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Effect of Intrinsic Layer Thickness on PIN Structure for Tandem Solar Cell Based on Indium Gallium Nitride Using AMPS -1D

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In this work we have studied The effect of thickness of the intrinsic layer in the PIN structure of InGaN tandem solar cells such as photo generation rate, efficiency and recombination rate through the cells. Improvement around of 13 % of PIN tandem solar cell over PN tandem solar cell is observed for low doping concentration ($N_A = 10^{16}\,cm^{-3}$; $N_D = 10^{18}\,cm^{-3}$) and surface recombination (10^3cm/s). The photo-generated short-circuit current density (*Jsc*) and the open-circuit voltage (*Voc*) of structures under AM 1,5G (one sun) illumination, are simulated for different thickness of intrinsic layer varying from 50 nm to 350 nm.

Keywords: Solar cell, Tandem, Simulation, PIN structure, AMPS-1D, Efficiency, InGaN.

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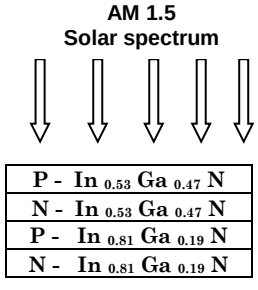
1. INTRODUCTION

Solar cells based on Indium Gallium Nitride ($In_xGa_{1-x}N$) were recognized recently as serious candidates in photovoltaic with high yields of conversion possibilities. To achieve the expected objectives of photovoltaic technology as a source of competitive energy compared to fossil fuels, a higher cell conversion efficiency, low cost and stability are the dominant factors. InGaN materials have an energy of interesting flexible gap varying from 0.7 eV to 3.42 eV and a high optical absorption more of 10^5/cm coefficient that indicates a better absorption of the solar spectrum [1, 2].

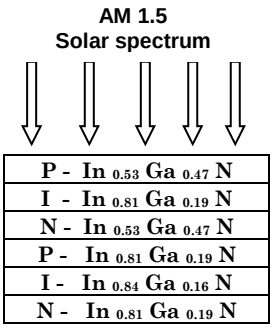
Its energy gap can be modulated by varying the rate of Indium in the alloy. The possibility of engineering of band with the InGaN on an interval that provides a good spectral match to sunlight makes the InGaN very suitable for photovoltaic solar cells. It is possible to grow several layers with different energies of InGaN gap since the material is relatively insensitive to defects introduced by the disagreement of meshes between the layers [3].

In this work, we have choose the thickness of intrinsic layer wish is one of the key parameters for designing tandem photovoltaic cell based on PIN structure.

The objective of the simulation of PIN structure tandem solar cell was to verify the performance of this cell by varying the thickness of intrinsic layer. The Fig. 1 shows the schematic design of $In_xGa_{1-x}N$ tandem solar cells, comprising two junctions, studied in this work.



a)



b)

Fig. 1 – Schematic of InGaN tandem solar cell a) PN structure and b) PIN structure

2. MODEL SIMULATION

The simulator adopted in this paper is the analyses of microelectronic and photonic structures (AMPS-1D) which is developed by the group from the Pennsylvania State University. It can calculate solar cell parameters, such as conversion efficiency (η) short circuit current (*Jsc*), open circuit voltage (*Voc*), fill factor (FF), and internal information including carrier recombination profile and electrical field distribution, by solving Poisson's equation and continuity equations for electrons and holes[4].

3. MODELING PARAMETERS

Material parameter equations used for the simulation of the $In_xGa_{1-x}N$ Solar Cells:

- **Band Gap (*Eg*) [5, 6]**

The direct band gap $In_xGa_{1-x}N$ material can be tuned from energy gap 3,4 eV of GaN to 0,7 eV of InN as a function of x by the following relation:

$$E_g(x) = (1-x)E_{gGaN} + xE_{gInN} - \beta(1-x) \qquad (1)$$

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where $E_{g\mathrm{GaN}} = 3.4$ eV and $E_{g\mathrm{InN}} = 0.7$ eV are, respectively, the energy gap for GaN and InN materials, x is the In mole fraction, and $\beta = 1{,}43$ eV be the bending factor.

- **Absorption Coefficient (α) [7] [11]**

$$\alpha(\mu m^{-1}) = A\sqrt{\frac{1.24}{\lambda} - E_g(x)}, \quad (2)$$

where λ be the wave length of incident photon in μm and A be the average weighing factor of the absorption coefficient which is $2.2 \times 10^5\ \mu m^{-1}\ (eV)^{-0.5}$.

- **Electron affinity (χ)** [7, 8]

The electron affinity is given by the following relation:

$$\chi\ (E_g)\ = \chi_{GaN} + 0.7(E_{gGaN} - Eg(x)) \quad (3)$$

where $\chi_{GaN} = 4.1$ eV be the electron affinity of GaN.

- **Relative Permittivity (ε_r) [8]**

The relative permittivity or dielectric constant is a measure of optical properties of InGaN alloy layers and is given by the following relation as a function of x:

$$\varepsilon_r(x) = (1 - x)\ \varepsilon_{GaN} + x\ \varepsilon_{InN}\ , \quad (4)$$

where $\varepsilon_{\mathrm{GaN}} = 10.4$ and $.\varepsilon_{InN} = 14.6$ be the dielectric constants of GaN and InN, respectively.

- **Effective Density of States (N_C, N_V) [8], [9]**

$$N_C = [0.9x + 2.3(1 - x)]\ 10^{18} \quad (5)$$

$$N_V = [5{,}3x + (1 - x).\,1{,}8]10^{19} \quad (6)$$

- **Electron and Hole Mobility (μ_n , μ_p) [10]**

$$\mu_i(N_Z) = \mu_{min,\ i} + \frac{\mu_{max,\ i} + \mu_{min,\ i}}{1+\left(\frac{N_Z}{N_{g,i}}\right)^{\gamma_i}}, \quad (7)$$

where Nz denotes the doping concentration such as for $Z = A$, D the acceptor and donor concentration of p and n-layers, respectively and the other model parameters $\mu_{\max,i}$, $\mu_{\min,i}$, $N_{g,i}$ and γ_i depend on the type of semiconductor which are given by [10] in Table 1.

Table 1 – Model parameters used in the calculation of the mobility of electron and hole

Type of carriers	Parameters			
	$\mu_{(\max,\ i)}$	$\mu_{(\min,\ i)}$	$N_{(g,\ i)}$	γ_i
Electron ($i = n$)	55	1000	$2{\cdot}10^{17}$	1
Hole ($i = p$)	33	170	$3{\cdot}10^{17}$	2

The description of the parameters used in the simulation and the basic parameter which are used in the study, the energy gap E_g, dielectric constant ε_r, acceptor / donor concentration NA/ND, mobility of electron μ_n, mobility of hole μ_p, effective density of states in conduction band NC, effective density of states in valence band NV, electron affinity χ, thickness d and indium fraction for $In_xGa_{1-x}N$ layers are given in Table 2.

4. SIMULATION RESULTS AND DISCUSSION

4.1 Effect of Intrinsic Layer Thickness on the Spectral Response

In this simulation we have studied the performance of tandem solar cell by varying the thickness of intrinsic layer in the PIN structure from 50 nm to 350 nm.

The influence of the Thickness of intrinsic layer on the spectral response is shown in the Fig. 2.

We can note the dependence between the thicknesses of intrinsic layer and photons absorbed by tandem solar cell.

4.2 Effect of Intrinsic Layer Thickness on the Current Density

We can observed from Fig. 3 that the photo-current increases when the thickness of intrinsic layer increases because the last widens the width of the depletion region, were electron-hole pairs created by photons absorbed are separated by the electric field, the electron is propelled towards the region type N and the hole towards the region of type P. These carriers give birth to a photocurrent generation.

Table 2 – Model parameters used in the simulation

Layers	$In_{0.53}Ga_{0.47}N$	$In_{0.81}Ga_{0.19}N$	$In_{0.53}Ga_{0.47}N$	$In_{0.81}Ga_{0.19}N$	$In_{0.84}Ga_{0.16}N$	$In_{0.81}Ga_{0.19}N$
	P	I	N	P	I	N
Eg (eV)	1.61	0.99	1.61	0.99	0.938	0.99
ε_r	12.63	13.8	12.63	13.8	13.93	13.8
N_A (cm^{-3})	10^{16}	/	/	10^{16}	/	/
N_D (cm^{-3})	/	/	10^{18}	/	/	10^{18}
μ_n (cm^2/V.s)	212.5	1000	212.5	212.5	1000	212.5
μ_p (cm^2/V.s)	169.82	170	169.82	169.82	170	169.82
Nc (cm^{-3})	$1.56\ 10^{18}$	$1.17\ 10^{18}$	$1.56\ 10^{18}$	$1.17\ 10^{18}$	$1.12\ 10^{18}$	$1.17\ 10^{18}$
Nv (cm^{-3})	$3.65\ 10^{19}$	$4.63\ 10^{19}$	$3.65\ 10^{19}$	$4.63\ 10^{19}$	$4.74\ 10^{19}$	$4.63\ 10^{19}$
χ (eV)	5.35	5.78	5.35	5.78	5.82	5.78
d (nm)	500	50 ~ 350	1000	500	50 ~ 350	1000

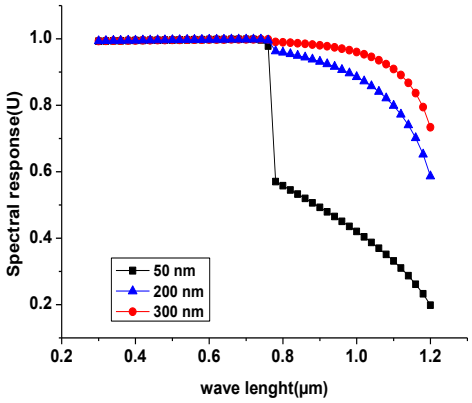

Fig. 2 – The spectral response as function of wave length for different thickness of intrinsic layer (50 nm, 200 nm and 300 nm)

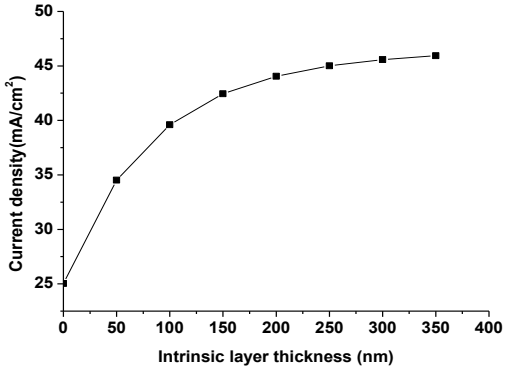

Fig. 3 – Current density as a function of intrinsic layer thickness

4.3 Effect of Intrinsic Layer Thickness on the Open Circuit Voltage

The open circuit voltage as a function of the thickness of intrinsic layer is represented in Fig. 4.

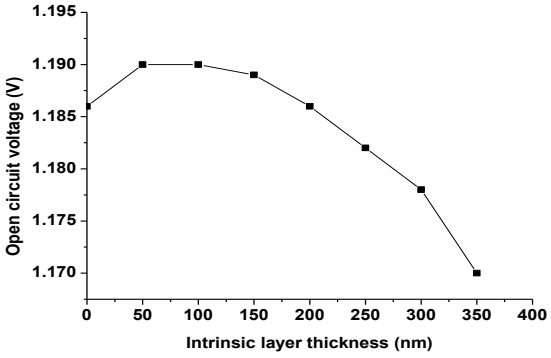

Fig. 4 – The open circuit voltage as a function of *i*-Layer thickness

We can see that the open circuit voltage decreases slowly (about 1.7 %) when the thickness of intrinsic layer increases from 50 nm to 350 nm.

4.4 Effect of Intrinsic Layer Thickness on the Fill Factor

The Fig. 5 represents the fill factor as a function of intrinsic layer thickness.

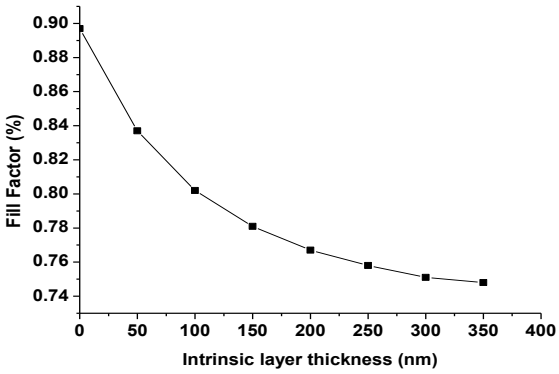

Fig. 5 – Fill factor as a function of intrinsic layer thickness

We observed that the fill factor decreases (about 17 %) when the thickness of intrinsic layer increases from 50 nm to 350 nm due to the decreases of open circuit voltage.

4.5 Effect of Intrinsic Layer Thickness on the Efficiency

The efficiency as a function of the thickness of intrinsic layer is represented in Fig. 6.

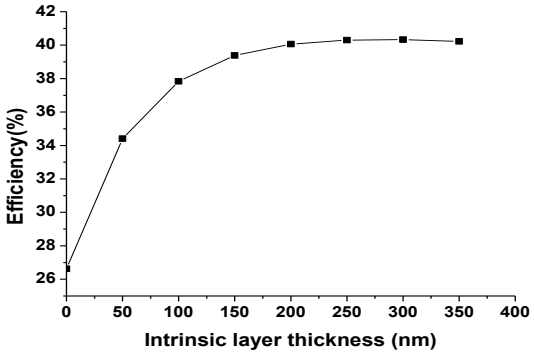

Fig. 6 – Efficiency as a function of intrinsic layer thickness

We observed from Fig. 6 that the efficiency increases also when the thickness of intrinsic layer increases because the efficiency depend of the photo-current , which is optimum (optimum 40.324 %) at 300 nm, and then it decreases due to degradation of drift electric field.

4.6 Optimal Structure

From the above results are obtained using the AMPS-1D software we can determine the solar cell which has the best performance while giving the thickness of intrinsic layer of the cell. The current-voltage characteristics for the device tandem solar cell layers with the optimal efficiency for PIN (at 300 nm) and PN structure are shown in Fig. 7, and the corresponding parameters PV (V_{OC}, J_{SC}, Fill Factor and efficiency) are summarized in Table 3.

5. CONCLUSION

In this design, it has been found that the inclusion of the intrinsic layer in the conventional PN structure widens the width of the depletion region as a consequence,

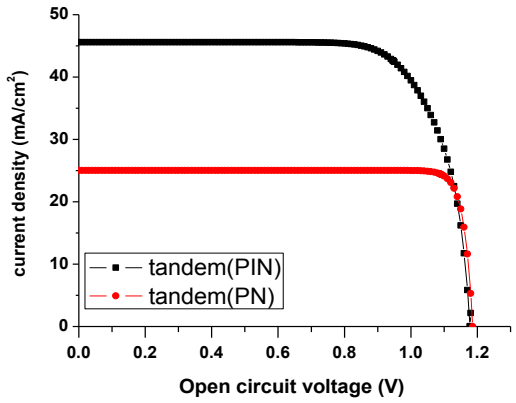

Fig. 7 – *I*(*V*) characteristic of the tandem solar cell (double junctions) with the optimum performance

Table 3 – Optimal parameters PV for tandem solar cell (double junctions)

Type of cell	*Jsc* (mA/cm²)	*Voc* (V)	Fill Factor (%)	Efficiency (%)
PN	25.028	1.186	89.7	26.619
PIN	45.584	1.178	75.1	40.324

the photo-current increases. It is also observed that the external quantum efficiency is increased with the inclusion of intrinsic layer.

The calculation of the photovoltaic parameters of the PIN tandem solar cell based on InGaN with tow junctions was designed and optimized with different thickness of intrinsic layer. It is shown that the electrical parameters such as, the density current , fill factor and efficiency has strong dependence on the thickness of intrinsic layer ,has allowed to achieve the best solar cell structure with optimum performances.

The optimum efficiency, found under normalized conditions is 40.324 % using 300 nm as thickness of intrinsic layer, as compared to the PN InGaN cell the PIN cell exhibited around 13 % higher efficiency.

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REFERENCES

1. M. Yamaguchi, *Sol. Energ. Mater. Sol. C.* **75**, 261 (2003).
2. J. Wu, W. Walukiewicz, K.M. Yu, J.W. Ager, E.E. Haller, et al, *Appl. Phys. Lett.* **80**, 3967 (2002).
3. T. Matsuoka, H. Okamoto, M. Nakao, H. Harima, E. Kurimoto, *Appl. Phys. Lett.* **81**, 1246 (2002).
4. M. Boukais, B. Dennai, A. Ould-Abbas, *J. Nano- Electron. Phys.* **7** No 3, 03015 (2015).
5. H.L. Xiao, X.L. Wang, J.X. Wang, N.H. Zhang, H.X. Liu, Y.P. Zeng, J.M. Li, Z.G. Wang, *J. Cryst. Growth* **276**, 401 (2005).
6. M. Nawaz, A. Ashfaq, *Semicond. Sci. Technol.* **27**, 035019 (2012).
7. N. Li, *Photoelectron. Dev.* 3 (2005).
8. M.E. Levinshtein, S.L. Rumyantsev, M.S. Shur, (Wiley: Chichester, UK: 2001).
9. O. Jani, C. Honsberg, A. Asghar, D. Nicol, L. Ferguson, A. Doolittle, S. Kurtz, *31st IEEE Photovoltaic Specialists Conf. (Lake Buena Vista)*, 37 (2005).
10. T.T. Mnatsakanov, M.E. Levinshtein, L.I. Pomortseva, S.N. Yurkov, G.S. Simin, M. Asif Khan, *Solid-State Electron.* **47**, 111 (2003).
11. B. Dennai, H. Benslimane, A. Helmaoui, *IRSEC* 23 (2013).