Research Article

Design and Performance Enhancement of a GaAs-Based Homojunction Solar Cell Using Ga$_{0.5}$In$_{0.5}$P as a Back Surface Field (BSF): A Simulation Approach

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The GaAs semiconductor is a solar energy promising material for photovoltaic applications due to its good optical and electronic properties. In this work, a homojunction GaAs solar cell with Al$_x$Ga$_{1-x}$As and Ga$_y$In$_{1-y}$P solar energy materials as window and back surface field (BSF) layers, respectively, was simulated and investigated using SCAPS-1D software. The performance of the GaAs-based solar cell is evaluated for different proportions of $x$ and $y$, which allowed us to obtain the values of 0.8 and 0.5 for $x$ and $y$, respectively, as the best values for high performance. We then continued the optimization by taking into account some parameters of the solar cell, such as thickness, doping, and bulk defect density of the p-GaAs base, n-GaAs emitter, and Ga$_{0.5}$In$_{0.5}$P BSF layer. Solar cell efficiency increases with emitter thickness, but the recombination phenomenon is more pronounced than that of electron-hole pair generation in the case of a thicker base. The effect of variation in the work function of the back contact has also been studied, and the best performance is for a platinum (Pt) electrode. The optimized GaAs-based solar cell achieves a power conversion efficiency of 35.44% ($I_{SC} = 31.52$ mA/cm$^2$, $V_{OC} = 1.26$ V, FF = 89.14%) and a temperature coefficient of -0.036%/°C. These simulation results provide insight into the various ways to improve the efficiency of GaAs-based solar cells.

1. Introduction

Nowadays, climate change is a real challenge for the society which, paradoxically, continues to increase its energy needs. Due to the limited lifespan of fossil fuels, scientific communities are looking for reliable, cost-effective, and environmentally friendly energy resources [1, 2]. Renewable energy is proving to be an essential asset in solving at least some of these problems. To this end, solar energy can be used as an efficient resource to produce usable electrical energy [3, 4]. Solar energy is the most abundant, clean, nonpolluting, and inexhaustible form of energy found in nature [5, 6], and solar photovoltaic is dominated by silicon solar energy materials.

The GaAs semiconductor is the most widely used solar energy material in photovoltaic cells for space applications [7] because of its high efficiency due to its direct bandgap of 1.42 eV [8], high carrier mobility, absorption coefficient similar to silicon, and low degradation in the face of space irradiation [6, 9]. However, the problems of surface recombination are hindering the development of this technology, which is why the efficiency achieved for the first solar cells was about 10% [10, 11]. These problems were partially solved by growing an Al$_x$Ga$_{1-x}$As layer on the front surface of the device. This layer acts as a window layer [12]. Similarly, as a window layer in the device, the semiconductor materials GaInP [13], ZnSe [14], and AlInP [15] can be used. The back contact of a solar cell is also the site of charge recombination processes. The recently simulated performance of GaAs-based solar cells is 28.8 ± 0.9% [16], which is close to the 27.8% efficiency obtained in the laboratory...
This performance is still below the Shockley-Queisser limit for this type of solar energy material. The improvement of this performance is therefore a focus of the research community and is becoming a central issue in the field of GaAs-based solar cells.

The main objective in GaAs-based solar cells is to reduce the surface recombination phenomena observed both at the top, i.e., the front surface, and at the bottom, i.e., the back contact of the cell. In GaAs-based solar cells, the insertion of a window layer and a back surface field (BSF) layer on the front and back surfaces, respectively, is essential to reduce recombination processes. The presence of an integrated electric field on the back surface, due to the presence of the BSF layer, significantly improves the performance of solar cells [18, 19]. For this purpose, the AlGaAs/GaAs(BSF), ZnS/GaAs(BSF), and Al0.8Ga0.2As/(Al0.7Ga0.3)0.5In0.5P(BSF) window layer/BSF pairs were designed by Abderrezek et al. [18], Najat and Benmoussa [19], and Saif et al. [20], respectively, to reduce the surface recombination phenomena in GaAs-based solar cells. In this work, we will use the AlGa1-xAs window layer and the Ga1In1-xP BSF layer. To the best of our knowledge, a study of the combination of these two layers in GaAs-based solar cells has not yet been done. It is very difficult to experimentally optimize solar cell structures due to their complex implementation, high cost, and manufacturing time. To reduce the time and cost of their implementation, numerical simulations are generally used. Numerical modeling and simulation of GaAs-based solar cell configurations have been proposed [13, 14, 16, 18, 19] to optimize and understand the main physical phenomena involved in these cells. In this work, we optimize the GaAs-based solar cell reported by Kamdem et al. [16], where we incorporate the Ga1In1-xP solar energy material as a BSF layer as mentioned above. Using the SCAPS-1D simulation software [21, 22], we will simulate the simultaneous influence of the x and y proportions on the performance of the GaAs-based solar cell. The output electrical characteristics of the GaAs-based solar cell are also investigated for different thicknesses, doping, and bulk defect densities of the emitter layer, base, and BSF layer.

2. Method and Solar Cell Structure

2.1. Simulation Software. The numerical simulations in this work are performed using the solar cell capacitance simulator in one dimension (SCAPS-1D) software, version 3.3.07, originally designed for CdTe and CIGS polycrystalline thin film solar cells. This one-dimensional solar cell simulation program has been developed at the Department of Electronics and Information Systems (ELIS) of the University of Ghent in Belgium [23]. It was made available to researchers in the photovoltaic community in 1998, after the Second World Photovoltaic Conference in Vienna [24]. SCAPS-1D is organized into several panels where the user defines parameters and where the results are displayed. Operating points such as temperature, thickness, voltage, frequency, and illumination, as well as a list of calculation actions to be performed (I-V, C-V, C-f, Q(λ)), can also be defined by the user [25]. The operating parameters in each calculation (V, f, or λ) are varied within the specified range, while all other parameters have the value specified at the operating point [26]. In order to obtain the performance of the simulated solar cell, SCAPS-1D solves the fundamental semiconductor equations [27]: Poisson’s equation (Equation (1)) and continuity equations for electrons and holes (Equations (2a), (2b)). The transport equations for electrons and holes are given by Equations (3a) and (3b), respectively.

\[
\frac{\partial^2 \varphi(x)}{\partial x^2} = \frac{q}{\varepsilon_s} \left[ N_D^+(x) - N_A^-(x) + P(x) - n(x) + \rho_p - \rho_n \right],
\]

where \( \varphi \), \( q \), \( \varepsilon_s \), \( N_D^+ \), \( N_A^- \), \( \rho_p \), and \( \rho_n \) are, respectively, the electrostatic potential, the electric charge, the permittivity of the semiconductor, the ionized donor density, the ionized acceptor density, the hole distribution, and the electron distribution.

\[
-\frac{1}{q} \frac{dJ_n(x)}{dx} - G(x) + U_R(x) = 0,
\]

\[
\frac{1}{q} \frac{dJ_p(x)}{dx} + G(x) - U_R(x) = 0,
\]

where \( G \) is the optical generation rate (cm^{-3}.s^{-1}) and \( U_R \) is the recombination rate (cm^{-3}.s^{-1}).

\[
J_n = -D_n \frac{dn}{dx} + \mu_n n \left( \frac{d\varphi}{dx} \right),
\]

\[
J_p = -D_p \frac{dp}{dx} - \mu_p p \left( \frac{d\varphi}{dx} \right),
\]

where \( J_n \) and \( J_p \) are the current densities of electrons and holes, respectively.

SCAPS-1D uses the Newton-Raphson approach and the Gummel approach for the numerical solution of these fundamental equations.

2.2. Solar Cell Structure and SCAPS-1D Simulation Parameters. The choice of materials to design the solar cell plays an important role in the photogeneration efficiency. Figure 1 shows the schematic structure of the GaAs-based solar cell proposed in this work, where zinc (Zn) is a front contact and molybdenum (Mo) is a back contact; the AlxGa1-xAs layer acts as a window layer; the p-GaAs active...
layer is between the n-GaAs emitter and the Ga₁₋ₓP back surface field (BSF) layer. The p⁺-GaAs layer is the substrate on which cell growth occurs; it plays the roles of support and protection. Ga₁₋ₓP semiconductor material is a promising candidate for a BSF layer because its electronic properties (gap and electronic affinity) can be modulated by the gallium. Its gap varies between 1.344 eV (InP) and 2.26 eV (GaP) [28]. The parameters used in this simulation are based on values from literature theory [16, 28]. The parameters used in this simulation are based on values from literature theory [16, 28]. The basic solar cell structure studied in this work is that of the common best window layer is susceptible to a wide bandgap material (Al) in the window layer (AlₓGa₁₋ₓAs) and gallium (Ga) in the BSF layer (Ga₁₋ₓP) on the performance of the solar cell. Then, we will proceed to improve its performance by studying the influence of thickness, doping, and bulk defect density on the emitter layer (n-GaAs), base (p-GaAs), and BSF layer (Ga₁₋ₓP). Finally, the influence of the back contact metal work function is studied, and the effect of the operating temperature of the optimized GaAs-based solar cell is presented.

3. Results and Discussion

The basic solar cell structure studied in this work is that from the work of Kamdem et al. [16], in which we introduce a back surface field (BSF) layer as shown in Figure 1. We will first study the effect of the x and y proportions of aluminum (Al) in the window layer (AlₓGa₁₋ₓAs) and gallium (Ga) in the BSF layer (Ga₁₋ₓP) on the performance of the solar cell. Then, we will proceed to improve its performance by studying the influence of thickness, doping, and bulk defect density on the emitter layer (n-GaAs), base (p-GaAs), and BSF layer (Ga₁₋ₓP). Finally, the influence of the back contact metal work function is studied, and the effect of the operating temperature of the optimized GaAs-based solar cell is presented.

3.1. Influence of the Proportions \(x\) and \(y\) on the Solar Cell Electrical Parameters. Changing the electronic properties of a solar energy material affects the device’s performance. A common best window layer is susceptible to a wide bandgap for efficient solar cells. Then, it is important to choose the correct values of \(x\) and \(y\) for compound semiconductors to satisfy the lattice matching between different alloys [31, 32]. The refractive index \((n)\) and extinction coefficient \((k)\) of the compound semiconductor vary with its mole fraction [33]. Table 2 shows the evolution of the bandgap and the electron affinity as a function of the proportions \(x\) and \(y\) of aluminum in the window layer and gallium in the BSF layer, respectively [28, 34]. From these equations, we first

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(\text{Al}<em>x\text{Ga}</em>{1-x}\text{As} [34])</th>
<th>(\text{Ga}_{1-y}\text{P} [28])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap energy (E_g) (eV)</td>
<td>(1.424 + 1.247x) for (x \leq 0.45)</td>
<td>(1.3399 + 0.69y + 0.48y^2)</td>
</tr>
<tr>
<td>Electronic affinity (\chi) (eV)</td>
<td>(4.07 - 1.1x) for (x \leq 0.45)</td>
<td>(4.38 - 0.58y)</td>
</tr>
</tbody>
</table>

Table 2: Electronic properties of \(\text{Al}_x\text{Ga}_{1-x}\text{As}\) and \(\text{Ga}_{1-y}\text{P}\) materials at 300 K.
Figure 2: Variation of the electrical parameters as a function of the x and y proportions: (a) $J_{SC}$, (b) $V_{OC}$, (c) FF, and (d) PCE.

Figure 3: (a) Current-voltage (J-V) characteristics and (b) quantum efficiency of the GaAs-based solar cell without and with Ga$_{0.5}$In$_{0.5}$P BSF layer.
calculated the corresponding values of gap energy and electronic affinity for each x and y pair considered in this work. Then, for each selected pair (x, y), we enter into the SCAPS-1D software, the corresponding values of the gap energy, and the electronic affinity of the Al$_x$Ga$_{1-x}$As window layer and the Ga$_y$In$_{1-y}$P BSF layer. Finally, using the “calculate: single shot” function in the SCAPS-1D action panel, the simulations are performed for each pair (x, y), and each result of the obtained electrical parameters (J$_{SC}$, V$_{OC}$, FF, and PCE) is recorded in a double entry table, from which the contour plots in Figure 2 are made. Figure 2 allows us to determine the (x, y) pair that achieves the optimal performance of the GaAs-based solar cell.

In Figure 2(d), we observe that the power conversion efficiency (PCE) of the solar cell gradually increases with the fraction of x up to its maximum value (x = 0.8) and then decreases, regardless of the fraction of y. Moreover, for x = 0.8, there is a better compromise between AlGaAs and GaAs semiconductors [35]; this is also in agreement with the work of Salem et al. [36]. The short circuit current density J$_{SC}$ (Figure 2(a)) and the fill factor FF (Figure 2(c)) follow the same trend as the solar cell efficiency. This is understandable because there is a proportional relationship between them (Equation (4)). The open circuit voltage V$_{OC}$ (Figure 2(b)), on the other hand, varies very little with the proportions x and y. According to the work of Olson et al. [37], Ga$_{In1-y}$P forms a good interface with the GaAs material for a Ga mole fraction equal to 0.5, and the resistivity of the Ga$_{0.5}$In$_{0.5}$P semiconductor is maximal [34]. We also observe that for this fraction, the electrical parameters (J$_{SC}$, FF, and PCE) in Figure 2 are optimal for x $\leq$ 0.8. Thus, the Al$_{0.8}$Ga$_{0.2}$As and Ga$_{0.5}$In$_{0.5}$P compounds used as window and BSF layers in Figure 1 lead to a better performance of the GaAs-based solar cell. The values x = 0.8 and y = 0.5 are in agreement with the values used by Bourbaba et al. in their work [13].

$$PCE = \frac{J_{SC} \times V_{OC} \times FF}{P_{in}}.$$  \hspace{1cm} (4)

### 3.2. Comparison of a Cell without and with Ga$_{0.5}$In$_{0.5}$P BSF Layer

Using the solar cell structure proposed in Figure 1, the parameters listed in Table 1, and the Ga$_{0.5}$In$_{0.5}$P BSF layer, Figures 3(a) and 3(b) show the J-V characteristics and quantum efficiency (QE(λ)) curves of the GaAs-based solar cell without and with the BSF layer, respectively. As we can see from Figure 3(a), the addition of the Ga$_{0.5}$In$_{0.5}$P BSF layer in the solar cell has a remarkable influence on its performance (Table 3). There is a significant improvement in the short circuit current density (J$_{SC}$) and open circuit

<table>
<thead>
<tr>
<th>Solar cell</th>
<th>J$_{SC}$ (mA/cm$^2$)</th>
<th>V$_{OC}$ (V)</th>
<th>FF (%)</th>
<th>PCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without BSF [16]</td>
<td>30.87</td>
<td>1.035</td>
<td>85.68</td>
<td>27.37</td>
</tr>
<tr>
<td>With Ga$<em>{0.5}$In$</em>{0.5}$P BSF layer</td>
<td>31.09</td>
<td>1.178</td>
<td>88.28</td>
<td>32.19</td>
</tr>
</tbody>
</table>

**Table 3: Comparison of the GaAs-based solar cell electrical parameters without and with Ga$_{0.5}$In$_{0.5}$P BSF layer.**
voltage ($V_{OC}$), as well as the power conversion efficiency (PCE), of the solar cell due to the additional absorption of photons with wavelengths between 700 nm and 900 nm in the case of the solar cell with a BSF layer (Figure 3(b)). These improvements are also reflected in the fact that the presence of the back surface field (BSF) creates a potential barrier on the backside of the solar cell in order to ensure passivation. This potential barrier, induced by the difference in doping level between the GaAs base and the Ga$_{0.5}$In$_{0.5}$P BSF layer, tends to confine the minority carriers in the GaAs base due to the presence of an additional internal electric field in the cell. These minority carriers are thus kept away from the backside where they can be recombined; consequently, they are pushed towards the space charge region for better collection. These observations are in agreement with the literature [38, 39].

Figure 4 shows the evolution of the capacitance-voltage (C-V) characteristic for the GaAs-based solar cell without and with BSF. The diffusion voltage ($V_d$) and the charge carrier density ($N_d$) can be extracted from the C-V measurements according to the Mott-Schottky analysis method (Equation (5)) used in conventional devices containing $p$-$n$ junctions. It is observed that the addition of the BSF layer favors the increase of the C-V curve due to the increase of the charge carrier density ($N_d$) in the space charge region (SCR) of the solar cell, from which a better performance is achieved (Table 3).

$$\frac{1}{C^2} = \frac{2\varepsilon_{s} \varepsilon_{0}}{qN_d}(V_d - V).$$

(5)

3.3. Influence of n-GaAs Emitter Layer on Electrical Parameters

3.3.1. Thickness and Doping of the n-GaAs Layer. In the GaAs-based solar cell, the most important layers are the emitter and the base, since they form the metallurgical interface and play the role of active layers in which the majority of photons with an energy greater than or equal to that of the bandgap of the semiconductor material are absorbed. To obtain interesting performances, it is therefore important
to control the thickness [40] and doping of each layer constituting the solar cell. In this subsection, we will evaluate the variations of the electrical parameters of the GaAs-based solar cell as a function of the thickness and doping of the n-GaAs emitter layer, by varying them from 0.1 μm to 1 μm and from $10^{17}$ cm$^{-3}$ to $10^{20}$ cm$^{-3}$, respectively. Figure 5 shows the results of the numerical simulation.

From Figure 5, we can see that for doping between $10^{17}$ cm$^{-3}$ and $10^{20}$ cm$^{-3}$, the electrical parameters $J_{SC}$ (Figure 5(a)), $V_{OC}$ (Figure 5(b)), and PCE (Figure 5(d)) increase with the thickness of the n-GaAs emitter; this is explained by the fact that as the thickness of the n-GaAs emitter increases, the number of absorbed photons increases and thus a large number of electron-hole pairs are generated. This increase in the generation rate ($G$) of the electron-hole pairs mainly increases the $J_{SC}$ (Equation (6) [41]), which in turn induces the increase in the $V_{OC}$ through Equation (7) [42]. Moreover, increasing the thickness of the n-GaAs emitter reduces the recombination phenomenon ($J_0$) at the level of the front contact of the solar cell.

The fill factor (FF) (Figure 5(c)) varies very little with the doping and remains unchanged with the increasing thickness of the n-GaAs emitter. Except for $J_{SC}$, $V_{OC}$, and PCE also vary with the doping and reach their maximum at $N_{G} = 10^{17}$ cm$^{-3}$. The low values of $V_{OC}$ and PCE at too high doping can be explained by the fact that this process affects the mobility of the free carriers, limiting their collection by the front contact of the solar cell; this is in agreement with the literature since the mobility of the emitter carriers decreases at high doping [43]. The efficiency increases with the n-GaAs emitter thickness and starts to vary very slightly beyond 0.7 μm; it is also maximal for doping of $10^{17}$ cm$^{-3}$. This leads us to choose the values 0.7 μm and $10^{17}$ cm$^{-3}$ as the thickness and doping of the n-GaAs emitter layer, respectively.

$$J_{ph} = J_{SC} = q \cdot G \cdot (L_n + W + L_p),$$  \hspace{1cm} (6)

$$V_{OC} = n \cdot \frac{kT}{q} \cdot \ln \left( \frac{I_{SC}}{I_0} + 1 \right).$$  \hspace{1cm} (7)

### 3.3.2. Density of Defects in the n-GaAs Emitter Layer
Defect densities are also considered limiting factors for solar cell performance. These defects affect the recombination of carriers, their lifetime, and their mobility [44]. In our simulations, we have used Gaussian-type defects, characterized by their concentration $N_{G}$, to evaluate their effects on the electrical parameters of the GaAs-based solar cell. They vary from $10^{12}$ cm$^{-3}$ to $10^{17}$ cm$^{-3}$, and Figure 6 illustrates their effects on $J_{SC}$ (Figure 6(a)), $V_{OC}$ (Figure 6(b)), FF (Figure 6(c)), and Efficiency (PCE) (Figure 6(d)). It can be seen that the performance of the simulated GaAs-based solar cell remains unchanged...
when the defect density is less than $10^{15}$ cm$^{-3}$; and beyond this concentration, the electrical parameters ($J_{SC}$ (Figure 6(a)), $V_{OC}$ (Figure 6(b)), FF (Figure 6(c)), and PCE) (Figure 6(d)) decrease drastically. Increasing the number of defects ($N_G > 10^{15}$ cm$^{-3}$) in the n-GaAs emitter introduces new recombination centers, which increase the recombination of photogenerated carriers in the solar cell, thus causing a decrease in the electrical parameters ($J_{SC}$, $V_{OC}$, FF, and PCE). For our further simulations, we choose the value $N_G = 10^{15}$ cm$^{-3}$ as the defect density in the n-GaAs emitter layer.

3.4. Influence of p-GaAs Active Layer on Electrical Parameters

3.4.1. Thickness and Doping of the p-GaAs Layer. In a solar cell, the photovoltaic conversion usually takes place at the base. Figure 7 shows the variations of the electrical parameters ($J_{SC}$, $V_{OC}$, FF, and PCE) of the GaAs-based solar cell as a function of the thickness and doping of the p-GaAs base, taken in the ranges (1 $\mu$m, 10 $\mu$m) and (10$^{14}$ cm$^{-3}$, 10$^{18}$ cm$^{-3}$), respectively. It is observed that these electrical parameters are affected by varying both the thickness and the doping of the p-GaAs base layer.

We observe that for a doping greater than $10^{16}$ cm$^{-3}$, the open circuit voltage (Figure 7(b)), the fill factor (Figure 7(c)), and the efficiency (Figure 7(d)) increase with doping, regardless of the thickness of the p-GaAs base and reach their maximum for a doping around $10^{18}$ cm$^{-3}$. For a given thickness of the p-GaAs base, however, the short-circuit current density (Figure 7(a)) is independent of doping. We also note that the increase in the p-GaAs layer thickness is accompanied by a progressive decrease in the $V_{OC}$ (Figure 7(b)) on the one hand and, on the other hand, an increase in $J_{SC}$ (Figure 7(a)). These observations are in agreement with those reported by other authors [45–47]. The increase in $J_{SC}$ with thickness is due to the increase in the space charge region (SCR) (Equation (6)) and the fact that more photons are absorbed in the p-GaAs substrate when it is thicker. As in the case of the n-GaAs emitter layer, we observe the generation of a larger number of electron-hole pairs. The decrease of the $V_{OC}$ with the thickness of the p-GaAs base can be caused by the increase of the defect density in this layer, which increases the saturation current $J_0$ and increases the probability of charge carrier recombination [48]. This can be explained by the dependence of $V_{OC}$ on $J_0$ and the photogenerated current ($J_{SC}$) given by Equation (7) [42].
The recombination phenomenon is more pronounced than the electron-hole pair generation in the case of a thicker base. The efficiency is maximal for a thickness of 2 μm and a doping of 10^{18} cm^{-3} of the p-GaAs layer; this leads us to choose these values as the thickness and doping of the p-GaAs active layer, respectively.

3.4.2. Effect of Defect Density in the p-GaAs Base. We use bulk defects whose energy distribution is of the Gaussian type, characterized by the concentration \( N_G \). To evaluate the effect of these defects on the electrical parameters of the GaAs-based solar cell, we vary their concentration between \( 10^{12} \) cm\(^{-3} \) and \( 10^{17} \) cm\(^{-3} \), and Figure 8 shows the results obtained from the numerical simulation. On the one hand, we find that \( V_{OC} \) (Figure 8(b)), FF (Figure 8(c)), and PCE (Figure 8(d)) remain almost unchanged when the bulk defect density of the p-GaAs layer is less than \( 10^{13} \) cm\(^{-3} \); this observation is the same for \( J_{SC} \) (Figure 8(a)) when the bulk defect density is less than \( 10^{13} \) cm\(^{-3} \). On the other hand, \( V_{OC} \), FF, and PCE decrease when the bulk defect density is greater than \( 10^{13} \) cm\(^{-3} \); this observation is the same for \( J_{SC} \) when this density is greater than \( 10^{15} \) cm\(^{-3} \). The increase in the number of volume defects in the base introduces new recombination centers which have the effect of increasing the recombination phenomenon of the photogenerated carriers; this therefore causes a decrease in \( J_{SC} \), \( V_{OC} \), FF, and PCE. For the rest of our simulations, we choose the value of \( 10^{13} \) cm\(^{-3} \) as the optimal value of the bulk defect density in the p-GaAs base.

3.5. Effect of Ga\(_{0.5}\)In\(_{0.5}\)P BSF Layer on Cell Performance

3.5.1. Thickness and Bulk Defect Density of the Ga\(_{0.5}\)In\(_{0.5}\)P Layer. A back surface field (BSF) layer is generally used to reduce the back contact recombination processes and improve the performance of a solar cell [20, 49, 50]. To study the effect of Ga\(_{0.5}\)In\(_{0.5}\)P BSF film on the electrical parameters of the proposed solar cell (Figure 1), we vary its thickness and bulk defect density between \( 0.01 \) μm and \( 0.07 \) μm and \( 10^{14} \) cm\(^{-3} \) and \( 10^{19} \) cm\(^{-3} \), respectively, as shown in Figure 9.

It can be seen that the electrical parameters (\( J_{SC} \), \( V_{OC} \), FF, and PCE) are not affected by the variation of the volume defects in the Ga\(_{0.5}\)In\(_{0.5}\)P BSF layer, regardless of its thickness. On the other hand, for a fixed volume defect density, \( J_{SC} \) (Figure 9(a)), \( V_{OC} \) (Figure 9(b)), and PCE (Figure 9(d)) increase very slightly with the thickness of the Ga\(_{0.5}\)In\(_{0.5}\)P BSF layer due to the fact that long-wavelength photons are absorbed and generate a small amount of electron-hole pairs. Furthermore, the back contact recombination rate decreases.
with the increasing thickness of the Ga$_{0.5}$In$_{0.5}$P BSF layer. These results are in agreement with those performed by Benzetta et al. [51] and Moon et al. [52]. Figure 9(c) shows the evolution of the fill factor, which is opposite to that of the $V_{OC}$; for a fixed value of the bulk defect density, the FF decreases slightly with increasing thickness of the Ga$_{0.5}$In$_{0.5}$P BSF layer; this may be due to the fact that large thicknesses can introduce resistive components that are detrimental to the fill factor [53]. For the remainder of our simulations, we set the thickness of the Ga$_{0.5}$In$_{0.5}$P BSF layer to 0.055 $\mu$m.

### 3.5.2. Effect of the Doping Density of the Ga$_{0.5}$In$_{0.5}$P BSF Layer

In this subsection, we will focus on the effect of Ga$_{0.5}$In$_{0.5}$P BSF layer doping on the electrical parameters of GaAs-based solar cell. To do this, we vary the doping between $10^{16}$ cm$^{-3}$ and $10^{19}$ cm$^{-3}$, and Figure 10 shows the results obtained from the simulation. We observe that the performance of the solar cell is slightly affected by the variation of the doping of the Ga$_{0.5}$In$_{0.5}$P BSF layer. On the one hand, we observe a slight increase in $V_{OC}$ (Figure 10(b)) and efficiency (Figure 10(d)), and on the other hand, we observe a slight decrease in $J_{SC}$ (Figure 10(a)) and FF (Figure 10(c)). The decrease in $J_{SC}$ with the increase in doping may be due to the fact that excessive doping of the Ga$_{0.5}$In$_{0.5}$P BSF layer promotes the recombination process of minority carriers before they reach the SCR. The improvement in $V_{OC}$ and PCE is due to the fact that the potential barrier, induced by the difference in doping level between the p-GaAs base and the Ga$_{0.5}$In$_{0.5}$P layer BSF, tends to confine the minority carriers in the p-GaAs base, thus keeping them away from the backside and pushing them back towards the SCR for better collection. This improves the electron-hole pair generation rate, which increases the power conversion efficiency of the solar cell. The decrease in the fill factor can be attributed to the fact that as the $V_{OC}$ increases, the integrated electric field in the space charge region of the absorber layer decreases [54]. The power conversion efficiency of the solar cell increases slightly and seems to stabilize beyond a doping of $5 \times 10^{18}$ cm$^{-3}$ of the Ga$_{0.5}$In$_{0.5}$P BSF layer.

### 3.6. Influence of the Back Contact

Metal contacts play an essential role in the collection of charge carriers from the absorber layer [55]. To investigate the influence of the back
contact work function on the solar cell performance, different metals (Mo, Ni, Au, and Pt) with work functions ranging from 5 eV to 5.93 eV are used. These metals are taken from the work of Michaelson [56] and Hölzl and Schulte [57]. Figure 11 and Table 4 show, respectively, the performance evolution and the synthesis of the electrical parameters of the GaAs-based solar cell for these different metals. In Figure 11, it is observed that the solar cell performance increases with the work function of the back contact; this is due to the decrease in the Schottky barrier height ($\phi_b$) for the majority of charge carriers (holes) at the p+-GaAs/metal interface. Thus, decreasing the Schottky barrier height ($\phi_b$) reduces the recombination rate at the back contact and improves the device’s performance. The platinum (Pt) electrode exhibits the highest solar cell performance (Table 4) due to its highest work function; these observations are in agreement with the work of other authors, including Thahab et al. [58] in the case of a GaN-based solar cell and Rana et al. [59] in the case of a CZTS-based solar cell.

3.7. Optimized Solar Cell and Comparison of Results. Based on the results obtained in the previous sections, we can determine the GaAs-based solar cell that gives the best performance using the maximum parameters of thickness, doping, and bulk defect density of the different layers studied; these values are summarized in Table 5. Using these values, we compare the J-V characteristics (Figure 12(a)) and the quantum efficiency (Figure 12(b)) of the GaAs-based solar cell without a BSF layer, with a BSF layer, and optimized. From Figure 12(a), we can see that there is a slight and clear improvement in $J_{SC}$ and $V_{OC}$, respectively, of different structures of the GaAs-based solar cell. The improvement in $J_{SC}$ is mainly due to the absorption of more photons at longer wavelengths (700 nm–900 nm (Figure 12(b)), which generates slightly more electron-hole pairs. The improvement in $V_{OC}$ is due to the reduction of the recombination rate at the back contact due to the presence of the Ga$_{0.5}$In$_{0.5}$P BSF layer and the reduction of the Schottky barrier height. Thus, the optimized solar cell achieves a power conversion efficiency of 35.44% ($J_{SC} = 31.52$ mA/cm$^2$, $V_{OC} = 1.26$ V, FF = 89.14%), which is an increase of about 29.5% in efficiency compared to the configuration proposed by Kamdem et al. [16]. In order to compare our results, Table 6 summarizes the values of the electrical parameters of the initial [16] and optimized solar cells, as well as those performed by other authors [16, 18–20, 60]. Figure 13 shows the band structure of the optimized GaAs-based solar cell under AM1.5G illumination. When

\begin{figure}
\centering
1E16 1E17 1E18
\begin{tabular}{c}
Jsc (mA/cm$^2$) \\
31,094 31,093 31,092 31,091 31,090
\end{tabular}
\begin{tabular}{c}
Na (cm$^{-3}$) \\
1E16 1E17 1E18
\end{tabular}
\begin{tabular}{c}
Voc (V) \\
1,1735 1,1730 1,1725 1,1720 1,1715 1,1710 1,1705 1,1700
\end{tabular}
\begin{tabular}{c}
FF (%) \\
88,33 88,32 88,31 88,30 88,29 88,28
\end{tabular}
\begin{tabular}{c}
PCE (%) \\
32,20 32,19 32,18 32,17 32,16 32,15 32,14 32,13
\end{tabular}
\begin{tabular}{c}
Na (cm$^{-3}$) \\
1E16 1E17 1E18 1E19
\end{tabular}
\begin{tabular}{c}
1E16 1E17 1E18 1E19
\end{tabular}
\begin{tabular}{c}
1E16 1E17 1E18 1E19
\end{tabular}
\begin{tabular}{c}
Figure 10: Variation of photovoltaic parameters of the GaAs-based solar cell as a function of doping of the Ga$_{0.5}$In$_{0.5}$P BSF layer: (a) $J_{SC}$, (b) $V_{OC}$, (c) FF, and (d) PCE.
\end{figure}

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the solar cell is illuminated, the conduction and valence bands of the materials constituting the solar cell are well observed, as well as the Fermi level $E_F$, which uniquely determines the probability of occupation of the different levels by an electron [47]. In addition to the levels at the bottom of the conduction band $E_C$ and at the top of the valence band $E_V$, the quasi-Fermi levels $F_n$ for the electrons and $F_p$ for the holes can be observed. These levels are due to the fact that

![Graph of solar cell parameters](image)

**Figure 11**: Variation of the electrical parameters of the GaAs-based solar cell as a function of back contact: (a) $J_{SC}$, (b) $V_{OC}$, (c) FF, and (d) PCE.

**Table 4**: Solar cell output parameters for different back contacts.

<table>
<thead>
<tr>
<th>Rear contact</th>
<th>Electron work function (eV)</th>
<th>$\Phi_b = E_g + \chi - \Phi_M$</th>
<th>$V_{OC}$ (V)</th>
<th>$J_{SC}$ (mA/cm²)</th>
<th>FF (%)</th>
<th>PCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>5.00</td>
<td>0.50</td>
<td>1.727</td>
<td>31.09</td>
<td>88.28</td>
<td>32.18</td>
</tr>
<tr>
<td>Ni</td>
<td>5.35</td>
<td>0.15</td>
<td>1.724</td>
<td>31.09</td>
<td>89.01</td>
<td>32.44</td>
</tr>
<tr>
<td>Au</td>
<td>5.47</td>
<td>0.03</td>
<td>1.724</td>
<td>31.09</td>
<td>89.01</td>
<td>32.45</td>
</tr>
<tr>
<td>Pt</td>
<td>5.93</td>
<td>-0.43</td>
<td>1.129</td>
<td>31.47</td>
<td>89.01</td>
<td>32.86</td>
</tr>
</tbody>
</table>

**Table 5**: Parameters optimized for this simulation.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (μm)</th>
<th>Doping (cm⁻³)</th>
<th>Bulk defect density (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter</td>
<td>0.70</td>
<td>$10^{17}$</td>
<td>$10^{15}$</td>
</tr>
<tr>
<td>Base</td>
<td>2.00</td>
<td>$10^{18}$</td>
<td>$10^{13}$</td>
</tr>
<tr>
<td>Back surface field</td>
<td>0.55</td>
<td>$5 \times 10^{18}$</td>
<td>$10^{16}$</td>
</tr>
</tbody>
</table>
the charge carriers have a thermal energy distribution during almost all of their lifetime as a result of their collisions with the lattice [61].

3.8. Effect of Temperature on the Optimized Solar Cell. Since the solar cell is exposed to different climatic conditions, it is important and even necessary to study the evolution of the solar cell parameters at different operating temperatures. Thus, the performance of the solar cell depends on the temperature [62]. At higher operating temperature, the electron and hole mobility, carrier concentration, bandgap, and density of state are affected [63]. The influence of temperature on the performance parameters of the GaAs-based solar cell is studied for temperatures ranging from 10°C to 90°C. As can be seen in Figure 14, the $V_{OC}$ (Figure 14(b)), FF (Figure 14(c)), and PCE (Figure 14(d)) decrease sharply with the increase in temperature, while the $J_{SC}$ (Figure 14(a)) increases weakly with temperature due to the high recombination process that occurs at high temperatures [64, 65]. Thus, there is a decrease in $V_{OC}$ from 1.2755 V to 1.2050 V, a decrease in FF from 89.70% to 87.00%, the PCE decreases from 36.0418% to 33.0530%, and finally, there is a slight increase in $J_{SC}$ from 31.4987 mA/cm² to 31.5269 mA/cm².
We can also attribute the degradation of the performance of the solar cell to the fact that, at a high temperature, more electrons are released from the valence band to the conduction band; however, the electrons are volatile and move between the valence band and the conduction band. Therefore, in the absence of displacement motion, the recombination process will occur, which will cause the efficiency of the solar cell to decrease [66, 67].

4. Conclusion

In this work, we have simulated the performance of a homojunction GaAs solar cell in the Zn/n⁺-AlₓGa₁₋ₓAs/n-GaAs/p-GaAs/p⁺-GaIn₁₋ₓP/BSF/p⁺-GaAs/Mo configuration using the SCAP-1D software. We first investigated the influence of the proportions of aluminum (Al) and indium (In) in the window (AlₓGa₁₋ₓAs) and back surface field (GaIn₁₋ₓP) layers, respectively, on the solar cell performance. The results show that the Al₀.₈Ga₀.₂As/Ga₀.₅In₀.₅P pair achieves better performance. Beyond these proportions (x = 0.8 and y = 0.5), the performance of the device degrades, mainly due to band offsets at the GaAs/AlGaAs and GaAs/GaInP interfaces (the donors thus spontaneously and irreversibly transfer their electrons into the low bandgap semiconductor). To emphasize the importance of the back surface field (BSF) layer, we compared the electrical parameters of the cell without and with the Ga₀.₃In₀.₇P BSF layer. The presence of the Ga₀.₃In₀.₇P BSF layer causes a significant improvement in the performance of the homojunction GaAs solar cell, with a power conversion efficiency of 32.19%. Subsequently, the performance of the obtained solar cell structure was analyzed as a function of different parameters (thickness, doping, and bulk defect density) of the p-GaAs base, n-GaAs emitter, and Ga₀.₅In₀.₅P BSF layer. The power conversion efficiency of the solar cell increases with the emitter thickness. The recombination phenomenon is more pronounced than the electron-hole pair generation in the case of a thinner base. An increased presence of bulk defect density (above 10¹⁵ cm⁻³) in the absorber introduces new recombination centers that reduce the solar cell performance. A thin Ga₀.₅In₀.₅P BSF layer reduces the carrier recombination rate at the back contact. The optimal values of 0.7 μm, 2 μm, and 0.55 μm in thickness; 10¹⁷ cm⁻³, 10¹⁸ cm⁻³, and 5 x 10¹⁸ cm⁻³ in doping; and 10¹⁵ cm⁻³, 10¹³ cm⁻³, and 10¹⁶ cm⁻³ in bulk defect density were obtained for the n-GaAs emitter, p-GaAs base, and Ga₀.₃In₀.₇P BSF layer, respectively. The type of back contact material of the solar cell was also investigated in this work. It is found that increasing the back contact work function improves the performance of the solar cell due to the reduction of the Schottky barrier height and the recombination rate.

Figure 14: Effect of operating temperature on the electrical parameters of the GaAs-based solar cell: (a) J_sc, (b) V_oc, (c) FF, and (d) PCE.
at the back contact. The maximum efficiency is achieved with a platinum (Pt) electrode. Finally, the optimized GaAs-based solar cell in the Zn/n'-Al0.8Ga0.2As/n-GaAs/p-GaAs/p+'-Ga0.5In0.5P(BSF)/p'-GaAs/Pt configuration allowed us to obtain a short-circuit current density of 31.52 mA/cm², an open-circuit voltage of 1.26 V, and a power conversion efficiency of 35.44%. The effect of varying the operating temperature of the optimized GaAs-based solar cell allowed us to obtain a temperature coefficient of -0.036%/°C.

Data Availability

The simulation data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Authors’ Contributions

C. Fotcha Kamdem provided substantial contributions to the conceptualization, methodology, software, writing the original draft, validation, and project administration. A. Teyou Ngoupo contributed to the conceptualization, methodology, software, writing the original draft, and validation. F. X. Abomo Abega and A. M. Ntouga Abena were assigned to the conceptualization, methodology, and software. J.-M. B. Ndjaka was responsible for the methodology, supervision, and validation.

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