Performance Analysis Based on Different Indium Content for InGaN/Si Hetero-Junction Solar Cell

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Abstract

An active InGaN layer is introduced on the existing Si-based solar cell technology to improve the energy harvesting at wider solar spectrum. The percentage content of Indium in Indium Gallium Nitride ($In_xGa_{1-x}N$) is much affecting the performance of InGaN/Si solar cell. As the In_x content increases, the Ga_{1-x} decreases accordingly as a result various compositional $In_xGa_{1-x}N$ compound semiconductor structure would appear on Si. Thus, this difference of Indium content make band bowing of InGaN from 3.42 eV (0% Indium content) to 0.7 eV (100% Indium content) which enhances absorption at wider solar spectrum as compared to single Si cell. Obviously it appears to make efficient management of photon and improve the performance of InGaN/Si solar photo voltaic. The performance of InGaN/Si solar cell is analyzed in this study by varying the Indium content in InGaN. InGaN/Si solar cell is designed by using N-type highly pure crystalline c-Si wafer using wxAMPS software. Indium content in the InGaN is varied to obtain the best composition of InGaN for performance optimization in terms of V_{oc}, J_{sc}, FF and efficiency. From the analysis, it is found that medium-ranged Indium content (40%-50% Indium) shows the best performance for InGaN/Si solar cell and it seems to be matched with the underneath Si cell current density as series configuration.

1 Introduction

Silicon is a well-known material for photovoltaic technology. This material has a better cooling capability compared to sapphire. Besides, it has faster thermal dissipation as it has larger thermal conductivity. However, Si-based solar cell is not so promising as it cannot covers wide solar spectrum. Because of that, an active InGaN layer is introduced on the existing Si-based solar cell. Several attempts have been made by the researchers to improve solar cell harvesting by using InGaN active layer on Si. This is proven that III-N semiconductors such as InGaN are robust, high thermal conductivity, high melting point and having direct band gap. The band gap of the InGaN can be adjusted from high energy to low energy (ultraviolet to infrared) depending on the Indium content. This active InGaN layer will provide a low sheet resistance which will enhance surface conductivity and the band gap is adjustable from 0.7 eV to 3.42 eV which makes InGaN a very promising material for photovoltaic applications. Besides that, III-Nitrides also exhibit special properties such as high mobility, large absorption coefficients, low effective masses of charge carriers, and a high resistance to radiation [1]. The InGaN technology has established its ability to grow crystal structures of excellent quality and fabricate tremendous optoelectronic devices [2]. InGaN is found to be an essential optoelectronic material which able to produce longer-wavelength light-emitting diodes, laser diodes and solar cells than other nitride semiconductor materials. $In_xGa_{1-x}N$ alloy is a promising material for radiation-resistant solar cells [3]. In addition, $In_xGa_{1-x}N$ has been proven to be possible to be grown directly on Si substrates by a low temperature process. Other researchers have done many simulations and reported that dual junction tandem $In_xGa_{1-x}N$/Si cells could have achieved efficiencies as high as 31%. One of the challenges towards increasing the Indium content in InGaN/Si solar cell is p-type doping for the active layer InGaN. P-type doping has only been established for InN and has been confirmed by variable magnetic field Hall effect, electrochemical capacitance voltage measurements and thermo power. A. Yamamoto stated that InGaN films with In content up to 50% are possible to grow without phase separation and metallic Indium incorporation by optimizing growth temperature and TMI/(TMI+TEG) molar ratio [4].

The efficiencies of $In_xGa_{1-x}N$ multi junction tandem solar cells with different indium content were theoretically found to be 27.49% for the double junction solar cell and 40.35% for six junction solar cells respectively [3]. Besides, seven junction tandem InGaN solar cells was calculated to be 46.01% in efficiency [3]. An n-$In_{0.46}Ga_{0.54}N$/ p-Si interface is predicted to form a low resistance Ohmic junction without highly-doped interface between these two materials since the conduction band of $In_{0.46}Ga_{0.54}N$ has the same energy level as the valence band of Si. The band gap combination of $In_{0.46}Ga_{0.54}N$ (1.8 eV)/ Si (1.1 eV) would provide the best conversion efficiency for double-junction solar cells [3]. Optimized band gap and thickness of double-junction InGaN/Si solar cells were expected to produce an energy conversion efficiency about 30%–32%. Simulation results show that the quantum efficiency, short-circuits current density, open-circuit voltage, and fill factor is strongly dependant on the indium content. Besides producing a good quality InGaN materials, the leakage current and the series resistance should be minimized to attain a high performance solar cell. In conjunction to these theoretical value, the expected short-circuit current density of InGaN/Si solar cell must match with the underneath Si solar cell as reported by Greg P. Smestad *et.al* [5] stated that a silicon solar cell with a bandgap of 1.1 eV, a band gap wavelength of 1100 nm and a FF and V_{OC} of 0.7 and 0.7 V, respectively, would be limited to an AM1.5 power conversion efficiency below 22%. Maximum possible photon harvesting is 62.9% (1100 nm) and short-circuit current density of 43.4 mA/cm^2 for non-concentrated (one sun) sunlight. So, adjustable percentage of Indium content will ensure the current to nearly adjustable with underneath Si series cell make this structure novelty for solar energy harvesting.

In this work, we report the matching of top InGaN cell with the bottom Si cell can be done by inserting proper interlayer and suitable choice of Indium content. The overall performance of the InGaN/Si solar can be improved as the severe stacking faults or defects can be reduced and current density matching between these two junctions can be obtained.

2 Methodology

A double junction tandem solar cell structure as shown in the Figure 1 is fabricated using wxAMPS software which was developed by Prof. Rockett and Dr. Yiming Liu of UIUC and Prof. Fonash of PSU. The solar cell is grown on a crystalline n-type silicon substrate. The InGaN p-n junction is grown on top of a Si p-n junction. Each junction is composed of a *p*-type layer grown on top of an *n*-type layer. A 30 nm AlN interlayer is used between the InGaN and c-Si junction to reduce severe stacking faults or defects between these two junctions.

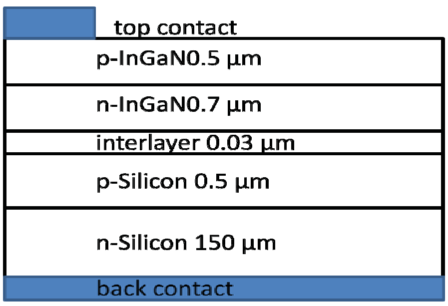

Figure 1: Structure of the solar cell

The Indium content is varied from 0% (3.42 eV) to 100% (0.7 eV). The doping concentration used for each layer is 5X10^{17} cm^{-3} (p-InGaN), 5X10^{18} cm^{-3} (n-InGaN), 6X10^{17} cm^{-3} (p-Si) and 6X10^{17} cm^{-3} (n-Si). The calculations for electrical and optical properties for each layers are performed using the standard characteristics equations of a tandem solar cell [6,7,8,9,10]. The output characteristics were studied under Air Mass 1.5 Global (AM 1.5G) solar spectrum 1000W/m^2 at 300^{o}K. The electrical properties such as band gap affinity and doping is inserted precisely based on standard value and equations. The simulation result of quantum efficiency and J-V curve is obtained for further analysis.

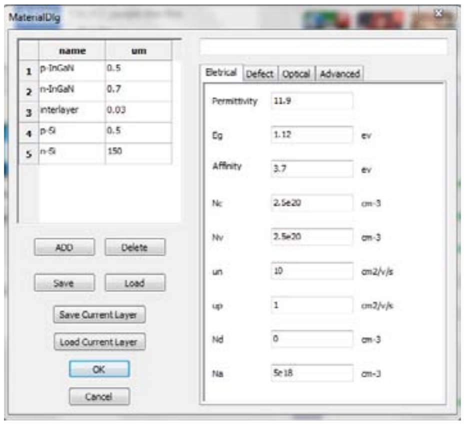

Figure 2: wxAMPS software interface

Figure 2 shows the software interface of wxAMPS. Defects and optical properties are also calculated and inserted into the software for device simulation. wxAMPS is written in C++ and includes a number of revisions to the basic algorithm.

3 Result and Discussion

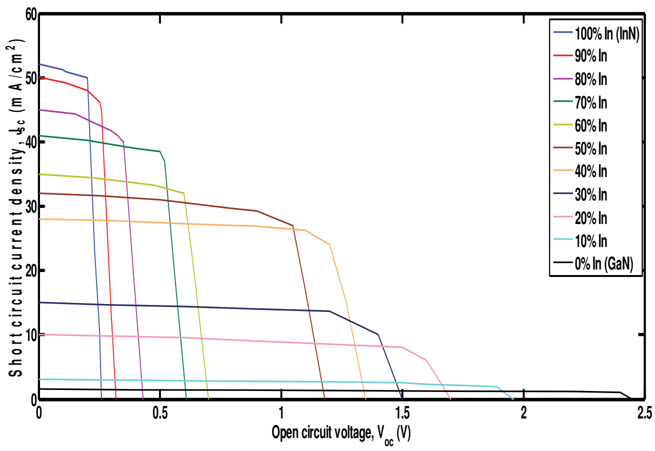

Figure 3: J-V curve for different Indium content of InGaN

From Figure 3 above, it can be seen that the V_{oc} of the InGaN/Si solar cell increases with the increment of Indium content. However, the J_{sc} decreases gradually when the percentage of Indium content increased. Photons have larger penetration depth which indirectly enhances the photon absorption. More photocurrent is produced in the InGaN solar cells with higher Indium content because smaller band gap and better penetration of long-wavelength photons absorption is improved. A lower J_{sc} of the GaN and InGaN solar cells with low Indium content will bring to lower conversion efficiency. Since the InGaN *p-n* junction structure is stacked, some photons are absorbed by the top contact and *p*-InGaN layer. Due to high densities of stacking faults, the efficiency of the InGaN solar cell becomes lower. These factors strengthen the reported J_{sc} having a lower value in the real solar cells. These stacking faults are reduced by introducing an AlN layer in between the two junctions [11]. Si and InGaN is having large relative in-plane lattice mismatch which is about -7.81% to -17% depending on the content of Indium and Gallium [11]. Because of that, AlN interlayer is desired to ensure InGaN layer and Si layer to match. Only a thin layer of AlN is required for this purpose; 30 nm is good enough as we need to consider the diffusion of AlN into the Si substrate during the fabrication process. Too thick AlN layer will restrict the flow of current from the InGaN layer to Si layer.

The Indium content is greatly affected the V_{oc} because the V_{oc} is determined by the band gap which refers to the difference of the Fermi energies of the hole and electron in the depletion region [10]. For Indium content that is greater than 40%, the Fermi-stabilization level lies above the conduction band of $In_xGa_{1-x}N$. Thus, it will cause native defects in $In_xGa_{1-x}N$ [2]. In addition, in p-type $In_xGa_{1-x}N$ with Indium content more than 60% leads to surface inversion layer forms.

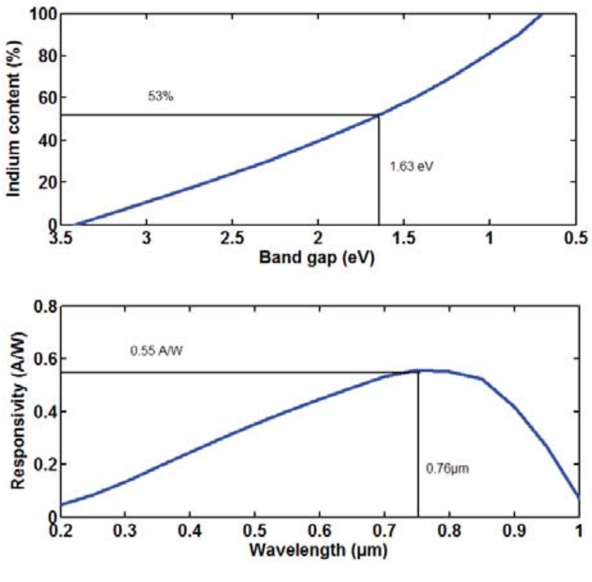

Figure 4: Maximum response of Si cell which related to wavelength, band gap and optimum indium content

From Figure 4 above, we can inter-relate between the bottom cell with suitable Indium content. The peak response of Si-based solar cell is obtained at 0.76 µm. By using $E_g = \frac{1.24}{\lambda\,(\mu m)}$ at λ= 0.76 µm, we get $E_g = 1.63\ eV$. The graph of Indium content vs band gap is plotted based on this equation [3], where x is the Indium content from 0 to 1:

$$E_{g,InGaN} = 0.7x + 3.4(1-x) - 1.43x(1-x). \quad (1)$$

From the graph of Indium content vs band gap, the 1.63 eV (peak response of Si-based cell) is related to 53% of indium content. Thus, ~50% Indium content is most likely true to produce the most efficient InGaN/Si cell as the top InGaN cell will match with the bottom Si cell. High Indium content InGaN is very challenging to grow. Researchers reported that there is high possibility for phase separation where areas of InGaN with dissimilar Indium concentrations appear when high Indium content is being used [12]. Thus, the process of fabricating high Indium content is challenging especially for p-type InGaN which is not yet verified. So far, growth of InGaN on Si is possible for 50% Indium content by using MOVPE as stated by A. Yamamoto *et. al* [4]. Choice of Indium content must be at par with the Si solar cell current technology which the J_{sc} can go up to 43.4 mA/cm^2 only. By choosing a too high or too low Indium content will not give the best result to the cell as the InGaN is grown on Si and therefore the behavior and properties of the Si itself must be considered. Adjustable Indium content will ensure the current to nearly adjustable with underneath Si series cell make this structure novelty for solar energy harvesting. Thus, more photons absorption is possible by photon management due to proper selection of Indium content. This result is strengthen by finding of others researchers stating that the $In_{0.46}Ga_{0.54}N$/Si junction has been analyzed to be ohmic due a special band alignment result and an ohmic junction between these two junctions (InGaN and silicon) in multi-junction tandem solar cells is desirable. As the result, the photons harvested are effectively converted into photo current.

At 40%-50% Indium content in InGaN/Si tandem solar cell, the conduction band is perfectly aligned with valence band of Si. The efficiency is improved when each of the multi junction cells efficiently converts photons from a narrow energy range. Band gap bowing are selected so that optimum coverage of solar spectrum and perfect alignment between InGaN and Si cell. InN has electron affinity of 5.8 eV which is quite high. Because of that, intense tendency for localization of n-type conduction and suface electron accumulation for InN and In-rich InGaN is possible which makes the cell is not so efficient. As discussed in the earlier part, the band edge of InGaN moves upwards to Si which provides better matching potential. This band bowing allows free control of conduction and valence band. GaN with 3.42 eV responses in UV band while InN with 0.7 eV responses in Infrared band (direct band gap). So, different combination of Indium linked to their band gap bowing where maximum solar spectrum absorption (from UV to IR band) seems to be possible as maximum conversion of photons occur. Besides that, its heating effect (InGaN) might be lower as compared to Si bottom cell because of its direct band gap properties. High thermal conductivity, high mobility, large absorption coefficients are the special properties of InGaN which helps in the enhancement of performance of solar cell in addition to band bowing and introduction of AlN interlayer.

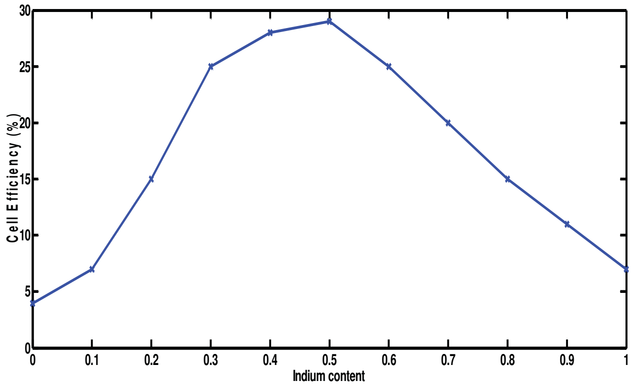

Figure 5: Solar cell efficiency with different Indium content

The structure of the device and penetration depth of the photon can explain the trend of J_{sc}. It explains that when the efficiency increases, absorption and J_{sc} increase, while V_{oc} and FF decrease. A high efficiency in the InGaN solar cell with medium Indium content is likely true. By considering the overall combined effects of the J_{sc}, V_{oc} and FF, it leads to efficiency showing an increasing and then decreasing pattern with the increment of Indium content. Thus, it can be said that 40%-50% Indium content in InGaN/Si solar cell is the optimum level to achieve the best performance. This explains that the reported InGaN solar cells with low Indium content show low conversion efficiencies. In addition, the combined effects of the J_{sc}, V_{oc}, and FF lead to an optimized efficiency in the InGaN solar cell with medium Indium content. This result also shows that the efficiency is much higher than the reported value because the simulated efficiency are higher than the actual fabricated solar cells because consideration of the leakage current and shunt resistance is not taken into account. High densities of threading dislocations and stacking faults can reduce the overall performance of InGaN/GaN solar cells.

Indium content (%)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)	Effciency (%)
20	10.01	1.69	59.12	15.00
30	15.12	1.51	60.35	25.29
40	27.44	1.40	62.39	27.31
50	31.76	1.23	64.55	28.11
60	34.91	0.78	67.33	25.28
70	40.91	0.66	70.06	19.93

Table 1: Simulation result of InGaN/Si with different Indium content

From the table above, it can be said that mid-ranged Indium content will give the best cell efficiency of InGaN/Si. Theoretically, it is not yet proven yet to have a very high Indium content because of the process and other native defects to the cell caused by a high Indium content. The high Indium content in this work is based on simulation result supported by electrical and optical properties of the device. 40%-50% Indium content is found to be promising to be used in InGaN/Si solar cell as the top InGaN cell is matched with the bottom Si cell. Photon management in the solar cell also can be enhanced by optimizing not only the doping and the thickness of each solar cell layer, but the Indium content as well.

4 Conclusion

From this work, performance analysis of InGaN/Si solar cell has been done by varying the Indium content from 0% to 100%. By varying the Indium content, the band gap and other properties of InGan will vary and indirectly affect the performance of the solar cell. The results have shown that Indium content of 40%-50% is optimum for an InGaN/Si double junction tandem solar cell because the top InGaN cell is matched with the bottom Si cell. An optimum Indium content in InGaN/Si solar cell is very important in order to improve the overall performance of the solar cell; open-circuit voltage, short-circuit current density, fill factor and quantum efficiency. Photon management seems to be more efficient with the presence of AlN interlayer an optimum Indium content in the InGaN/Si solar cell. The stacking faults are reduced by introducing 30nm AlN interlayer and current density matching between the two junctions is possible by choosing proper Indium content.

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