Simulation of multi-junction solar cells based on InGaN using AMPS-1D

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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. In this paper, we designed series of InxGa1-xN multi-junction solar cells. Key properties of InxGa1-XN tandem solar cells (for two junctions up to six junctions) are simulated by using AMPS-1D software, including I-V characteristic, conversion efficiency, band structure etc. Our calculation shows that the efficiency can be improved from 10.09% for a single junction up to 40.05% for six junctions obtained in 1-sun AM1.5 illumination and at room temperature, using realistic material parameters..

1. Introduction

Semiconductors of the type III-N are of growing interest in the scientific world. This is justified by the fact that III-N semiconductors are robust, having a high thermal conductivity and a high melting point, and, moreover, a direct forbidden band gap. They currently represent ideal materials for the development of light emitting diodes (LEDs) operating in the green-blue and UV ranges of the electromagnetic spectrum. Among these semiconductors, we find mainly aluminum nitride (AlN), gallium nitride (GaN) and indium nitride (InN), respectively with a gap of 6.2eV, 3.4eV and 0.7eV [1].

Tandem solar cells and multi-junction solar cells, which consist of a stack of p/n solar cells, are sometimes classified as third generation solar cells. They achieve the highest conversion efficiencies, even exceeding 40 % [6].

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, three, four, five and six InxGa1-XN junctions with a one dimensional simulation program called a analysis of microelectronic and photonic structures (AMPS-1D).

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 reflection losses and no surface recombination velocity.

2. Modelling and simulations

*2.*1About AMPS-1D

AMPS-1D is the first-principles simulation tool developed by the Penn State/Electric Power Research Institute (EPRI)[15]. AMPS software used in this study is based on the first-principles, basic equations of semiconductors and solar cells: Poisson's equation, the continuity equation for free holes, and the continuity equation for free electrons.

. Determining transport characteristics then becomes a task of solving the three coupled non-linear differential equations, each of which has two associated boundary conditions.

In AMPS, these three coupled equations are solved simultaneously to obtain a set of three unknown state variables at each point in the device: the local vacuum level, the electron, and hole quasi-Fermi levels. From these three state variables, the free carrier concentrations, fields, currents, etc. can then be computed.

Besides the classical continuity equations, other semi-classical or quantum transport equations such as the Boltzmann equation, Quantum Hydrodynamic

(QHD) model, Wigner function method, and non-equilibrium Green's function method have also been applied to study the trans-port processes in photovoltaic devices so far [16–18].

AMPS-1D supplies two different approaches to the process of recombination/generation. One is the density of states (DOS)/capture cross section model and the other is the carrier lifetime model. Zhang et al. [7]

In this study, we use the DOS model in the simulation of InGaN solar cells because the DOS model could provide much more information about recombination/generation in semiconductors than the lifetime.

2.2. Parameters for the simulation

Material parameter equations used for the simulation of the $In_XGa_{1-X}N$ SCs

Band gap[2]

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

Electron affinity [8,9]:

$$\chi = 4.1 + 0.7(3.4 - E_g) \quad (2)$$

Absorption coefficient

$$\alpha(\lambda) = 2.2 \times 10^5 \sqrt{(1.24/\lambda) - E_g} \quad (3)$$

Effective density of states in the conduction band [8]

$$N_c = [0.9x + (1-x)2.3] \times 10^{18} \quad (4)$$

Effective density of states in the valence band [4]

$$N_v = [5.3x + (1-x)1.8] \times 10^{19} \quad (5)$$

Relative permittivity [8]:

$$\varepsilon_r = 14.6x + (1-x)10.4 \quad (6)$$

Carrier mobility [10]:

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

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 I
MODEL PARAMETERS USED IN THE CALCULATIONS OF THE CARRIER MOTILITIES

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

. InxGa1-xN tandem cells comprising two, three, four, five, six and seven junctions were simulated. The energy gap and indium fraction for $In_XGa_{1-X}N$ alloys computed for a six junction are given in table II.

TABLE I I
ENERGY GAPS FOR A SIX-JUNCTION TANDEM CELL

Junction N°	indium fraction for $In_XGa_{1-X}N$ alloys	Band gap (eV)
1	0.11718	2.25
2	0.613	1.79
3	0.766659	1.475
4	0,8535	1.19
5	0,921	0.927
6	1	0.7

3. Results and discussions

3.1. Simulations for a six-junction tandem cell

InxGa1-xN tandem cells comprising two, three, four, five and six junctions were simulated.

Hereafter, the results computed for a InxGa1-xN tandem structure comprising six junctions are given.

The following table (Table III) shows the energy gaps of the identified materials, the thicknesses of the junctions and that of the n-side.

TABLE III
ENERGY GAPS AND THICKNESSES FOR A SIX-JUNCTION TANDEM CELL

Junction N°	Band gap (eV)	n-side thickness (μm)	Junction thickness (μm)
1	2.25	0.1	0.3
2	1.79	0.1	0.3
3	1.475	0.1	0.3
4	1.19	0.1	0.5
5	0.927	0.1	0.5
6	0.7	0.1	0.5

We can see from Table III that the energy gaps of the junctions decrease from the top to the bottom of the tandem cell.

Table IV gives the computations of the photocurrent

densities, the open-circuit voltages and the output peak power for a six-junction InxGa1xN tandem cell.

Simulations show that the six-junctions InxGa1-xN tandem cell could reach an efficiency of more than 40% with a short-circuit current density of 52.27mA/cm^2 and an open-circuit voltage of 0.51V.

TABLE IV
SIMULATION RESULTS FOR A SIX-JUNCTIONS TANDEM CELL

Junction N	Isc mA/cm^2	Voc (V)	Fill factor(%)	Efficiency (%)
1	5.79	1.87	0.92	10.09
2	19.66	1.31	0.90	23.35
3	27.29	1.00	0.88	24.30
4	40.74	0.86	0.86	30.64
5	46.32	0.63	0.83	36.57
6	52.27	0.51	0.80	40.05

We can notice from Table VI and Fig.1 that the open-circuit voltages produced by the junctions of the tandem cell decrease almost linearly from the top to the bottom.

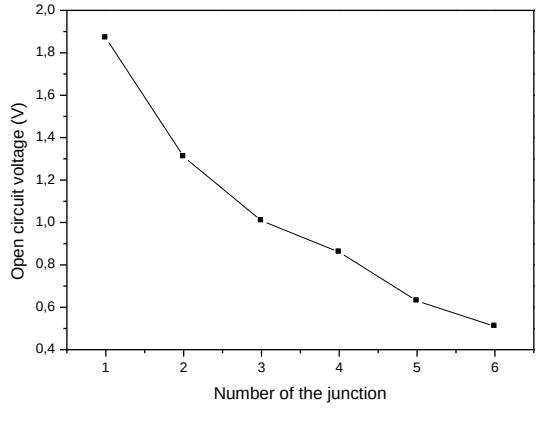

Fig. 1: Variation of the Open-circuit voltage versus the junction number for a six-junction tandem structure.

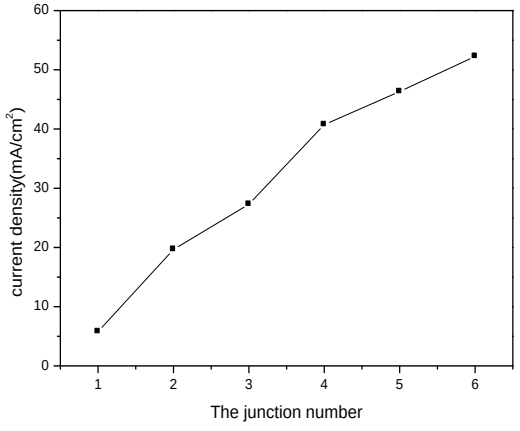

Fig.2: Variation of the short-circuit current density versus the number of junctions in the cell

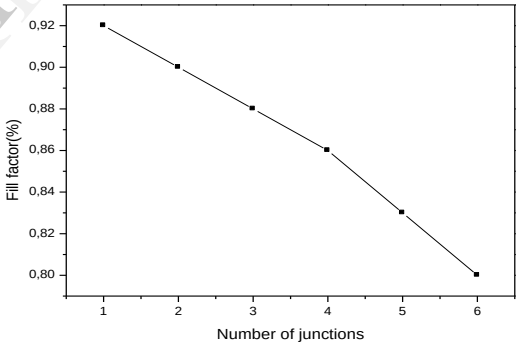

Fig.3. Variation of Fill factor versus the number of junctions in the cell

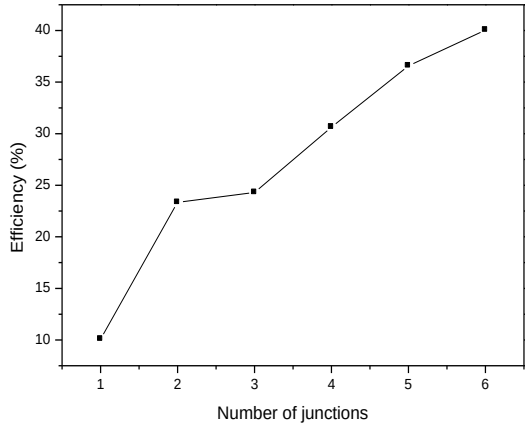

Fig. 4: Variation of the efficiency with the number of junctions included in the tandem cell.

We notice from Table 2and Fig. 1that the achievable open-circuit voltages decreases as the tandem cell. Contains more layers However, the increase of the short-circuit current density as a function of the number of junctions is almost linear; hence, it compensates the decrease of the open-circuit voltages, which is a function of the inverse of the same variable; this explains the increase of the output maximum power and the cell efficiency with the number of junctions.

The highest efficiency (40.05%) was reached for the six-junction cell (Fig. 4)with a short-circuit current density of 52.27mA/cm2 and an open circuit voltage of about 0.51V.

InxGa1-xN tandem cells comprised of two and three junctions have also interesting potentials with efficiency of 23.35% for the two-junction tandem cell and of 24.3% for the three-junction one.

It is noticeable that the increase of the efficiency is more important when we move from a two-junction to a three-junction InxGa1-xN tandem cell.

4. Conclusion

The theoretical design and performance of InxGa1-xN-based MJ solar cells for high efficiency have been studied by developing a simulation model. The simulation with AMPS-1d result shows that the $In_xGa_{1-x}N$ alloys have interesting performances for tandem cells applications. The efficiency is evaluated from 10.09% for single junction to 40.05% for six junctions.

$In_xGa_{1-x}N$ tandem cells have an additional advantage as they can be produced with a simpler technology than the ones used to produce tandem junctions made of different materials. In fact, the $In_xGa_{1-x}N$ alloys have similar properties, which make their deposition in successive films easier.

5.Acknowledgements

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6.References

[1] Wu J, Walukiewicz W, Yu K M, Ager J W III, Haller E E,Lu H, Schaff W J, Saito Y and Nanishi Y 2002Appl. Phys.Lett.803967)

[2] Xiao H L, Wang X L, Wang J X, Zhang N H, Liu H X,Zeng Y P, Li J M and Wang Z G 2005J. Cryst. Growth276401I.

[3] S. Jacobs and C. P. Bean, "Fine particles, thin films and exchange anisotropy," in Magnetism, vol. III, G. T. Rado and H. Suhl, Eds. New York: Academic, 1963, pp. 271–350.

[4] Jani O, Honsberg C, Asghar A, Nicol D, Ferguson L,Doolittle A and Kurtz S 2005 31stIEEEPhotovoltaic SpecialistsConf.(Lake Buena Vista, FL,2005)pp 37–42.

[5 R. Nicole, "Title of paper with only first word capitalized," J. Name Stand. Abbrev., in press

[6] Zhang, X. B. et al., "Simulation of In0.65Ga0.35N single-junction solar cells," J. of Phys. D: Appl. Phys. 40, 7335-7338 (2007)..

[7] Hamzaoui, H., Bouazzi, A. S. and Rezig, B., "Theoretical possibilities of InxGa1-xN tandem PV structures," Sol. Energy Mater. Sol. Cells 87, 595-603(2005).

[8] Levinshtein, M. E., Rumyantsev, S. L. and Shur, M. S., [Properties of Advanced Semiconductor Materials],Wiley, Chichester,UK,1–90(2001).

[9] Li, N., "Simulation and Analysis of GaN-based Photoelectronic Devices," Dissertation (in Chinese), Institute of Semiconductors, Chinese Academy [2] ofSciences, Beijing, 3(2005).

[10] Li, N., "Simulation and Analysis of GaN-based Photoelectronic Devices," Dissertation (in Chinese), Institute of Semiconductors, Chinese Academy ofSciences, Beijing, 3(2005).