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Potentials of $In_xGa_{1-x}N$ photovoltaic tandems

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Abstract – *During the past few years a great variety of multi-junction solar cells has been developed with the aim of a further increase in efficiency beyond the limits of single junction devices. In this work, the solar power conversion efficiency of $In_xGa_{1-x}N$ based tandem solar cells was investigated. With this intention, one simulation of the spectral response and the current-voltage characteristic was carried out using a simulation program designed under 'Visual Basic 5' language for this reason. Our cal culation indicates that the attainable efficiency can be enhanced up to 34 % and 37% for tandems with double and triple junctions respectively, obtained under 1-sun AM1.5 illumination and at ambient temperature, using realistic material parameters. A comparison has been made of our results with those of other models.*

Résumé – *Pendant les dernières années, une grande variété de cellules solaires à multi-jonction a été développée dont le but est d'élever le rendement énergétique au delà des limites des dispositifs à une jonction. Dans ce travail, l'efficacité de conversion de l'énergie solaire des tandems basés sur $In_xGa_{1-x}N$ été étudiée. Pour ce faire, une simulation de la réponse spectrale et de la caractéristique courant-tension a été effectuée, en utilisant un programme de simulation développé sous langage 'Visual Basic 5' pour cette raison. Notre calcul indique que le rendement possible peut être supérieur à 34 % et 37 % pour des tandems à doubles et triples jonctions respectivement, sous une illumination 1-soleil AM1.5 et une température ambiante, en utilisant des paramètres matériels réalistes. Une comparaison de nos résultats avec d'autres modèles a été faite.*

Keywords: Tandem - InGaN - Spectral response - I-V characteristics.

1. INTRODUCTION

Much research effort in the last few years has been made on the improvement of multi-junction solar cells. The aim has been to raise the efficiency beyond the limit of single junction cells. This development has lead to a great variety of multi-junction cells, which can be classified according to the materials used, the kind of combination of the junctions, mechanically stacked or monolithic and the number of terminals used to contact the device.

In late 2001 and early 2002 Davydov *et al.* [1], Wu *et al.* [2] and Matsuoka *et al.* [3] measured the photoluminescence from Indium Nitride InN films not at 1.9 eV as expected, but at approximately 0.7 eV, this indicating that the band gap was lower than previously thought. This new value of InN band gap has attracted research attention due to new technology opportunities for implementation of $In_xGa_{1-x}N$-based solar cells.

The direct band gap of the $In_xGa_{1-x}N$ alloy system, extends continuously from InN band gap which is 0.7 eV [4] in the medium infra red, to that of the Gallium Nitride

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GaN which is 3.42 eV [4] in the near ultraviolet, makes the $In_xGa_{1-x}N$ alloy a promising candidate for radiation and temperature resistant single or multi-junction solar cells [5].

In this paper, we have modelled the photovoltaic conversion efficiency for a double and triple $In_xGa_{1-x}N$ tandems in terms of their physical parameters, including the spectral response and the current-voltage characteristics employing a simulation program developed for this reason.

We compared the results of our simulation with other theoretical calculations published in the literature.

2. MODEL DESCRIPTION

In this work, calculations were all performed under 1-sun AM1.5 illumination and a temperature of 300 K using the one diode ideal model, and for convenience, several simplifying assumptions were made, including no series resistance losses, no reflection losses and contact shadowing. Currents calculation follows the general methodology described in the ref. [6].

2.1 Analytical model

The total output current drawn from single cells under illumination is given by [6] as:

$$I_{Total} = I_{Light} - I_{Dark} \tag{1}$$

$$I_{Light} = \int_{\lambda min}^{\lambda max} \left[I_p(\lambda) + I_n(\lambda) + I_{dr}(\lambda) \right] d\lambda \tag{2}$$

where:

$I_p(\lambda)$ is the photocurrent due to holes collected at the depletion edge x_j;

$I_n(\lambda)$ is the photocurrent due to electrons collected at the depletion edge $x_j + w$, where x_j and w are the junction depth and the width of the depletion region respectively;

$I_{dr}(\lambda)$ is the contribution of the depletion region to the photocurrent;

λ_{min} is the wavelength corresponding, for the bottom cell in case of double junction system, to the top cell band gap, or corresponds to the middle cell band gap for the bottom cell in case of triple junction system, and equals zero for the top cell;

λ_{max} is the wavelength corresponding to the cell band gap.

The dark current can be expressed as:

$$I_{Dark} = I_0 \times \left[\exp\left(\frac{q.v}{k.T} \right) - 1 \right] \tag{3}$$

where:

I_0 is the saturation current which was calculated following the method described in the ref. [6]; v is the applied voltage; k is the Boltzmann constant and T is the temperature.

The open circuit voltage is given by [6] as:

$$V_{oc} = \frac{k.T}{q} \times \ln\left(\frac{I_{sc}}{I_0} + 1\right) \tag{4}$$

where I_{sc} is the short circuit current.

The open circuit voltage of the tandem is taken to be the sum of the open circuit voltages of the tandem junctions:

$$V_{oc} = \sum_{i=1}^{n} V_{oc,i} \tag{5}$$

where n is the number of junctions incorporated in the tandem.

The cell output power is given as:

$$P = I_{Total} \times V \tag{6}$$

The cell conversion efficiency is usually taken to be:

$$\eta = \frac{I_m \times V_m}{P_{inc}} \tag{7}$$

where I_m and I_m are coordinates of the maximum power point; P_{inc} is the total incident solar power.

The fill factor is defined by:

$$FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}} \tag{8}$$

The spectral response can be written as [6]:

$$SR(\lambda) = \frac{j_{sc}}{p_{inc}} \tag{9}$$

where j_{sc} is the short circuit current density.

2.2 $In_xGa_{1-x}N$ parameter equations used in our program

The equation relating the bandgap energy to the mole fraction x is given by [7, 8] as:

$$E_g(x) = x \times E_g(InN) + (1-x) \times E_g(GaN) - x(1-x) \times C \tag{10}$$

where: $E_g(InN) = 0.7$ eV, $E_g(GaN) = 3.42$ eV and C is a bowing parameter which is taken to be equal to 1.43.

The electron and hole mobilities are calculated as a function of doping using [9]:

$$\mu_i(N) = \mu_{min,i} + \frac{\mu_{max,i} - \mu_{min,i}}{1 + \left(N / N_{g,i}\right)^{\gamma_i}} \tag{11}$$

where i represent either electrons (e) or holes (h), N is the doping concentration and the specific parameters μ_{min} , μ_{max} , γ and N_g are given in **Table 1**.

Table 1: Parameters used in the simulation of the InN and GaN carrier mobilities

	$\mu_{min,e}$ (cm^2/vs)	$\mu_{max,e}$ (cm^2/vs)	$\mu_{min,h}$ (cm^2/vs)	$\mu_{max,h}$ (cm^2/vs)	γ_e	γ_h	$N_{g,e}$ (cm^3)	$N_{g,h}$ (cm^3)
GaN	55	1000	3	170	1	2	2e17	3e17
InN	30	1100	3	340	1	2	2e17	3e17

$In_xGa_{1-x}N$ electron mobilities are taken as a linear interpolation between the InN and GaN values; however, hole mobilities of the $In_xGa_{1-x}N$ alloys are assumed to be similar to the GaN hole mobility.

The absorption coefficient of the $In_xGa_{1-x}N$ alloys is taken to be [2, 10]:

$$\alpha(E) = 10^5 \times \sqrt{a\times(E - E_g) + b\times(E - E_g)^2} \quad cm^{-1} \tag{12}$$

Where E is the incoming photon energy given in eV, a and b are dimensionless fitting parameters. The fitting parameters used in our program are shown in **Table 2**.

Table 2: Fitting parameters used to calculate the absorption coefficient of the $In_xGa_{1-x}N$ alloys

Indium composition	a-	b-
0.57	0.60946	0.92182
0.69	0.58108	0.66902
0.82	0.66796	0.68886

The relative dielectric constant for InN and GaN are 10.5 and 8.9 respectively [11, 12], so a linear interpolation has been made to find the relative dielectric constant of the $In_xGa_{1-x}N$ alloys.

Effective masses for electrons and holes were determined using the following equations [13]:

$$me^* = m_0 . (0.2 - 0.105x) \tag{13}$$

$$mh^* = m_0 . (1.25 + 0.8x) \tag{14}$$

Where m_0 is the electron rest mass.

3. RESULTS AND DISCUSSION

The parameter values assigned for the two tandems are presented in **Table 3**.

Table 3: Physical and geometrical parameters used in simulations

		x	E_g (eV)	N_a (cm^3)	N_d (cm^3)	$\tau_{e,h}$ (cm^3)	$S_{e,h}$ (cm^3)	x_j (µm)	d (µm)	S (cm^2)
Double	Top cell	0.53	1.622	1e17	1e16	4e-9	1e3	2e-2	3	1

junction tandem	$In_{0.53}Ga_{0.47}N$ Bottom cell $In_{0.81}Ga_{0.19}N$	0.81	0.997	1e17	1e16	4e-9	1e3	2e-2	3	1
Triple junction tandem	Top cell $In_{0.53}Ga_{0.47}N$	0.53	1.622	1e17	1e16	4e-9	1e3	2e-2	3	1
	Top cell $In_{0.69}Ga_{0.31}N$	0.69	1.237	1e17	1e16	4e-9	1e3	2e-2	3	1
	Top cell $In_{0.84}a_{0.16}N$	0.84	0.943	1e17	1e16	4e-9	1e3	2e-2	3	1

All of the cells having the same junction depths x_j, cell thicknesses d, doping levels, surfaces S and recombination velocities for electrons and holes $S_{e,h}$.

We can see from **Table 3** that the energy gaps of the two tandems decrease from the top cell to the bottom cell.

3.1 Effect of minority carriers lifetimes on the conversion efficiency

The minority carrier lifetime is one of the most critical parameters in determining the efficiency of a solar cell. We simulated the effect that lower lifetimes would have on device performance, and the results were shown in figure 1.

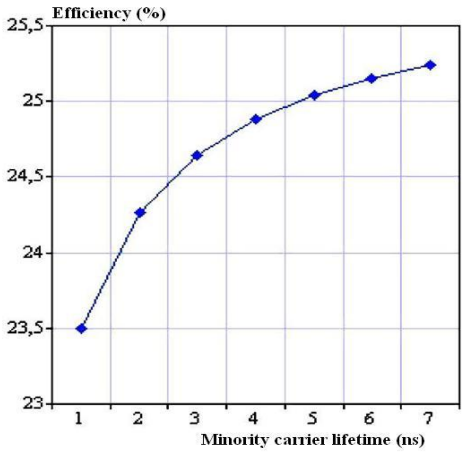

Fig. 1: Effect of minority carriers lifetimes on the conversion efficiency of a single junction $In_{0.53}Ga_{0.47}N$ solar cell.

The large absorption coefficient in the direct band gap $In_xGa_{1-x}N$ alloys causes the majority of the electron-hole pairs to be generated less than a diffusion length away from the junction. So for short carrier lifetimes, the carriers recombine quickly what implies a reduction in the conversion efficiency [14].

Hole lifetimes as high as 6.5 ns and 5.4 ns have been observed in GaN and InN respectively [15, 16]. However, $In_xGa_{1-x}N$ alloys are likely to have lower lifetimes due to compositional fluctuations, and therefore a 4 ns minority carrier's lifetime was assumed in our calculations for both electrons and holes.

3.2 Spectral response simulation

In order to obtain information about the useful wavelength range in our tandem structures, spectral response simulation was performed. The spectral responses of the

single cells for both double and triple junction tandems to the 1-sun AM1.5 illumination are shown in figure 2.

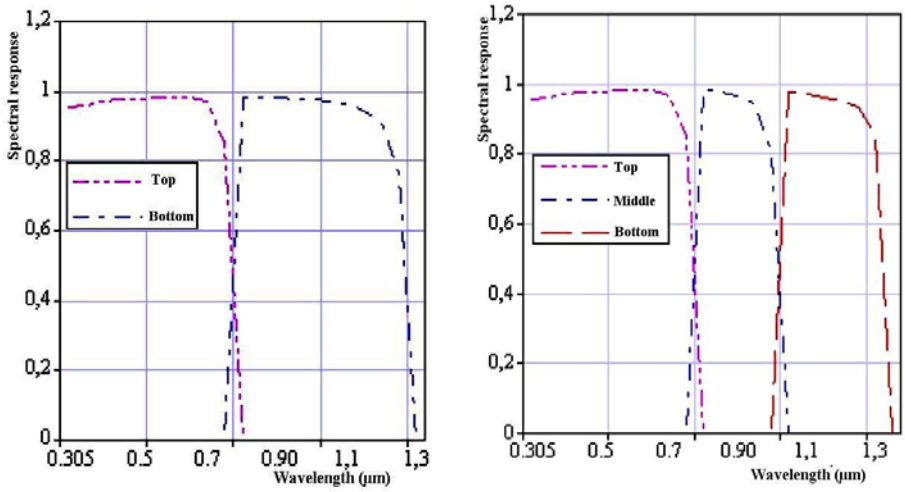

Fig. 2: Spectral responses of the double (left) and triple (right) junction tandems

As it is expected from the values of the band gap energies and equations (2) and (9), figure 2 indicates that the top cell has higher collection efficiency for carriers generated by shorter wavelengths which haves higher photon energy; however the bottom cell has higher collection efficiency for carriers generated by longer wavelengths. So the collection efficiencies of the junctions are complementary and the tandem has higher collection efficiency than single junctions.

3.3 I (V) characteristics simulation

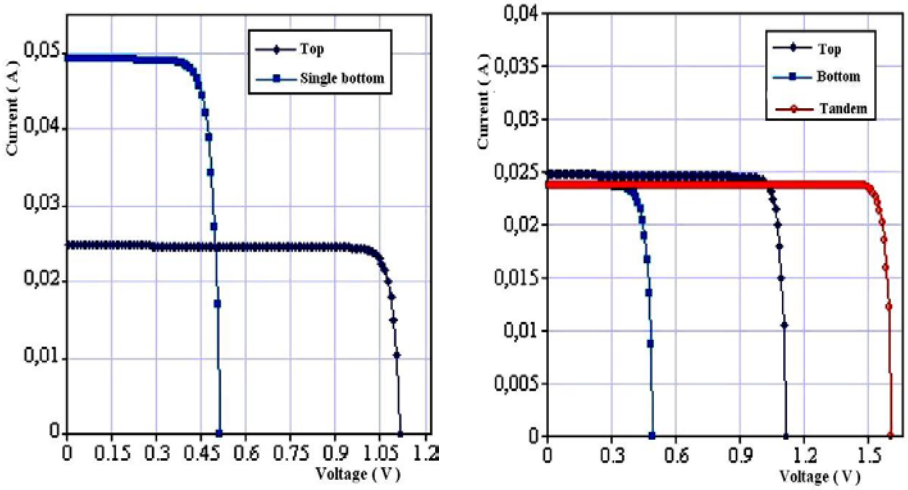

Fig. 3: Simulated I (V) characteristics of the double junction tandem: (left) for top and bottom single junctions, (right) for top, bottom and the tandem

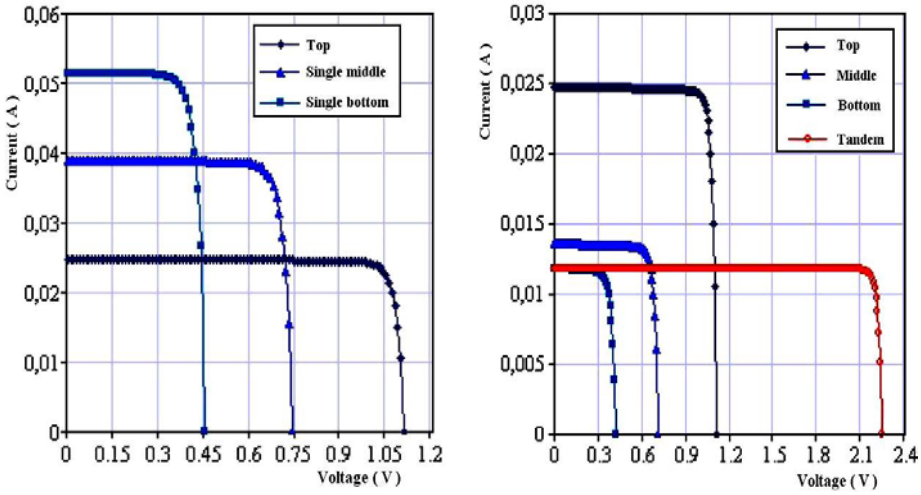

Fig. 4: Simulated I (V) characteristics of the triple junction tandem: (left) for top, middle and bottom single junctions, (right) for top, middle, bottom and the tandem

Table 4: Photovoltaic parameters of the double and triple junction tandems

		V_{oc} (V)	I_{sc} (A)	FF 5%)	η (%)
Double Junction tandem	Top cell: $In_{0.53}Ga_{0.47}N$	1.11	24.76	87.47	24.88
	Single bottom cell: $In_{0.81}Ga_{0.19}N$	0.51	49.17	79.97	20.71
	Bottom cell: $In_{0.81}Ga_{0.19}N$	0.49	23.78	79.15	9.55
	Double junction tandem	1.61	23.78	91.84	34.43
Triple Junction tandem	Top cell: $In_{0.53}Ga_{0.47}N$	1.11	24.76	87.47	24.88
	Single middle cell: $In_{0.69}Ga_{0.31}N$	0.74	38.95	84.39	25.18
	Single bottom cell: $In_{0.84}Ga_{0.16}N$	0.46	51.51	78.54	19.14
	Middle cell: $In_{0.69}Ga_{0.31}N$	0.71	13.59	83.22	8.35
	Bottom cell: $In_{0.84}Ga_{0.16}N$	0.42	11.77	76.70	3.92
	Top and middle tandem	1.83	13.59	92.64	33.23
	Triple junction tandem	2.25	11.77	93.78	37.15

Fig. 3 and Fig. 4 shows the current-voltage characteristics of the single junctions and those of the tandems, while **Table 4** gives the computations of the open circuit voltage, short circuit current, fill factor and the conversion efficiency for both double and triple junction tandems.

According to the results represented in **Table 4** and the preceding curves, one note that, the I(V) curve of the top cell stayed the same, while the I(V) curve of the middle and bottom cells had a current drop.

This current decrease was expected because the incident spectrum was diminished while crossing the components of the tandems, and since the junctions are mechanically stacked in series, the overall current-voltage characteristic is limited in its current level by the characteristic with the lowest current.

In addition, there is a significant increase in efficiency from single junctions to the tandems (Fig. 5).

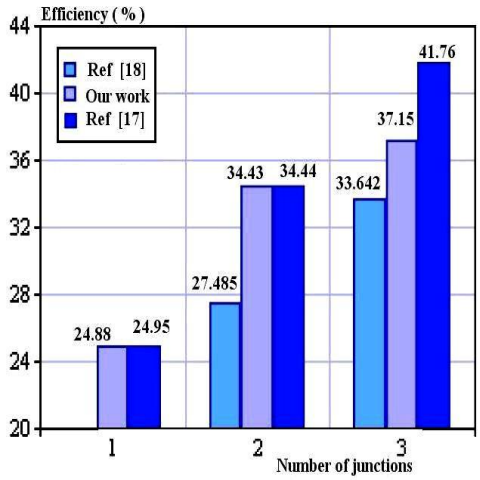

Fig. 5: Variation of the efficiency with the number of junctions included in the tandem

Our calculations predict, for single and double junction $In_xGa_{1-x}N$ tandem, an efficiency of 24.88 % and 34.43 % respectively. These results are very similar to those obtained by Xiaoming Shen *et al.* [17]. They calculated the conversion efficiency of a single and double junction $In_xGa_{1-x}N$ tandem, by employing AMPS-1D software, and they obtained 24.95 % and 34.44 % respectively.

However, for triple junction $In_xGa_{1-x}N$ tandem, we obtained a conversion efficiency of 37.15 % instead of 41.76 % in the ref. [17]. Hamzaoui *et al.* [18] calculated the conversion efficiency of $In_xGa_{1-x}N$ tandems, using the ideal PN junction model under 1-sun AM1.5 illumination, and they obtained the values sited in Fig. 5.

The differences in efficiency results can be partly attributed to the difference in parameter formulas used. All formulas seek to duplicate results from actual measurements. Therefore, all formulas are approximations only and it is difficult to state which formula is more correct.

It may be seen also that the open circuit voltages, produced by the junctions included in the tandems, decrease from the top to the bottom cell. This is the consequence of the increase that undergoes the saturation currents, due to the decrease of the band gap energies of the junctions, moving from the top to the bottom of the tandem (Fig. 6).

4. CONCLUSION

Double and triple junction tandems were simulated using realistic parameters by employing a comprehensive model. The spectral response of the two tandems has been simulated using 1-sun AM1.5 illumination. Results show that the use of three $In_xGa_{1-x}N$ junctions, with quite selected energy band gaps, extends the spectral response to lower photon energies, which means an increase in the useful wavelength range of the specter.

An improvement of the conversion efficiency has been observed for the suggested band gap combination ($In_{0.53}Ga_{0.47}N$ / $In_{0.81}Ga_{0.19}N$) and ($In_{0.53}Ga_{0.47}N$ / $In_{0.69}Ga_{0.31}N$ /

$In_{0.84}Ga_{0.16}N$) for double and triple junction tandems respectively. This improvement should be enough to continue to pursue the development of InGaN based solar cells.

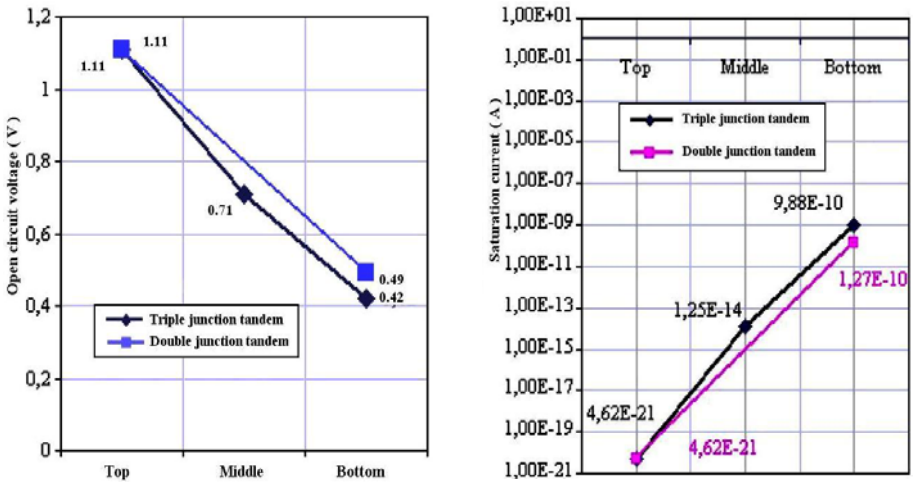

Fig. 6: (Left) The open circuit voltage of the junctions included in the tandems (Right) The saturation current of the junctions included in the tandems

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