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Influence of temperature on silicon solar cell shunt resistance under monochromatic illumination

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Abstract The shunt resistance of the solar cell is an important parameter which can be obtained from the Photocurrent - Photovoltage characteristic knowing the recombination velocity of the minority charge carriers at the junction initiating the short circuit. This study was carried out in the presence of the temperature and the solar cell is subjected under monochromatic illumination in static regime. Thus, for a given wave length, the study of the impact of the temperature on the shunt resistance is presented, which will make it possible to obtain values of the shunt resistance for given temperatures. From the equation of continuity, the minority carrier's density is determined. The expression of this minority carrier's density makes it possible to obtain the photocurrent, the photovoltage and the Photocurrent - Photovoltage characteristic. From this Photocurrent - Photovoltage characteristic and of the recombination velocity of the minority charge carriers at the junction initiating the short circuit, the shunt resistance is determined and then studied for different values of the temperature.

Keywords Silicon Solar Cell, wave length, shunt resistance, temperature, recombination velocity

Introduction

The shunt resistance is due to manufacturing defects and also to the light design of solar cells. It corresponds to an alternating current path for the photocurrent density [1-3]. It can be studied: in static regime [4] or in dynamic regime [5-7]. Thus, studies have been carried out in order to determine the shunt resistance of the solar cell. Numerous methods have been used for the determination of the shunt resistance. Among these methods, we have the simple models and double exponential [8], the numerical method [9-10], the method of the characteristic (I-V) using the grain size (g) and the recombination velocity to grain boundaries [4]. Our work will consist in determining the shunt resistance from Photocurrent - Phototension characteristic knowing the recombination velocity of the minority charge carriers at the junction initiating the short circuit. The application of temperature will allow study its influence on the recombination velocity of the minority charge carriers at the junction initiating the short circuit and thus on the series resistance. Thus, the minority charge carriers density is determined from the continuity equation, which allows us to access the photocurrent and the photovoltage. From the photocurrent - photovoltage characteristic and the determination of the recombination speed of the minority charge carriers at the junction initiating the short circuit the shunt resistance is studied as a function of the temperature.

Etude Theorique

In this study we consider a type of solar cell n^+-p-p^+[11] under polychromatic illumination. The structure of this solar cell is shown in Figure 1:

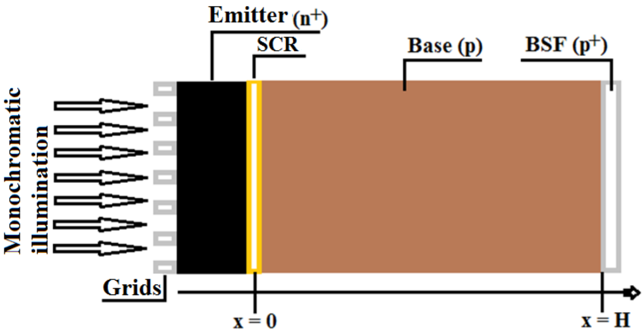

Figure 1: Photopile au silicium de type n^+pp^+

When the solar cell is illuminated by polychromatic light various phenomena such as the creation of electron-hole pairs, the diffusion of the minority charge carriers in the base as well as the recombination can occur. The whole of these phenomena is governed by an equation called: continuity equation which is relative to the density of excess minority carriers in the base. It is represented by Equation 1:

$$\frac{\partial\delta(x)}{\partial x^2}-\frac{\delta(x)}{L(T)^2}=-\frac{G(x)}{D(T)} \qquad (1)$$

In this equation, D (T) represents the diffusion coefficient which is a function of temperature according to equation (2):

$$D(T)=\mu(T)\frac{k_b}{q}T \qquad (2)$$

$\mu(T)$ characterizes the mobility of electrons **[**12,13**]** and is a function of temperature, its expression is given by:

$$\mu(T)=1{,}43.10^9T^{-2{,}42}cm^2V^{-1}s^{-1} \qquad (3)$$

k_b is the Boltzmann constant, q the elementary charge of the electron and T the temperature.

L(T) represents the diffusion length which depends on the diffusion coefficient according to the relationship:

$$\left(L(T)\right)^2=\tau D(T) \qquad (4)$$

τ is the lifetime of the minority charge carriers photogenerated in the base

G(x) represents the rate of generation of the minority load carriers which depends on the depth in the base according to relation**:**

$$g(x)=\phi(\lambda)\alpha(\lambda)\left(1-R(\lambda)\right)e^{(-\alpha(\lambda)x)} \qquad (5)$$

ϕ(λ) characterizes the monochromatic incident flux of light, α(λ) is the monochromatic absorption coefficient of the material at wavelength λ and R(λ) the monochromatic reflection coefficient of the material at the wavelength λ.

δ(x,λ,T) represents the minority carriers density of charge. It is determined from the resolution of equation 1 and has given:

$$\delta(x,\lambda,T)=A\cosh\left(\frac{x}{L(T)}\right)+B\sinh\left(\frac{x}{L(T)}\right)-\frac{\phi(\lambda)\alpha(\lambda)\left(L(T)\right)^2\left(1-R(\lambda)\right)e^{(-\alpha(\lambda)x)}}{D(T)\left[\left(L(T)\right)^2\left(\alpha(\lambda)\right)^2-1\right]} \qquad (6)$$

The expressions of A and B are determined from the boundary conditions [14,15]:

- at the junction $(x=0)$

$$\left.\frac{\partial\delta(x,\lambda,T)}{\partial x}\right|_{x=0}=\frac{S_f}{D(T)}\delta(x,\lambda,T)\Big|_{x=0} \qquad (7)$$

- at the back surface $(x=H)$:

$$\left.\frac{\partial\delta(x,\lambda,T)}{\partial x}\right|_{x=H}=-\frac{S_b}{D(T)}\delta(x,\lambda,T)\Big|_{x=H} \qquad (8)$$

S_f represents the recombination velocity of the minority charge carriers at the junction. It characterizes the operating point of the solar cell but also the minority carrier flux at the junction [14,15]. Sb is the recombination velocity of the minority charge carriers at the back surface [15]. The expression of the density of the minority carriers makes it possible to access the photocurrent and the photovoltage according to the equations:

$$J_{ph}(S_f,T)=qD(T)\left.\frac{\partial\delta(S_f,T)}{\partial x}\right|_{x=0} \qquad (9)$$

$$V_{ph}(S_f,T)=V_T\ln\left[\frac{N_b}{\left(n_i^2(T)\right)}\delta(0,S_f,T)+1\right] \qquad (10)$$

Jph represents the photocurrent density, Vph the photovoltage and N_b the doping rate.
$n_i(T)$ is the intrinsic density of the minority carriers, its depends on the temperature according to the relation [16] :

$$n_i=C.T^{\frac{3}{2}}\exp\left(-\frac{E_g}{2.k_b.T}\right) \qquad (11)$$

With C a constant equal to $3.87.10^{16}$ cm^{-3} $K^{-3/2}$ and Eg the gap energy. This energy is the difference between the energy of the conduction band E_c and that of the valence band E_v. It is equal to $1.12x1.6x10^{-19}$ J for the silicon.
V_T represents the thermal voltage given by:

$$V_T=\frac{k_b}{q}T \qquad (12)$$

Results and Discussions

Les équations (9) et (10) ont permis d'obtenir les profils suivants:

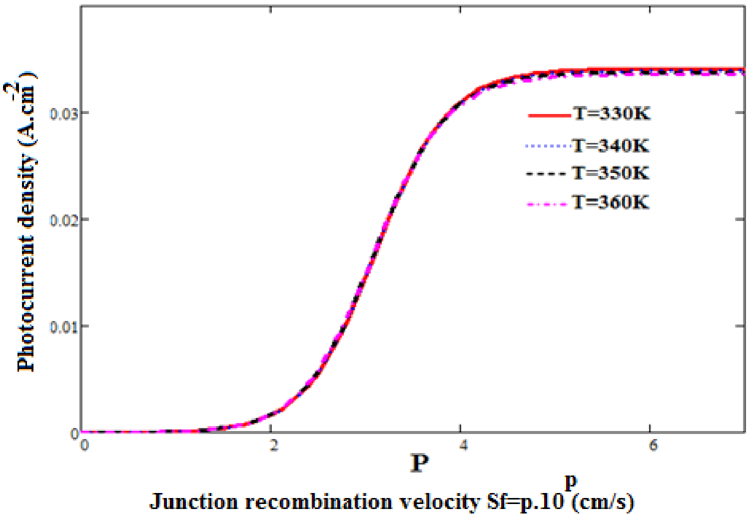

Figure 2: Photocurrent Density as a function of the recombination velocity of the minority charge carriers at the junction for different values of the temperature.

λ= 0,78 μm.

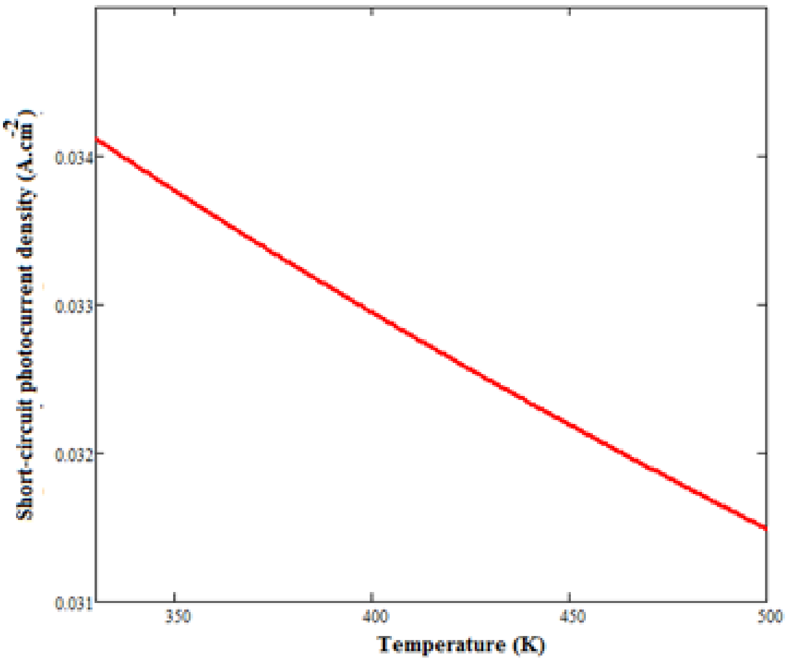

Figure 3: Short-circuit photocurrent density as a function of temperature

λ= 0,78 μm

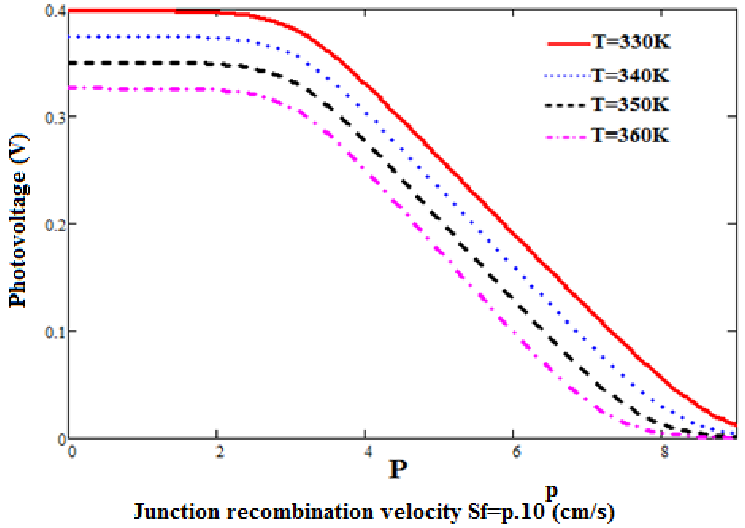

Figure 4: Photovoltage as a function of the recombination velocity of the minority charge carriers at the junction for different temperature values.

λ= 0,78 μm

Figure 2 shows a very weak photocurrent in the vicinity of the open circuit (at the low Sf values): the minority carriers are blocked at the junction because they lack energy to cross the potential barrier located at the junction. When Sf increases, the minority charge carriers cross through the junction and photocurrent increases to reach a maximum value at large Sf values: this is the short-circuit photocurrent. We also observe a decrease in the short-circuit photocurrent when the temperature increases with very low sensitivity. This observation is confirmed by figure 3.Indeed, at the large values of Sf, the flux of the minority charge carriers at the junction is maximal, so there remains a small amount of minority carriers that can be affected by the temperature. Everything happens as if the increase of Sf tends to inhibit the process umklapp **[17-19],** that is to say an increase in the conductivity of the material. On the other hand, at the low values of Sf (in the vicinity of the short-circuit), the minority charge carriers are blocked at the junction leading to a maximum photovoltage: this is the open circuit voltage (figure 4). It decreases when Sf increases to cancel out in the vicinity of the short circuit. Indeed, when Sf increases the amount of stored minority charge carriers decreases which results in a decrease in photovoltage. We also observe that the increase in temperature decreases the open circuit voltage with a sharper sensitivity: here with the umklapp process results in an increase in the strength of the material. The observations described above are confirmed in the Photocurrent - photovoltage characteristic. It is represented by figure 5:

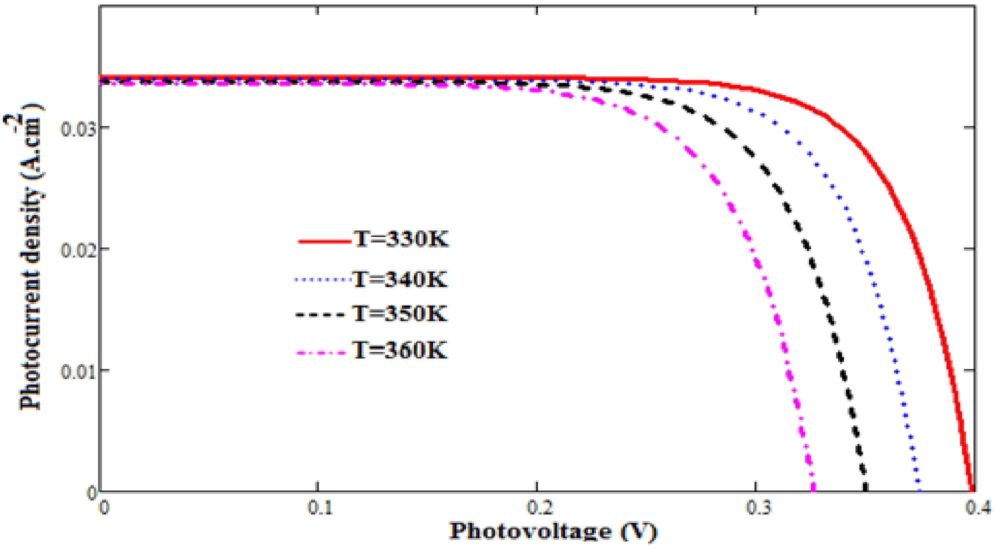

Figure 5: Figure 5: Photocurrent - Photovoltage characteristic for different temperature values (λ= 0,78 μm)

Study of the shunt resistance

The shunt resistance represents the set of leakage currents within the solar cell. It models the imperfections at the edge of the solar cell and on the space charge area. It may be related to the recombination velocity at the junction. For its determination, we consider the low photovoltage values of the Photocurrent - photovoltage characteristic. This part of the curve corresponds to the short-circuit situation. Under these circumstances, the characteristics to the solar cell are comparable to a short-circuit current generator in parallel with the shunt resistance and a load resistance **[25].**We represent in Figure 6 the equivalent circuit of the solar cell working in the vicinity of the short circuit **[20-24]:**

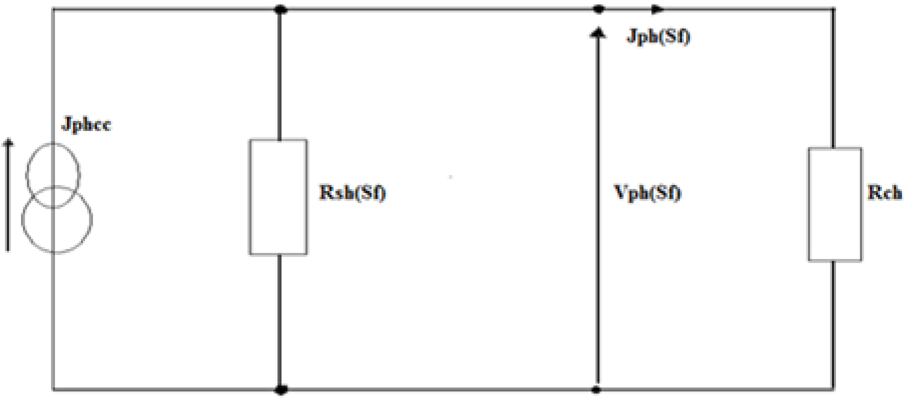

Figure 6: Electrical equivalent circuit of the solar cell unit when it operates practically in short-circuit

Using the circuits of figure 6, the shunt resistances can be expressed as:

$$R_{sh}(S_f,T)=\frac{V_{ph}(S_f,T)}{J_{phcc}(T)-J_{ph}(S_f,T)} \tag{13}$$

Jphcc is short-circuit photocurrent density. Jph (Sf, T) and Vph (Sf, T) respectively represent the photocurrent density and the photovoltage. Rch is a low resistance of load producing large values of Sf and Rsh (Sf, T): shunt resistance. From expression 13, we represent in Figure 7 the profile of the shunt resistance as a function of the recombination velocity of the minority charge carriers at the junction for different values of the temperature.

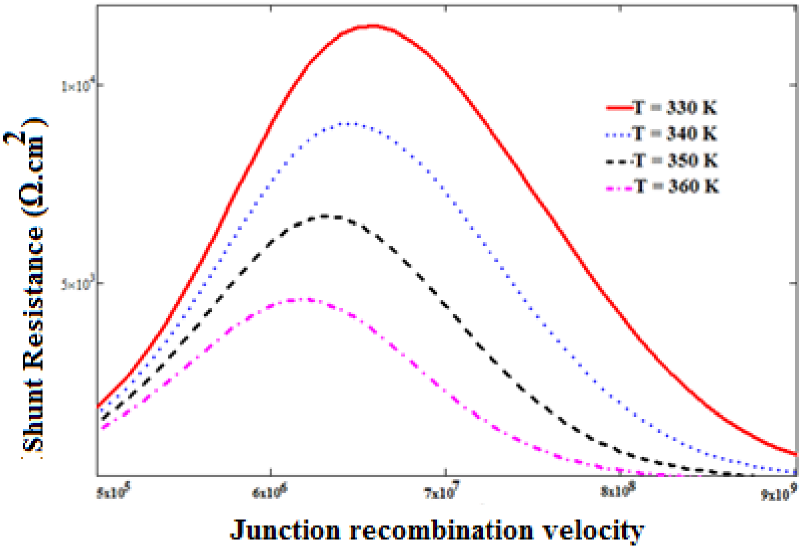

Figure 7: Shunt resistance as a function of the recombination rate at the junction for different temperature values (λ= 0,78µm).

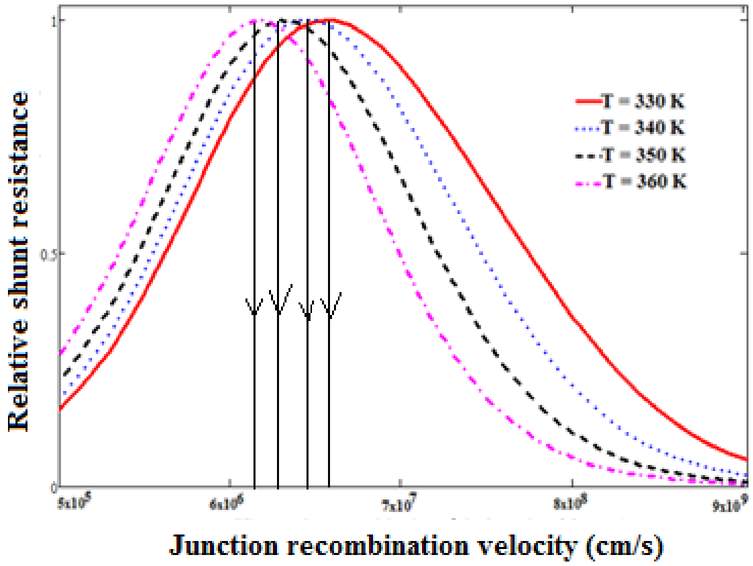

Figure 8: Relative shunt resistance as a function of the recombination velocity at the junction for different temperature values (λ = 0.78 µm).

FIG. 7 shows that a increasing the shunt resistance Rsh with the recombination speed Sf up to reach a maximum called Rshmax corresponding to a value of Sf called Sf opt and then decreases for the large values of Sf. We also observe that the maximum of the Rshmax resistance decreases As and when temperature increases. Indeed, when Sf increases, the flux of minority charge carriers at the junction increases which minimizes leakage currents and increases the current available for the external load. When Sf reaches its large values ($Sf \geq 6.10^6$ cm / s), there are practically not minority charge carriers available for the external load, which means that when the short-circuit situation is reached the base is emptied of these minority carriers and therefore leads at decrease in shunt resistance. The decrease in shunt resistance with the increasing temperature is due to an increase in the resistivity of the silicon material with the process umklapp [17-19], which, in high temperature, causes the reduction of the mobility of minority charge carriers. Thus, the current available for the external load decreases and causes a decrease in the Shunt resistance. We also observe that the recombination velocity (Sfopt) which corresponds to the maximum of the Rshmax resistance decreases with the increase in temperature. To better visualize this phenomenon, we propose in figure 8 the profile of the relative shunt resistance to its maximum value as a function of the recombination speed at the junction for different values of the temperature.

Figure 8 shows and confirms the decrease in the recombination velocity Sfopt with the increase in temperature. Indeed, always with the umklapp process [17-19], the increase in temperature favors the increasing of the resistivity of the material by attenuating the motion of minority charge carriers and consequently acts on the recombination velocity Sfopt. From FIG. 7, we have determined some Rshmax values as a function of temperature. The results obtained are shown in Table 1 :

Table 1: Shunt resistance maximum values with their corresponding temperatures (λ= 0,78 μm)

T(K)	R_{shmax} (Ω.cm^2)	Sfopt (cm/s)
330	11475	7,84.10^6
340	9014,4	8,79.10^6
350	6680	2,04.10^7
360	4595,1	0,94

Table 1 shows that the resistance Rshmax and Sfopt decrease with temperature, which confirms our previous assertions on the decrease Rshmax and Sfopt. Thus, these results allowed to plot the profile of the maximum of the shunt resistance as a function of the temperature. It is represented by FIG. 9

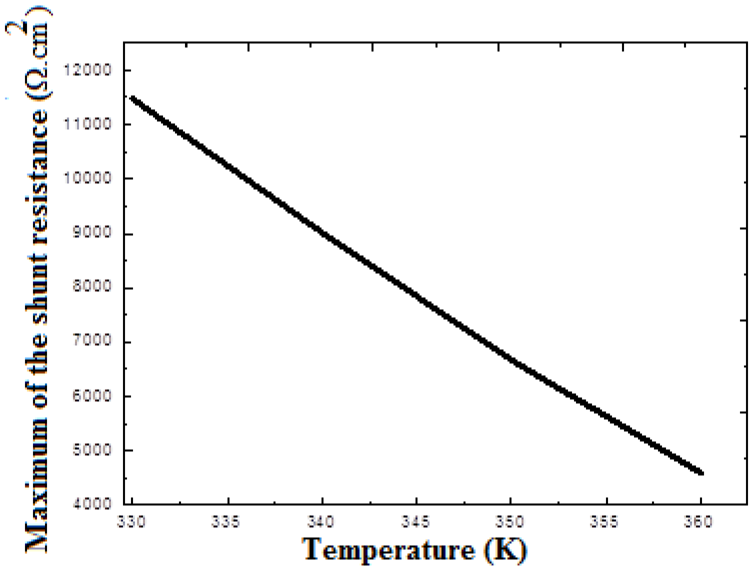

Figure 9: Maximum shunt resistance as a function of temperature
λ= 0,78 μm

Figure 9 shows a right of equation:

$$R_{sh\max} = \alpha T + \beta \tag{14}$$

with $\alpha = 239,7$ Ω.cm^{2}T^{-1}The slope and $\beta = 77232,5 (\Omega.cm^2)$ for T=330K

Determination of the shunt resistance from the recombination velocity of the minority charge carriers initiating the short circuit (Sfcc)

The expression of Sfcc is obtained from the resolution of Equation 14 [26, 27]:

$$Jph(S_f, \lambda, T) - Jphcc(\lambda, T) = 0 \quad (15)$$

Thus, we obtain

$$Sf_{cc}(\lambda,T) = \frac{L(T)K(\lambda,T)\left[L(T)E(\lambda,T) - M(T)\alpha(\lambda)D(T)\right] - \gamma_a(\lambda,T)D(T)M(T)}{L(T)\left[\gamma_a(\lambda,T)M_1(T) + K(\lambda,T)M(T)\right]} \quad (16)$$

Avec,

$$K(\lambda,T) = \frac{\phi(\lambda)\alpha(\lambda)L(T)^2\left[1 - R(\lambda)\right]}{D(T)\left[L(T)^2\alpha(\lambda)^2 - 1\right]}$$

$$\mathrm{E}(\lambda,T) = L(\mathrm{T})\left[S_b - \alpha(\lambda)D(T)\right]e^{-\alpha(\lambda)H}$$

$$M(T) = L(T)Sb\cosh\left(\frac{H}{L(T)}\right) + D(T)\sinh\left(\frac{H}{L(\mathrm{T})}\right)$$

$$M_1(T) = L(T)Sb\sinh\left(\frac{H}{L(T)}\right) + D(T)\cosh\left(\frac{H}{L(\mathrm{T})}\right)$$

$$\gamma_a(\lambda,T) = L(T)\left(\frac{Jphcc(\lambda,T)}{qD(\mathrm{T})} - \alpha(\lambda)K(\lambda,T)\right)$$

Referring to figure 7, the values of the temperature have allowed, after their introduction in equation 15, to obtain the values of Sfcc. These latters, projected at the level of the curves of figure 7, have made it possible to determine the shunt resistance for different temperature values. The results are recorded in Table 1.

Table 2: Sfcc and Rsh values for different temperature

T(K)	Sfcc(cm/s)	Rsh(Ω.cm²)	λ(μm)
330	$3{,}128.10^7$	7311,9	0,78
340	$3{,}253.10^7$	6952,5	0,78
350	$3{,}376.10^7$	6041,2	0,78
360	$3{,}495.10^7$	4569,3	0,78

Table 2 shows that the temperature increase the recombination velocity of the minority carriers at the junction initiating the short circuit. Thus, more the temperature increases, more the resistance of the material increases (with the umklapp process [17-19]), which means that the short-circuit situation is difficult to reach for high temperaturesand confirms the decrease of the shunt resistance.

Conclusion

We have just presented a work on the effect of temperature on the shunt resistance determined from the Photocurrent - Photocurrent characteristic knowing the recombination velocity of the minority charge carriers at the junction initiating the short circuit. Thus, the expressions of the photocurrent and of the photovotage are determined from the of the minority charge carriers density at the junction, which makes it possible to represent the Photocurrent - Photovoltage characteristic for different values of the temperature. The study showed a slight decrease in the short-circuit photocurrent and a considerable drop in the open circuit voltage. From the Photocurrent - phototensing characteristic, the shunt resistance is determined and then studied as a function of the recombination velocity of the minority charge carriers at the junction for different values of the temperature.

This study made it possible to obtain a maximum shunt resistance called Rshmax which corresponds to a value of the recombination velocity at the junction called Sfopt and to establish an array of values of these parameters for different temperatures. Ainsi, nous avons constaté que Rshmax et Sfopt diminuent en augmentant la température. Finally, the expression of the recombination velocity of the minority charge carriers at the junction initiating the short circuit (Sfcc) made it possible to obtain the values of the shunt resistance for different temperatures and showed a decrease in the shunt resistance and a Increase of Sfcc As and when the temperature increases.

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