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Study of the Series Resistance of a Solar Cell Silicon under Magnetic Field from of Junction Surface recombination Velocity of Minority Charge Carriers at the junction limiting the open circuit (Sfoc)

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Abstract The open circuit is a operation point the solar cell corresponding to a maximum photovoltage and a almost nul photocurrent. The phenomenological parameter that sets this operating point of the solar cell is the junction recombination velocity of minority charge carriers at the junction. The open circuit is set when the recombination rate is low. In this article, we consider an operation point near the open circuit of solar cell, that is to say the one that limits the operation of the solar cell open circuit and its study versus to an external magnetic field is proposed. This study allowed the determination of the series resistance of the solar cell according to the external magnetic field. Thus, expression of the minority charge carrier density is determined from the continuity equation and studied for different values of the magnetic field. From this study, the open circuit voltage (Voc) and the junction surface recombination velocity limiting the open circuit (Sfoc) are determined and studied for different values of magnetic field. The determination of the series resistance is proposed from the curve of series resistance versus of the solar cell operation point by considering Sfoc.

Keywords Silicon Solar Cell, Magnetic Field, Series Resistance, Open circuit voltage, Junction Recombination velocity.

Introduction

Improvement of the performance of solar cells through the quality control during the various stages of manufacture. The quality of a solar cell is closely linked to its electronic parameters [1] and power [2], many studies have been conducted in order to control during manufacture of the solar cell. It is therefore necessary, under certain operating conditions, to devise methods of measurement and of characterization of electrical parameters [2] and electronic [3] of the solar cell under static conditions [4] and in dynamic mode [5]. The open circuit condition is an operating state of the solar cell where the charge minority carriers are stored in the base. This situation corresponds to low values of the junction recombination velocity [6-7]. Sfco represents the value of the junction recombination velocity from which the solar cell is not in open circuit position. This work will be focused on the study of an external magnetic field on Sfco.

2. Theory

In this study we consider a type of solar cell n + -p-p + [3] under polychromatic illumination and subjected to an external magnetic field. The structure of this solar cell is shown in Figure 1:

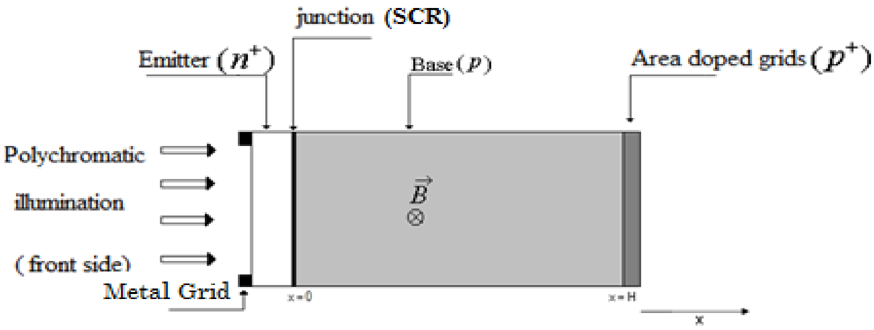

Figure 1: Silicon Solar Cell structure to the n^+pp^+ P type under magnetic field and polychromatic illumination

2.1. Excess minority carrier's density

In the remainder of this work, the solar cell is subjected to a constant magnetic field applied perpendicular to the base of the solar cell [8-11]. The study will be done at the base and a dimension. The continuity equation for the minority charge carrier density photo generated in the base under the influence of a magnetic field is given by:

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

where D* and L* are respectively the diffusion coefficient and diffusion length of the minority charge carriers photogénérés in the base in presence of a magnetic field given by [12,13]:

$$D^*=\frac{D}{1+(\mu.B)^2} \qquad (2)$$

$$L^*=\sqrt{D^*.\tau} \qquad (3)$$

τ is the lifetime of the minority charge carriers and μ = 103 $cm^2.V^{-1}s^{-1}$ mobility of minority charge carriers in the base at 298K. [14] δ (x) is the minority charge carrier density in the base and G (x) the generation rate of minority charge carriers. Its expression is given by: [15]

$$G(x)=\sum_{i=1}^{3}a_i.\mathrm{e}^{-b_i.H} \qquad (4)$$

The coefficient ai and bi are obtained from tabulated values of the radiation in A.M1,5 [16]. These coefficients are given by:

$a_1=6{,}13.10^{20}\ cm^{-3}/s$; $a_2=0{,}54.10^{20}cm^{-3}/s$; $a_3=0{,}0991.10^{20}cm^{-3}/s$; $b_1=6630cm^{-1}$; $b_2=1000cm^{-1}$; $b_3=130cm^{-1}$

The excess of minority carrier's density is obtained from equation (1) resolution and is given by:

$$\delta(x)=A.ch\left(\frac{x}{L^*}\right)+C.sh\left(\frac{x}{L^*}\right)-\sum_{i=1}^{3}k_i.e^{-b_i.x} \qquad (5)$$

with : $k_i=-\dfrac{n.a_i.L^{*2}}{D^*.(b_i.^2L^{*2}-1)}$ et $D^*.(b_i.L^*-1))\neq 0$

A and *B* are obtained with the boundary condition at the emitter – base junction and at the back surface of the cell **[16,17]:**

-at the junction *(x=0)* :

$$\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=0}=\frac{Sf^*}{D^*}.\delta(0) \qquad (6)$$

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

$$\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=H}=-\frac{Sb^{*}}{D^{*}}.\delta(H) \tag{7}$$

The parameters Sf* and Sb* are respectively excess minority carrier's recombination velocities at the junction and at the back surface [17, 18]. Sf* characterizes the solar cell operation point. It also corresponds to the gradient of the minority carrier's at the junction. It is equal to the sum of the junction recombination velocity of minority charge carriers Sfj = $j.10^{j}$ cm s^{-1} due to the external load and speed of intrinsic recombination Sfo* which is a effective recombination velocity of minority carriers at the interface emitter-base that is a function of the external magnetic field ($Sf^{*}=Sfo^{*}+Sfj$). Sb* determines the losses by recombination at the rear face (back surface field BSF). It is a function of the magnetic field [19-20]. The expressions of Sfo* and Sb* are given from of the solving of equations [21-22]:

$$\left.\frac{\partial J_{ph}}{\partial Sb}\right|_{Sb\to 0}=0 \text{ and } \left.\frac{\partial J_{ph}}{\partial Sf}\right|_{Sf\to\infty}=0$$

Jph represents the photocurrent density given by:

$$J_{ph}=q.D^{*}\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=0}$$

Thus we have:

$$Sfo^{*}=\sum_{i=1}^{3}\frac{D^{*}\cdot\left[b_i\cdot L^{*}-\exp(-b_i\cdot H)\cdot\left(sh(\frac{H}{L^{*}})+b_i\cdot L^{*}\cdot ch(\frac{H}{L^{*}})\right)\right]}{L^{*}\cdot\left[\exp(-b_i.H)\cdot\left(ch(\frac{H}{L^{*}})+b_i\cdot L^{*}\cdot sh(\frac{H}{L^{*}})\right)-1\right]}$$

$$Sb^{*}=\sum_{i=1}^{3}\frac{D^{*}\cdot\left[sh(\frac{H}{L^{*}})+b_i\cdot L^{*}\cdot\left(\exp(-b_i\cdot H)-ch(\frac{H}{L^{*}})\right)\right]}{L^{*}\cdot\left[b_i\cdot L^{*}\cdot sh(\frac{H}{L^{*}})+\exp(-b_i\cdot H)-ch(\frac{H}{L^{*}})\right]}$$

We plot in figure 2a and b, the recombination velocity Sf* and Sb* versus magnetic field.

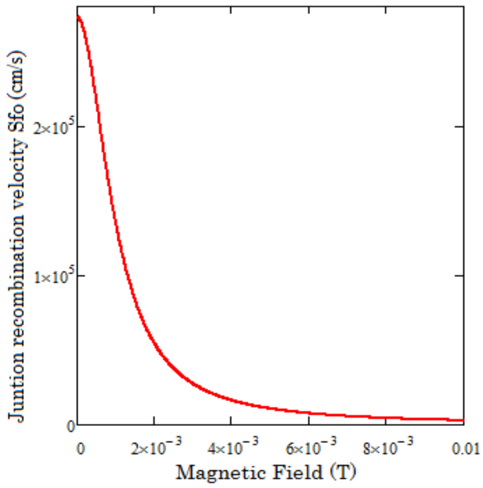

Figure 1a : Junction recombination velocity Sfo versus magnetic field ($D=26cm^2/s$, $\mu=10^3 cm^2.V^{-1}s^{-1}$, $\tau=10^{-5}s$, H=0,03cm)*

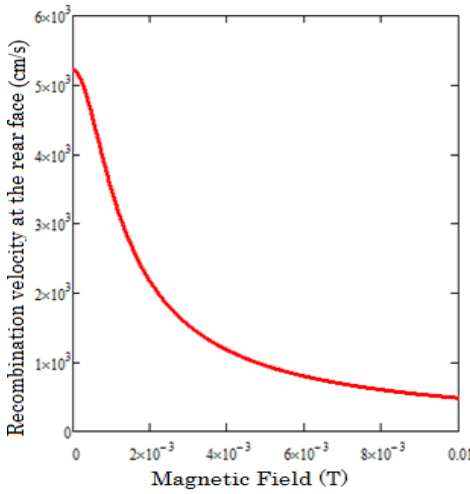

Figure 1b : Recombination velocity at the rear face Sb versus magnetic field ($D=26cm^2/s$, $\mu=10^3 cm^2.V^{-1}s^{-1}$, $\tau=10^{-5}s$, H=0,03cm)*

Figures 1a and 1b show a decrease in recombination velocity of the minority carriers of intrinsic charge at the junction and at the rear side with increasing magnetic field. Indeed, the minority charge carriers are deflected by the magnetic force to the side faces of the solar cell. Therefore there is less recombination of minority charge carriers at the junction and to the rear face of the solar cell with application of the magnetic field which causes a blocking of minority charge carriers in the base of the solar cell.

2.2. Photovoltage

The photovoltage is a parameter that can determined an excited solar cell. His expression is given by the Boltzmann law:

$$Vph = V_T . \ln\left(\frac{Nb}{n_i^{\ 2}} . \delta(0) + 1 \right) \tag{8}$$

V_T is the thermal voltage, n_{Ri} *R* the intrinsic carrier density at thermal equilibrium and Nb *R* the base doping density.

We plot in figure 2, the photovoltage versus magnetic field for different values of the junction recombination velocity near the open circuit.

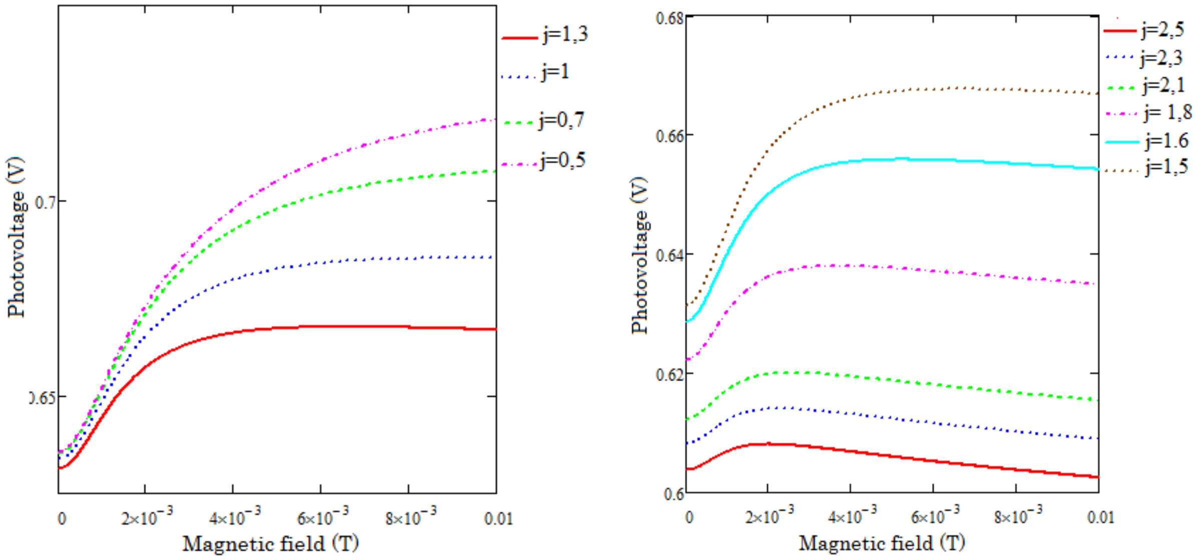

Figure 2: Photovoltage versus magnetic field for different values of the junction recombination velocity near the open circuit

($D=26cm^2/s$, $\mu=10^3 cm^2.V^{-1}s^{-1}$, $\tau=10^{-5}s$, $H=0{,}03cm$)

For a fixed value of the upper operating point to $1{,}5.10^{1,5}$ cm / s in the vicinity of the open circuit, the augment photovoltage to a maximum value corresponding to an optimum magnetic field Bopt (j) and then decreases as a function of magnetic field . Indeed, when the field is less than Bopt (j), the diffusion coefficient decreases with the intensity of the magnetic field. The Mobility and the diffusion of the minority carriers decreases depending on the magnetic field [11, 24]. The minority carriers are blocked by the magnetic force and cause the increase in the photovoltage. When the magnetic field is greater than Bopt (j) the photovoltage decreases with the intensity of the magnetic field. Thus, we assist of a decrease in electrical parameters including the photocurrent and photovoltage [25-27]. Hence the interest of determining bopt (j). When the operating point is lower $1{,}5.10^{1,5}$cm/s, the photovoltage increases with the magnetic field. We can also observe that the optimum magnetic field increases with the operating point the vicinity of the open circuit. In the course of this work, the choice of magnetic field values is given by the optimal values of the magnetic field depending on the operating point. Thus, the effect of magnetic field on the photovoltage as a function of the speed of recombination of minority charge carriers at the junction is repésenté in Figure 3.

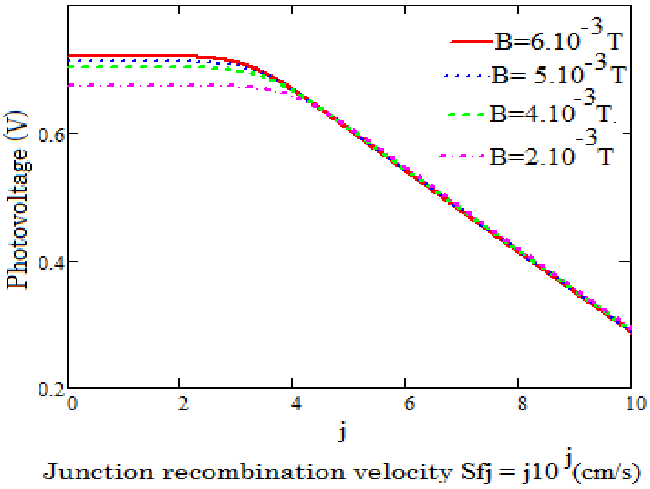

Figure 3: Photovoltage versus junction recombination velocity for different values of the magnetic field. ($D=26cm^2/s$, $\mu=10^3cm^2.V^{-1}s^{-1}$, $\tau=10^{-5}s$, $H=0,03cm$)

Figure 4 shows that at low values of the junction recombination velocity of minority charge carriers (vicinity the open circuit), the photovoltage is maximum and constant: this is the open circuit voltage (Voc). The minority carriers are blocked at the junction. When the junction recombination velocity increases, the photovoltage decreased and it become low in the vicinity of the short circuit (for large values of Sf): the minority charge carriers passed through the junction to participate in the production of photocurrent. We also observe an increase of the photovoltage with the magnetic field. This increase is more sensitive in the vicinity of the open circuit because the minority carriers are blocked at the junction (increased Voc). This remark is more pronounced than the magnetic field is intense. For large values of the junction recombination velocity of the minority charge carriers, the magnetic field has no effect on the photovoltage because the minority charge carriers crossed the junction for the production of the photocurrent. The magnetic field tends therefore maintain the solar cell near the open circuit.

2.3. Determination of the junction recombination velocity limiting the open circuit (Sfoc)

the junction recombination velocity limiting the open circuit is determined by solving the equations [6,7]:

$$Vph(Sf) - Voc = 0 \tag{9}$$

$$Voc = \lim_{Sf \to Sfoc} Vph \tag{10}$$

The expression of this junction recombination velocity is given by:

$$Sfoc = \sum_{i=1}^{3} \frac{D^{\ddot{}*}.b_i.I_1.\left[1 - D^*..L^*.Sb_1.ch\left(\frac{H}{L^*}\right)\right] - D^{*3}b_i.I_1.sh\left(\frac{H}{L^*}\right)}{Sb.L^{*2}.I_1.D^*.b_i.sh\left(\frac{H}{L^*}\right) + D.^*.L^*.I_1.D.b_i.ch\left(\frac{H}{L^*}\right) + L.M_1.J_1 - I_1} \tag{11}$$

with :

$$E_1 = L^{*2}.Sb.sh\left(\frac{H}{L^*}\right) + D^*.L^*.ch\left(\frac{H}{L^*}\right) \tag{11-1}$$

$$F_1 = L^{*2}.\left(Sb - D^*.b_i\right)e^{-b_i.H} + \left(L^*.Sb.ch\left(\frac{H}{L^*}\right) + D^*.sh\left(\frac{H}{L^*}\right)\right) \tag{11-2}$$

$$G_1 = D^*.sh\left(\frac{H}{L^*}\right) + L^*.Sb.ch\left(\frac{H}{L^*}\right) \qquad (11\text{-}3)$$

We respectively represent in Figure 4 the profile of the junction surface recombination velocity of minority charge carriers limiting the open circuit versus of magnetic field.

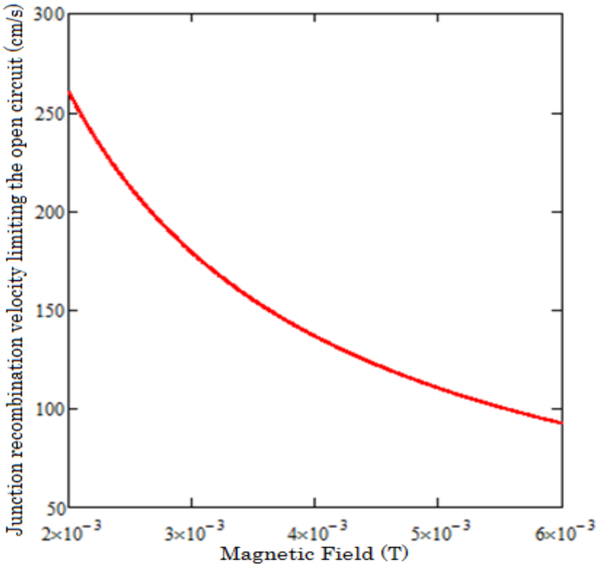

Figure 4: The junction surface recombination velocity of minority charge carriers limiting the open circuit versus of magnetic field
$D=26cm^2/s$, $\mu=10^3 cm^2.V^{-1}s^{-1}$, $\tau=10^{-5}s$, $H=0{,}03cm$)

Figure 4 shows a decrease in the recombination velocity at the junction of minority charge carriers limiting the open circuit with increasing magnetic field. This observation show that the magnetic field helps maintains the solar cell of the vicinity the open circuit.

2.4. Study of the series resistance

The series resistance (Rs) materializes all imperfections due to contact of the front face and the rear face, contacts between metal and semiconductor and the resistivity of the semiconductor material [28-29]. For the determination of the séries resistance expression, we consider the neighborhood of the open circuit of the solar cell and in these operating conditions an equivalent circuit of the solar cell is presented [4, 30-31]. Using this circuit equivalent, the series resistance can be expressed:

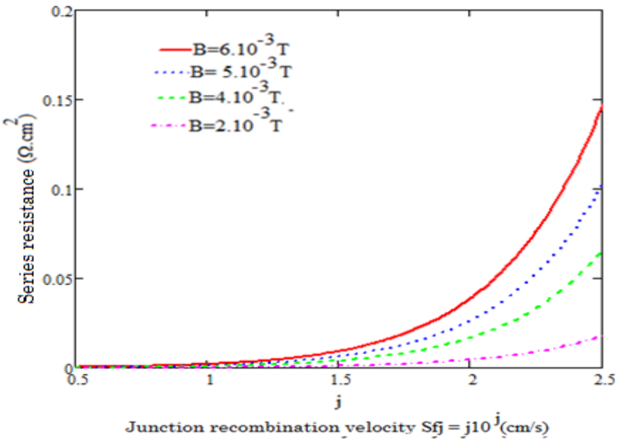

Figure 5: Series resistance versus junction recombination velocity for different values of the magnetic field.
$D=26cm^2/s$, $\mu=10^3 cm^2.V^{-1}s^{-1}$, $\tau=10^{-5}s$, $H=0{,}03cm$)

$$Rs(Sf) = \left. \frac{Vphco - Vph(Sf)}{Jph(Sf)} \right|_{Sf \to Sfoc} \qquad (12)$$

The curve of series resistance versus junction recombination velocity is plotted in figure 6 for different values of the magnetic field.
Figure 5 shows an increase of series resistance with the recombination velocity of the minority carriers at the junction in the vicinity of the open circuit. There was also an increase in the series resistance with the magnetic field. So the magnetic field also helps to strengthen the silicon material resistivity. From the junction recombination velocity of minority charge carriers limiting the open circuit, the series resistance of the solar cell is determined for each value of the magnetic field. The technique is illustrated in Figure 7:

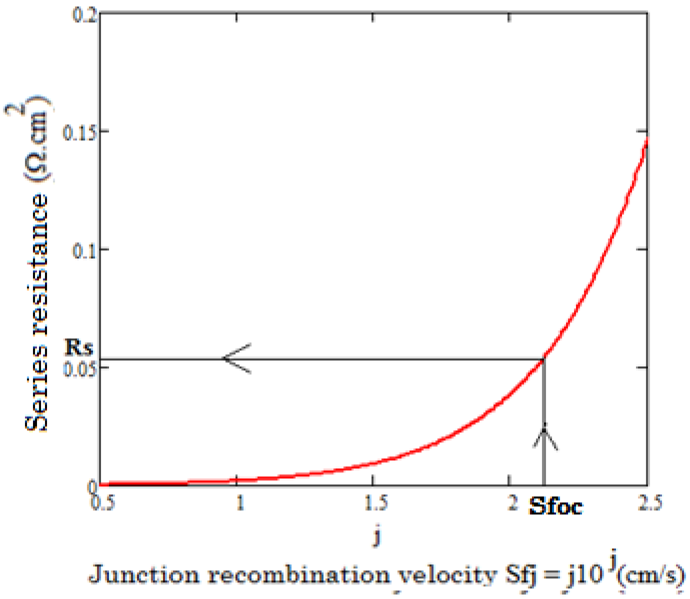

Figure 6: Determination of the series resistance

Figure 6 shows a method of determining the series resistance from the recombination velocity at the junction of minority carriers limiting the open circuit (Sfoc). The application of this technique has yielded some series resistance values using the magnetic field values previously defined. The results are shown in Table 1.

Table1: series resistance values obtained for different values of the magnetic field

Magnetic Field (T)	Voc (V)	Sfoc (cm/s)	Rs ($\Omega.cm^2$)
0	0,618	$7{,}134.10^2$	0,0032
2.10^{-3}	0,675	$4{,}077.10^2$	0,0057
4.10^{-3}	0,703	$1{,}227.10^2$	0,0235
5.10^{-3}	0,712	81,47	0,0601
6.10^{-3}	0,720	58,27	0,1457

Table 1 shows that the open circuit voltage and the series resistance increases with the intensity of the magnetic field. By cons, the recombination velocity of minority charge carriers at the junction limiting the open circuit decreases with increasing magnetic field.

3. Conclusion

We have presented a study of the recombination velocity of minority charge carriers at the junction limiting the open circuit (Sfoc) and of the series resistance (Rs) of the solar cell in the presence of an external magnetic field. The determination of the minority charge carrier density in the base has enabled the study of the photovoltage as a function of magnetic field the vicinity of the open circuit. Thus, for a value of the solar cell operating point upper to $1{,}5.10^{1.5}$cm / s in the vicinity of the open circuit, the photovoltage increases with the intensity of the magnetic field until a maximum value called optimal magnetic field then decreases with the increase in the magnetic field. This relation obtained between the maximum value of the photovoltage and the optimal magnetic field allows to justify the choice of magnetic field values to study Sfoc (B) and Rs (B). The study of the photovoltage shows an increase of the open circuit voltage (Voc) to the intensity of magnetic field. From Voc and photovoltage, the expression of the recombination velocity of minority charge carriers at the junction limiting the open circuit (Sfoc) is determined and studied for different values of the magnetic field. This study showed a decrease Sfoc with the magnetic field. The magnetic field thus helps maintain the solar cell at the vicinity the open circuit. Knowing Sfoc, the series resistor (Rs) is determined and then studied for different values of magnetic field. The study showed that the magnetic field increases the series resistance and the resistivity of the silicon material.

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