

Comparison between the Efficiency of Heterojunction Thin Film InGaP/GaAs/Ge and InGaP/GaAs Solar Cell

F. Djaafar, B. Hadri, G. Bachir

Abstract—This paper presents the design parameters for a thin film 3J InGaP/GaAs/Ge solar cell with a simulated maximum efficiency of 32.11% using Tcad Silvaco. Design parameters include the doping concentration, molar fraction, layers' thickness and tunnel junction characteristics. An initial dual junction InGaP/GaAs model of a previous published heterojunction cell was simulated in Tcad Silvaco to accurately predict solar cell performance. To improve the solar cell's performance, we have fixed meshing, material properties, models and numerical methods. However, thickness and layer doping concentration were taken as variables. We, first simulate the InGaP/GaAs dual junction cell by changing the doping concentrations and thicknesses which showed an increase in efficiency. Next, a triple junction InGaP/GaAs/Ge cell was modeled by adding a Ge layer to the previous dual junction InGaP/GaAs model with an InGaP /GaAs tunnel junction.

Keywords—Heterojunction, modeling, simulation, thin film, Tcad Silvaco.

I. INTRODUCTION

TO improve a PV cell performance it is necessary to limit the losses and improve the efficiency of photovoltaic cells. From a technological viewpoint, it is necessary to place cells of different materials in tandem; by stacking junctions possessing descending gaps (heterojunctions). These cells are connected with a tunnel junction in order to minimize shadowing of the sub-cells and maximize the number of photons absorbed. A second response is to minimize the layers' thickness by applying thin film technology.

Among the different technologies available for photovoltaic electricity production; thin film heterojunction solar cell is one of the most promising candidates for industrialization. Indeed, this technology offers two crucial advantages. First, it presents high efficiencies thanks to high open-circuit values. Secondly, it enables production cost reduction compared to classical technologies [1]. Efficiencies over 28% have been already achieved using this concept [2]. An in-depth understanding of the device physics appears mandatory to pursue cell performance increase. Owing to the large number of variables (layer thicknesses, doping concentration, etc...), scrutinizing the effect of each variable on the overall performance of the

solar cell is experimentally unfeasible. Numerical simulation using TCAD Silvaco is done to evaluate the role of various parameters [3], [4].

This paper provides a simulation of thin film 3J InGaP/GaAs/Ge solar cell with an InGaP/GaAs tunnel junction. It highlights the importance of a heterojunction thin film technology, and the most critical issues in improving 3J solar cell efficiency. Finally, simulation results are shown, illustrating the driving role of simulation on technology improvement.

The majority of photovoltaic cells use semiconductors to collect the pairs electron-hole created by collision of photons in the material. The performance of the solar cell can be improved by optimizing the internal physical parameters in order to assure at a time a short circuit current, a fill factor and a high open circuit voltage.

The simulation is done by using the software TCAD Silvaco, which allows modeling the performance of solar cells precisely.

II. MODELING

A. The Spectrum

To increase efficiency, multi-junction solar cells have been developed in order to absorb a wider array of the solar spectrum.

By stacking cells of different semiconductor materials in tandem, efficiency can theoretically be increased to more than 30%. For a given solar spectrum AM1.5, a triple junction solar cell is simulated to take advantage of the spectral response of each layer's band gaps as shown in Fig. 1.

The III-V solar cells are able to achieve a conversion efficiency of over 30% for dual-junction and over 40% for three-junction cells under concentration [3].

The multi-junction (MJ) solar cells with stacked p-n junctions of different bandgap energies can exploit the solar spectrum very effectively [5]. However, due to complex interactions between the junctions, modeling of MJ solar cells is more complex than single junction cells.

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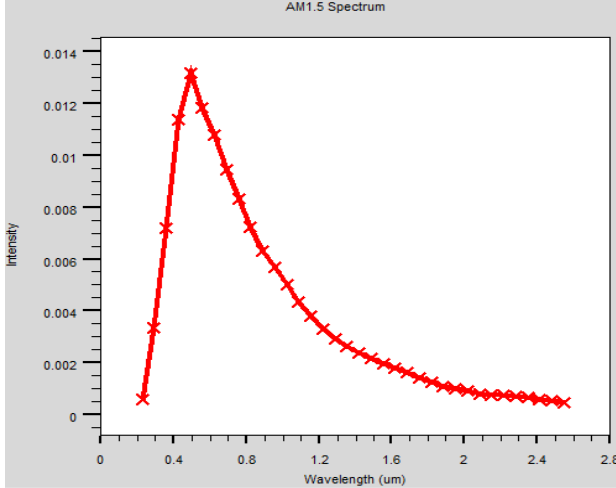


Fig. 1 Spectral Response of a Simulated Triple Junction InGaP/GaAs/Ge Solar Cell

B. Mathematical Approach

In order to understand solar cell issue, it is necessary to know about lights theories, interaction of light with materials, and how the electron and hole are produced in a pn junction, and consequently about creative current electricity. We used geometric optics in our calculation. In geometrical optic, light is defined by the rays. Every ray moves with a special amount of energy. Because of interaction of light with material, we need to know a formula that expresses the electrical field of ray at any place. We can also calculate such formula for any transmitted or reflected ray (we have used the transfer matrix method [4]). The transmission and reflection electrical field of the light can be calculated as clarified in (1)-(4). Their coefficients are represented in (5) and (6) [6]:

$$E_r = \frac{n_2 \cos \theta_i - n_1 \cos \theta_t}{n_1 \cos \theta_t + n_2 \cos \theta_i} E_i \text{ (Parallel polarization)} \quad (1)$$

$$E_t = \frac{2n_2 \cos \theta_i}{n_1 \cos \theta_t + n_2 \cos \theta_i} E_i \text{ (Parallel polarization)} \quad (2)$$

$$E_r = \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} E_i \text{ (Perpendicular polarization)} \quad (3)$$

$$E_t = \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_i + n_2 \cos \theta_t} E_i \text{ (Perpendicular polarization)} \quad (4)$$

$$R = \left(\frac{E_r}{E_i} \right)^2 \quad (5)$$

$$T = \frac{\left(\frac{E_r}{E_i} \right)^2 (n_2 \cos \theta_t)}{n_1 \cos \theta_i} \quad (6)$$

where E_i , E_r and E_t refer to electric field of the incident wave, field of the reflected wave and field of the transmitted wave, respectively. R refers to the reflection coefficient and T refers to the transmission coefficient. While θ_i is the angle of incidence, θ_t is the angle of transmission; n_1 and n_2 refer to

the refractive index on the incident side and to the refractive index on the transmission side, respectively [4], [7]-[10].

Poisson's equation relates the electrostatic potential to the space charge density as shown in (7):

$$\Delta(\varepsilon \Delta \varphi) = -\rho \quad (7)$$

where φ is the electrostatic potential, ε is the local permittivity, and ρ is the local space charge density. The local space charge density is the sum of contributions from all mobile and fixed charges, including electrons, holes, and ionized impurities.

The continuity equations for electrons and holes are defined by [4], [5], [11], [12]:

$$\partial n / \partial t = 1/q \operatorname{div} \vec{j}_n + G_n - R_n \quad (8)$$

$$\partial p / \partial t = -1/q \operatorname{div} \vec{j}_p + G_p - R_p \quad (9)$$

n is the electron concentration and p is the hole concentration, \vec{j}_n is electron current density and \vec{j}_p is the hole current density. G_n is the generation rate for electrons and G_p is the generation rate for holes. Besides R_n referred to the recombination rate for electrons and R_p referred to the recombination rate for holes, and q is the magnitude of electron charge [13].

In the transport equations, the currents densities are defined by:

$$\vec{j}_n = -q \mu_n n \nabla \phi_n \quad (10)$$

$$\vec{j}_p = -q \mu_p p \nabla \phi_p \quad (11)$$

where μ_n and μ_p are the electron and hole mobilities; ϕ_n and ϕ_p are the electron and hole quasi-Fermi levels.

C. Material Properties for Different Layers

Silvaco is a simulation software tool targeting the area of electronic design [1]. It is used to predict the electrical characteristics of heterojunction solar cells' structures. Simulation can help to gain time and money and give solar cell characteristics that are difficult to measure using experimentation [14]. The accuracy of this simulation tool depends very much on the accuracy of the material parameters used in building the solar cell model. Critical parameters needed for solar cell modeling in Tcad silvaco include band gap energy, electron and hole state densities, electron and hole mobility, permittivity, electron affinity.

Table I presents different material parameters which are used in the considered structure. These parameters have been produced by literature research and calculations as well as calibration from well-known cells. To produce optical transparency and maximum current conductivity between the top and bottom cells in multi-junction devices, all layers must have similar crystal, or lattice structures. It is extremely desirable to match the lattice constants of the various layers [1], [4], [9], [15], [16].

TABLE I
PARAMETERS FOR MATERIAL PROPERTIES OF DIFFERENT LAYERS

Material	InGaP	GaAs	InAlAsP	AlGaAs
Band gap E_g (eV) at 300°K	1.42	1.90	2.30	1.80
Lattice constant a (Å)	5.65	5.65	5.65	5.64
Permittivity ϵ_r/ϵ_0	13.10	11.60	11.70	11.00
Affinity χ (eV)	4.07	4.16	4.20	4.100
e- mobility MUN ($\text{cm}^2/\text{V}\cdot\text{s}$)	8800	1945	2150	2000
h+ mobility MUP ($\text{cm}^2/\text{V}\cdot\text{s}$)	400	141	141	138
Lifetime (e) (s)	1.10^{-09}	1.10^{-09}	1.10^{-07}	1.10^{-09}
Lifetime (h) (s)	2.10^{-08}	1.10^{-09}	1.10^{-07}	$2*10^{-08}$
Radiative recombination rate Copt ($\text{cm}^3 \text{s}^{-1}$)	0	$1.5*10^{-10}$	$1.5*10^{-10}$	$1.8*10^{-10}$
Electron Auger coefficient Augn ($\text{Cn}\cdot\text{cm}^6 \text{s}^{-1}$)	0	$5*10^{-30}$	$8.3*10^{-32}$	$5*10^{-30}$
Hole Auger coefficient Augp ($\text{Cn}\cdot\text{cm}^6 \text{s}^{-1}$)	0	$1*10^{-31}$	$1.8*10^{-31}$	$1*10^{-31}$

III. SIMULATION RESULT

A. InGaP/GaAs (DJ) Simulation

Model verification requires obtaining both the detailed design parameters of doping and thicknesses along with the performance results. Table II and Fig. 2 show simulation results under AM1.5 illumination.

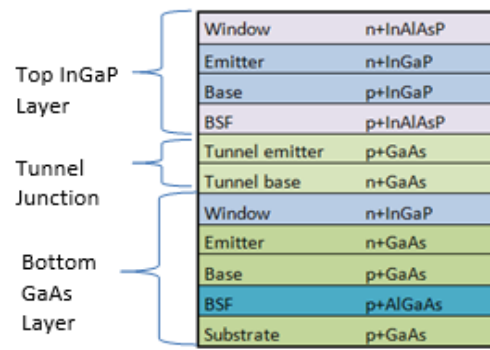


Fig. 2 Schematic Diagram of InGaP/GaAs Dual- Junction Design [3]

Table II shows the extrapolated performance results for AM1.5 illumination.

TABLE II
DUAL JUNCTION CELL PERFORMANCE, AM1.5 [3], [4], [12], [16]

2Jcell M1.5	Voc(V)	Jsc(mA/cm^2)	Efficiency (%)
Published InGaP/GaAs cell	2.43	14.22	23.33

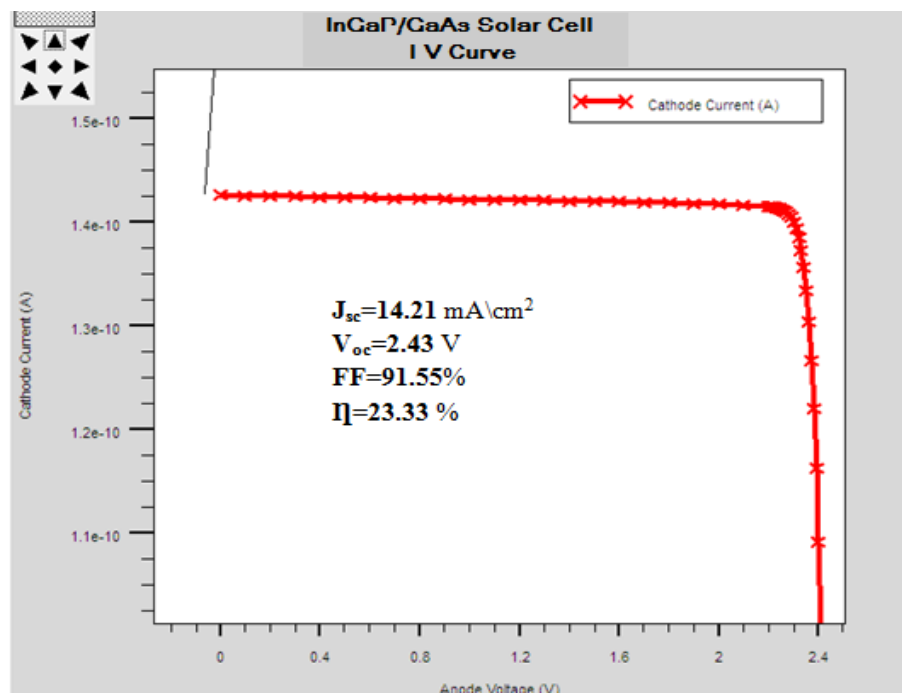


Fig. 3 I-V Curve of 23% InGaP/GaAs solar cell

B. InGaP/GaAs/Ge (3J) Cell Simulation

The initial model was constructed with three stacked Ge, GaAs, and InGaP cells [3]

The design of the multi-junction solar cell to be constructed is pushed by both the desire to have maximally efficient junction layers and the need to match the current produced in each junction layer under optimal conditions using ATLAS

silvaco greatly by providing I-V characteristics and spectral responses. This allows the solar cell designer to adjust the parameters of the junction layers such as thickness to produce an optimal design. The thickness of the InGaP layer was varied to allow light to pass through the GaAs cell below it. The GaAs and the Ge layer could likewise vary their cell thicknesses to balance their currents.

Two Tunnel junctions InGaP/GaAs were also implemented

and placed between each of the three cells in order to minimize shadowing of the sub-cells and maximize the number of photons absorbed [2], [8]. Some characteristics of this solar cell are shown in Table III.

The final heterojunction cell as simulated (Fig. 4) produced an efficiency of 32.11%. Fig. 5 shows the I-V characteristic of the cell.

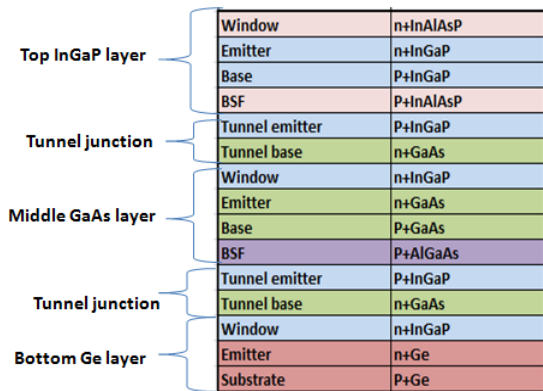


Fig. 4 Schematic Diagram of InGaP/GaAs/Ge 3J Design

After simulating the InGaP/GaAs solar cell model, a 3J solar cell is simulated to find an optimal cell design parameters through a process of varying doping concentration levels and layer thicknesses. The InGaP, GaAs, Ge junctions were selected for optimization. Each junction has separate layers (Fig. 4) that have three independent variables, molar fraction, thickness and doping.

TABLE III

Regions	Materials	Thickness(μm)	Doping(cm^{-3})	Affinity(eV)
1	InAlAsP	0.03	1×10^{18}	4.2
2	InGaP	0.05	2×10^{18}	4.08
3	InGaP	0.55	10^{18}	4.08
4	InAlAsP	0.02	10^{19}	4.2
5	InGaP	0.02	8×10^{19}	4.08
6	GaAs	0.02	3×10^{19}	4
7	InGaP	0.04	3×10^{20}	4.08
8	GaAs	0.55	1×10^{18}	4
9	GaAs	3	1×10^{17}	4
10	AlGaAs	0.01	10^{19}	3.54
11	InGaP	0.02	2×10^{17}	4.08
12	GaAs	0.02	2×10^{17}	4
13	InGaP	1	8×10^{15}	4.08
14	Ge	0.2	6×10^{18}	3.24
15	Ge	300	7×10^{17}	3.24

The parametric results from varying each parameter at room temperature (300 K) gives an optimum InGaP/GaAs/Ge with an optimal efficiency (32.10%) at 300 K shown in Table IV.

TABLE IV
3J SOLAR CELL PERFORMANCE, AM1.5G

3J thin film solar cell AM1.5	Simulation result
V_{oc} (V)	2.51
J_{sc} (mA)	14.21
P_{max} (mW/cm ²)	25.09
Fill factor (%)	90.10
Efficiency (%)	32.1052

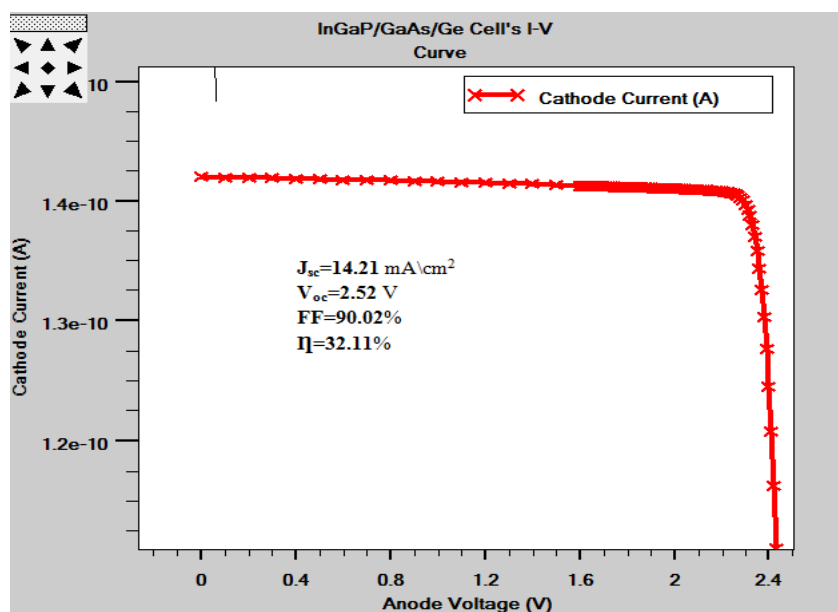


Fig. 5 I-V Curve of 32.11 % InGaP/GaAs/Ge solar cell

IV. CONCLUSION

In this paper, we gave much importance to extract the

parameters which are characteristics (V_{oc} and I_{sc}) of the 3J solar cell using TCAD Silvaco. Simulations were carried on

dual junction III–V solar cells (InGaP/GaAs). Then, a comparison between the dual junction (InGaP/GaAs) cell and the triple junction (InGaP/GaAs/Ge) cell is done.

The obtained optimal conversion efficiencies are 32.11% and 23.33% for the triple junction (3J) and the dual junction (DJ) respectively.

Finally, in order to improve the solar cell performances, especially the conversion efficiency, we plan in future works, to use multi layers (four) owing to their high conversion efficiency and wide future applications.

Tcad silvaco simulator [7] is accurately used to extract solar cell characteristics. Using these tools, an InGaP/GaAs/Ge cell was designed and simulated showing spectral and I-V characteristics.

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