is the recombination current in the depletion region. Details of the calculations of total current density, J , are described in Reference [16].

Assuming that the recombination current in the depletion region ($J_{s2}(e^{qV_a/2kT} - 1) \cong 0$) is very small, the open-circuit voltage, V_{oc} , can be obtained by setting the J in Eq. (2) to be zero.

$$J = J_{sc} - J_{s1}(e^{qV_a/kT} - 1) - J_{s2}(e^{qV_a/2kT} - 1) \approx J_{sc} - J_{s1}(e^{qV_a/kT} - 1) \equiv 0 \quad (6)$$

$$\Rightarrow V_{oc} = \frac{kT}{q} \ln \frac{J_{sc} + J_{s1}}{J_{s1}} \quad (7)$$

when $J_{sc} \gg J_{s1}$

$$\Rightarrow V_{oc} \cong \frac{kT}{q} \ln \frac{J_{sc}}{J_{s1}} \quad (8)$$

The fill factor, FF , is defined as:

$$FF = \frac{P_{max}}{V_{oc} \cdot I_{sc}} = \frac{V_{max} \cdot I_{max}}{V_{oc} \cdot I_{sc}} = \frac{V_{max} \cdot J_{max}}{V_{oc} \cdot J_{sc}} \quad (9)$$

The power conversion efficiency of a solar cell, η , is defined as:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{FF \cdot V_{oc} \cdot I_{sc}}{P_{in}} \quad (10)$$

The intrinsic carrier concentration, n_i , can be described by [3]:

$$n_i^2 = 2.31 \times 10^{31} \left(\frac{m_n \cdot m_p}{m_e^2} \right)^{2/3} \times T^3 \times \exp\left(-\frac{E_g}{kT}\right) \quad (11)$$

The band-gap energy, $E_g(x)$, for $\text{In}_x\text{Ga}_{1-x}\text{N}$ is expressed as [1]:

$$E_g(x) = 0.65x + 3.425(1-x) - 1.43x(1-x) \quad (12)$$

Donor and acceptor concentrations for InN and GaN are both set at $5 \times 10^{17} \text{ cm}^{-3}$ [4]. Hole and electron surface recombination velocities for InN and GaN are both set at $10^3 \text{ (cm} \cdot \text{s}^{-1})$. Except for the band gap energy, the physical parameters of $\text{In}_x\text{Ga}_{1-x}\text{N}$ are expressed as the linear interpolation formula of wurtzite InN and GaN and are listed in Table 1 [1,4,17–21].

Table 1. The parameters of wurtzite InN and GaN used for theoretical simulations.

	InN	GaN
Electron effective mass m_n	0.11 m_e [1]	0.2 m_e [1]
Hole effective mass m_p	1.63 m_e [1]	0.8 m_e [1]
Dielectric constant ϵ_{si}	15.3 [1]	8.9 [1]
Hole lifetime τ_p (ns)	5.4 [17]	2 [18]
Electron lifetime τ_n (ns)	1.3 [19]	0.1 [20]
Hole diffusion constant D_p ($\text{cm}^2 \cdot \text{s}^{-1}$)	8 [21]	0.75 [1]
Electron diffusion constant D_n ($\text{cm}^2 \cdot \text{s}^{-1}$)	80 [21]	39 [4]

Operation mechanisms of InGaN p - n junction solar cells are explored through the calculation of characteristic parameters such as the short circuit current density (J_{sc}), open circuit voltage (V_{oc}), fill factor (FF), and conversion efficiency (η). Two situations are considered for theoretical simulation:

- (I) Situation I: the dependence on the width ($w_p = 50\text{-}4,000\text{nm}$) and the indium composition ($x_p = 0\text{-}1$) of the upper p -InGaN junction. The width of the lower n -InGaN substrate is set at 1,000 nm.
- (II) Situation II: the dependence on the width ($w_n = 50\text{-}4,000\text{nm}$) and the indium composition ($x_n = 0\text{-}1$) of the lower n -InGaN substrate. The p -InGaN width is set at 300 nm.

3. Simulation results and discussions

3.1 The effects of the width and the indium composition of the upper p -InGaN on the performance of InGaN p - n junction solar cells

In simulation I, the effects of the width ($w_p = 50\text{-}4,000\text{nm}$) and indium composition ($x_p = 0\text{-}1$) of the upper p -InGaN junction on the performance of InGaN p - n junction solar cells are investigated. Figure 2 shows the J - V characteristic of InGaN p - n junction solar cells with 300 nm p -InGaN and 1,000 nm n -InGaN for various indium compositions. Dramatic variations of the J - V characteristic, depending on indium content, are obtained. As the indium content decreases, V_{oc} increases, while J_{sc} and FF decrease. The operation mechanism of InGaN solar cells will be discussed later.

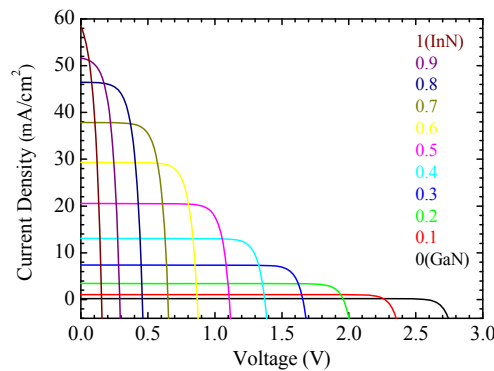


Fig. 2. The J - V characteristic of InGaN p - n junction solar cells with 300 nm p -InGaN and 1,000 nm n -InGaN for various indium compositions.

Figures 3(a) and 3(b) show the short circuit current densities, $J_{sc}(w_p, x_p)$, of InGaN p - n junction solar cells as a function of p -InGaN width (w_p) and indium composition (x_p), respectively. In Fig. 3(a), simulation results show that as the w_p increases, $J_{sc}(w_p, x_p)$ very slightly decreases and then droops at around 1,000 nm. The varied width of the p -InGaN layer changes not only the amount of light absorbed in the depletion region, but also the drift length to the p -contact. Although a thicker p -InGaN layer enhances the absorption and generates more carriers in the p -InGaN, a longer drift length makes it harder for the photogenerated carriers to drift to the p -contact. $J_{sc}(w_p, x_p)$ slightly decreases. As the w_p is above 1,000 nm, fewer carriers are collected in the p -contact due to both less absorption in the depletion region and longer drift length. The smaller absorption in the n -InGaN layer also makes photon-generated carriers contribute less to photocurrent. Those factors lead to $J_{sc}(w_p, x_p)$ drooping above 1,000 nm. Also, $J_{sc}(w_p, x_p)$ shows a strong dependence on w_p and x_p of the solar cells. A larger $J_{sc}(w_p, x_p)$ in the high-indium-content InGaN solar cells strongly depends on w_p , while smaller $J_{sc}(w_p, x_p)$ in the low-indium-content ones weakly depends on it. Due to the photons being incident from the p -InGaN side of the solar cell, photon-generated carriers in the p -InGaN layer of the solar cell contribute more current than those in the n -InGaN. Also, because the penetration depth of longer-wavelength photons in the high-indium-content InGaN solar cells is larger than that of shorter-wavelength photons in low-indium-content ones, photo-generated carriers in the n -InGaN of the high-indium-content solar cells would contribute more current than those of the low-indium-content ones. Those factors lead to the fact that the wider the p -InGaN in the high-indium-content InGaN solar cells, the larger the variation of $J_{sc}(w_p, x_p)$.

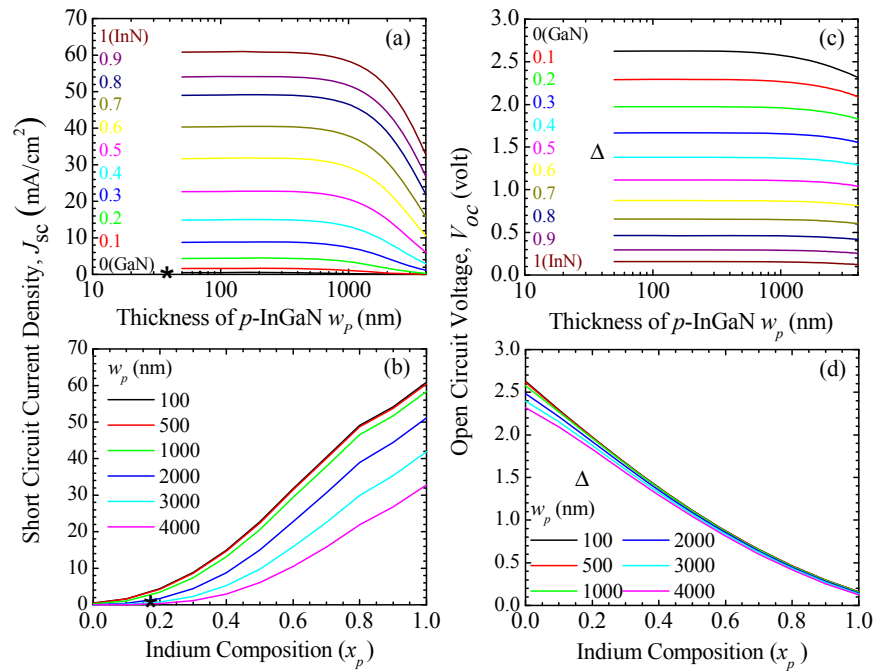


Fig. 3. Short circuit current density, $J_{sc}(w_p, x_p)$, of InGaN p - n junction solar cells as a function of p -InGaN (a) width (w_p) and (b) indium composition (x_p). Open circuit voltage, $V_{oc}(w_p, x_p)$, of InGaN p - n junction solar cells as a function of p -InGaN (c) width (w_p) and (d) indium composition (x_p). The reported J_{sc} (* in Figs. 3(a) and 3(b)) and V_{oc} (Δ in Figs. 3(c) and 3(d)) of p -In_{0.168}Ga_{0.832}N(35nm)/ n -In_{0.148}Ga_{0.852}N(45nm) junction solar cell under AM 1.5 illumination are plotted for comparison [11].

In addition, in Fig. 3(b), $J_{sc}(w_p, x_p)$ increases with increasing indium content. $J_{sc}(w_p, x_p)$ of the InN solar cell corresponding to the same width of the p -InGaN is about one order of magnitude larger than that of the GaN solar cell. With a small bandgap in the high-indium solar cell, more photons with energy larger than the bandgap can be absorbed. The larger penetration depth of infrared photons also enhances the photon absorption. Smaller bandgap and larger penetration depth of long-wavelength photons enhance absorption such that more photocurrent is generated in the high-indium-content InGaN solar cells. A lower $J_{sc}(w_p, x_p)$ of the GaN and low-indium-content InGaN solar cells will lead to a lower conversion efficiency. Furthermore, the reported J_{sc} (0.26 mA/cm²) of p -In_{0.168}Ga_{0.832}N(35nm)/ n -In_{0.148}Ga_{0.852}N(45nm) junction solar cell under AM 1.5 illumination are plotted with (*) in Figs. 3(a) and 3(b) for comparison [11]. The reported J_{sc} is much lower than that of the simulation result (in the range of 1.62-4.37 mA/cm² for In content 10-20%). Because the InGaN p - n junction structure is sandwiched between p - and n -GaN layers, some photons are absorbed by the p -contact and p -GaN layer. Due to high densities of threading dislocations, stacking faults, strain-induced piezoelectric polarization effects, and V-shaped defects, the collection efficiency of the InGaN p - n junction solar cell becomes lower [7–15]. These factors lead to the reported J_{sc} showing a lower value in the actual fabricated solar cells.

Figures 3(c) and 3(d) show the open circuit voltage, $V_{oc}(w_p, x_p)$, of InGaN p - n junction solar cells as a function of p -InGaN width (w_p) and indium composition (x_p), respectively. Simulation results show that the $V_{oc}(w_p, x_p)$ depends on x_p , but only slightly on w_p . The $V_{oc}(w_p, x_p)$ is determined by the difference of the Fermi energies (ΔE_F) of the electron and the hole in the depletion region, which in turn is affected by the bandgap energy [16]. In Fig. 3(c), except for the wider cells, the V_{oc} is nearly independent of w_p . Note that $V_{oc}(w_p, x_p)$ starts to decrease slightly in the wider cells, due to the larger saturation current, J_0 , in the wider cells. In Fig. 3(d), because V_{oc} is determined by the bandgap energy of the subcell [17], smaller V_{oc} in the high-In-content InGaN solar cell is expected. Furthermore, the reported V_{oc} (1.47 volt) of p -In_{0.168}Ga_{0.832}N(35nm)/ n -In_{0.148}Ga_{0.852}N(45nm) junction solar cell under AM 1.5 illumination is plotted with (Δ) in Figs. 3(c) and 3(d) for comparison [11]. The reported V_{oc} is lower than that of the simulation result (in the range of 1.97-2.29 V for In content 10-20%). According to Eq. (8), V_{oc} is proportional to J_{sc} . Due to a smaller J_{sc} , a smaller reported V_{oc} is expected.

Figures 4(a) and 4(b) show the fill factor, $FF(w_p, x_p)$, of InGaN p - n junction solar cells as a function of p -InGaN width (w_p) and indium composition (x_p), respectively. For GaN solar cells in Fig. 4(a), it is found that the $FF(w_p, x_p)$ can be as high as 0.90 and decreases slightly in the wider cells. This is due to the fact that the $V_{oc}(w_p, x_p)$ of GaN solar cells shows larger variations with varying p -InGaN width, as shown in Fig. 3(c). In addition, in Fig. 4(b), as the indium content increases, the $FF(w_p, x_p)$ decreases and has slightly larger variation with varying p -InGaN width, in particular for InN solar cells. This is due to a larger variation of $J_{sc}(w_p, x_p)$ with varying p -InGaN width in the high-indium-content solar cells, as shown in Fig. 3(a). As the indium content increases, the steeply increasing $J_{sc}(w_p, x_p)$ (Fig. 3(b)) and smoothly decreasing $V_{oc}(w_p, x_p)$ (Fig. 3(d)) lead to a smaller $FF(w_p, x_p)$ in the high-indium-content InGaN solar cells, which basically verifies the fact that $V_{oc}(w_p, x_p)$ is roughly proportional to $FF(w_p, x_p)$ [16]. Currently, the reported FF (0.57) of p -In_{0.168}Ga_{0.832}N(35nm)/ n -In_{0.148}Ga_{0.852}N(45nm) junction solar cell under AM 1.5 illumination is plotted with (*) in Figs. 4(a) and 4(b) for comparison [11]. Without consideration of the effects of the current leakage and shunt resistance, the simulated FF can be higher than those of the actual fabricated solar cells.

Figures 4(c) and 4(d) show the conversion efficiency, $\eta(w_p, x_p)$, of InGaN p - n junction solar cells as a function of p -InGaN width (w_p) and indium composition (x_p), respectively. Simulation results help us to better understand the operation mechanisms of and provide important information for the structure design of InGaN p - n junction solar cells. In Fig. 4(c), high $\eta(w_p, x_p)$ solar cells show strong dependence on the p -layer width for longer p -layer

solar cells, while low $\eta(w_p, x_p)$ ones show slight dependence on that. This trend is similar to the fact that the wider the p -layer width, the larger the variation of the $J_{sc}(w_p, x_p)$. Device structures and photon penetration depth proposed to explain the trend of $J_{sc}(w_p, x_p)$ can explain that of $\eta(w_p, x_p)$ as well. In addition, in Fig. 4(d), as the indium content in the cell increases, absorption and $J_{sc}(w_p, x_p)$ increase, while $V_{oc}(w_p, x_p)$ and $FF(w_p, x_p)$ decrease. A high $\eta(w_p, x_p)$ in the medium-indium-content InGaN solar cell is expected. The combined effects of the absorption, $J_{sc}(w_p, x_p)$, $V_{oc}(w_p, x_p)$, and $FF(w_p, x_p)$ lead to $\eta(w_p, x_p)$ showing an increasing and then decreasing trend with indium content. Furthermore, $\eta(w_p, x_p)$ can be classified into three regions: (I) low-indium-content ($x = 0\sim0.3$), (II) medium-indium-content ($x = 0.3\sim0.7$), and (III) high-indium-content ($x = 0.7\sim1$). (I) Due to very lower $\eta(w_p, x_p)$, GaN and low-indium-content InGaN solar cells are not suitable for application in solar cells. This explains that the reported low-indium-content InGaN solar cells show low conversion efficiencies [7–13]. (II) The combined effects of the J_{sc} , V_{oc} , and FF lead to an optimized η in the medium-indium-content InGaN solar cell. Medium-indium-content InGaN solar cells with high $\eta(w_p, x_p)$ are useful for photovoltaic applications. With p -layer width less than 500 nm and 1,000 nm n -InGaN, a high-quality $\text{In}_{0.6}\text{Ga}_{0.4}\text{N}$ solar cell can exhibit as high a $\eta(w_p, x_p)$ as ~22%. This demonstrates that medium-indium-content InGaN is an appealing candidate to realize a high efficiency solar cell. However, the difficulty of high quality devices would be a potential obstacle to fabricate such solar cells. Growth of In-rich InGaN can be obtained by using high-pressure chemical vapor deposition [22,23]. (III) InN and high-indium-content InGaN solar cells could be useful for making tandem solar cells with other material such as Si, provided that it can be grown on that other material. Also, nonpolar and semipolar GaN substrates were studied for the growth of high-indium-content InGaN/GaN multiple quantum wells (MQWs). It has been shown that growth of high-indium InGaN/GaN MQWs on the $(11\bar{2}2)$ and $(20\bar{2}1)$ semipolar planes exhibits a higher indium incorporation [24]. High-indium-content InGaN solar cells can be fabricated on the $(11\bar{2}2)$ and $(20\bar{2}1)$ semipolar GaN substrates. Furthermore, the reported η (0.05%) of $p\text{-In}_{0.168}\text{Ga}_{0.832}\text{N}(35\text{nm})/n\text{-In}_{0.148}\text{Ga}_{0.852}\text{N}(45\text{nm})$ junction solar cells under AM 1.5 illumination is plotted using (Δ) in Figs. 4(c) and 4(d) for comparison [11]. Also, the conversion efficiencies of $p\text{-GaN}/i\text{-InGaN}/n\text{-GaN}$ heterojunction [7–9], $p\text{-InGaN}/i\text{-InGaN}/n\text{-InGaN}$ homojunction [10], and InGaN/GaN MQW [12,13] solar cells with a low-indium-content are lower than 2%. The reported η is much lower than that of the simulation result (in the range of 3.26–7.49% for In content 10–20%). Without consideration of the effects of the current leakage and shunt resistance, the simulated η are higher than those of the actual fabricated solar cells. High densities of threading dislocations, stacking faults, and strain-induced piezoelectric polarization effect can reduce the efficiencies of InGaN/GaN solar cells [7–15].

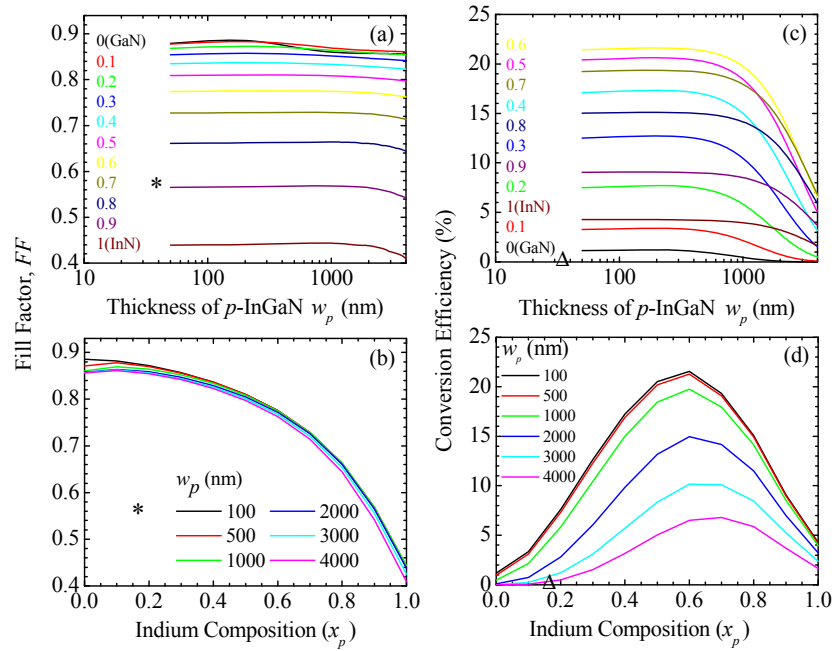


Fig. 4. Fill factor, $FF(w_p, x_p)$, of InGaN p - n junction solar cells as a function of p -InGaN (a) width (w_p) and (b) indium composition (x_p). Conversion efficiency, $\eta(w_p, x_p)$, of InGaN p - n junction solar cells as a function of p -InGaN (c) width (w_p) and (d) indium composition (x_p). The reported FF (*) in Figs. 4(a) and 4(b)) and η (Δ in Figs. 4(c) and 4(d)) of p - $\text{In}_{0.168}\text{Ga}_{0.832}\text{N}(35\text{nm})/n$ - $\text{In}_{0.148}\text{Ga}_{0.852}\text{N}(45\text{nm})$ junction solar cell under AM 1.5 illumination are plotted for comparison [11].

3.2 The effects of the width and the indium composition of the n -InGaN substrate on the performance of InGaN p - n junction solar cells

In simulation II, the effects of the width ($w_n = 50$ – $4,000\text{nm}$) and the indium composition ($x_n = 0$ – 1) of the lower n -InGaN substrate on the performance of InGaN p - n junction solar cells are investigated. The p -InGaN width is set at 300nm . Figures 5(a) and 5(b) show the short circuit current densities, $J_{sc}(w_n, x_n)$, of InGaN p - n junction solar cells as a function of n -InGaN width (w_n) and indium composition (x_n), respectively. In Fig. 5(a), simulation results show that the J_{sc} very slightly increases with increasing w_n . Although a thicker n -InGaN enhances the absorption and generates more carriers in the n -InGaN, a longer drift length makes it harder for the photogenerated carriers to drift to the n -contact. The nearly constant $J_{sc}(w_n, x_n)$ as a function of w_n can be the balance of a larger absorption and a longer drift length. Also, regardless of the n -InGaN width, $J_{sc}(w_n, x_n)$ is equal to $J_{sc}(w_p, x_p)$ corresponding to the same indium composition in Fig. 3(a) when the p -InGaN width is smaller than a few hundred nm. Due to larger absorption by InGaN, most light is absorbed by the p -InGaN junction, and less light is absorbed by the n -InGaN substrate. This shows that the J_{sc} of InGaN solar cells is determined by the $J_{sc}(w_p, x_p)$ of the upper p -InGaN junction. In addition, in Fig. 5(b), $J_{sc}(w_n, x_n)$ increases with increasing indium content. $J_{sc}(w_n, x_n)$ of the InN solar cell corresponding to the same width of the n -InGaN is about one order of magnitude larger than that of the GaN solar cell. Both smaller bandgap and larger penetration depth of long-wavelength photons enhance absorption such that more photocurrent is generated in the high-indium-content InGaN solar cells.

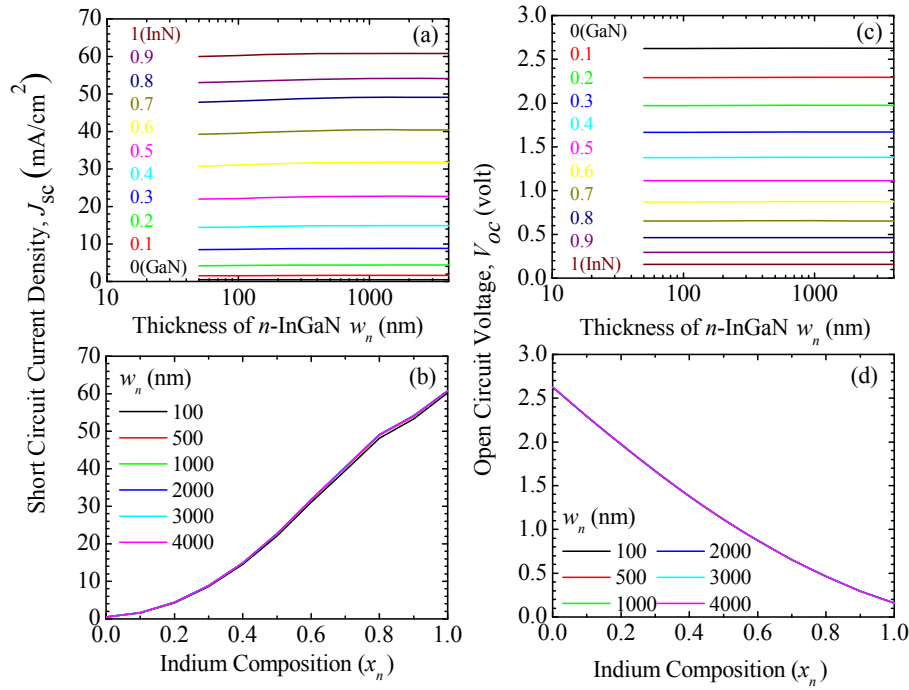


Fig. 5. Short circuit current density, $J_{sc}(w_n, x_n)$, of InGaN p - n junction solar cells as a function of n -InGaN (a) width (w_n) and (b) indium composition (x_n). Open circuit voltage, $V_{oc}(w_n, x_n)$, of InGaN p - n junction solar cells as a function of n -InGaN (c) width (w_n) and (d) indium composition (x_n).

Figures 5(c) and 5(d) show the open circuit voltage, $V_{oc}(w_n, x_n)$, of InGaN p - n junction solar cells as a function of n -InGaN width (w_n) and indium composition (x_n), respectively. In Fig. 5(c), because $V_{oc}(w_n, x_n)$ is determined by the material bandgap [16], the $V_{oc}(w_n, x_n)$ is nearly independent of w_n . Similar to the J_{sc} of InGaN solar cells, the $V_{oc}(w_n, x_n)$ is equal to the $V_{oc}(w_p, x_p)$ corresponding to the same indium composition in Fig. 3(c) when the p -InGaN width is smaller than a few hundred nm. It is reasonable that the V_{oc} of InGaN solar cells is also determined by the $V_{oc}(w_p, x_p)$ of the upper p -InGaN junction. In addition, in Fig. 5(d), $V_{oc}(w_n, x_n)$ becomes smaller in the high-indium-content InGaN solar cells. This is due to the difference of the Fermi energies (ΔE_F) of the electron and the hole in the depletion region, which in turn is affected by the bandgap energy [16].

Figures 6(a) and 6(b) show the fill factor, $FF(w_n, x_n)$, of InGaN p - n junction solar cells as a function of n -InGaN width (w_n) and indium composition (x_n), respectively. In Fig. 6(a), because the $J_{sc}(w_n, x_n)$ (Fig. 5(a)) and $V_{oc}(w_n, x_n)$ (Fig. 5(c)) are nearly independent of w_n , the $FF(w_n, x_n)$ is also nearly independent of w_n . Similar to the J_{sc} of InGaN solar cells, the $FF(w_n, x_n)$ is nearly equal to the $FF(w_p, x_p)$ corresponding to the same indium composition in Fig. 4(a) when the p -InGaN width is smaller than a few hundred nm. The FF of InGaN solar cells is also determined by the $FF(w_p, x_p)$ of the upper p -InGaN junction. Also, in Fig. 6(b), the $FF(w_n, x_n)$ decreases as the In composition increases. The steeply increasing $J_{sc}(w_n, x_n)$ (Fig. 5(b)) and the smoothly decreasing $V_{oc}(w_n, x_n)$ (Fig. 5(d)) lead to a smaller $FF(w_n, x_n)$, in the high-indium-content InGaN solar cells.

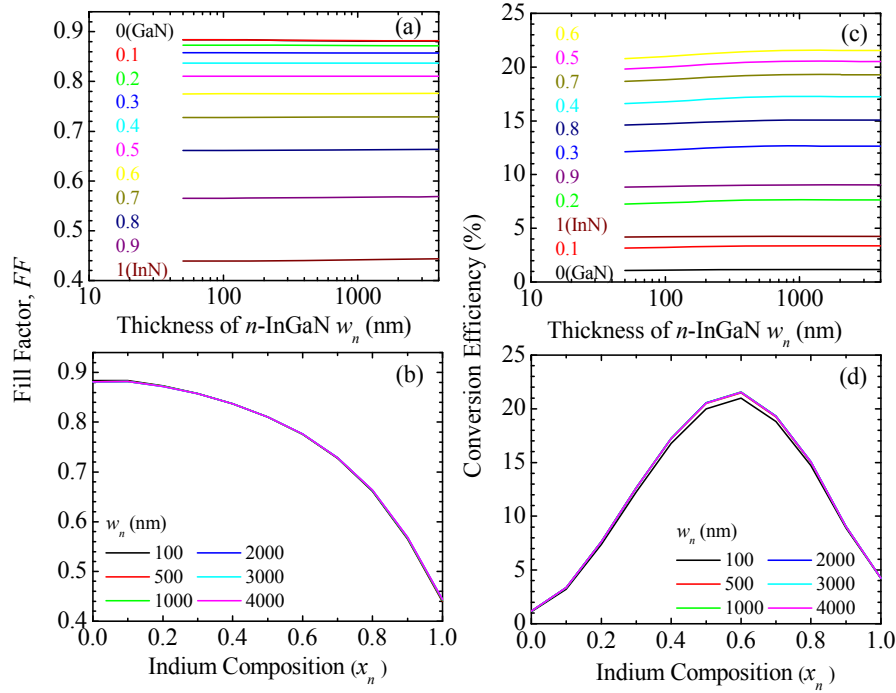


Fig. 6. Fill factor, $FF(w_n, x_n)$, of InGaN p - n junction solar cells as a function of n -InGaN (a) width (w_n) and (b) indium composition (x_n). Conversion efficiency, $\eta(w_n, x_n)$, of InGaN p - n junction solar cells as a function of n -InGaN (c) width (w_n) and (d) indium composition (x_n).

Figures 6(c) and 6(d) show the conversion efficiency, $\eta(w_n, x_n)$, of InGaN p - n junction solar cells as a function of n -InGaN width (w_n) and indium composition (x_n), respectively. The conversion efficiency represents the combined effects of the J_{sc} , V_{oc} , and FF . In Fig. 6(c), because $J_{sc}(w_n, x_n)$, $V_{oc}(w_n, x_n)$, and $FF(w_n, x_n)$ are nearly independent of the n -InGaN width, it is reasonable that the $\eta(w_n, x_n)$ is also nearly independent of w_n . In addition, in Fig. 6(d), the combined effects of the absorption, $J_{sc}(w_n, x_n)$, $V_{oc}(w_n, x_n)$, and $FF(w_n, x_n)$ lead to $\eta(w_n, x_n)$ showing an increasing and then decreasing trend with the indium content. With 300 nm p -layer width and a few hundred nm n -InGaN, a high-quality $\text{In}_{0.6}\text{Ga}_{0.4}\text{N}$ solar cell can exhibit as high a $\eta(w_n, x_n)$ as $\sim 22\%$. Also, the relationship between $\eta(w_n, x_n)$ and x_n in Fig. 6(d) is similar to that between $\eta(w_p, x_p)$ and x_p in Fig. 4(d), but the relationship between $\eta(w_n, x_n)$ and x_n is almost independent of w_n . Similar arguments can be used to explain this relationship. Because most light is absorbed by the p -InGaN junction, η of InGaN p - n junction solar cells is determined by the $\eta(w_p, x_p)$ in the upper p -InGaN layer, not the $\eta(w_n, x_n)$ in the n -InGaN substrate.

4. Conclusions

In summary, the J_{sc} , V_{oc} , FF , and η are shown to strongly depend on the indium content and width of the upper p -InGaN junction in the InGaN solar cells. With proper thicknesses of p - and n -InGaN, an $\text{In}_{0.6}\text{Ga}_{0.4}\text{N}$ solar cell can exhibit a $J_{sc} \sim 31.8 \text{ mA/cm}^2$, $V_{oc} \sim 0.874 \text{ V}$, $FF \sim 0.775$, and $\eta \sim 21.5\%$, demonstrating that medium-indium-content InGaN is an appealing candidate to realize a high efficiency solar cell. Also, InN and high-indium-content InGaN solar cells could be useful for making tandem cells with other materials. In addition, due to larger absorption of p -InGaN junction, the performance of InGaN solar cells is determined by

the upper p -InGaN junction, not the n -InGaN substrate. By appropriate design of the devices, the performance of InGaN p - n junction solar cells can be optimized.

Acknowledgment

This research was supported by the National Science Council, Taiwan, R.O.C., under grants NSC 100-3113-E-110-004, NSC 99-2112-M-390-002-MY3, and NSC 99-2515-S-390-001.