On the optimization of InGaP/GaAs/InGaAs triple-junction solar cell

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Abstract. This paper presents an optimization procedure for the design parameters of InGaP/GaAs/InGaAs Triple-Junction (TJ) solar cell by using SILVACO TCAD. The solar cell design parameters include layers' materials, thicknesses and doping concentrations. Firstly, the optimization technique is performed on an InGaP/GaAs/Ge cell. The Ge sub-cell is then replaced by an InGaAs sub-cell. A comparison between the performance parameters of InGaP/GaAs/InGaAs and InGaP/GaAs/Ge TJ solar cells is investigated. The compared parameters are the open circuit voltage ($V_{OC}$), short circuit current density ($J_{SC}$), Fill Factor ($FF$) and the conversion efficiency ($\eta$). Finally, a comparison between these optimized devices against some previously published work is presented. All simulations for triple-junction solar cells are accomplished under light intensity of 1-sun of standard AM1.5G solar spectrum at 300 K. The electrical characteristics for the proposed TJ solar cell are $V_{OC}=2.9$ V and $J_{SC}=15.97$ mA/cm² with conversion efficiency = 42.01%.

1. Introduction
Monolithic multi-junction (MJ) solar cells, fabricated from III-V compound semiconductors, have been developed in order to achieve high power conversion efficiencies for terrestrial and space applications [1–3]. An MJ solar cell is a combination of different types of photovoltaic junctions; each junction forms a sub-cell, stacked over one another via homo-junctions, intrinsic materials or tunnel junctions. Each sub-cell absorbs sunlight at a specific wavelength region of the solar spectrum and converts it into electricity. Moreover, matching the current generated by each sub-cell is crucial to obtain a maximum power from the solar cell. MJ solar cells are capable of generating a power approximately twice the power generated by the conventional solar cells [4].

An Experimental efficiency of around 41.6% was obtained by Boeing Spectrolab Inc. with a state-of-art TJ GaInP/GaInAs/Ge solar cell under 484 suns, AM1.5D and 25°C. Furthermore, high efficiency inverted metamorphic (IMM) InGaP/GaAs/Ge multi-junction solar cells are developed as the next space solar cell architecture. Spectrolab's achieved an efficiency of 33% at 1-sun and AM0 [5,6].

There were many publications that introduced studies of MJ solar cells and compared their simulation results with the experimental results. The earlier designs for TJ devices were based on GaAs and Ge substrates due to the well-known electronic and optical properties of the lattice-matched hetero-structures [7]. Remarkable progress in this field led to efficiencies higher than 34.5% under 1-sun global illumination and higher than 40.6% under concentrated direct sunlight [8].

The rest of the paper is organized as follows: In section 2, the design and simulation of the TJ solar cells are introduced. In section 3, the optimization for InGaP/GaAs/InGaAs TJ solar cell is performed.
Then, the simulation results are compared with some previously published results in section 4. Finally, section 5 is devoted to identifying paper’s conclusions.

2. TJ solar cell design

2.1. Device structure
The InGaP/GaAs/InGaAs triple-junction solar cell structure shown in figure 1 consists of three p-n junctions and two n+GaAs/p+GaAs tunnel junctions. The top InGaP and middle GaAs cells, each consists of a window, p-n junction, Back Surface Field (BSF) layer and Buffer layer. The InGaAs material is added as epitaxial layers to form the bottom cell. Real-like doping concentration levels are used. InGaP and GaAs doping concentrations never exceed $5 \times 10^{19}$ cm$^{-3}$ while InGaAs doping concentration of $3 \times 10^{18}$ cm$^{-3}$ is selected. To design an optimized solar cell, the window must be chosen carefully to be lattice-matched with that of the emitter layer, having a wide energy bandgap compared to the emitter and providing a potential barrier for minority carrier of the emitter. In this work, AlGaAs is used as a top window. The BSF layer is selected in order to passivate the surface recombination between the base of sub-cell and the emitter of the tunnel diode. So, the BSF must be lattice-matched to the GaAs and has a higher energy bandgap than the base of the bottom cell. The InGaP layer is selected to be the BSF. The tunnel junction is provided between two sub-cells in order to avoid the performance degradation of the MJ solar cells [10].

![Figure 1. Optimized InGaP/GaAs/InGaAs TJ solar cell structure used in this design indicating the design parameters.](image)

2.2. Simulation of InGaP/GaAs/Ge triple-junction solar cell
The TJ solar cell device is simulated using SILVACO ATLAS® tool and the performance of the cell is evaluated under 1-sun of AM1.5G standard spectrum. The physical models are reported as follows. To model the doping-dependent low-field mobilities of holes and electrons, the Concentration-Dependent Low Field Mobility (CONMOB) is used. Regarding recombination, Optical Recombination (OPTR) and Shockley-Read-Hall (SRH) recombination models are enabled. SRH recombination model considers the electrons being emitted or captured by donor and acceptor-like traps. The OPTR determines the possibility that a photon is generated when an electron and hole recombine. To model
the non-local band-to-band tunneling, (BBT.NONLOCAL) model is selected [11]. As well, LUMINOUS is an ATLAS module which determines the photo-generation at each mesh point of the generated structure. Extinction coefficients as well as refractive index of each material are important parameters for the simulation of solar cells. Both extinction coefficients as well as refractive index are obtained from [12-14].

Figure 2 shows the simulated I-V characteristics for the InGaP top cell, the GaAs middle cell, the Ge bottom cell and the InGaP/GaAs/Ge TJ solar cell under 1-sun of AM1.5G illumination. The simulation results show that the open circuit voltages for InGaP, GaAs and Ge sub-cells are 1.5 V, 1.06 V and 0.35 V, respectively. Moreover, the InGaP cell produces the least current among the three individual sub-cells, which is 15.5 mA/cm², while GaAs and Ge sub-cells produce 30.78 mA/cm² and 59.74 mA/cm², respectively. As well, the InGaP/GaAs/Ge TJ solar cell has the following parameters, 

\[ V_{OC} = 2.76 \text{ V} \text{ and } J_{SC} = 15.5 \text{ mA/cm}^2 \]

It is clear that the value for \( V_{OC} \) of TJ solar cell is approximately, the sum of \( V_{OC} \) of the three sub-cells, while the current of the TJ solar cell is determined by the sub-cell which has the lowest current density among the three sub-cells i.e. the top cell.

2.3. InGaP/GaAs/InGaAs triple-junction solar cell Design and Simulation

In this section, the Ge bottom cell of TJ solar cell is replaced by the In\(_{0.53}\)Ga\(_{0.47}\)As bottom cell with no change in all cell parameters. By simulating In\(_{0.53}\)Ga\(_{0.47}\)As cell, we can notice that it has an \( V_{OC} \) greater than that of Ge cell, since In\(_{0.53}\)Ga\(_{0.47}\)As has higher energy bandgap than Ge cell. Furthermore, although the short circuit current of In\(_{0.53}\)Ga\(_{0.47}\)As sub-cell is slightly higher than the short circuit current of Ge cell, it does not affect on the performance of the TJ solar cell as the current is limited by the top InGaP sub-cell.

In\(_{0.53}\)Ga\(_{0.47}\)As has a lattice constant of 5.8687 Å while GaAs lattice constant is 5.653 Å. Because of this mismatch in lattice constant, atoms create chemical bonds in heterointerface by adjusting their positions. This creates strain and cause crystal dislocation and structure imperfection in depth [15]. This mismatch forms traps acting as recombination centers which will affect adversely the short circuit current produced by the cell. In InGaP/GaAs/InGaAs TJ solar cell, the lattice mismatch will appear between the middle cell and bottom cell. To overcome this mismatch between GaAs and In\(_{0.53}\)Ga\(_{0.47}\)As lattice constants, two buffer layers with heavily doping concentration are used in the design. The buffer layer increases the excess minority carriers to the junction. Additionally, these layers drive out the photo-generated carriers with minimum recombination losses. The simulation results of InGaP/GaAs/Ge cell and InGaP/GaAs/InGaAs cell show that the InGaP/GaAs/InGaAs cell has higher \( V_{OC} \) than the other, however both produce the same \( J_{SC} \). This results in the efficiency obtained by InGaP/GaAs/InGaAs TJ solar cell is higher than that obtained by InGaP/GaAs/Ge TJ solar cell. Figure 3 shows the I-V characteristics for InGaP/GaAs/Ge and InGaP/GaAs/InGaAs TJ solar cells. It is clear that the open circuit voltage of InGaP/GaAs/InGaAs TJ solar cell (2.9 V) is higher than that of InGaP/GaAs/Ge TJ solar cell (2.76 V) and the short circuit current is almost the same for both cells.

![Figure 2. I-V characteristics for InGaP cell, GaAs cell, Ge cell and InGaP/GaAs/Ge TJ cell.](image1)

![Figure 3. I-V characteristics of InGaP/GaAs/Ge and InGaP/GaAs/InGaAs TJ solar cells.](image2)
3. Optimization for InGaP/GaAs/InGaAs TJ solar cell

From the previous sections, we can conclude that the short circuit current is limited and controlled by both the top and middle cells. So, to optimize the short circuit current, the top and middle cells should be optimized. One way to optimize these cells is optimizing their thicknesses. In this section, a design of experiment (DOE) technique is accomplished in order to show how to optimize the thickness for each cell and hence the efficiency of the TJ solar cell. Table 1 summarizes the change in the performance parameters of solar cell with respect to the base thickness of the top InGaP cell and keeping all the cell parameters constant. It is clear that the optimized base thickness of the top cell is 600 nm at which the efficiency of TJ solar cell is 42.01%. After the top base thickness is optimized, the base of the middle cell could be varied in order to obtain the maximum allowable efficiency. Table 2 summarizes how the efficiency is varied using different values for the base thickness of the middle cell and keeping the base thickness of the top cell at 600 nm.

**Table 1. Variation of the InGaP/GaAs/InGaAs TJ cell parameters w.r.t the top base thickness.**

| Thickness (nm) | 400 | 500 | 550 | 600 | 670 | 820 |
|----------------|-----|-----|-----|-----|-----|-----|
| Parameter      |     |     |     |     |     |     |
| VOC (V)        | 2.916 | 2.91 | 2.91 | 2.90 | 2.90 | 2.90 |
| JSC (mA/cm²)   | 15.17 | 15.66 | 15.83 | 15.97 | 15.94 | 15.75 |
| FF (%)         | 91.94 | 91.37 | 90.93 | 90.47 | 90.71 | 91.3 |
| Efficiency (%) | 40.64 | 41.63 | 41.86 | 42.01 | 41.99 | 41.69 |

**Table 2. Variation of the InGaP/GaAs/InGaAs TJ cell parameters w.r.t the middle base thickness.**

| Thickness (µm) | 2 | 2.4 | 3 | 3.4 | 4 | 5 |
|----------------|---|-----|---|-----|---|---|
| Parameter      |   |     |   |     |   |   |
| VOC (V)        | 2.92 | 2.91 | 2.91 | 2.91 | 2.90 | 2.90 |
| JSC (mA/cm²)   | 14.57 | 15.01 | 15.83 | 15.76 | 15.97 | 15.977 |
| FF (%)         | 92.16 | 91.76 | 90.93 | 90.77 | 90.47 | 91.09 |
| Efficiency (%) | 39.24 | 40.21 | 41.22 | 41.63 | 42.01 | 42.2 |

Although the highest possible efficiency could be obtained at a bottom base thickness of 5 µm, we choose the thickness of 4 µm because the device size will be increased (which results in a higher fabrication cost) with only an increase in the efficiency less than 0.2%.

Using the same previous methodology and geometric conditions of InGaP/GaAs/InGaAs TJ solar cell, an InGaP/GaAs/Ge TJ cell will be optimized. The results are as follows: $V_{OC} = 2.767$ V, $J_{SC} = 16$ mA/cm² and the $\eta = 39.68\%$. The short circuit current of both cells are the same, so, the difference in efficiency results from the increase in open circuit voltage for InGaAs over Ge.

The generated P-V and the I-V characteristics of the optimized InGaP/GaAs/Ge TJ cell and the proposed InGaP/GaAs/InGaAs TJ cell are shown in figures 4a and 4b, respectively.

![Figure 4. P-V and I-V characteristics for a) an optimized InGaP/GaAs/Ge TJ solar cell and b) a proposed InGaP/GaAs/InGaAs TJ cell device, under 1 sun of AM1.5G illumination.](image)

From the P-V curves, we can notice that the maximum power obtained from the proposed InGaP/GaAs/InGaAs solar cell (42.259 mW/cm²) is higher than that is obtained from the optimized...
InGaP/GaAs/Ge solar cell ($\approx 40$ mW/cm$^2$). Also, for InGaP/GaAs/Ge TJ solar cell, the voltage at which maximum power is achieved is 2.675 V. Finally, the electrical characteristics for the proposed TJ solar cell are $V_{OC} = 2.9$ V, $J_{SC} = 15.97$ mA/cm$^2$ and the conversion efficiency $\eta = 42.01\%$.

4. Results comparison

The obtained results from this optimized devices are now compared with corresponding experimental and theoretical published data [3, 7, 8, 16]. Table 3 shows a comparison between the proposed structure and the previously published data. From table 3, it is clear that the performance of either optimized InGaP/GaAs/Ge TJ solar cell or the proposed InGaP/GaAs/InGaAs TJ solar cell is better than the other designs. As seen, the open circuit voltage as well as the short circuit current are higher than that are introduced by [3, 7, 8, 16]. That leads to a higher efficiency for the proposed InGaP/GaAs/InGaAs cell or the optimized InGaP/GaAs/Ge cell higher than that obtained from the other published work.

| Solar Cell               | Spectrum | Sun | $V_{OC}$ (V) | $J_{SC}$ (mA/cm$^2$) | FF (%) | $\eta$ (%) |
|-------------------------|----------|-----|-------------|----------------------|--------|------------|
| Huang et al. [16]       | AM1.5    | 1   | 2.609       | 13.368               | N/A    | 29.67      |
| R.R. King et al. [7]    | AM1.5    | 1   | 2.622       | 14.37                | 85     | 32         |
| J.W. Leem et al. [3]    | AM1.5    | 1   | 2.55        | 13.92                | 86.55  | 30.72      |
| M.A. Green et al. [8]   | AM1.5    | 1   | 2.66        | 13.1                 | 85.6   | 34.5       |
| Our optimized InGaP/GaAs/Ge cell | AM1.5 | 1 | 2.767 | 16 | 89.46 | 39.68 |
| Our proposed InGaP/GaAs/InGaAs cell | AM1.5 | 1 | 2.9 | 15.97 | 90.47 | 42.01 |

5. Conclusion

In this work, MJSCs are designed and simulated using SILVACO TCAD tool. InGaP/GaAs/Ge and InGaP/GaAs/InGaAs TJ solar cells are simulated and the obtained results are compared. The efficiency of optimized InGaP/GaAs/Ge TJ solar cell is 39.61% while it is 42.01% for the proposed InGaP/GaAs/InGaAs cell. The increase in efficiency is due to increasing the open circuit voltage for the InGaAs sub-cell (0.48 V) over the Ge sub-cell (0.35 V) while the short circuit current still constant. All these results are obtained under 1 sun illumination of AM1.5 solar spectrum.

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