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PROJECTED PERFORMANCE OF $In_XGa_{1-X}N$-BASED MULTI-JUNCTION SOLAR CELLS

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ABSTRACT

This paper reports the theoretical design and projected the performance of $In_xGa_{1-x}N$ MJ solar cells for high efficiency. The design and performance evaluation are made by developing a simulation model which optimizes the design of MJ solar cells for high efficiency. The efficiency was optimized by optimizing the band gap and n-side thickness of different cells while keeping the current mismatch between different cells below 0.2%. The efficiency is found to be varied from 24.94% for single junction to 45.22% for six junctions. Further increase of junction does not significantly increase the efficiency. Use of concentrator increases the efficiency. The calculation of the photocurrent density and open circuit voltage of each junction has done under AM 1.5 and assumed that each junction absorbs the solar photons that are not absorbed by the preceding one.

Keywords: : *Multi-junction, concentrator and efficiency..*

1. INTRODUCTION

To be competitive with the conventional energy source the efficiency of solar cell must be improved. Currently used multi-junction (MJ) solar cells are based on two or three junctions of different semiconductor materials connected in series [1–3]. It has been shown that, theoretically, the efficiency of MJ solar cells increases as it incorporates more and more junctions [4]. However, practically, there is a very little range of materials that could be used to make these cells. The primary requirements for the materials to be used for MJ solar cells is band gap matching with the solar spectrum, high mobilities and lifetimes of charge carriers, similar thermal expansion coefficient, the electron affinity, lattice constant etc. The currently used conventional materials for MJ solar cells are not suitable to fulfill the above requirements. Recently, $In_xGa_{1-x}N$ alloys have become very potential for high performance MJ solar cells. Because the band gap of $In_xGa_{1-x}N$ 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 mobilities and lifetime of charge carriers and superior resistance against irradiation damage. These all make $In_xGa_{1-x}N$ alloys very promising for high performance solar cells.

In order to realize the high performance $In_xGa_{1-x}N$-based MJ solar cells theoretical design and performance evaluation are very much essential. However, compared to the theoretical work on conventional material based MJ solar cells there

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is very little work on $In_xGa_{1-x}N$ based MJ solar cells. Bouazzi et al. observed the theoretical possibilities of $In_xGa_{1-x}N$ tandem PV structure [5]. However, the work is very preliminary one and the efficiency was not remarkable. More work on the theoretical design of InGaN based MJ solr cells for high efficiency is urgently required. In this work we have designed theoretically $In_xGa_{1-x}N$-based MJ solar cell for high efficiency and evaluated the performance. The design and performance evaluation are made by developing a simulation model which automatically optimizes the design of MJ solar cells for high efficiency.

2. THEORETICAL MODEL

The theoretical simulation model is developed using C++ programming with the following calculation procedure. It is developed in such a way that it optimizes the design of MJ solar cells for high efficiency for any number of junction and any material parameters. In case of few parameters data of GaN is considered since the required parameters of different InGaN cells are not available in reality. More accurate material parameters may improve the efficiency, since diffusion length and diffusion coefficient of InN based alloys are expected to be higher.

i) THE IDENTIFICATION OF THE SEMICONDUCTORS

For proper identification of the energy gaps of the $In_xGa_{1-x}N$ alloys that should be used for the tandem cells we have assumed perfect quantum response of materials and equal photo current densities of each junction. The indium fraction was calculated from reference [6].

ii) CALCULATION OF THE SHORT CIRCUIT CURRENT DENSITY

In MJ solar cells the solar photons with energies less than the band gap E_g are not absorbed at that junction and solar photons with energies greater than or equal to E_g are absorbed and generate electron-hole pairs which produce current. The junctions are arranged highest band gap as top and so on. The solar photons absorbed in one junction will not absorbed in other junction and the remaining photons will transmit to the lower junction. The current in the cell will be limited by the smallest current allowed in any junction. So it is important to match the current in each junction to ensure that no junction limits the output power.

The photo current density of each cell is equal to $\mathrm{Jph} = \mathrm{Jp} + \mathrm{Jn} + \mathrm{Jw}$ where J_p, J_n and J_w are respectively the holes current, electron current and depletion region current. In this work the photo current in depletion region has been neglected.

J_p and J_h for each photon were calculated using the conventional equations [7].
The n side, p side and total thickness are adjusted to produce same current densities.

iii) THE PROPERTIES OF $In_xGa_{1-x}N$

The properties of the material used in the calculations are as follows:
The majority carrier concentration was taken equal to 10^{18} cm^{-3} on each side of the junction.
The surface and the rear recombination velocities were taken to be equal to 10^3 cm/s.
The electronic properties are assumed to be same in all junction [8,9]
L_n= 125 X 10^{-6} cm, L_p= 79 X 10^{-6} cm,
D_p = 9 cm^2/s, D_n = 25 cm^2/s.
The absorption coefficients for each junction are taken from reference [10].

iv) CALCULATION OF OPEN CIRCUIT VOLTAGE, V_{oc}

The open circuit voltage of a tandem cell is

$$V_{oc} = \sum V_{oc}(i) \qquad \ldots\ \ldots\ \ldots\ \ldots\ \ldots\ \ldots \quad (2)$$

i=1, 2 …...n, n is number of junction incorporated in the tandem cell.
The open circuit voltage of a PN junction is given by

$$V_{oc} = \frac{kT}{q} \times \ln\left(\frac{J_L}{J_0} + 1\right) \qquad \ldots\ \ldots\ \ldots\ \ldots\ (3)$$

where J_L is the junction photo current density, J_0 is the saturation current density, k is the boltzmann constant, T is the temperature which was taken equal to 300K and q is the absolute electric charge of electrons.
The saturation current density J_0 was calculated for all the $In_xGa_{1-x}N$ alloys

$$J_0 = qn_i^2\left(\frac{D_{nj}}{L_{nj}N_A} + \frac{D_{nj}}{L_{nj}N_D}\right), \text{ j=1, 2 … n.} \quad (4)$$

Where j is the number of jth junction. n_i^2 is the squire of intrinsic carrier concentration. It is given by the following equation.

$$n_i^2 = N_C N_V \exp\left(-\frac{Eg}{kT}\right) \text{ ... ... (5)}$$

where N_C N_V for each junction are taken from reference [11].

v) EFFICIENCY CALCULATION

The efficiency of the tandem cell is given by

$$\eta = \frac{J_{ph} * V_{oc} * FF}{\Phi_0} * 100 \quad \text{.... . ... (6)}$$

The Φ_0 is the incident irradiance per unit area in mW/cm^2 [12]. The fill factor (FF) is considered as 85%.

vi) MISMATCH CALCULATION

The lattices constant are predicted to follow the composition-weighted average. Lattice constant has been calculated according to Vegard's law [13].

vii) CONCENTRATOR TO INCREASE EFFICIENCY

The main drawback of solar cell is its low conversion efficiency and high cost. To reduce the cost of solar cell securing high performance, concentrator is necessary. The efficiency calculations using concentrator have been carried out through [14].

3. RESULTS AND DISCUSSIONS

$In_xGa_{1-x}N$ tandem cells comprising two, three, four, five, six and seven junctions were simulated. The results computed for a six junction are given in table 1. The following table shows energy gaps of the identified materials, current density of each junction, In fraction (x) of the alloys, n-side thickness and total thickness.

Table 2 gives the computations of the current densities, the open circuit voltages and the efficiencies up to seven junctions tandem cell

Table 1: *Energy gaps, current densities and thicknesses for a six junction tandem cell.*

Band Gap Eg (eV)	I_{sc} (mA/ cm^2) 1.	In Fraction for $In_xGa_{1-X}N$ Alloys	N- Side Thickness (µm)	Total Thickness (µm)
2.228	9.86	0.257	0.2	2.0
1.778	9.86	0.382	0.21	2.0
1.462	9.86	0.486	0.23	2.0
1.19	9.87	0.596	0.21	2.0
0.957	9.87	0.717	0.2	2.0
0.700	9.85	1.0	0.12	2.0

Table2: Simulation results up to seven junctions tandem cell

Number of Junction	I_{sc} (mA/cm^2)	V_{oc} (V)	Efficiency (%)
1	31.75	0.8915	24.94
2	21.08	1.839	34.2
3	16.44	2.686	38.99
4	12.51	3.755	41.47
5	10.05	4.898	43.46
6	9.85	5.198	45.22
7	8.33	6.256	46.01

Simulations show that the seven-junction $In_xGa_{1-x}N$ tandem cell could reach an efficiency of more than 46% with a short-circuit current density of 8.33 mA/cm^2 and an open-circuit voltage of 6.256V.

Fig. 1 shows the variation of the short-circuit current density, the open-circuit voltage and the efficiency as a function of the number of junctions included in the cell. It seems that the efficiency saturates when the number of junction increases. More than seven junctions the efficiency would not further increase as with increase in the junction numbers the open circuit voltage will increase but short circuit current will decrease.

The variation of the short-circuit current density, the open-circuit voltage and the efficiency as a function of the n-side thickness of a six junction tandem cell has shown in fig. 2. It seems that the efficiency increases when the n-side thickness of each junction decreases and vice versa.

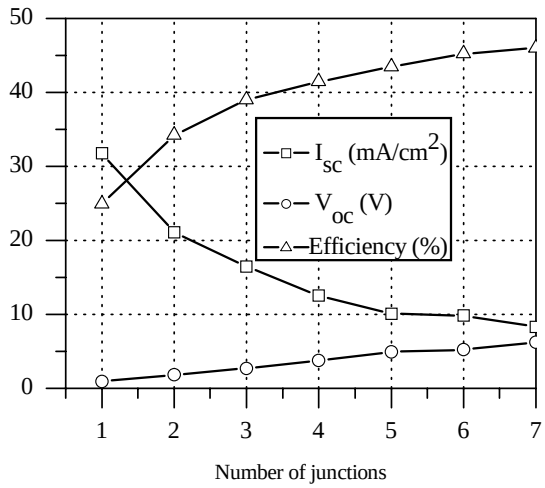

Fig. 1 *Variation of the open-circuit voltage, the short-circuit current density and efficiency with number of junctions in the cells.*

The variation of lattice mismatch (minimum to maximum) between the junctions in the cell has shown in fig. 3. It is noticeable that with increasing the junction numbers, the lattice mismatch between the junctions decreases and efficiency increases. This is because; increasing number of junction the difference in Indium fraction between two adjacent junctions decreases. As lattice mismatch occurs due to the composition difference between two adjacent junctions.

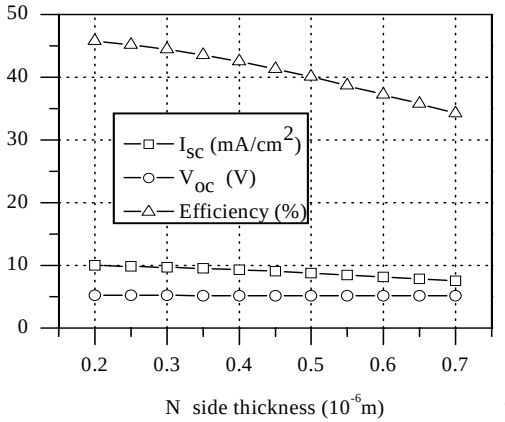

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Fig. 2 Variation of the open-circuit voltage, the short-circuit current density and efficiency with the N-side thickness in the cells.

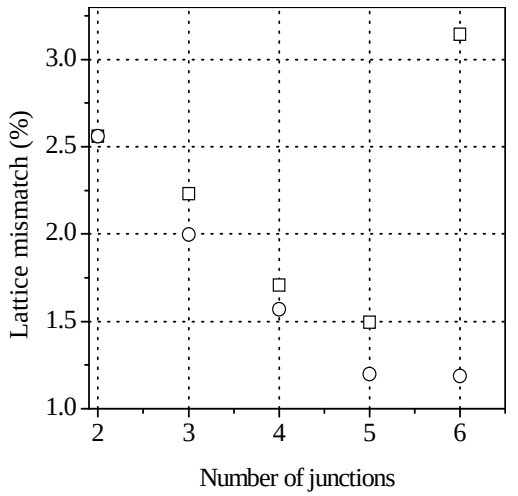

Fig. 3 *Variation of the lattice mismatch with the number of junctions in the cells.*

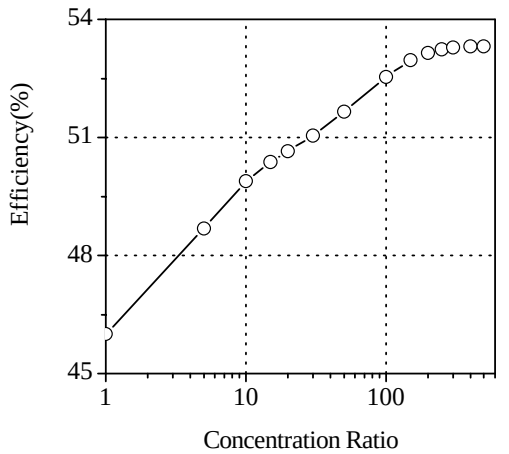

Fig. 4 *Variation of efficiency with concentration ratio of seven junction cell.*

The efficiency variation of MJ solar cells with concentrator is shown if fig. 4. It can be explained that the efficiency increases with increasing the solar concentration but the trend is nonlinear

4. CONCLUSION

The theoretical design and performance of $In_xGa_{1-x}N$-based MJ solar cells for high efficiency have been studied by developing a simulation model. The simulation result shows that the $In_xGa_{1-x}N$ alloys have interesting performances for tandem cells applications. The efficiency is evaluated from 24.94% for single junction to 46.01% for seven junctions.

The efficiency of two, three, four, five and six junctions are 34.2%, 38.99%, 41.47%, 43.46% and 45.22% also found respectively. A photocurrent density of 8.33 mA/cm^2 and an open-circuit voltage of 6.26 V are found for seven junction cells. The efficiency increases when the n-side thickness decreases of each cell of a six junction structure have shown. The current mismatch is significantly low and is achieved below 0.2% for six junctions. The efficiency is achievable to 53% for seven junctions at concentration of 500x. All these results suggest that the $In_xGa_{1-x}N$ alloy is an excellent candidate for high performance solar cells.

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