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Simulation model of multi-junction $In_xGa_{1-x}N$ Solar Cells

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In this model we investigate theoretically the characteristics of multi junction $In_xGa_{1-x}N$ series-connected solar cells under air mass 1.5 global irradiance spectrum using Matlab program. The doping levels of p-type and n-type were $5\times10^{18}cm^{-3}$ and $1\times10^{18}cm^{-3}$ respectively. The efficiency is found to be varied from 18.01% for single junction to 42.55% for five junctions. The enhancement in V_{OC} was observed from the lower values of total thickness.

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1. Introduction

The goal of achieving photovoltaic conversion efficiencies of 50% or higher not only attributes as a scientific achievement and aids specialized applications, but can also reduce the cost of large-scale solar electric generation. The maximum reported photovoltaic efficiency of 39% at 236 suns is achieved by a triple-junction GaInP/GaInAs/Ge tandem solar cell [1]. While the achievable efficiency of triple-junction tandem solar cells is restricted to about 40% [2], modeling results show that a tandem solar cell of five junctions or greater, or an equivalent structure, is required to achieve practical efficiencies of greater than 50% under an AM1.5 spectrum and a realistic concentration of 500x [3]. These structures require band gaps of the top cell to be at least 2.4 eV, InGaN has the appropriate optical properties and has been well demonstrated for light-emission applications.

2. Model calculations

The photo current density of each cell is equal to $J_{ph}= J_n+J_p+J_{SCR}$ were calculated by using the equations [4].

$$J_p=\frac{qF(1-R)\alpha L_n}{\alpha^2L_n^2-1}\left[\alpha L_n-\frac{\frac{S_nL_n}{D_n}\left(\cosh(\frac{x_p}{L_n})-\exp(-\alpha x_p)\right)+\sinh\left(\frac{x_p}{L_n}\right)+\alpha L_n\exp(-\alpha x_p)}{\frac{S_nL_n}{D_n}\sinh\left(\frac{x_p}{L_n}\right)+\cosh(\frac{x_p}{L_n})}\right] \quad (1)$$

$$J_n=\frac{qF(1-R)\alpha L_p}{\alpha^2L_p^2-1}\left[\frac{\frac{S_nL_n}{D_n}+\alpha L_p-\exp(-\alpha x_n)\left[\left(\frac{S_pL_p}{D_p}\right)\cosh(\frac{x_n}{L_p})+\sinh(\frac{x_n}{L_p})\right]}{\frac{S_pL_p}{D_p}\sinh\left(\frac{x_n}{L_p}\right)+\cosh(\frac{x_n}{L_p})}-\alpha L_p\exp(-\alpha x_n)\right] \quad (2)$$

$$J_{SCR}=qF(1-R)\exp(-\alpha x_n)(1-\exp(-\alpha w)) \quad (3)$$

Such

$$L_n=\sqrt{D_n\tau_n}\qquad ,L_p=\sqrt{D_p\tau_p} \quad (4)$$

we take the thicknesses of the p-$In_xGa_{1-x}N$ and n-$In_xGa_{1-x}N$ layers to be

$$x_p=t_T\left(\frac{L_e}{L_h+L_e}\right) \quad (5)$$

$$x_n=(0.1,0.15,0.2,0.25,0.3)$$

The absorption coefficient for direct band gap is [5]

$$\alpha(\mu m^{-1})=7.91(E-E_g)^4-14.9(E-E_g)^3+5.32(E-E_g)^3+5.32(E-E_g)^2+9.61(E-E_g)+1.98 \quad \text{for } (E>E_g) \quad (6)$$

Or [6]

$$\alpha_\lambda=C(h\frac{c}{\lambda}-E_g)^{\frac{1}{2}}=C(h\nu-E_g)^{\frac{1}{2}} \quad (7)$$

This value for the constant C is approximately $2x10^4$ for direct semiconductor, if the absorption coefficient α is given in cm^{-1} So

$$S_n=70\left(\frac{N_D}{7*10^{17}}\right)\quad \text{and}\quad S_P=70\left(\frac{N_A}{7*10^{17}}\right) \quad (8)$$

We calculated the reflection from relation below

$$R=\left(\frac{n_1-n_2}{n_1+n_2}\right)^2 \quad (9)$$

Where the refractive index n_2 for $In_xGa_{1-x}N$ material equal [7].

$$n_{(In_xGa_{1-x}N)} = xn_{(InN)} + (1-x)n_{(GaN)} - bx(1-x) \quad (10)$$

Or

$$n(In_xGa_{1-x}N) = 2.506 + 0.91x \quad (11)$$

The band gap calculate from

$$E_g(In_xGa_{1-x}N) = xE_g(InN) + (1-x)E_g(GaN) - bx(1-x) \quad (12)$$

Where:

$$b=1.43 \text{ eV} \quad (13)$$

Or can calculate the band gap from

$$E_g=(3.39-2.5x+x^2) \quad (14)$$

The lattice constant term [8].

$$a_{(In_xGa_{1-x}N)} = xa_{(InN)} + (1-x)a_{(GaN)} \quad (15)$$

The mismatch equation is

$$mismatch = \frac{a_{film} - a_{substrate}}{a_{substrate}} * 100\% \quad (16)$$

The open circuit voltage

$$V_{oc} = \frac{KT}{q} \times \ln\left(\frac{J_L}{J_0} + 1\right) \quad (17)$$

And the short circuit current density

$$J_{SC} = -J_L \quad (18)$$

The saturation current density J_0 was calculated for all the $In_xGa_{1-x}N$ alloys

$$J_0 = qn_i^2\left(\frac{D_{nj}}{L_{nj}N_A} + \frac{D_{nj}}{L_{nj}N_D}\right), j = 1,2...n \quad (19)$$

where

$$n_i^2 = N_C N_V \exp\left(-\frac{E_g}{kT}\right) \quad (20)$$

$$N_C = 2M_c\left(\frac{2\pi k_B T m_e^*}{h^2}\right)^{3/2}, \quad N_V = 2M_V\left(\frac{2\pi k_B T m_h^*}{h^2}\right)^{3/2} \quad (21)$$

The efficiency of the multi junction solar cells is given by

$$\eta = \frac{P_m}{P_{in}} = \frac{V_m J_m}{P_{in}} = \frac{V_{oc} J_{ph} \eta_{fill}}{P_{in}} * 100\% \quad (22)$$

$$\eta_{fill} = \frac{J_m V_m}{J_{ph} V_{oc}} = \left(\frac{J_m}{J_{ph}}\right) * \left(\frac{V_m}{V_{oc}}\right) \quad (23)$$

$$V_m = V_{OC} - 3V_t \quad (24)$$

$$J_m = J_{ph} - j_s\left[\exp\left(\frac{V_m}{V_t}\right) - 1\right] \quad (25)$$

4. Result and discussions

We first test the equations to verify which of the best one for absorption coefficient, refractive index and energy band gap.

So the first step we enhance the our calculation by choosing the best parameters and equations from the parameters and equations above.

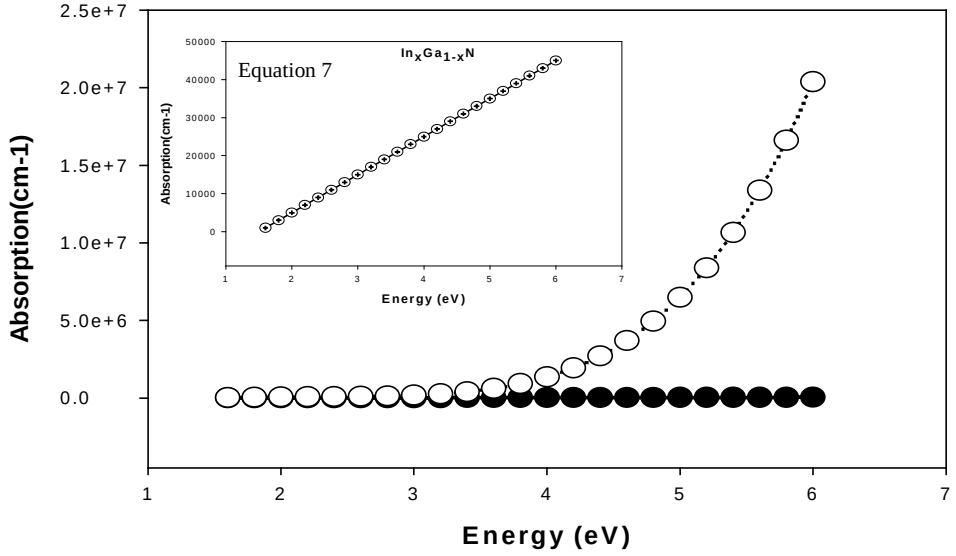

Fig. 1. The energy(eV) vs. absorption coefficient (cm-1).

In Fig. 1 we used the band gap equal 1.5 eV just to test these curves, From this compare appear the behavior the equation (6) abnormal because the curve take big change to reach the value power $10^7 cm^{-1}$ and the absorption coefficient in $In_xGa_{1-x}N$ around power $10^5 cm^{-1}$, on other side the behavior of equation (7) it seem very credible values, for that we used the equation (7) in our calculations.

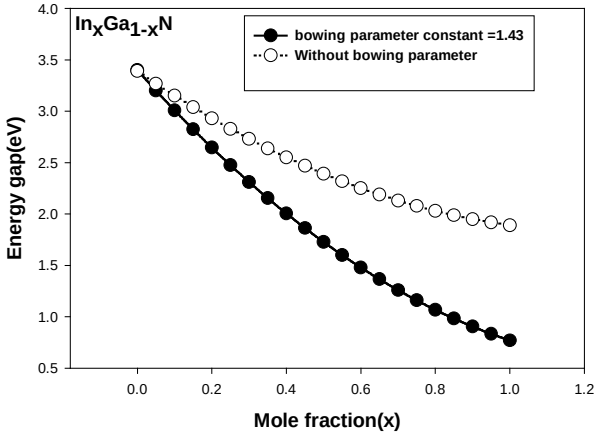

Fig. 2. The mole fraction(x) vs. energy band gap(eV).

In Fig. 2 show the best equation with bowing parameter is constant and equal (1.43).

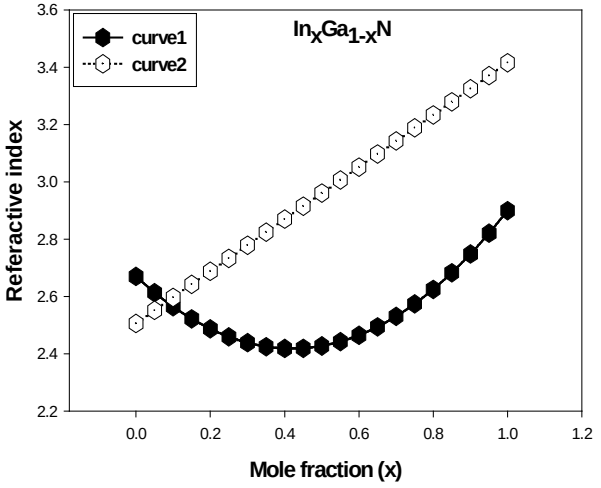

Fig. 3. The mole fraction(x) vs. refractive index(n).

Fig. 3 show the behavior of refractive index(n) opposite the mole fraction according to equations (10), (11) such can see the equations (11) that with out bowing parameter its values exceed the 3.4 value, but suppose in refractive index to be between the range (2.9-2.65) because these values represent the refractive indices for InN and GaN respectively, so the equation (10) is the best between them.

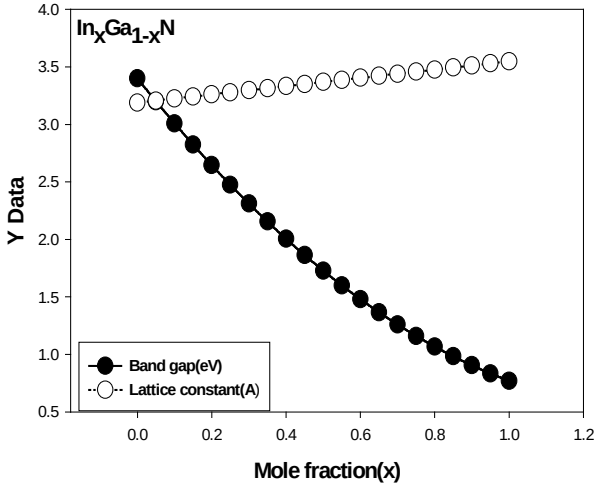

Fig. 4. The mole fraction(x) vs. band gap(eV) and lattice constant(A).

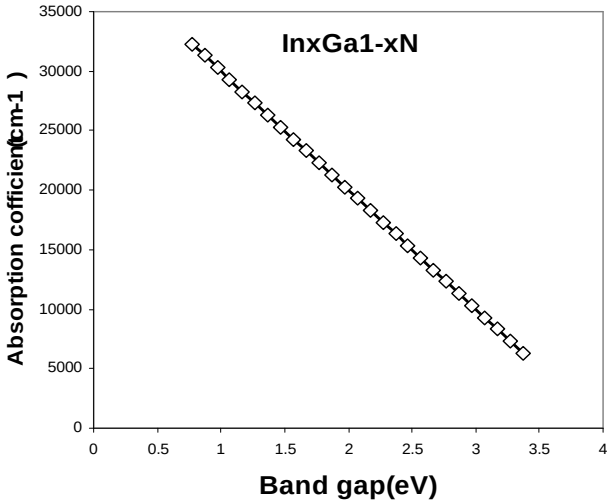

Fig. 5. The band gap(eV) vs. absorption coefficient (cm^{-1}).

Fig. 4 show the increase in mole fraction decrease the band gap because when increase the mole fraction the composition of InN increase too until reach the mole fraction (x=1) to become the composition of $In_xGa_{1-x}N$=InN and to be the band gap value =0.77eV, but in lattice constant the curve increase because the value of lattice constant for InN bigger than GaN.

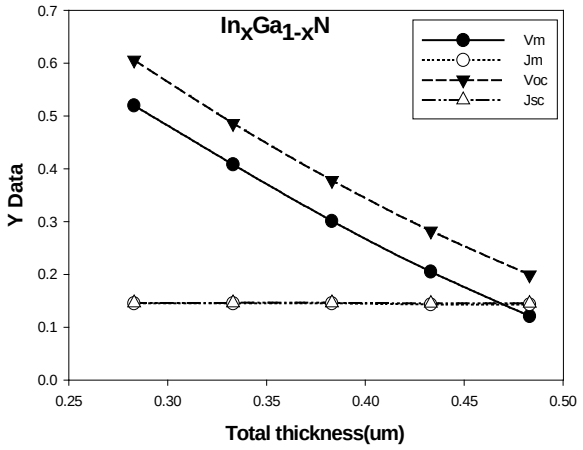

Fig. 6. Variation of the total thickness with a-open circuit voltage, short-circuit current density, maximum voltage and current density

In Fig. 6 is shown the variation of V_{oc}, V_m, I_{sc} and I_m as a function of the total thickness. It seems the V_{oc} and V_m are in reverse relation with the total thickness but the J_{sc} and J_m show stability with thickness The Fig. 7 show the efficiency and fill factor decreases when the total thickness of each junction increases and vice versa.

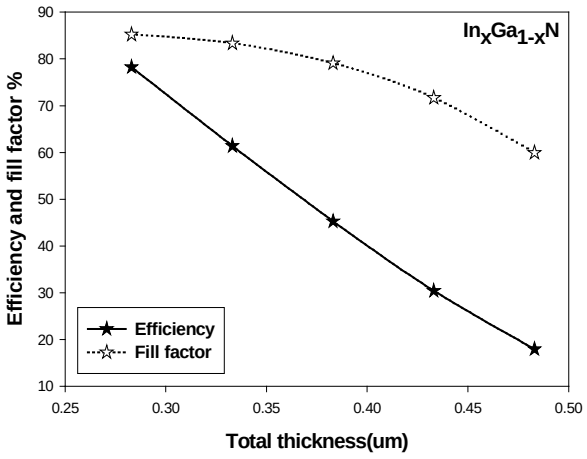

Fig. 7. Variation of the total thickness with fill factor and efficiency.

Table 1. Mole fractions, band gaps, current densities, voltages and thicknesses for a five junctions tandem solar cells.

Mole fraction(x)	Band gap(eV)	Thick of n-type μm	Total thickness μm	V_m(eV)	J_m(mA/cm2)	V_{OC}(eV)	I_{SC} mA/cm^2
0.4	2.024	0.1	0.283	0.52	0.145	0.606	0.146
0.5	1.75	0.15	0.333	0.408	0.145	0.486	0.146
0.6	1.504	0.2	0.383	0.301	0.145	0.378	0.146
0.7	1.286	0.25	0.433	0.205	0.143	0.282	0.145
0.8	1.096	0.3	0.483	0.121	0.143	0.199	0.145

Table 2. Numbers of junctions, fill factors and efficiencies for a five junctions tandem solar cells.

No. of junctions	V_{OC}(eV)	J_{OC} (mA/cm^2)	Fill factor (FF)%	Efficiency(η)%
1	0.19	0.149	62.7	18.01
2	0.24	0.145	67.4	23.78
3	0.286	0.143	72.5	30.07
4	0.336	0.142	75.6	36.34
5	0.39	0.138	78	42.55

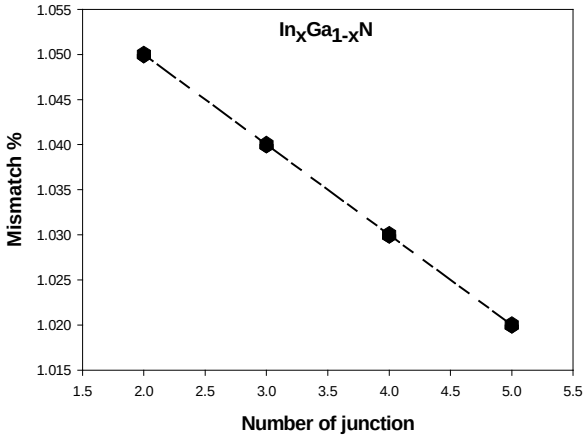

Fig. 8. Variation of the lattice mismatch with the number of junctions.

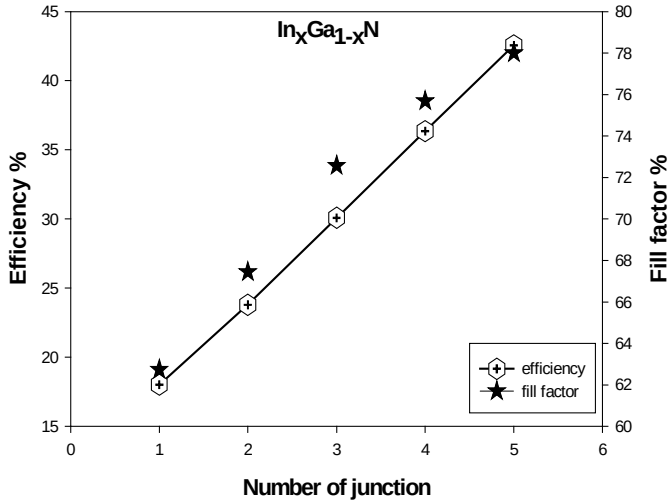

Fig. 9. Variation of the efficiency and fill factor with number of junctions.

In Fig. 8 it is noticeable that an increasing of junction numbers, the lattice mismatch between the junctions decreases and in a same time the efficiency and the fill factor increases. This is because of increasing number of junction resulting in the lattice constant decrease when decrease Indium fraction (decreased mole fraction makes the properties of composition $In_xGa_{1-x}N$ from InN to GaN and this shifts the band gap of $In_xGa_{1-x}N$ from $E_{g(InN)}$= 0.77 eV to $E_{g(GaN)}$= 3.4 eV as shown in table (1), and lattice constant from $a_{(InN)}$= 3.548 Å to $a_{(GaN)}$= 3.189 Å) for this reason decrease the difference in lattice constant between two adjacent junctions, and according to the relation $(a_f - a_s)/a_s$, the term in the top will become small, smaller,…smallest, so the lattice mismatch will be less than the previous one between two adjacent junctions.

5. Conclusions

In this work we built a model to calculate the most of parameters for $In_xGa_{1-x}N$ material in solar cells theoretically. From this study we found from our testing the best equation for absorption equation (6), refractive index equation (10) and the band gap equation (16) with bowing parameter constant and equal 1.43. From the tables (1,2) one observes the increase in number of junctions causes the increase in the solar cell performance which ascribe to increase of the open circuit voltage (Voc) of the solar cell, without significant loss in the short circuit current (Jsc). Fig. 9 and tables (1,2) show the efficiency of one junctions is 18.01% and for five junction is 42.55%. A photocurrent density of five junction is 0.138 mA/cm^2 and an open-circuit voltage is 0.39 eV. The efficiency and fill factor increases when the total thickness decrease of each cell, the mismatch is low and is achieved below 1.05% to four junctions.

Parameters Values

$L_n = 125 \times 10^{-6}$ cm $L_p = 79 \times 10^{-6}$ cm $E_{g(InN)}$= 0.77 eV $E_{g(GaN)}$= 3.4 eV

$a_{(InN)}$= 3.548 A $a_{(GaN)}$= 3.189 A $q=1.6*10^{-19}$C Pin=0.084 w/cm^2

$\left(\frac{m_e^*}{m_e}\right) = 0.07$ $\left(\frac{m_h^*}{m_h}\right) = 0.7$

D_p = 9 cm^2/s D_n = 25 cm^2/s

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