Influence of doping concentration on the performances of multi-junction solar cell InGaP/InGaAs/Ge

Khadidja Djeriouat, Salim Kerai, Kheireddine Ghaffour
Materials and Renewable Energies Research Unit URMER, Faculty of Sciences, Abou Bekr Belkaïd University, Tlemcen, Algeria

Article Info

Article history:

Received Apr 7, 2025
Revised Dec 13, 2025
Accepted Jan 16, 2026

Keywords:

III-V material
Doping
Efficiency
Heterojunction
Solar cell
Tandem

ABSTRACT

Recently, because of the high costs of experimentation, researchers have turned to simulation. This type of simulation makes it possible to determine, at any point in the volume of a component, the densities of carriers, electrons and holes, the energies, the recombination rates, the electric fields and other parameters that can be deduced from it, such as currents and voltages. Our paper presents the simulation results of the heterojunction solar cell made of GaInP/GaInAs/Ge materials using Silvaco's Atlas software to optimize its electrical efficiency by acting on the doping of photoactive layers. We have chosen a tandem structure when the top cell is constructed by $Ga_{0.4}In_{0.6}P$, in the middle cell, we used $Ga_{0.1}In_{0.9}As$ and the bottom cell is formed by germanium (Ge). The simulation is performed under the following conditions: 1-sun (0.1 w/cm^2), AM1.5G illumination and at temperature 300 K. We obtained an efficiency of 24.65%.

Corresponding Author:

Khadidja Djeriouat
Materials and Renewable Energies Research Unit URMER, Faculty of Sciences, AbouBekr Belkaïd University
Tlemcen Algeria
Email: djeriouat.kh@gmail.com

1. INTRODUCTION

The photovoltaic effect is generally defined as the generation of an electrical potential when a radiant light is projected onto a system of two electrodes separated by a solid or liquid material. The concepts of solar energy began in 1839 when Becquerel discovered the photovoltaic effect, which is utilized to transform solar radiation into electricity [1]. Fritt created the first purpose-built, working photovoltaic gadget in 1883 [2]. Therefore, photovoltaic systems are considered a hopeful advancement in technology that directly utilizes the sun, the primary power source of our world. Solar cells may generate electricity when exposed to light without endangering gadgets or the environment. As a result, they can provide electricity for a long time at least 20 years with low maintenance and operating expenses. However, the prevalent adoption of photovoltaic technology over alternative energy sources is hindered by the comparatively high costs and low efficiency of solar cells [3].

There are various categories of photovoltaic cells such as thin-film, crystalline, multi-junction or tandem cells. Tandem solar cells were proposed in 1955 by Jackson [4] and in 1960 by Wolf [5]. Furthermore, ultra-high efficiency photovoltaic devices can be implemented using some of the most effective device topologies and their superior radiation resistance and excellent conversion efficiency will make them extensively utilized in space. Improving conversion efficiency and lowering cost are essential for the widespread use of super high-efficiency cells [6], [7].

For many satellites and spacecraft, III-V cells are a desirable alternative to silicon cells due to their increased efficiency and radiation resistance. Consequently, multi-junction solar cells III–V have the added advantage of operating at high voltage and low current and having exceptional radiation resistance. Additionally, because they have a lower temperature coefficient than silicon cells, they perform better in space applications' operating conditions. It suggests improved performance in space applications under operating conditions [8].

Additionally, their efficiency is increased by reducing potential losses in a photovoltaic system. Impurities, dislocations, and other flaws in the semiconductor absorber serve as hotspots for non-radiative recombination and are the source of bulk recombination losses. By guaranteeing the development of superior epitaxial layers to lower the density of defects in each multijunction solar cell layer, the bulk recombination losses can be reduced [6].

Two main challenges are detected in multijunction solar cells. On one side, the primary barrier to replacing the market domination of established Si single junction solar cells is the expensive cost of multijunction solar cell modules, which limits multijunction solar cells to specialized applications where surface area is the limiting constraint for example, space applications, drones, and unmanned aircraft. On the other hand, for long-term solutions in renewable energy sources, the increased efficiency of multijunction solar cells may outweigh their high cost. Therefore, while choosing solar cells, efficiency and cost must be traded off [9]. Tandem solar cells are made by stacking some single-junction solar cells on top of one another so that each layer from top to bottom has a smaller bandgap than the one before it. As a result, photons with energies higher than that layer's bandgap and lower than the higher layer's bandgap are absorbed and converted [10], [11].

In this article, our structure was chosen precisely; it is a tandem structure that has a top cell made of GaInP, a middle cell formed with GaInAs, and a bottom cell composed of germanium, the concentration of Indum in GaInP and GaInAs was chosen to be 60% and 90% respectively to satisfy the adaptation of constant lattice within the crystal structure of the tandem cell and with the aim of avoid the maximum number of crystal defects. In the first part of this work, we presented the results of simulation and in the second part, we have studied the impact of the doping concentration of the photoactive layers on the conversion efficiency and we achieved excellent results.

2. MODELING AND SIMULATION

The relationship between doping concentration, photoactive layer thickness, depletion zone, electric field and potential is a key element to improve research on hetero-structures in multi-junction cells. The major difficulty lies in the large number of parameters that affect the solar cell's efficiency. Moreover, the hetero-structure aspect is important because of the discontinuities between the photoactive layers in the tandem solar cell, this allows control of the position of free carriers, which vary according to the doping concentration, by forcing them to localize and/or move in a well-defined region (called confinement) due to the bandgap offset. In this study, we presented the impact of doping concentration on the conversion efficiency of a tandem solar cell made of $Ga_{0.4}In_{0.6}P/Ga_{0.1}In_{0.9}As/Ge$ using Silvaco's Atlas software under illumination of 0.1 W/cm^2 AM1.5G at room temperature.

2.1. Silvaco

A software environment called Silvaco (Silicon Valley corporation) makes it possible to design and forecast semiconductor device performance. Before semiconductor devices are built, they are modeled using this tool. It greatly aids in the advancement of numerous research initiatives. In order to get very close simulation results to those in practice, the Silvaco TCAD incorporates new physical models that use efficient numerical algorithms, new grid technologies, and optimization linear solutions. The ability to depict physical events that are challenging to access and so see is the main benefit of this kind of simulator [12].

2.2. Description of structure

The design of the tandem solar cell must ensure that the minimum current is supplied by the junction formed by the material with the highest resistance to irradiation. It is apparent that there are further qualities that should be considered to improve the efficiency of multijunction devices. For instance, every junction should be designed to generate the same amount of photocurrent. The bandgap of the semiconductor, the absorptivity of the material, and the thickness of the cells are the main determinants of this current-matching [13].

In a lattice matched (LM) GaInP/GaInAs/Ge 3-junction cell, the split of the solar spectrum by the 1.8 eV/1.4 eV/0.67 eV combinations of bandgaps results in an excess photogenerated current density in the Ge sub cell. If the middle cell's bandgap is reduced, as in lattice mismatched or metamorphic (MM) GaInP/GaInAs/Ge 3-junction cells with a 1.2-1.3 eV GaInAs middle cell, some of this wasted current can be employed efficiently in the middle cell [14]–[22].

To enhance the efficiency of a tandem solar cell, several parameters control the increase or decrease in efficiency, including the doping concentration of photoactive layers which is the aim of our study. We realized a multijunction solar cell made of III-V semiconductor materials when the top cell is constructed by $In_{0.6}Ga_{0.4}P$, in the middle cell we used $In_{0.9}Ga_{0.1}As$ and the bottom cell is formed by Ge having band gap of 2.11, 1.73 and 0.66 eV respectively. Then; doping concentration is n-type $10^{20}/cm^3$ and thickness of 0.4 µm of emitter of the top cell, doping concentration is p-type $10^{17}/cm^3$ and thickness of 1.6 µm at base of the top cell, the thickness of the base of the middle cell is about 7.95 µm and doping concentration is $10^{20}/cm^3$, the emitter thickness of the middle cell and doping concentration is 0.05 µm and $10^{17}/cm^3$ respectively, the emitter and the base thickness of the bottom cell are about 0.75 and 42.25 µm respectively with doping concentration of n-type of $10^{17}/cm^3$ in the emitter and p-type $10^{15}/cm^3$ in the base. Moreover, the bulk surface field (BSF) is about 1 µm of thickness and n-type with $10^{17}/cm^3$ of doping concentration. The ohmiques electrodes are situated at the top and bottom of the tandem cell, as depicted in Figure 1. The mesh is refined at the top and between the cell's electrodes to achieve high resolution and accuracy in calculations, and the sides are wider to shorten calculation time, as illustrated in Figure 2.

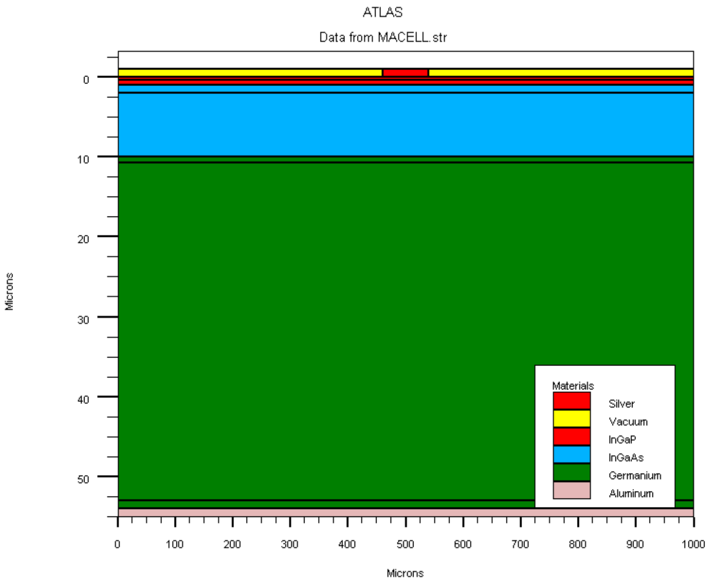

Figure 1. Structure of the model simulated

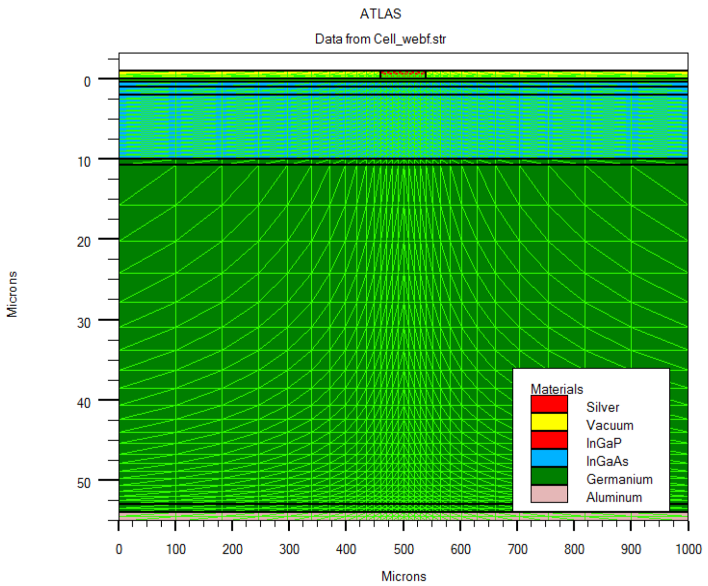

Figure 2. Mesh of the structure simulated

3. RESULTS AND DISCUSSION

We reported a numerical simulation of a tandem solar cell; in the Figure 3, we exhibit the I(V) characteristic of our model simulated. The short circuit condition, which describes how the cell functions if a wire is attached between its terminals and shorts it out, is the point where the curve intersects the vertical axis. This current flow is referred to as short-circuit current, or I_{sc}. The open circuit condition is the point where a curve crosses the horizontal axis. V_{OC}, or open-circuit voltage [23], then we extracted its electrical characteristics using (1)-(4).

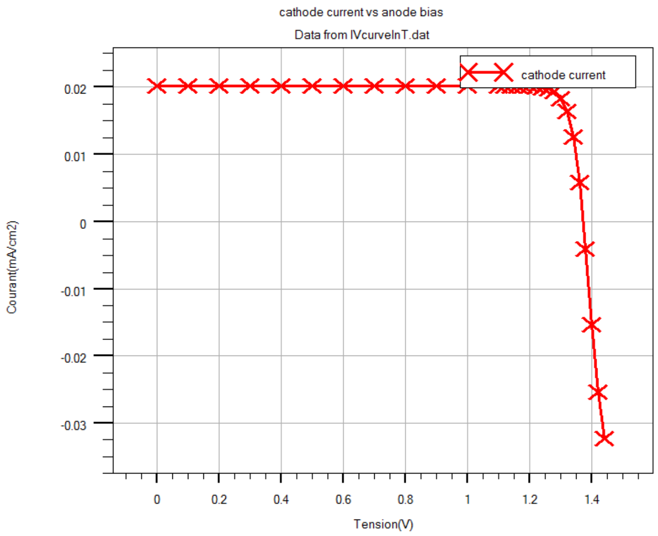

Figure 3. I-V Characteristic of the model simulated

- Current-voltage function is donne by (1) [24]:

$$J = J_s\left(e^{qV/nkT} - 1\right) - J_{sc} \tag{1}$$

where kT/q is thermal voltage, n is ideality factor, J_s is reverse saturation current density, and V is bias voltage.
- Open-circuit voltage V_{OC}:
When $J = 0$, the expression defining the open-circuit voltage may be formulated as (2) [25]:

$$V_{oc} = \frac{nkT}{q} ln\left(\frac{J_{sc}}{J_s} + 1\right) \tag{2}$$

- The energy conversion efficiency is defined as (3) [25]:

$$\eta = \frac{P_{max}}{P_{in}} \times 100\% = \frac{j_{max}V_{max}}{P_{in}} 100\% \tag{3}$$

P_{in}: input power (1000 W/m^2)
- The fill factorcan be obtained by (4) [25]:

$$FF = \frac{j_{max}V_{max}}{j_{sc}V_{co}} \tag{4}$$

All results are recapulated in Table 1.

Table 1. The cell's short circuit current I_{sc}, open-circuit voltage V_{OC}, fill factor FF and conversion efficiency η

$I_{SC}(mA/cm^2)$	V_{OC}(V)	FF(%)	η(%)
20.07	1.37	89.46	24.65

These results are obtained under an illumination of 0.1 W/cm^2, a surface of 1 mm^2, and room temperature. A p-type semiconductor and an n-type semiconductor are combined to form a p-n junction. The union of these two semiconductor categories, influenced by the concentration gradient, enables a fraction of the majority holes in the p-type section to migrate to the n-type territory, subsequently revealing negative acceptor ions, referred to as NA−. The same holds true for the electrons traveling in the reverse direction, leaving behind specific positive donor ions, ND+. Consequently, a positive spatial charge is created near the n-side, while a negative spatial charge forms near the p-side of the junction. An area that does not have mobiles charges devoid is known as the space charge region (depletion zone). The importance of this region in solar cells is crucial, as it creates an electric field .This field causes negatively charged particles to move in one direction and positively charged particles in the other direction, thus, producing an electrical voltage [26], [27]. Figure 4 and Figure 5 present the internal potential and the electric field across the structure. The latter reaches 4e^{5}V/cm in the interface of heterojunction $In_{0.6}Ga_{0.4}P/In_{0.9}Ga_{0.1}As$.

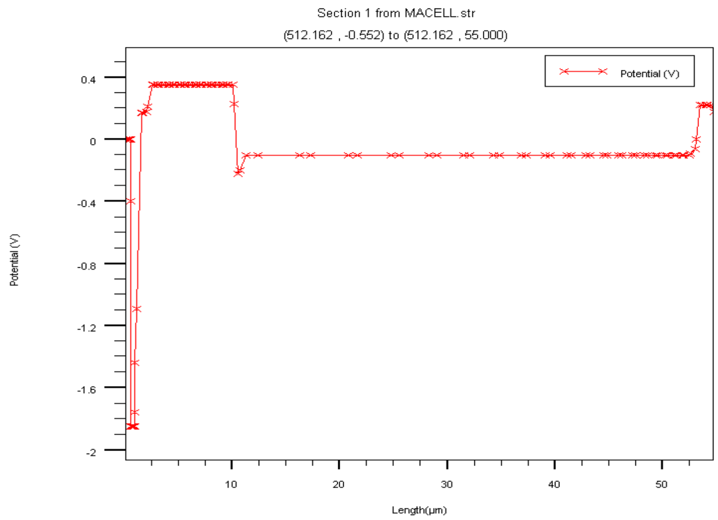

Figure 4. Internal potential across the structure

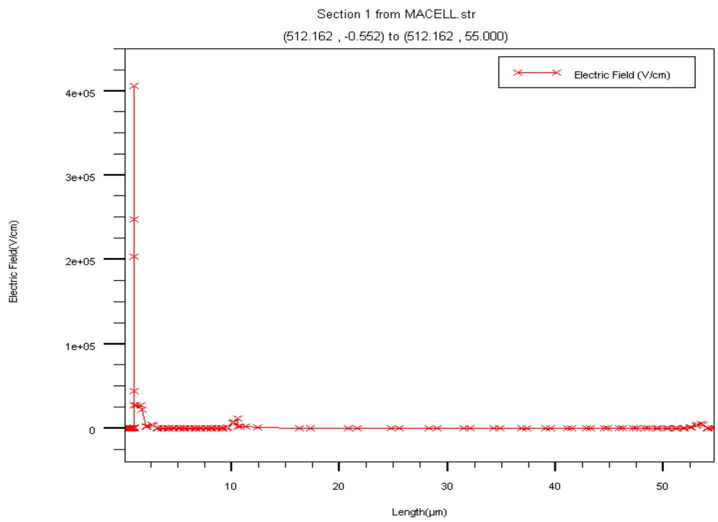

Figure 5. Electric field across the structure.

Quantum efficiency represents one of the most fundamental properties of a tandem solar cell; it is determined by how well a solar cell can transform incident photons (of different wavelengths) into electrons depending on how much energy they contain. The definition of spectral quantum efficiency (QE) is the ratio of the collected electrons and the incident photons at a given wavelength. There are two forms of QE [28]:

– External quantum efficiency (EQ_{ext}) includes losses due to reflection, non-productive absorption, and so on.
– Internal quantum efficiency (EQ_{int}) solely takes into account the photons that the cell really absorbs.
Figure 6 represents the (EQ_{ext}) and (EQ_{int}) of the model simulated. It varies from 40% at 200 nm up to 65% at 800 nm.

$$EQ_{int} = \frac{EQext}{1-Reflectivity} \quad (5)$$

Understanding how a multi-junction device works is important for the design of next-generation high efficiency solar cells [29]. One of the elements that affect the characteristics of the tandem cell is the doping concentration of the photoactive layers (emitter, base and BSF) which plays a primordial role on the depleted zone and the electric field separating the charges created contributing in the electric conversion, which is the aim of our study to improve the efficiency of the tandem cell by acting on the doping concentration.

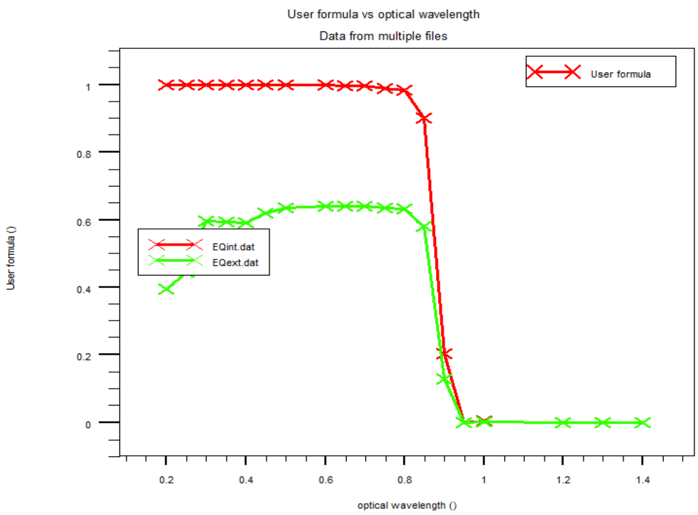

Figure 6. EQ_{ext} and EQ_{int} of the solar cell $In_{0.6}Ga_{0.4}P/In_{0.9}Ga_{0.1}As/Ge$

3.1. Variation of doping concentration of the emitter

From the results found in Figure 7 and Figure 8, the elevation of the doping concentration of the emitter of the top and middle cells from $10^{18}/cm^3$ to $8\times10^{20}/cm^3$ and $10^{16}/cm^3$ to $8\times10^{17}/cm^3$ respectively causes a slight increase of the maximum current and so improve the efficiency, while the open-circuit voltage remains stable. Contrary to what happens in the case of an increase of doping concentration of the emitter of the bottom cell illustrated in Figure 9, higher doping concentration of the latter leads to decrease of conversion efficiency due to Auger recombination, the doping concentration of this layer must not exceed $10^{17}/cm^3$ in our model.

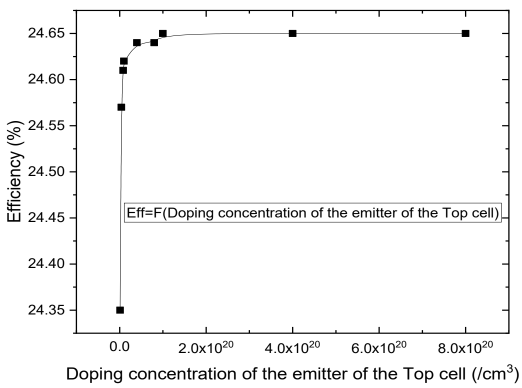

Figure 7. Efficiency according doping concentration of the emitter of the top cell

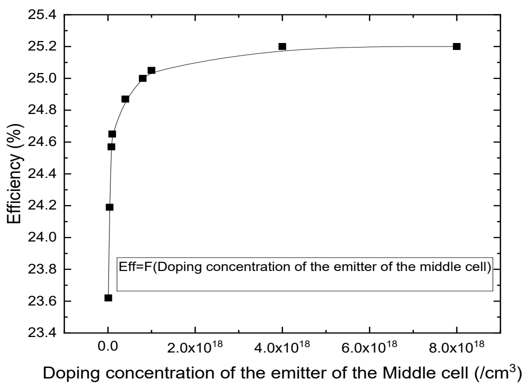

Figure 8. Efficiency according doping concentration of the emitter of the middle cell

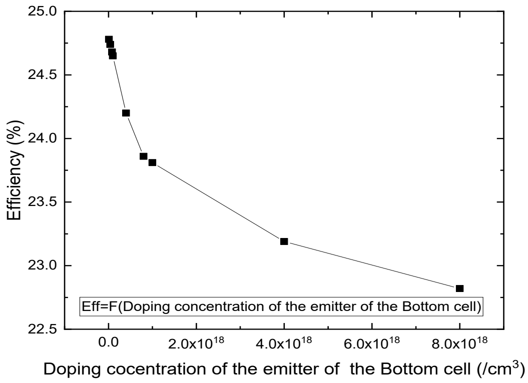

Figure 9. Efficiency according doping concentration of the emitter of the bottom cell

3.2. Variation of doping concentration of the base

Figure 10 and Figure 11 show that when doping of concentration of the base of the top and middle cells increase from 10^{18}/cm^3 to 8×10^{20}/cm^3 and 10^{15}/cm^3 to 10^{17}/cm^3 respectively, open-circuit voltage remains stable but the short-circuit current increases slightly, resulting an improvement in the cell efficiency. On the other hand, the solar cell efficiency decreases from 24.65% to 22.12% when the doping concentration of the base of the bottom cell increases from 10^{15}/cm^3 to 10^{18}/cm^3, the reason is the decay of the potential barrier causing the decrease of the depleted zone, therefore there are reducing in the separating field and hence reduction of photogenerated carriers. We can deduce from Figure 12 that doping concentration of the base of the bottom cell must not be more then 10^{15}/cm^3.

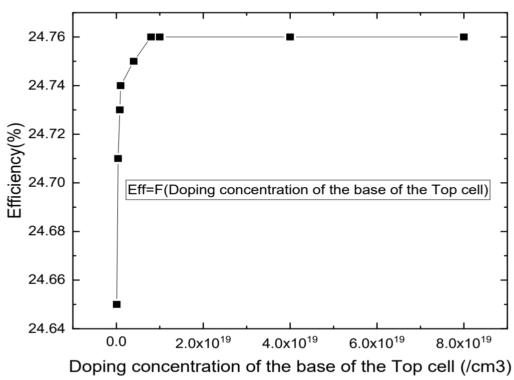

Figure 10. Efficiency versus doping concentration of the base of the top cell

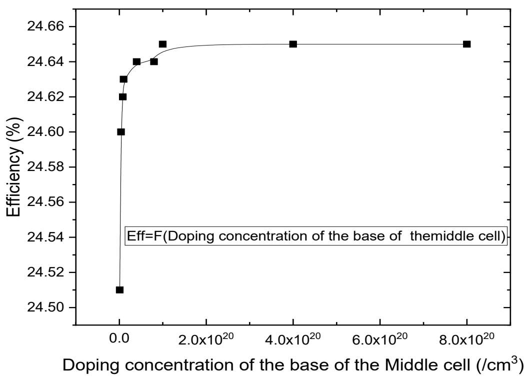

Figure 11. Efficiency versus doping concentration of the base of the middle cell

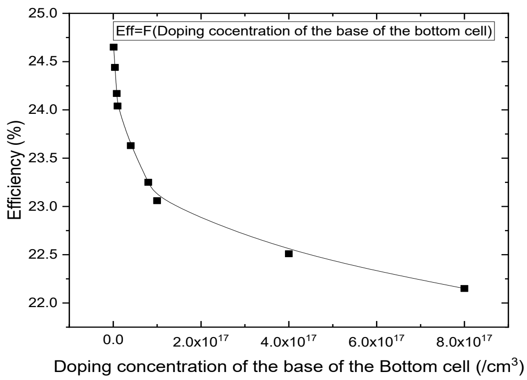

Figure 12. Efficiency versus doping concentration of the base of the bottom cell

3.3. Variation of doping concentration of BSF

From the Figure 13, we extract that increasing the doping level of the BSF of the bottom cell from $10^{17}/cm^3$ to $8\times10^{19}/cm^3$ gives a significant improvement in all the tandem cell characteristics. Recombination in the BSF is very low given its location on the back side of the tandem cell. It has the role of creating a delay field on the rear face. A highly doped BSF reduces recombination at the semiconductor-metal contact.

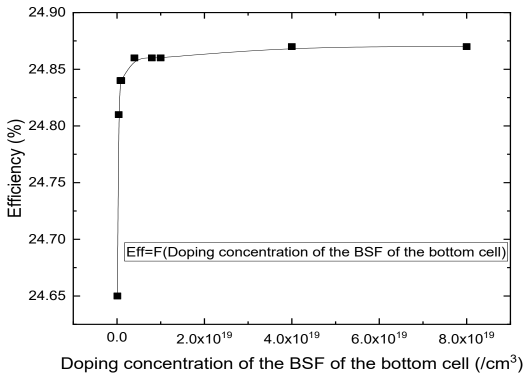

Figure 13. Efficiency according the doping concentration of the BSF of bottom cell

4. CONCLUSION

This work aims to study the influence of doping concentration on the efficiency of the multi-junction (tandem) solar cell made of $In_{0.6}Ga_{0.4}P$/ $In_{0.9}Ga_{0.1}As$/Ge. For the purpose of prevent crystal defects in the tandem cell structure and meet lattice constant matching, we selected Indium concentrations of 60% and 90% for GaInP and GaInAs. Next, we extract the I-V characteristic, the electric field and the potential across the structure simulated and the quantum efficiency. Then, we varied the doping concentration of each photoactive layers (Emitter, Base and the BSF). We arrived at a short-circuit current and voltage open circuit equal to 20.07 mA/cm^2 and 1.37 V respectively, the fill factor equal to 89.46% and electrical efficiency of 24.65%. Our study revealed that achieving higher efficiency for the chosen tandem structure requires the emitter to be heavily doped in both the top and the middle cells, unlike the bottom cell, where the emitter must not exceed a doping concentration of $10^{17}/cm^3$. The base of the top cell and the middle cell must have moderate doping to decrease recombination and enhance increase the lifetime of the charge carriers on the front and back faces, but the base of the bottom cell should have enough doping in relative to the concentration level chosen in the other layers. According to our findings, the doping in this layer should not exceed $10^{15}/cm^3$. Finally, the BSF must be heavily doped to produce a retarding electric field, leading to a decrease in recombination and thus the performance of the tandem cell will be improved.

ACKNOWLEDGEMENTS

The authors thank the Research Unit for Renewable Energy Materials (URMER) of the Republic of Algeria for supporting this work.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Khadidja Djeriouat	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	
Salim Kerai		✓		✓		✓		✓		✓		✓	✓	
Kheireddine Ghaffour	✓	✓		✓		✓		✓		✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] A. Goetzberger, J. Luther, and G. Willeke, "Solar cells: Past, present, future," *Solar Energy Materials and Solar Cells*, vol. 74, no. 1–4, pp. 1–11, Oct. 2002, doi: 10.1016/S0927-0248(02)00042-9.

[2] A. Cabraal, M. Cosgrove-Davies, and L. Schaeffer, "Accelerating sustainable photovoltaic market development," *Progress in Photovoltaics: Research and Applications*, vol. 6, no. 5, pp. 297–306, 1998, doi: 10.1002/(SICI)1099-159X(1998090)6:5<297::AID-PIP226>3.0.CO;2-C.

[3] G. J. Lin, J. Bi, M. Song, J. Liu, W. Xiong, and M. Huang, "III-V multi-junction solar cells," in *Optoelectronics-Advanced Materials and Devices*, p. 1.

[4] E. D. Jackson, "Areas for improvement of the semiconductor solar energy converter," in *Transactions of the Conference on the Use of Solar Energy: The Scientific Basis*, 1955, vol. 5, pp. 122–126.

[5] M. Wolf, "Limitations and possibilities for improvement of photovoltaic solar energy converters: Part I: Considerations for Earth's surface operation," in *Proceedings of the IRE*, 1960, vol. 48, no. 7, pp. 1246–1263, doi: 10.1109/JRPROC.1960.287647.

[6] E. García-Tabarés and I. Rey-Stolle, "Impact of metal-organic vapor phase epitaxy environment on silicon bulk lifetime for III-V-on-Si multijunction solar cells," *Solar Energy Materials and Solar Cells*, vol. 124, pp. 17–23, 2014, doi: 10.1016/j.solmat.2014.01.034.

[7] M. Yamaguchi, T. Takamoto, and K. Araki, "Present and future of super high efficiency multi-junction solar cells," in *Physics and Simulation of Optoelectronic Devices XVI*, 2008, vol. 6889, p. 688906, doi: 10.1117/12.784117.

[8] D. J. Friedman, J. M. Olson, and S. Kurtz, "High-efficiency III-V multijunction solar cells," In *A. Luque and S. Hegedus (Eds.), Handbook of Photovoltaic Science and Engineering: Second Edition*, John Wiley and Sons, 2011.

[9] A. Baiju and M. Yarema, "Status and challenges of multi-junction solar cell technology," *Frontiers in Energy Research*, vol. 10, Sep. 2022, doi: 10.3389/fenrg.2022.971918.

[10] B. Burnett, "The basic physics and design of III-V multijunction solar cells," *National Renewable Energy Laboratory*, Golden, Co. 2002, doi: 10.1063/1.3658334.

[11] S. A. Kozhukhovskaia, E. D. Filimonov, and M. Z. Shvarts, "Experimental model of multi-junction solar cell: IV curve tailoring and photoresponce artifact simulation," *Journal of Physics: Conference Series*, vol. 586, no. 1, p. 12014, 2015, doi: 10.1088/1742-6596/586/1/012014.

[12] A. El karkri, I. El mhamedi, and Z. El malki, "Prediction and simulation of electrical and optical characteristics of an OLED based on P3BEdotBT3A organic material," in *E3S Web of Conferences*, 2022, vol. 336, p. 62, doi: 10.1051/e3sconf/202233600062.

[13] S. Makham, M. Zazoui, and J. C. Bourgoin, "Analysis of multijunction solar cells: Electroluminescence study," *MJ Condensed Matter*, vol. 5, no. 2, pp. 181–185, Jun. 2004.

[14] R. R. King *et al.*, "Bandgap engineering in high-efficiency multijunction concentrator cells," in *International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen*, May 2005.

[15] R. R. King *et al.*, "Metamorphic III-V materials, sublattice disorder, and multijunction solar cell approaches with over 37% efficiency," in *Proceedings of the 19th European Photovoltaic Solar Energy Conference and Exhibition*, Jun. 2004, no. June, pp. 7–11.

[16] R. R. King *et al.*, "Metamorphic GaInP/GaInAs/Ge solar cells," in *Proceedings of the 28th IEEE Photovoltaic Specialists Conference*, 2000, p. 982.

[17] F. Dimroth, U. Schubert, and A. W. Bett, "25.5% efficient Ga0.35In0.65P/Ga0.83In0.17As tandem solar cells grown on GaAs substrates," *IEEE Electron Device Letters*, vol. 21, no. 5, pp. 209–211, 2000, doi: 10.1109/55.841298.

[18] R. R. King *et al.*, "High-efficiency space and terrestrial multijunction solar cells through bandgap control in cell structures," in *Conference Record of the IEEE Photovoltaic Specialists Conference*, 2002, pp. 776–781, doi: 10.1109/pvsc.2002.1190685.

[19] R. R. King *et al.*, "Lattice-matched and metamorphic GaInP/GaInAs/Ge concentrator solar cells," in *Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion*, 2003, vol. A, pp. 622–625.

[20] C. M. Fetzer *et al.*, "High-efficiency metamorphic GaInP/GaInAs/Ge solar cells grown by MOVPE," *Journal of Crystal Growth*, vol. 261, no. 2–3, pp. 341–348, 2004, doi: 10.1016/j.jcrysgro.2003.11.026.

[21] C. M. Fetzer, H. Yoon, R. R. King, D. C. Law, T. D. Isshiki, and N. H. Karam, "1.6/1.1 eV metamorphic GaInP/GaInAs solar cells grown by MOVPE on Ge," *Journal of Crystal Growth*, vol. 276, no. 1–2, pp. 48–56, 2005, doi: 10.1016/j.jcrysgro.2004.11.401.

[22] D. C. Law *et al.*, "Multijunction solar cells with subcell materials highly lattice-mismatched to germanium," in *Conference Record of the IEEE Photovoltaic Specialists Conference*, 2005, pp. 575–578, doi: 10.1109/pvsc.2005.1488196.

[23] G. P. Smestad, *Optoelectronics of solar cells*. Bellingham, WA, USA: SPIE Press, 2009, doi: 10.1117/3.446028.

[24] C. Boudaoud, A. Hamdoune, and Z. Allam, "Simulation and optimization of a tandem solar cell based on InGaN," *Mathematics and Computers in Simulation*, vol. 167, pp. 194–201, Jan. 2020, doi: 10.1016/j.matcom.2018.09.007.

[25] W. J. Aziz and K. Ibrahim, "Simulation model of multi-junction $In_xGa_{1-x}N$ solar cell," *International Journal of Nanoelectronics and Materials*, vol. 3, pp. 43–52, 2010.

[26] N. Guerra, M. Guevara, C. Palacios, and F. Crupi, "Operation and physics of photovoltaic solar cells: an overview," *I+D Tecnológico*, vol. 14, no. 2, pp. 84–95, Dec. 2018, doi: 10.33412/idt.v14.2.2077.
[27] S. Bouslit, "Simulation of CZTS-based thin-film solar cells (Simulation des cellules solaires en couches minces à base de CZTS," Ph.D. dissertation, Department of Physics, University of Mohamed Khider, 2024.
[28] U. E. James, C. C. Dim, M. L. Akinyemi, and I. E. Ogunrinola, "Theoretical study of quantum efficiency and spectral response of solar cells," in *IOP Conference Series: Earth and Environmental Science*, 2024, vol. 1342, no. 1, p. 12043, doi: 10.1088/1755-1315/1342/1/012043.
[29] H. Cotal *et al.*, "III-V multijunction solar cells for concentrating photovoltaics," *Energy and Environmental Science*, vol. 2, no. 2, pp. 174–192, Dec. 2009, doi: 10.1039/b809257e.

BIOGRAPHIES OF AUTHORS

Khadidja Djeriouat was born in Tlemcen, Algeria, in January 1, 1985. She graduated from Tlemcen University in Algeria with a magister degree in microelectronics in 2011. She was a Ph.D. student at the Department of Electronic and Electrical Engineering, Faculty of Technology, University of Tlemcen, Algeria. She is a member of the Research Unit of Materials and Renewable Energies (URMER). Solar cells and III–V semiconductor devices are among her research areas. She can be contacted at email: Djeriouat.kh@gmail.com.

Salim Kerai was born in June 1975 in Maghnia, Algeria. He graduated from Tlemcen University in Algeria with a magister degree in microelectronics in 1999 and a Ph.D. in the same field in 2010. He received his habilitation in electronic engineering in 2016 and he is now an associate professor at Tlemcen University's Department of Biomedical Engineering. His current areas of interest are microelectronic systems and circuits, as well as diagnostic methods based on biosensors. He is a member of Tlemcen University's Materials and Renewable Energy Research Unit. He can be contacted at email: vdpg.factech.univtlemcen@gmail.com.

Kheireddine Ghaffour received his degree in electronics engineering from the Higher School of Electricity (Supelec) in Paris, France, in 1981. From 1985 to 1988, he worked in the field of electrical and optical characterizations of silicon carbide, as part of his magister at the University of Tlemcen in Algeria. His doctoral research work, carried out in alternating training at the Laboratory of Physics of Matter (LPM) of INSA-Lyon, France, focused on the electrical characterization of SiC diodes using the DLTS technique. His current areas of interest in research are semiconductor device physics and device modeling, with a focus on interdigital photovoltaic cells and heterojunction electronic devices. He is a professor at the University Abou Bekr Belkaïd in Tlemcen, Algeria, in the Department of Electronic Engineering at the Faculty of Technology. He is a member of Tlemcen University's Materials and Renewable Energy Research Unit. He can be contacted at email: ghaffourkheireddine@gmail.com.