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STUDY OF THE PHYSICAL PARAMETERS ON THE GaAs SOLAR CELL EFFICIENCY

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The physical parameters of GaAs solar cell have an importance on the determination of energy conversion efficiency and the optimization of electricity production. In this work, we proceed analytically to optimize the performance of GaAs solar cell with internal and external physical parameters. These latter are Junction temperature, lifetime and surface recombination velocity of carriers. An analytical model is used to solve both the minority carriers continuity and Poison's equations to find the delivered current densities. Results show that the values of the obtained J-V characteristics by the analytical model are in good agreement with the experimental data. The difference between the two results does not exceed 6.8%. On the other side, the performance lifetime of the solar cell is improved with the high value of electrons and holes minority carriers with values $\tau_n = 2 \times 10^{-9}$s and $\tau_p = 2 \times 10^{-8}$s. Additionally, the low cell temperature and the decrease of surface recombination velocity at the front and back layers improve the solar cell efficiency. The optimal values of minority carrier surface recombination velocity are $S_n = S_p = 10^2$ cm/s and the best performing cell gives a conversion efficiency of 34.58%. .

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Keywords: Conversion efficiency, Minority carrier lifetime, Solar cell parameters, Surface recombination velocity, GaAs junction.

1. Introduction

In recent years, the performance of solar cells keeps an important place in the production of electrical energy. Improving the conversion efficiency of a photovoltaic cell (PV) is a main objective of research and helps manufacturing PV technologies cost-competitive with more traditional sources of energy. The recent research was directed towards the use of the GaAs solar cell compared to the silicon solar cell because the former contains some very interesting properties such as lower temperature coefficient and higher electron mobility [1]. The solar cell based on Gallium Arsenide GaAs is applied in space satellites and takes a place in scientific studies. The obtained energy conversion efficiency of GaAs in laboratories is 24.1% in 2011 [2], 28.2% in 2012 [3] and currently reaches 29.1% in 2016 [4]. The researchers have tried to improve the performance of these cells by studying their physical parameters. In addition, the experience shows that the functioning of the solar cells depend on several parameters of materials forming these cells (doping, lifetime, diffusion length,..) [5]. The studied parameters are internals and external such as surface recombination velocity, doping level, minority carrier lifetime, irradiation and temperature [6, 7]. The influence of these parameters on the cell efficiency can be determined via analyzing its J-V characteristic. To validate the developed approach, found results are compared with cell measurements made at Molecular Beam Epitaxy (MBE) material [8]. Details about the main parameters of the semiconductors used in our simulation are summarized in Melloch et al [8].

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A numerical simulation study was carried out on the analytical solution of the Poisson and the continuity minority carriers equations to determine the current density in different regions of the p-n GaAs junction with a great accuracy [9]. The utility of this model is to obtain the distribution of the current density according to the sunlight parameters such as the wavelength. In addition, it allows to vary the physical parameters of the semiconductor material such as the minority carrier lifetime, the temperature and finally the surface velocity recombination.

In this paper, we have simulated the generated photocurrent density J_i, in each region of GaAs p-n junction solar cell, as function of wavelength. We have calculated both the photocurrent and open circuit voltage, and show how the cell conversion efficiency can be improved by changing the physical parameters involved in this computation.

2. Solar cell structure

The photovoltaic (PV) cell consists of a p^+- type layer of high doping concentration, and a n- type layer separated by a space charge area; where the thickness of the emitter and base are x_p and x_n respectively. The cell structure can be represented in figure 1 and its parameters are presented in table.1.

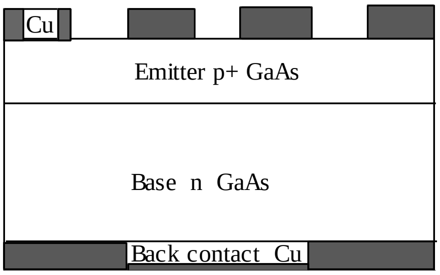

Fig. 1. Schematic of a p-n GaAs solar cell structure.

Table. 1. Physical parameters of the p-n GaAs solar cell used for numerical calculation.

Parameters	Emitter	Base
Thickness (µm)	0.5	3
Acceptor doping density N_a (cm^{-3})	4×10^{18}	-
Donor doping density N_d(cm^{-3})	-	2×10^{17}
Hole recombination velocity S_p($cm.s^{-1}$)	10^{16}	-
Electron recombination velocity S_n($cm.s^{-1}$)	-	10^{16}
Hole diffusion coefficient D_p($cm^2.s^{-1}$)	200	-
Electron diffusion coefficient D_n($cm^2.s^{-1}$)	-	7.78
Hole lifetime τ_p(s)	2.29×10^{-8}	-
Electron lifetime τ_n(s)	-	5×10^{-9}

When the solar cell is exposed directly to light, the absorbed photon having an energy greater than the energy gap Eg of the semiconductor creates electrons-hole pairs. These pairs generate a photocurrent due to the electric field at the p-n junction.

For incident light of wavelength λ, we use the model of solar spectral described by a black body curve, corresponding to a temperature of T =5760K. Hence, the incident flux on the cell surface under the condition $AM_{1.5}$ can be written as [10].

$$F(\lambda) = 3.5 \times 10^{21}\lambda^{-4}(\exp\left(\frac{hc}{k_B T\lambda}\right) - 1)^{-1} \quad (\frac{photon}{cm^2.s.\mu m}) \tag{1}$$

Where h is the planck’s constant, c is the velocity of light, $\mathbf{k_B}$ is the Boltzmann’s constant.

3. Modelling of electrical parameters cell

3.1. Photocurrent density formula

The generated photocurrent density J_{ph} by the incident photons at different wavelengths λ is the sum of the three components. The first is the drift current of the electrons in the p type region J_n. The second is the drift current of holes in the n type region J_p. In the space charge zone, the holes are being accelerated towards the zone P while the electrons are directed to the zone N, create the photogeneration J_g in this region. The photocurrent density can be expressed as follows:

$$J_{ph}(\lambda) = J_n(\lambda) + J_g(\lambda) + J_p(\lambda) \tag{2}$$

In p-type region, the photocurrent density of the minority electrons at $\mathbf{x = x_p}$ for each wavelength λ is given by [9, 10]:

$$J_n(\lambda) = qD_n \frac{d\Delta n}{dx}\bigg|_{x_p} = \frac{qF(\lambda)\big(1 - R(\lambda)\big)\alpha(\lambda)L_n \exp\big(-\alpha(\lambda)x_p\big)}{\alpha(\lambda)^2 L_n^2 - 1}$$
$$\times \left[\alpha(\lambda)L_n - \frac{\frac{S_n L_n}{D_n}\cosh\left(\frac{x_p}{L_n}\right) + \sinh\left(\frac{x_p}{L_n}\right) - \left(\frac{S_n L_n}{D_n} - \alpha(\lambda)L_n\right)\exp\big(-\alpha(\lambda)x_p\big)}{\frac{S_n L_n}{D_n}\sinh\left(\frac{x_p}{L_n}\right) + \cosh\left(\frac{x_p}{L_n}\right)}\right] \tag{3}$$

In n-type region, the photocurrent density from the base due to holes $\mathbf{J_p}$ collected at the edge of junction $\mathbf{x = x_p + w}$, is given by:

$$J_p(\lambda) = -qD_p \frac{d\Delta p}{dx}\bigg|_{x_p+w} = \frac{qF(\lambda)(1 - R(\lambda))\alpha(\lambda)L_P \exp\Big(-\alpha(\lambda)\big(x_p + w\big)\Big)}{\alpha(\lambda)^2 L_P^2 - 1}$$
$$\times \left[\alpha(\lambda)L_P - \frac{\frac{S_p L_P}{D_p}\cosh\left(\frac{x_n}{L_p}\right) + \sinh\left(\frac{x_n}{L_p}\right) - \exp(-\alpha(\lambda)x_n) + \alpha(\lambda)L_P\exp(-\alpha(\lambda)x_n)}{\frac{S_p L_P}{D_p}\sinh\left(\frac{x_n}{L_p}\right) + \cosh\left(\frac{x_n}{L_p}\right)}\right] \tag{4}$$

In the depletion region, the photocurrent density results by the collection of every photocarrier generated in this layer can be determined by the following formula:

$$J_{SRC} = -q\int_{x_p}^{x_p+w} G(x)dx = qF(\lambda)\big(1 - R(\lambda)\big)\exp\big(-\alpha(\lambda)x_p\big)\,(1 - \exp(-\alpha(\lambda)w)). \tag{5}$$

Where q is the electric charge, L_n and L_p are the electrons and holes diffusion length respectively. S_n and S_p are the surface recombination velocity of electrons and holes respectively and D_n , D_p are the electrons and holes diffusion coefficients respectively. R(λ) is the reflection coefficient, $\alpha(\lambda)$ is the absorption coefficient and F(λ) is the incident photon flux.

The total photocurrent density of the cell is the result of integration on all solar spectrum:

$$J_{ph} = -q\int_{\lambda_{min}}^{\lambda_{max}} J_{ph}(\lambda)d\lambda \tag{6}$$

The output current J(V) that flows through the photovoltaic device when a bias voltage (V) is applied can be described using single exponential model as [11]:

$$J(V) = J_{ph} - J_s\left(\exp\left(\frac{V}{V_{th}}\right) - 1\right) \tag{7}$$

Where J_{ph} is the current density generated by the absorbed light and the V_{th} is the thermal voltage given by:

$$V_{th} = \frac{K_B T}{q} \tag{8}$$

With K_B the Boltzmann's constant and T is the cell temperature.
J_s is the saturation current of the p-n junction which is shown by the following expression:

$$J_s = q\left(\frac{P_{n_0} D_p}{L_p} + \frac{n_{p_0} D_n}{L_n}\right) \tag{9}$$

n_{p_0}, P_{n_0} are the concentration of the minority carriers (electrons and holes) at the equilibrium in the (p) and (n) regions respectively. The minority carrier diffusion coefficients can be estimated as [12]:

$$D_n = 200\,\mathrm{cm}^2/\mathrm{s} \tag{10}$$

$$D_p \approx V_T/(2.5 \times 10^{-3} + 4 \times 10^{-21} N_D) \tag{11}$$

The minority carrier lifetime in GaAs junction is given by the following empirical formula [12]:

$$\tau_n = 0.1\ \mu\mathrm{s} \quad \text{for } N_A \le 10^{16}\mathrm{cm}^{-3}, \tag{12}$$

$$\tau_n = \frac{0.1}{[(N_A - 10^{16})/10^{16}]^{0.5}}\ \mu\mathrm{s} \quad \text{otherwise}, \tag{13}$$

$$\tau_p = 0.1\ \mu\mathrm{s} \quad \text{for } N_D \le 10^{16}\mathrm{cm}^{-3}, \tag{14}$$

$$\tau_p = \frac{0.1}{[(N_D - 10^{16})/10^{16}]^{0.5}}\ \mu\mathrm{s} \quad \text{otherwise} \tag{15}$$

3.2. Open circuit voltage equation

The open-circuit voltage V_{oc} can be calculated from the equation as shown below [13]:

$$V_{oc} = \frac{K_B T}{q} \ln\left(\frac{J_{sc}}{J_s}\right) \tag{16}$$

Where J_{sc} is the short circuit current density assumed equals to the photocurrent density under illumination:

$$J_{sc} \approx J_{ph} \tag{17}$$

Concerning the expression of the saturation current $J_S(\mathrm{mA/cm^2})$ is given by [14]:

$$J_s = 2 \times 10^{10}\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right) T^3 \exp(-E_g/K_B T) \tag{18}$$

The band gap energy E_g depends on the intrinsic carrier concentration (n_i), which is written in the following form [15]:

$$n_i = 3.62 \times 10^{14} T^{3/2} \exp(-E_g/2K_B T) \tag{19}$$

3.3. Conversion efficiency

The cell conversion efficiency is the ratio of maximum output power P_m to the incident solar power P_i which equals $90.6\mathrm{mW/cm^2}$ at $AM_{1.5}$:

$$\eta = P_m/P_i \tag{20}$$

The maximum output power P_m (W/cm^2) of a solar cell can be determined numerically from the the maximum current J_m and maximum voltage : V_m :

$$P_m = J_m V_m \tag{21}$$

4. Results and discussion

We present in this section, the numerical simulation results concerning the effect of the following: the temperature, the minority carriers lifetime and the surface velocity recombination on the output parameters of the GaAs solar cell. These last parameters are: the open circuit voltage V_{oc}, the short circuit density current J_{sc} and the conversion efficiency η.

4.1. Simulation of photocurrent densities

Figure 2 shows the variation of current density as function as the wavelength; the J_{ph} curve is the sum of the three other partial which are the photocurrent densities J_p , J_n and J_g of the layers p-GaAs, n-GaAs and space charge regions respectively. It illustrates that current densities depend on the wavelength λ under the same conditions and it shown that the maximum value of the photocurrent J_{ph} is located at λ=0.6μm. Additionally, the regions responsible for the production of current are the emitter layer with a great percentage and in second place is the depletion region.

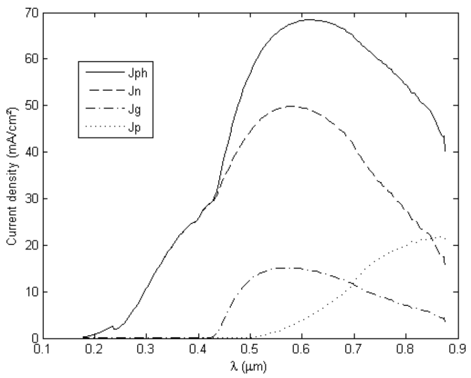

Fig. 2. Variation of current density versus wavelength λ.

4.2. Determination and comparison of J-V characteristics

Figure 3 shows the experimental and the simulated J-V characteristics of the GaAs solar cell. As it is seen in this figure, the analytical curve is in agreement with that obtained by Melloch et al [8]. However, there is a difference between the two curves which can approximated around 6.8%. This difference is due to the electrical equivalent model of solar cell adopted in this calculation using ideal exponential model. In fact, the latter ignores the intrinsic parameters namely series resistance, parallel resistance and ideality factor; which have an effect on the cell performance [16]. The output electrical parameters extracted from the J-V characteristics are listed in Table 2. Values of parameters are $J_{sc} = 29.18mA/cm^2$, $V_{oc} = 1.01V$ and a conversion efficiency cell with 28.7% which are close to each other on the level of the experimental data shown in Table 2.

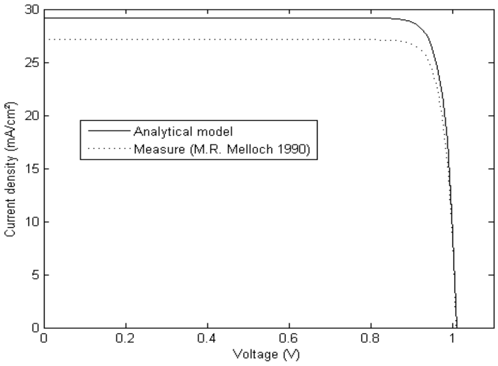

Fig. 3. The J-V characteristics of a p-n GaAs solar cell obtained by the analytical model (continuous curve) and experimental values (dashed curve).

Table. 2. Comparison between the analytical model result and the experimental reference [8].

	Simulation results	Experimental results[8]
J_{sc} $(\mathbf{mA/cm^2})$	29.18	27.12
V_{oc} $(\mathbf{V})$	1.01	1.05
η (%)	28.7	24.0

4.3. Temperature effect

In figures (4) and (5), it can be noted that the open circuit voltage and the conversion efficiency decrease when the temperature increases. As far as the short circuit current density is concerned, it normally shows a little change. In this study, we'll consider it constant. This result is caused by the decrease of the band gap energy (E_g) of a semiconductor as the temperature increases. Similarly, the short-circuit current density marginally increases, and the open-circuit voltage and energy conversion efficiency decrease when the temperature increases. This phenomena is described by the empirical expression outlined by Varshni [17]:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta} \tag{22}$$

Where $E_g(0) = 1.52\text{eV}$, $\alpha = 5.4 \times 10^{-4}$, $\beta = 204$, for GaAs.

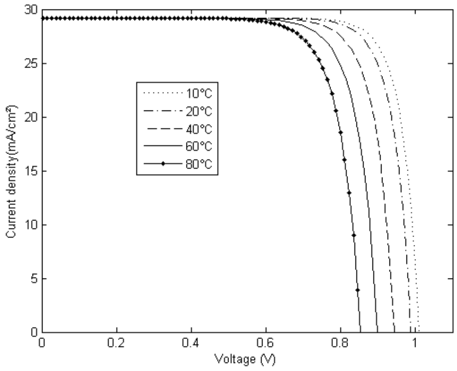

Fig. 4. Influence of temperature on the J-V characteristics of GaAs solar cell.

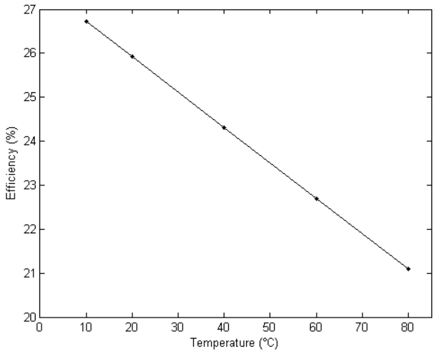

Fig. 5. Effect of temperature on GaAs solar cell efficiency.

4.4. Minority carrier lifetimes effect

Figure 6 shows the influence of the minority electrons lifetime τ_n keeping minority holes lifetime τ_p constant that of holes and (vice versa). We can note that when τ_n increases, the current short circuit J_{sc} , and the open circuit voltage V_{oc} increase as well. Similarly, in Figure 7, there is also an increase in cell's output power when the minority carrier's lifetime increases. The obtained optimal values are $\tau_n = 5 \times 10^{-9}$s, $\tau_p = 2 \times 10^{-8}$s which are product a $J_{sc} = 32.66\ \mathrm{mA/cm^2}$, $V_{oc} = 1.03\ \mathrm{V}$ and an corresponding efficiency $\eta = 28.77\%$. This increase of the current short circuit J_{sc} is due to the increase of the diffusion length $(L_n = \sqrt{D_n \tau_n})$ [18]. Thus, the minority electrons in p-region will have enough time to reach the n-region where they can become the majority carriers and then they efficiently participate in the production of photocurrent. On what concerns the effect of the minority carrier's lifetime on the open circuit voltage, it can be analytically explained by the following equation [19]:

$$V_{oc} = \frac{KT}{q}\left(\frac{\Delta n(N_a + \Delta p)}{n_i^2} + 1\right) \tag{23}$$

Where, Δn and Δp are both the excess electron and excess hole concentrations respectively. Whereas, the rate r_n at which the electron disappears or recombines in p-type material, is given by:

$$r_n = \frac{\Delta n}{\tau_n} \tag{24}$$

Based on the preceding equations (23) and (24), we conclude that the output voltage is proportional to the minority electrons lifetime.

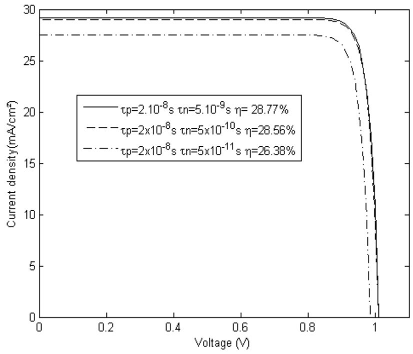

Fig. 6. Effect of the minority electrons lifetime on the solar cell J-V characteristics

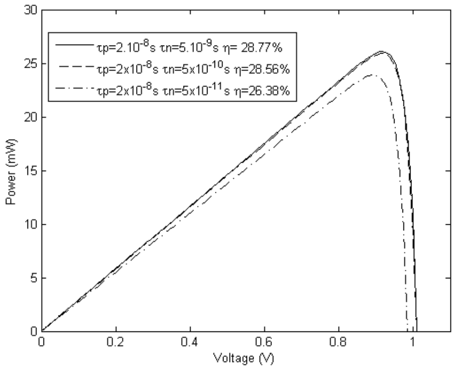

Fig. 7. Calculated P-V characteristics as a parameter of electrons lifetime with same holes lifetime.

4.5. Surface recombination velocity effect

The recombination carriers depend primarily on the steps of cell material manufacturing like the surfaces and the bulk recombinations. Indeed, the solar cell surface is a site of particularly high recombination due to a severe disruption of the crystal lattice. Besides, the recombination phenomenon is modelled by surface recombination velocity, which have a crucial impact on both open circuit voltage and short circuit current density [20].

In the preceding paragraphs, we've obtained optimal values of the minority carriers lifetime whose values are equal to $\tau_n = 5 \times 10^{-9}s$, $\tau_p = 2 \times 10^{-8}s$. These latter are going to be used in the following simulation of the effect of the minority electrons surface recombination velocity S_n, keeping the minority hole surface recombination velocity S_p constant. The result of this calculation is described in figure 8. We can see that when the minority electrons surface recombination velocity is decreased, the open circuit voltage V_{oc}, the short circuit current density J_{sc} and the energy conversion efficiency are increased. The obtained optimal values are $S_n = 10^2 cm/s$, $J_{sc} = 32.66\ mA/cm^2$ and $V_{oc} = 1.03\ V$ which give a conversion efficiency of $\eta = 33.06\%$. The influence of minority holes surface recombination velocity on the J-V characteristics is represented in figure 9; it is shown that it has the same effect on the conversion efficiency as the minority electrons surface recombination velocity. The optimal value is $S_p = 10^2 cm/s$ which gives a conversion efficiency value of $\eta = 29.99\%$.

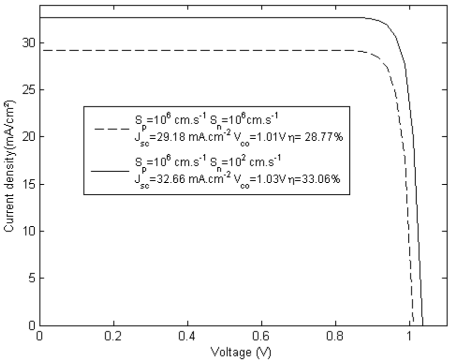

Fig. 8. Influence of the electrons velocity recombination surface on the J-V characteristics with same hole velocity recombination surface.

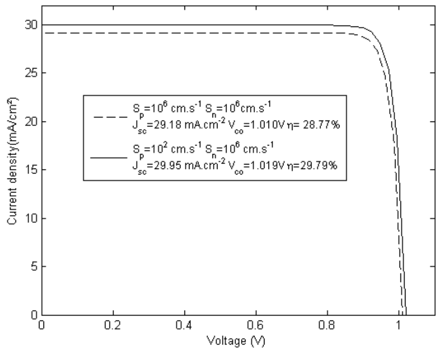

Fig. 9. J-V characteristics of p-n GaAs solar cell for different hole velocity recombination surface.

To conclude, the best cell's conversion efficiency can be found using the pre-found optimal values of the physical parameters at a low temperature. The obtained values of these parameters are listed in the table 3, so their final values can be deduced as follows:
$\mathrm{J_{sc}} = 32.66\ \mathrm{mA/cm^2}$, $\mathrm{V_{oc}} = 1.03\ \mathrm{V}$ and $\eta = 34.58\%$.

Table 3: Calculated optimization physical parameters of p-n GaAs.

$\mathrm{p-n}$ GaAs	$\tau_\mathrm{n}(\mathrm{s})$	$\tau_\mathrm{p}(\mathrm{s})$	$\mathrm{S_n(cm/s)}$	$\mathrm{S_p(cm/s)}$
Optimal Physical parameters	5×10^{-9}	2×10^{-8}	10^2	10^2

In practice, the reduction of the minority carriers surface recombination velocity is realized by the effective passivation of both the front and the back of the cell. This protection is carried out through the addition of two layers to the cell, one to the front and is called "window", and the other one to the back and is called "Back Surface Field". The study of this the cell passivation will be the aim in our next coming research work.

5. Conclusion

The numerical simulation of the current-voltage (JV) characteristics of p-n GaAs solar cell has been studied and performed using the analytical model. The comparison between simulation and experimental shows a good agreement between the two. In fact, the current relative error of this difference does not exceed 6.8%. The found results show that the temperature has a significant effect on the open circuit voltage which will decrease; however, the photocurrent remains constant with increasing the temperature. Concerning the impact of surface recombination velocity shows an increase of cell efficiency with reducing the values of this parameter. Their optimal values of electrons and holes minority are equal $\mathrm{S_n} = 10^2\mathrm{cm/s}$ in the emitter layer and $\mathrm{S_p} = 10^2\mathrm{cm/s}$ in the base region respectively. Also, the results show a significant effect of the minority carriers lifetime on the performance of GaAs solar cell. We can conclude that when the minority carriers lifetime became short, its energy conversion efficiency increases. Additionally, the values of the minority electrons and holes lifetime are $\tau_\mathrm{n} = 0.005\ \mu\mathrm{s}$ and $\tau_\mathrm{p} = 0.02\ \mu\mathrm{s}$ respectively which produced an optimal cell efficiency of $\eta = 34.58\%$. The obtained results of this research paper contribute; first, to the reducing of the manufacturing costs by increasing the minority carrier lifetime in fabrication process steps and, second, make us profit from the GaAs solar cells in low-temperature environment.

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