Modelling of the indium gallium nitride tandem solar cell performances with the tunnel junction

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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. InxGa1-xN is one of a few alloys that can meet this key requirement. While in mechanically stacked multi-junction (MJ) cells the subcells usually have separate contacts, monolithic MJ cells are epitaxial grown on one substrate and the sub cells are interconnected in series by tunnel diodes leading to a standard two-terminal contact.**

In this paper describes a simple model for tunnel junction $In_{0.65}Ga_{0.35}N$) between the top cell ($In_{0.52}Ga_{0.48}N$) and bottom cell ($In_{0.84}Ga_{0.16}N$) of cascade solar cells. We theoretically studied the electrical characteristics (IV) of $In_{0.65}Ga_{0.35}N$ tunnel diode with the accounting program MATLAB for doping concentration of the junction after Using this model between two cascaded solar cell ($In_{0.52}Ga_{0.48}N$ / $In_{0.84}Ga_{0.16}N$)) and we calculate the electrical characteristics and performance using AMPS-1D software. The conducting properties of this tunnel diode show a good ohmic conduct and low contact resistance.

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Keywords⸺ **Indium Gallium Nitride, Tunnel Junction, Tandem Solar Cell, Performances**

I. INTRODUCTION

The major loss processes of thermalization and non-absorption can be largely eliminated if the energy of the absorbed photon is marginally higher than the band gap of the cell material. This leads to the concept of the tandem cell [1], where multiple cells are used with different band gaps, each cell converting a narrow range of photon energies close to its band gap as shown in Figure 1.
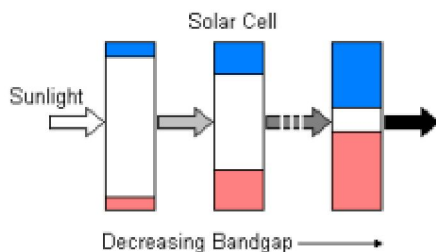

Fig1 Concept of tandem cell

The high-gap cells are stacked on the top, which efficiently absorb the high-energy photons, transmitting the lower energy photons to the cells with lower band gaps. Earlier tandem cells used in space applications were mechanically stacked and individually probed. 17nWith the improvement in growth technology, individual cells are monolithically grown on top of each other. Such devices function in series with only two probes for external connection, while they are internally connected through tunnel-junctions, which display ohmic characteristics. Performance of a tandem increases as the number of cells in the stack increases, with a direct sunlight conversion efficiency of 86.8% calculated for an infinite stack of independently operated cells under maximum concentration. However, increasing the number of stacks adds complications and makes the tandem sensitive to the irradiating spectrum as these individual cells have to be connected in series with low Ohmic contact resistance and have to be current matched.

Recently, InxGa1-xN alloys have become very potential for high performance MJ solar cells. Because the band gap of InxGa1-XN alloys can be varied continuously from 0.7 to 3.4 eV. This provides an almost perfect fit to the full solar spectrum offering a unique opportunity to design MJ solar cells using a single ternary alloy system. This will be technologically very significant because of easy fabrication, similarity in thermal expansion coefficient, electron affinity and lattice constant. In addition, InN based alloys are predicted to show high nobilities and lifetime of charge carriers and superior resistance against irradiation damage. These all make InxGa1-xN alloys very promising for high performance solar cells.

In order to evaluate the possibilities of these alloys, we tried, in this work, to model and simulate tandem cells made of two InxGa1-xN junctions without and with tunnel junction a one dimensional simulation program called a analysis of microelectronic and photonic structures (AMPS-1D).

II. MODELLING AND SIMULATIONS

A. Analytical model

The total of the photo current density from single cells under illumination is given by:

$$j_{ph} = j_n + j_p + j_w \qquad (1)$$

Where: j_n the photo current density in the base region is expressed by:

$$J_n = -eD_n \frac{d\Delta n}{dx}\bigg|_{x=w_e+w} \qquad (2)$$

J_p the photo current density in the emitter region is expressed by

$$J_p = -eD_p \frac{d\Delta p}{dx}\bigg|_{x=w_{e_1}} \qquad (3)$$

J_w the photo current density in space charge layer pn is expressed by

$$j_w = I_o \exp(-\alpha(\lambda)w_e)[1 - \exp(\alpha(\lambda)w)] \qquad (4)$$

The open circuit voltage is given by

$$V_{CO} = \frac{kT}{q} \times Log \left\{ 1 + \frac{I_{ph}}{I_0} \right\} \qquad (5)$$

B. PV characteristic

The power supplied to the external circuit by the solar cell under illumination depends on the load resistor (external resistor placed across the cell). This power is maximum for an operating point (P_m (I_m, V_m) of the current-voltage curve.

To this point we can write after approximations

$$V_{mp} = V_{CO} - \frac{K.T}{q}.\log\left(1 + \frac{q.V_{mp}}{K.T}\right) \qquad (6)$$

$$I_{mp} = \left[I_{ph} + j_0 \left(e^{\frac{qV_{mp}}{KT}} - 1 \right) \right] \qquad (7)$$

The cell conversion efficiency is usually taken to be:

$$\eta_{mk} = \frac{P_{\max k}}{P_{in}} = \frac{I_{mk}.V_{mk}}{P_{in}} \qquad (8)$$

P_{in} is the total incident solar power.

For maximum efficiency, each cell should be operated at its optimal J-V parameters, which are not necessarily equal for each cell. If they are different, the total current through the solar cell is the lowest of the tow. By approximation, it results in the same relationship for the short-circuit current of the multi-junction mode tandem solar cell:

$$I = \min(I_{mk}). \qquad (9)$$

An operating voltage V_{mk} and power output will be obtained

$$P_k = V_{mk}.\min(I_{mk}) \qquad (10)$$

The total conversion efficiency to be

$$\eta = \frac{\sum_{k=1}^{n} P_k}{P_{in}} \qquad (11)$$

C. Parameters for the simulation

Material parameter equations used for the simulation of the $In_xGa_{1-x}N$-xN.

Band gap [2]

$$E_g(x) = 0.7x + 3.4(1-x) - 1.43(1-x) \qquad (12)$$

Electron affinity [8, 9]:

$$\chi = 4.1 + 0.7(3.4 - E_g) \qquad (13)$$

Absorption coefficient

$$\alpha(\lambda) = 2.2 \times 10^5 \sqrt{(1.24/\lambda) - E_g} \qquad (14)$$

Effective density of states in the conduction band [8]

$$N_c = [0.9x + (1-x)2.3] \times 10^{18} \qquad (15)$$

Effective density of states in the valence band [4]

$$N_v = [5.3x + (1-x)1.8] \times 10^{19} \qquad (16)$$

Relative permittivity [8]:

$$\varepsilon_r = 14.6x + (1-x)10.4 \qquad (17)$$

Carrier mobility [10]:

$$\mu_i(N) = \mu_{min,i} + \frac{\mu_{max,i} + \mu_{min,i}}{1 + \left(N/N_{g,i} \right)^{\gamma_i}} \qquad (18)$$

The above formulae with asterisk are obtained from the linear fitting of the corresponding parameters of InN and GaN. The carrier mobility of InGaN is assumed to be similar to GaN, where i= n, p denotes electrons and holes, respectively, and N the doping concentration, while the model parameters $\mu_{min,i}$, $\mu_{max,i}$, $N_{g,i}$ and γ_i depend on the type of semiconductor [10].

TABLE 1.

MODEL PARAMETERS USED IN THE CALCULATIONS OF THE CARRIER MOBILITY.

Type of carriers	$\mu_{max,i}$ $(cm^2V^{-1}S^{-1})$	$\mu_{max,i}$ $(cm^2V^{-1}S^{-1})$	$N_{g,i}$ (cm^{-3})	γ_i
Electrons	100	55	**2E17**	1
Holes	170	3	**3e17**	2

D. Optimal device structure

The major objectives of numerical modeling and simulation in solar cell research are testing the validity of proposed physical structures, geometry on cell performance and fitting of modelling output to experimental results. Any numerical program capable of solving the basic semiconductor equations could be used for modeling thin film solar cells. The fundamental equations for such numerical programs are (i) Poisson's equation for the distributions of electric field (φ) inside the device and (ii) the equation of continuity for conservation of electrons and holes currents. [5]

The AMPS-1D program has been developed for pragmatically simulate the electrical characteristics of multi-junction solar cells. It has been proven to be a very powerful tool in understanding device operation and physics for single crystal, poly-crystal and amorphous structures. To date, more than 200 groups worldwide have been using AMPS-1D for solar cell design [6]. One-dimensional AMPS-1D simulator has been used to investigate the effect of different top cell layers. The structure of conventional $In_{0.52}Ga_{0.48}N$ /$In_{0.84}Ga_{0.16}N$ solar cell is shown in Fig.1. The tunnel junction $In_{0.65}Ga_{0.35}N$ layers thickness was varied from 0.01 µm to 0.05 µm and the change of performance parameters are observed.
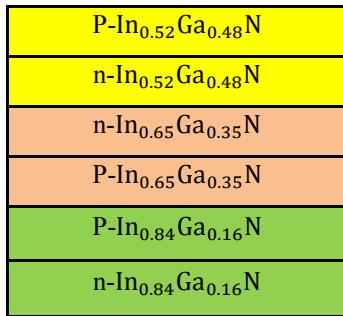

Fig 2 Cascade solar cell -$In_{0.52}Ga_{0.48}N$ /$In_{0.84}Ga_{0.16}N$ structure used for the modelling

The base parameters used for different structures adopted from some standard references are shown in Table 2:

TABLE 2.

DESCRIPTION OF THE SPECIAL PARAGRAPH STYLES

Layers / Parameters	P-$In_{0.52}Ga_{0.48}N$	n-$In_{0.52}Ga_{0.48}N$	n-$In_{0.65}Ga_{0.}$	p-$In_{0.65}Ga_{0.}$	P-$In_{0.84}Ga_{0.16}N$	n-$In_{0.84}Ga_{0.16}N$
Thickness (µm)	0.1	0.2	0.005	0.005	0.1	0.15
Dielectric constant, ε	12.58	12.58	13.13	13.13	13.93	13.93
Electron mobility μ_n (cm²/Vs)	685	685	685	685	685	685
Hole mobility μ_p (cm²/Vs)	153	153	153.3	153.3	153.3	153.3
Carrier density, n or p (cm^{-3})	10^{17}	10^{17}	10^{19}	10^{19}	10^{17}	10^{17}
Optical band gap,E_g (eV)	1.64	1.64	1.32	1.32	0.94	0.94
Effective density,N_c (cm^{-3})	$1.57*10+18$	$1.57*10+18$	$1.39*10+18$	$1.39*10+18$	$1.12*10+18$	$1.12*10+18$
Effective density, N_v (cm^{-3})	$3.62*10+19$	$3.62*10+19$	$4.075*10+18$	$4.075*10+18$	$4.74*10+19$	$4.74*10+19$
Electron affinity, χ (eV)	5.33	5.33	5.56	5.56	5.82	5.82

III. RESULTS AND DISCUSSION

A. Total efficiency versus tunnel junction layer doping

The simulation work has been performed aiming to compare the different types of cell structure made by changing doping of The tunnel junction emitter layers $In_{0.65}Ga_{0.35}N$ -P and base layers $In_{0.65}Ga_{0.35}N$ -N to find out best structure for higher efficiency and more stable - $In_{0.52}Ga_{0.48}N$ / $In_{0.84}Ga_{0.16}N$ solar cells.

The effect of tunnel junction on performance such as effect on general performance parameters, quantum efficiency (QE), shunt and series resistance, light and dark I-V characteristics
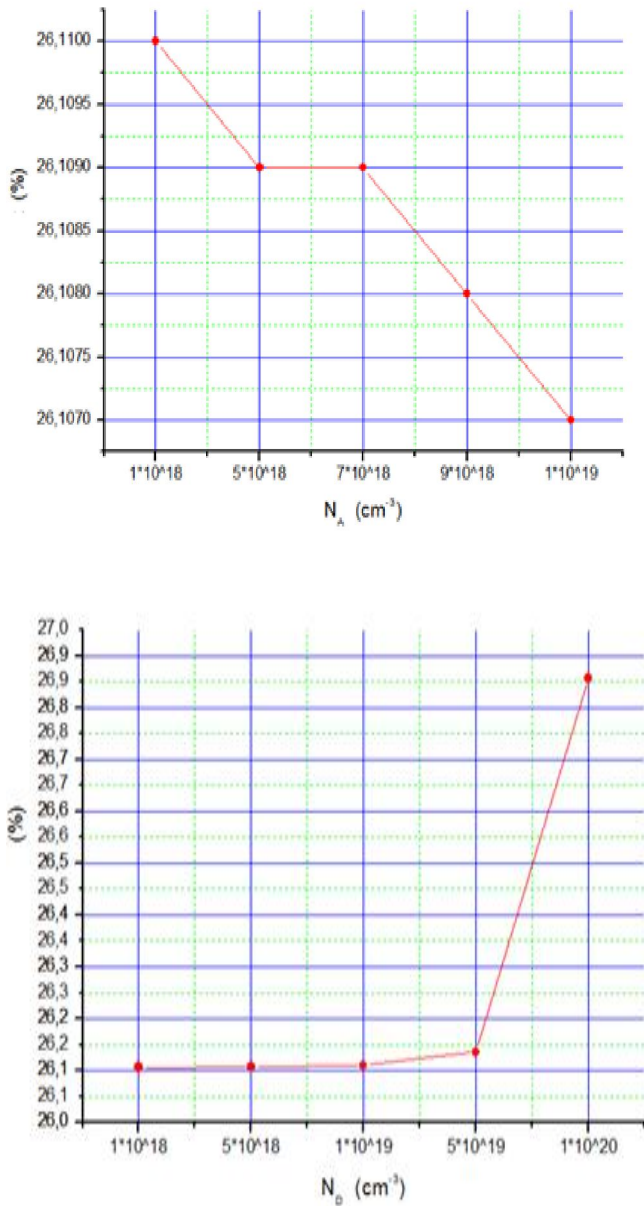
E.

parameters (open-circuit voltage Voc, short-circuit current Isc, fill-factor FF and efficiency (η) are all summarized in Table3

TABLE 3

PARAMETERS PV OF THE OPTIMIZED $-In_{0.52}Ga_{0.48}N$ $/In_{0.84}Ga_{0.16}N$ DEVICE

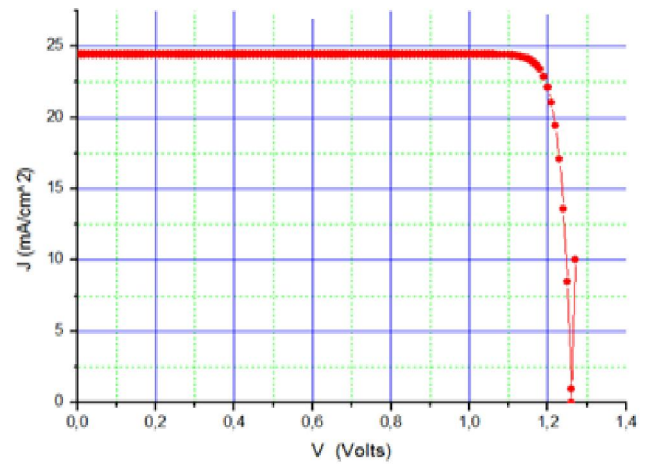| Parameters photovoltaic	$V_{oc}(V)$	$J_{sc}(A)$	FF	$\tau(\%)$
	24.44	1.26	0.88	26. 91

Fig 4. Current density-voltage characteristics $-In_{0.52}Ga_{0.48}N$ $/In_{0.84}Ga_{0.16}N$ device

IV. CONCLUSIONS

In this investigation, we have shown that a relatively thin double-junction $In_{0.52}Ga_{0.48}N$ / $In_{0.84}Ga_{0.16}$ device can achieve a remarkably high power output. An extended spectral coverage due to a careful choice of the materials and optimization of the thickness and doping levels of each layer led to an enhanced overall power output from the $In_{0.52}Ga_{0.48}N$ / $In_{0.84}Ga_{0.16}$ cascade device. Under the standard solar spectrum and one sun, the efficiency of the device is 26.91%

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Fig 3. Device total efficiency versus tunnel junction layer doping: (a) emitter layer p, (b) base layer n.

Figure 3 (a,b) shows the device total efficiency. The sum of the efficiency of top and bottom cells versus the doping of the emitter layer of the tunnel junction. The results on the Figure (3 a) show that the optimum doping is 7.1018. Figure 3 (b) shows the device total efficiency versus the doping of the base layer of the tunnel junction cell is 1.1020.

B. Device operation

The current-voltage and power-voltage characteristics generated by the $- In_{0.52}Ga_{0.48}N$ / $In_{0.84}Ga_{0.16}N$ optimized device under the AM1.5G spectrum and one sun are displayed in figure 4 for multi-junction solar cell. The corresponding PV

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