American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-5, Issue-11, pp-64-69
www.ajer.org
Research Paper Open Access

Design and Performance of InGaAs/GaAs Based Tandem Solar Cells

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Abstract: *GaAs is a very promising for solar cell due to its inherent material properties. InGaAs/GaAs based solar cells have been designed with structural modification and evaluated their performances. The tandem structure exhibited better output efficiency as compared to conventional p-n, p-i-n and p-i-n with SiO_2 structures. The values of open-circuit voltage (V_{OC}), short-circuit current (I_{SC}) and efficiency are 0.95 V, 7 mA/cm2 and 46% respectively. The efficiency was optimized by optimizing the band gap and thickness of different cells. All the calculations have been done under 1-sun illumination at room temperature using SILVACO ATLAS. Therefore, the proposed GaAs-based tandem solar cells as one of the excellent promising candidates to substitute currently used solar cells for future high efficiency. The simulation results show that the InGaAs/GaAs alloys have interesting performances for tandem cells applications.*
Keywords: *Tandem solar cells, p-n, p-i-n, p-i-n with SiO2, Top cell GaAs, Lower band gap.*

I. INTRODUCTION

Tandem (multi-junction) solar cells fabrication techniques have been used to realize substantial increase in conversion efficiency (efficiency values over 30%) due to their wide-band photo response in comparison with single-junction cells. Tandem solar cells have been studied since 1960 [1].
44% for two junctions and up to 65% for an infinite stack of junctions under 1-sun illumination [2]. The additional complexity and cost of fabricating tandem solar cells has so far limited their use in terrestrial applications, but they are likely to become more competitive as single-junction module efficiencies [3].
In 2007, Cheyns et al. studied different metals as efficient recombination centers of holes and electrons at the contact between the two sub cells [4]. In 2012, Lassiter et al. combined solution- processed and evaporated small molecules in a 6.6% efficient tandem cell [5].

The first organic tandem cells with solution-processed photoactive and intermediate layers were published by Gilot et al. in 2007. Later that year, Kim et al. presented a fully solution-processed tandem cell of sub-cells with complementary absorption spectra with a power conversion efficiency of 6.5% [6].

Due to lack of consistency and reliability, Solar systems rely on the steady absorption of sunlight-particularly, subatomic particles called photons-which can be easily deterred. A large solar array is required to power an entire building. Due to infancy of photovoltaic technology it becomes necessary to build large arrays to compensate for the very poor efficiencies of single panel deterioration [7]. Like anything else left out in the sun, solar panels gradually become damaged by ultraviolet radiation. The number of solar array panels needed to capture energy for an entire home typically costs tens of thousands of dollars, to make the electricity they produce cost substantially more than that provided by conventional power source [8].
This research is mainly based on InGaAs/GaAs based tandem solar cell. We were trying to improve the efficiency of solar cell using the tandem cell of different materials. Group III–V compound tandem solar cells are usually used as the energy sources on satellites and spacecraft's due to their ultra-high conversion efficiency, this materials are well known for their stability, radiation harness, miscibility and most notably the tenability of the band-gap energy [9]. Simulation has been performed using SILVACO's ATLAS in the research.

II. DEVICE STRUCTURE AND SIMULATIONS

The reliable approaches to design a GaAs based single junction p-n, p-i-n solar cells and InGaAs/GaAs based tandem solar cell requires a cautious selection of adequate the p-type doping , n-type doping, Intrinsic level, Front layer, Back layer with a suitable insulator material to confine the carriers and a suitable substrate for fabrication process. Electrical characteristics of the solar cells were simulated for device parameters as shown in

Table 1. For all kind of simulation, uniform doping concentrations throughout the cells are taken. The simulations are carried out using p-type doping for 200 nm, n-type doping for 400nm, i-layer concentration for 100 nm. For Tandem solar cells we have taken different materials. For top cell GaAs, for tunneling junction AlGaAs and for bottom cell InGaAs has been taken.

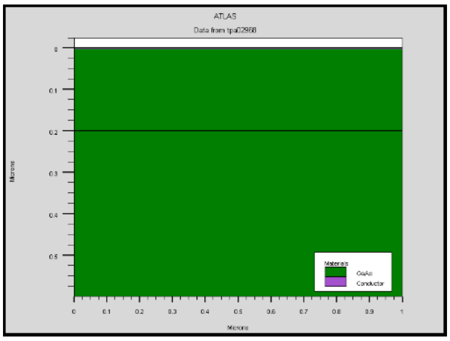

Fig. 1.1. P-N Single junction Solar Cell

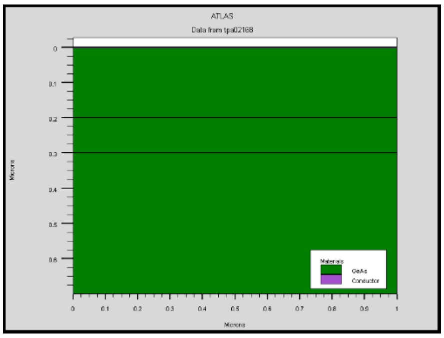

Fig. 1.2. P-i-N Single junction Solar Cell

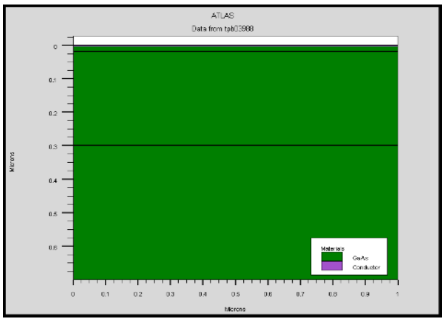

Fig. 1.3. P-i-N Single junction Solar Cell withSiO2 insulator

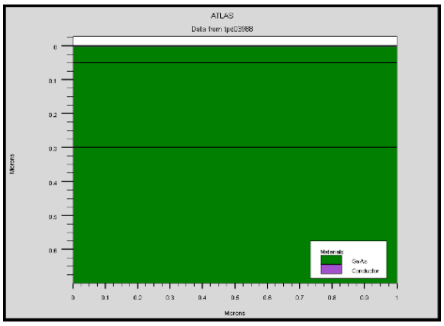

Fig. 1.4. GaAs based P-N Solar Cell withPdoping 200 nm, N doping 400 nm

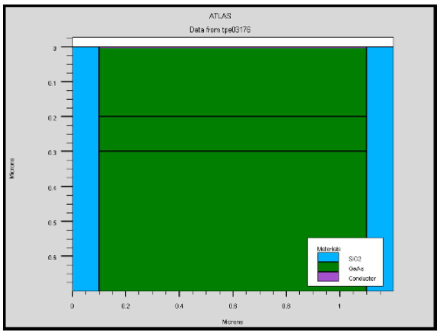

Fig. 1.5. GaAs based P-i-N Solar Cell with Pdoping 20 nm, N doping 400 nm

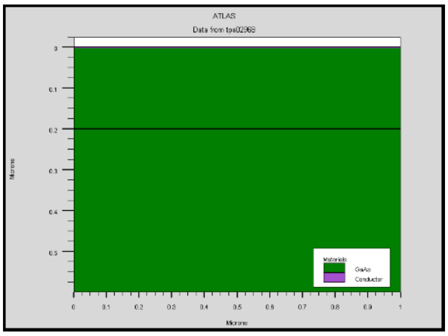

Fig. 1.6. GaAs based P-i-N Solar Cell with Pdoping 50 nm, N doping 400 nm

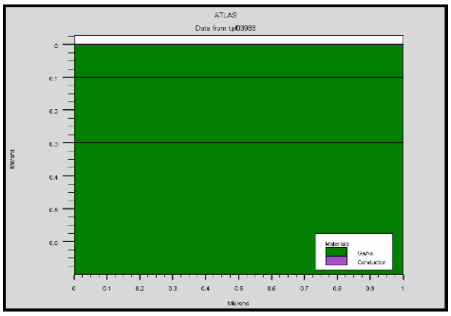

Fig. 1.7. GaAs based P-i-N Solar Cell with P doping 100 nm, N doping 400 nm

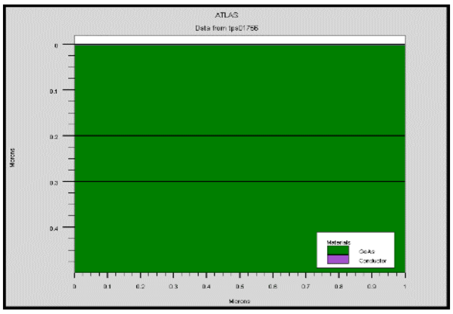

Fig. 1.8. GaAs based P-i-N Solar Cell with P doping 200 nm, N doping 200 nm

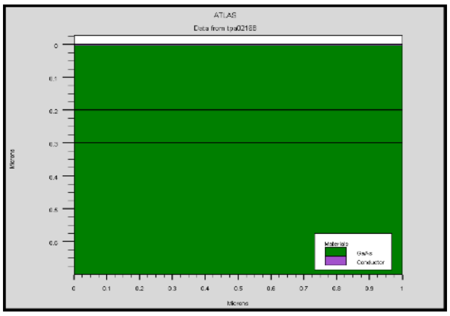

Fig. 1.9. GaAs based P-i-N Solar Cell with P doping 200 nm, N doping 400 nm

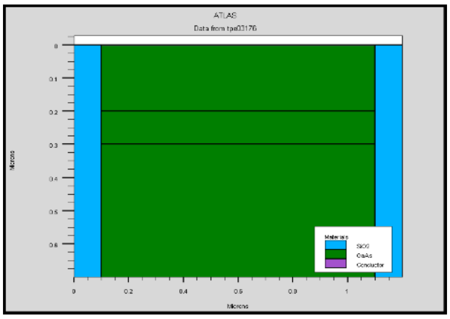

Fig.1.10. GaAs based P-i-N Solar Cell with P doping 200 nm, N doping 400 nm, 100 nm SiO_2 insulator.

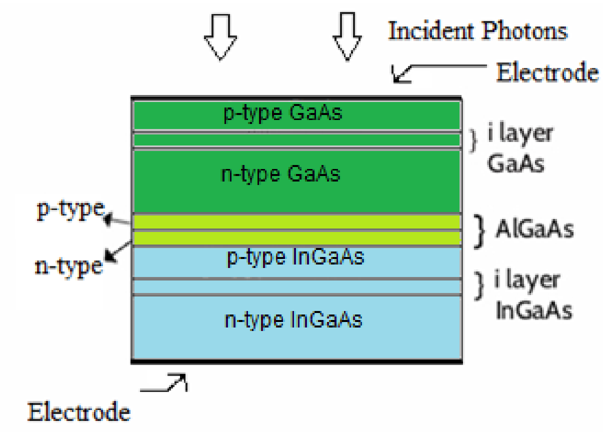

Fig. 2. Schematic diagram of Tandem Solar Cells

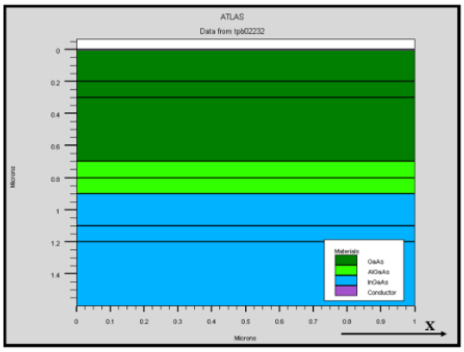

Fig. 3. Simulated diagram Based of InGaAs/GaAs InGaAs/GaAs Based Tandem Solar Cells

III. SHORT-CIRCUIT CURRENT DENSITY

Photocurrent is produced by the absorption of photons generates electron hole pairs. The density of short-circuit current of a tandem cell J_{SC} is given by the least of the photocurrent densities produced by the junctions of the tandem cell. The photocurrent density J_{ph} of an n-p junction with energy gap E_g (i) and receiving light by the n side is taken equal to

$$J_{phi} = \sum_{AM\ 1.5} J_{Pi}(hv) + J_{ni}(hv) + J_{Wi}(hv),\ Eg(i) \le hv \qquad (1)$$

Where J_{pi} (hv), J_{ni} (hv) and J_{Wi} (hv) are denoted respectively the holes, electron and depletion region current densities which are produced by the photons of energy $hv \geq E_g$ (i), which have been calculated using the theoretical conventional equations [10]. To produce same current densities the thickness of the cells is adjusted. Theoretically, the current mismatch between the junction's photocurrent densities should not exceed 5%. In this research work the current mismatch was kept below 0.3%.

IV. OPEN-CIRCUIT VOLTAGE

The open circuit voltage (V_{OC}) of a tandem cell is taken to be equal to the sum of the open circuit voltages of each junction.

$$V_{OC} = \sum V_{OC}(i) \qquad (2)$$

Where i=1, 2, 3 ……n, n is number of junction incorporated in the tandem cell.
The open circuit voltage of an n-p junction is given by

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

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 was taken equal to 300K and q is the electron charge. The saturation current density J_0 was calculated for all the InGaN alloys and is given by

$$J_0 = qn_i^2 \left(\frac{D_{nj}}{L_{nj} N_A} + \frac{D_{pj}}{L_{pj} N_D} \right), \; j = 1, 2, 3 \ldots . n \qquad (4)$$

Where j is the number of j_{th} junction and n_i is the intrinsic carrier concentration. The following equation can be written for the intrinsic carrier concentration,

$$n_i^2 = N_C N_V \exp\left(- \frac{E_g}{kT} \right) \qquad (5)$$

Where N_C is the density of states for conduction band and N_V is valence band for each junction are taken from reference [11].

V. EFFICIENCY

The efficiency of the tandem cell can be written by

$$\eta = \frac{J_{ph} * V_{OC} * FF}{\phi_0} * 100 \qquad (6)$$

Where Φ_0 is denoted the incident irradiance per unit area in mW/cm^2[11]. Here, 85% is considered as the fill factor (FF).

Table 1. Device dimension and material parameters

Parameter Name	Value
P-type thickness	200 nm
N-type thickness	400 nm
Intrinsic layer thickness	100 nm
Insulator thickness (SiO_2)	100 nm
Tunneling Junction Thickness	100 nm
P-type Doping Concentration	1×10^{15} cm^{-3}
N-type Doping Concentration	1×10^{22} cm^{-3}

VI. RESULT ANALYSIS

The optimized result for p-type doping concentration is 1×10^{15} cm^{-3} and for n-type doping concentration is 1×10^{22} cm^{-3} . In the p-i-n single junction solar cell with SiO_2 insulator we got better results relative to p-n and p-i-n solar cell. The thickness of the insulator layer was 100 nm. The top cell was GaAs p-i-n with the thickness of 200nm, 100 nm and 400nm respectively. The tunneling junction was based on p-n AlGaAs with the thickness of 100 nm for each. The bottom cell was InGaAs p-i-n with the thickness of 200nm, 100 nm and 400nm respectively.

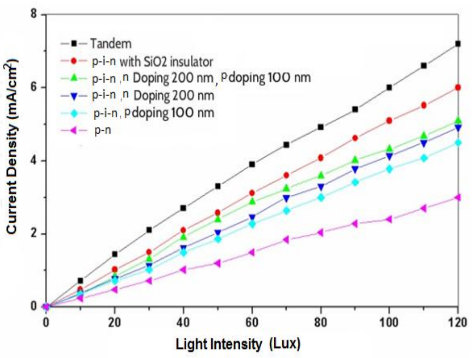

Fig. 4. Current Density Vs Light Intensity

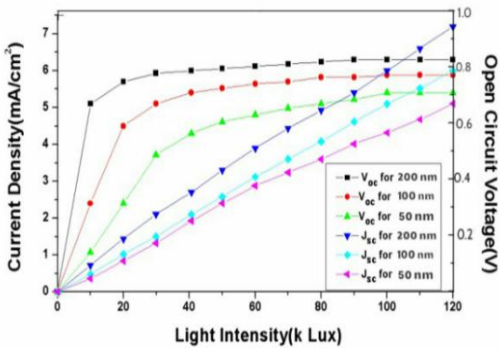

Fig. 5. Current Density Vs Light Intensity Vs Open Circuit Voltage

Fig. 4 is shown for 50 nm of doping concentration of p–layer, the open circuit voltage is 0.72 V and short circuit current density is 4.6 mA/ cm2.For 100 nm of doping concentration of p –layer, the open circuit voltage is 0.78 V and short circuit current density is 5.8 mA/cm2. For 200 nm of doping concentration of p–layer, the open circuit voltage is 0.82 V and short circuit current density is 7.2 mA/cm^2.

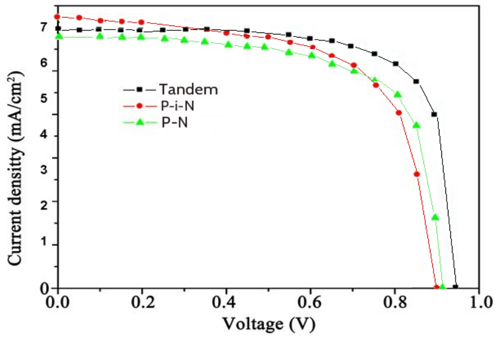

Fig. 6. I vs.V Characteristics Curve with SiO2

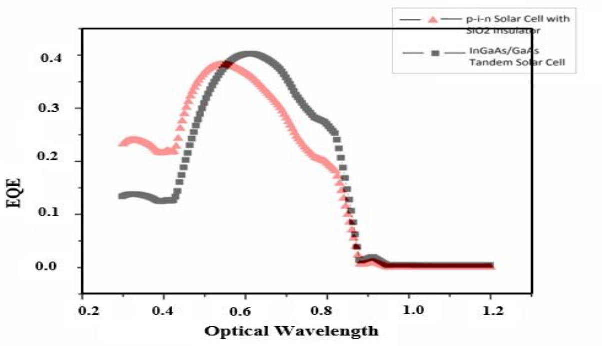

Fig. 7. External Quantum Efficiency for p-i-n Solar Cell Insulator and for InGaAs/GaAs Tandem Solar Cell

Fig. 6 represents I-V characteristics curve for different cell. For p-n junction solar cell I-V curve is the Black line. Short circuit Current Density is 6.9 mA/cm2and Open circuit voltage is 0.92 V. For p-i-n junction solar cell I-V curve is the Green line. Short circuit Current Density is 7.1 mA/cm2 and Open circuit voltage is 0.91 V. For Tandem solar cell I-V curve is the Red line. Short circuit Current Density is 7 mA/ cm2 and Open circuit voltage is 0.95 V.

Fig. 7 represents the comparison with p-i-n singe junction solar cell with the SiO2 insulator and InGaAs/ GaAs based Tandem solar cell have shown.

Stacking two solar cells one over the other has advantages. Because the energy is 'harvested' in two stages, and overall the sunlight can be converted to electricity more efficiently. Researchers have come up with a procedure that makes it possible to produce thin film tandem solar cells in which a thin perovskite layer is used.

Table 2: Comparison Table of Results

Parameter Name	P-N	P-I-N	P-I-N with SiO2 insulator	InGaAs/ GaAs Based Tandem
V_{OC} (V)	0.92	0.91	0.72	0.95
J_{SC} (mA/cm^2)	6.9	7.1	5.4	7
Efficiency (%)	11	19	39	46

VII. CONCLUSION

A performance investigation of GaAs based P-N and P-i-N single junction solar cell and GaAs/InGaAs based Tandem Solar cell were done for better Short Circuit Current (I_{SC}), Open Circuit Voltage (V_{OC}) and External Quantum Efficiency (EQE). The thickness of P-type layer and N-type layer for P-N, P-i-N and P-i-N with SiO_2 insulator were varied from 20 nm to 400 nm. The optimum result were 200 nm for P- type layer and 400 nm for N- type layer. The optimized doping concentration for P-type is found 1 x 10^{15} cm^{-3}and doping concentration for N-type is found 1 x 10^{22} cm^{-3}.The GaAs/InGaAs based tandem solar cell has shown better Short Circuit Current Density, Open Circuit Voltage (V_{OC})and External Quantum Efficiency (EQE) as expected. The effect of band gap optimization increases the efficiency. The Short Circuit Current Density for Tandem is 7.2mA/cm^2. The Open Circuit Voltage (V_{OC}) is 0.95 V. The Efficiency for the Tandem is achieved 46%. The efficiency for the P-i-N Single junction Solar Cell with SiO_2 insulator is achieved 39%. The results showed that the performance of GaAs/InGaAs tandem Solar Cell is much more efficient than the P-i-N Single junction Solar Cell with SiO_2 insulator and also the simple GaAs based P-N junction Solar Cell. Tandem Solar Cells will be a promising technology for future applications.

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