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Influence of Magnetic Field on Electrical Model and Electrical Parameters of a Solar Cell Under Intense Multispectral Illumination

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Abstract - In this work we present a 3D modeling of the magnetic field influence on electrical model and electrical parameters (J_{ph} , V_{ph} , R_s , R_{sh} , C) of a polycrystalline silicon solar cell under intense multispectral illumination. For intense light, the electric field in the base of the solar cell has to be considered; taking into account this electric field and the applied magnetic field in our model lead to two major things: Firstly, new analytical expressions of the continuity equation, the photocurrent and the photovoltage are proposed; secondly an equivalent electrical model of the solar cell under constant magnetic field is proposed and the influence of the magnetic field is pointed out on electrical parameters such as shunt and series resistances and space charge capacitance.

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I. INTRODUCTION

The decrease of oil reserves in the world, the raise cost of hydrocarbons, the consequences of oil derivative garbage on health, environment and climate obliges everybody to move toward new sources of energy more proper and less polluting. In this sense, one of the possible alternatives for electric energy production is photovoltaic solar energy, that is clean silent shape of energy and whose source is available. However, although this shape of energy is advantageous, it is confronted to a crucial problem that is the weakness of solar cells energy efficiency. Thus, the numerous research tracks nowadays solar cells have for object to find good quality materials, news manufacture technologies or solar cells operating conditions that minimize solar cells performances factors limiting factors: minority carrier recombination photogenerated in base (Shockley - Read - Hall, Auger and Radiative) [1], in surface and grains boundaries [2],

photocurrent and photovoltage losses, shadiness effects and resistive losses [3],...

Whatever is solar cell quality, it is necessary at its installation moment to take into account an outside factor susceptible to lower efficiency: the magnetic field. Indeed, whatever is their installation place, the solar cells by their operating principle (electrons movement) can be influenced by magnetic field [4] that can be of various origin: terrestrial magnetic field ($5 \cdot 10^{-5}$ T), magnetic component of electromagnetic wave coming from the radio emitters, television emitters and telecommunication emitter [5]: *AM antenna, power of radiance: 50W-5kW, magnetic field values: $B \leq 1,29 \cdot 10^{-7}$ T; FM antenna, power of radiance: 500W - 2MW, magnetic field values $4 \cdot 10^{-8} \text{ T} \leq B \leq 2,58 \cdot 10^{-6} \text{ T}$.*

Since the electrical parameters (J_{ph} , V_{ph} , P_{el} , R_s , R_{sh} , C) and electronic parameters (S_b , S_f , S_{fo} , L , D) of the solar cell are closely dependent carrier distribution in the cell, the magnetic field will perturb these parameters. In this work we present a 3D study of the influence of magnetic field on the electrical parameters of a silicon solar cell under multispectral intense light [6] (more than 50 suns). For this intense light our model takes into account the electric field due to concentration gradient in the bulk of the base.

II. THEORETICAL MODEL

This study is based on a 3D modeling of a polycrystalline silicon solar cell; we made the following assumptions:

- A columnar model is considered [3] with the grains having square cross section ($g_x = g_y$) so that their electrical properties are homogeneous; we can then use the cartesian coordinates; the base depth is H.
- The grain boundaries are perpendicular to the junction and their recombination velocities independent of generation rate under AM1.5 illumination. So the boundary conditions of continuity equation are linear;
- The illumination is uniform. We then have a generation rate depending only on the depth in the base z;
- The contribution of the emitter and space charge region is neglected [3], so this analysis is only developed in the base region.

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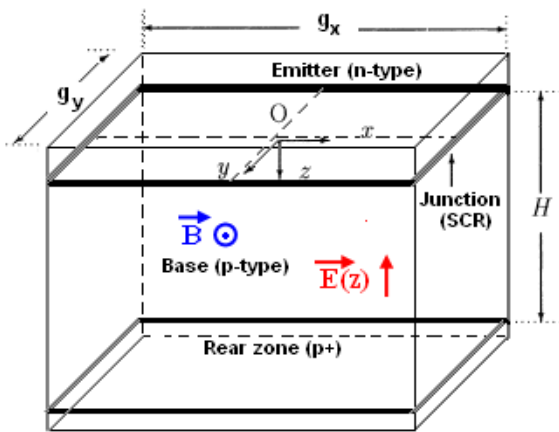


Figure 1 : Theoretical model of square grain with an external magnetic field and internal electric field.

The solar cell is front side illuminated with more than 50 suns; the external magnetic field is parallel to the junction and the electric field due to concentration gradient along the z axis in the base region can be expressed as [6,8]:

$$E(z) = \frac{D_p - D_n}{\mu_p + \mu_n} \cdot \frac{1}{\delta(x, y, z)} \frac{\partial \delta(x, y, z)}{\partial z} \quad (1)$$

D_n et μ_n are respectively electrons diffusion constant and mobility, $\delta(x, y, z)$ is the minority carrier's density in the base of the solar cell, τ_n is the electrons lifetime and C indicates the concentration factor (in suns).

We supposed also that carrier distribution along x and y axes are uniform for a given z plane so that there is no conduction current along these axis; we can write:

$$E(x) = E(y) = 0 \quad (2)$$

Taking into account the electric field given by Equation 1, the continuity equation can be written as:

$$\frac{\partial \delta(x, y, z)}{\partial t} = \frac{1}{e} \nabla \cdot \vec{J}_n + G(z) - R(z) \quad (3)$$

$G(z)$ is the carrier generation rate at the depth z in the base: $G(z) = C \cdot \sum_{i=1}^3 a_i \cdot e^{-b_i z}$

Parameters a_i and b_i are coefficients deduced from modeling of the generation rate considered for overall the solar radiation spectrum when AM = 1.5 [9].

$R(z)$ is the recombination rate at depth z given by: $R(z) = \frac{\delta(x, y, z)}{\tau_n}$

$\vec{J}_n$ can be written as the sum of [10]:

→

→

1. the drift current, $J_c = e \cdot \mu_n \cdot \delta_n(x, y, z) \cdot E$
 2. the current induced by the magnetic field $\vec{J}_{In} = -\mu_n \cdot \vec{J}_n \wedge \vec{B}$ and
 3. the diffusion current $\vec{J}_d = e \cdot D_n \cdot \nabla \delta_n(x, y, z)$
- We then have:

$$\vec{J}_n = \vec{J}_d + \vec{J}_{In} + \vec{J}_c = e \cdot D_n \cdot \nabla \delta(x, y, z) - \mu_n \cdot \vec{J}_n \wedge \vec{B} + e \cdot \mu_n \cdot \delta(x, y, z) \cdot \vec{E} \quad (4)$$

with $\vec{B} = B \vec{j}$, $B(x) = B(z) = 0$

$$\vec{E} = E(z) \vec{k}$$

The drift current is zero along x and y axes, that

$$\text{is: } \frac{\partial J_c}{\partial x} = \frac{\partial J_c}{\partial y} = 0$$

Using the components of the scalar product

$\nabla \cdot \vec{J}_n$ and inserting them in equation 3 in static regime $\frac{\partial \delta(x, y, z)}{\partial t} = 0$, we obtain the following differential equation:

$$C_x \cdot \frac{\partial^2 \delta(x, y, z)}{\partial x^2} + C_y \cdot \frac{\partial^2 \delta(x, y, z)}{\partial y^2} + \frac{\partial^2 \delta(x, y, z)}{\partial z^2} + \frac{G(z)}{D^*} - \frac{\delta(x, y, z)}{L^2} = 0 \quad (5)$$

and

$$D^* = \frac{(D_n - \mu_n A)}{1 + \mu_n^2 \cdot B^2}, \quad L^2 = \tau_n \cdot D^* \quad \text{with} \quad A = \frac{D_p - D_n}{\mu_p + \mu_n}$$

III. SOLUTION OF THE CONTINUITY EQUATION

Equation 6 is a partial differential equation with general solution in the form:

$$\delta(x, y, z) = \sum_j \sum_k Z_{j,k}(z) \cdot \cos(C_{xj} x) \cdot \cos(C_{yk} y) \quad (7)$$

$$\text{with } C_{xj} = \frac{C_j}{C_x}, \quad C_{yk} = \frac{C_k}{C_y}$$

Coefficients C_j et C_k are determined by mean of

boundary conditions at the grain boundaries $x = \pm \frac{g_x}{2}$

et $y = \pm \frac{g_y}{2}$ given respectively by:

$$\left[\frac{\partial \delta(x, y, z)}{\partial x} \right]_{x=\pm \frac{g_x}{2}} = \pm \frac{Sgb}{D^*} \cdot \delta(\pm \frac{g_x}{2}, y, z)$$

and

$$\left[\frac{\partial \delta(x, y, z)}{\partial y} \right]_{y=\pm \frac{g_y}{2}} = \pm \frac{Sgb}{D^*} \cdot \delta(x, \pm \frac{g_y}{2}, z) \quad (8)$$

Coefficients C_{xj} et C_{yk} are solution of the following transcendental equations:

$$C_{xj} \tan(C_{xj} \cdot \frac{g_x}{2}) = \frac{Sgb}{D^*} \quad (9.1)$$

and
$$C_{yk} \tan(C_{yk} \cdot \frac{g_y}{2}) = \frac{Sgb}{D^*} \quad (9.2)$$

Taking into account the orthogonality of the cosine functions, $Z_{jk}(z)$ can be written in the form [11]:

$$Z_{jk}(z) = A_{jk} \cosh\left(\frac{z}{L_{j,k}}\right) + B_{jk} \sinh\left(\frac{z}{L_{j,k}}\right) - \sum_{i=1}^3 K_i e^{-b_i \cdot z} \quad (10)$$

With
$$K_i = C \cdot \frac{a_i \cdot L_{j,k}^2}{D_{j,k} \cdot [b_i^2 \cdot L_{j,k}^2 - 1]}$$

$$\frac{1}{L_{j,k}} = \left[C_j^2 + C_k^2 + \frac{1}{L_n^2} \right] \quad \text{and}$$

$$\frac{1}{D_{j,k}} = \frac{16 \cdot \sin(C_{xj} \cdot \frac{g_x}{2}) \cdot \sin(C_{yk} \cdot \frac{g_y}{2})}{D^* \cdot [\sin(C_{xj} \cdot g_x) + C_{xj} \cdot g_x] \cdot [\sin(C_{yk} \cdot g_y) + C_{yk} \cdot g_y]}$$

Coefficients A_{jk} and B_{jk} are obtained by inserting equation 7 and boundary conditions into equation 6 [11]:

$$A_{jk} = \sum_{i=1}^3 K_i \cdot \frac{\frac{1}{L_{j,k}} \cdot \left(\frac{S_f}{D^*} - b_i \right) \cdot \exp(-b_i \cdot H) + \beta_{j,k} \cdot \left(\frac{S_f}{D^*} + b_i \right)}{\frac{S_f}{D^*} \cdot \beta_{j,k} + \frac{1}{L_{j,k}} \cdot \alpha_{j,k}} \quad (11.1)$$

and

$$B_{jk} = \sum_{i=1}^3 K_i \cdot \frac{\frac{S_f}{D^*} \cdot \left(\frac{S_b}{D^*} - b_i \right) \cdot \exp(-b_i \cdot H) - \alpha_{j,k} \cdot \left(\frac{S_f}{D^*} + b_i \right)}{\frac{S_f}{D^*} \cdot \beta_{j,k} + \frac{1}{L_{j,k}} \cdot \alpha_{j,k}} \quad (11.2)$$

with:

$$\alpha_{j,k} = \frac{1}{L_{j,k}} \cdot \sinh\left(\frac{H}{L_{j,k}}\right) + \frac{S_b}{D^*} \cdot \cosh\left(\frac{H}{L_{j,k}}\right)$$

$$\beta_{j,k} = \frac{1}{L_{j,k}} \cdot \cosh\left(\frac{H}{L_{j,k}}\right) + \frac{S_b}{D^*} \cdot \sinh\left(\frac{H}{L_{j,k}}\right)$$

With these coefficients A_{jk} and B_{jk} the final solution of the continuity equation is well known.

IV. DETERMINATION OF THE EQUIVALENT ELECTRICAL MODEL OF THE SOLAR CELL UNDER MAGNETIC FIELD

We present on figure 2 the equivalent electrical model of the solar cell without magnetic field.

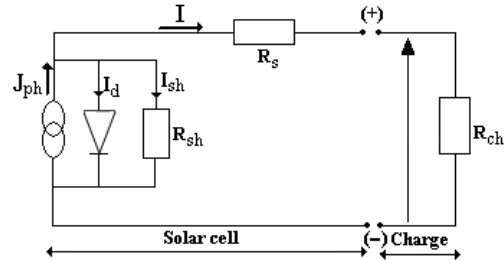


Figure 2 : One diode equivalent electrical model of the solar cell without magnetic field.

In this model, the diode characterizes not only the diffusion saturation current in the base and the emitter but also the generation-recombination current in the space charge region [1, 12]. It appears also in this model two parasitic resistances [13]:

The shunt resistance R_{sh} characterizes current losses at the junction. These losses are induced by intrinsic recombination (S_{fo}) at the junction. Then a part of the photocurrent is derived into this resistance and could not be used by the external load.

The series resistance characterizes the contacts resistance, the resistivity of the base material and the dynamic resistance of the junction [3]. The presence of this resistance leads to a decrease of the voltage across the external load.

a) Space charge region capacitance variation with magnetic field

Figure 3 below show the dependence of the carriers' density on the magnetic field and the depth in the base. In figure 4, we present a closer view (near the junction) of the influence of the magnetic field for various depths in the base.

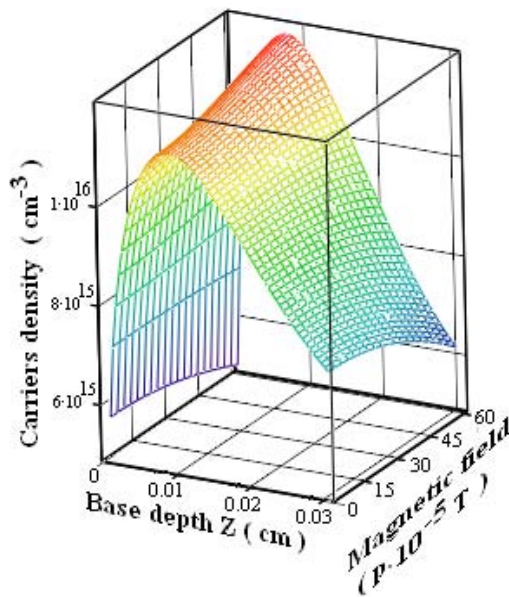


Figure 3 : Excess minority carriers profile in the base of a photoexcited cell versus base depth and magnetic field: $C=200$ suns; $g_x=g_y=3\cdot10^{-3}\text{cm}$; $S_i=10^4\text{cm}\cdot\text{s}^{-1}$; $S_b=10^3\text{cm}\cdot\text{s}^{-1}$; $S_{gb}=100\text{cm}\cdot\text{s}^{-1}$.

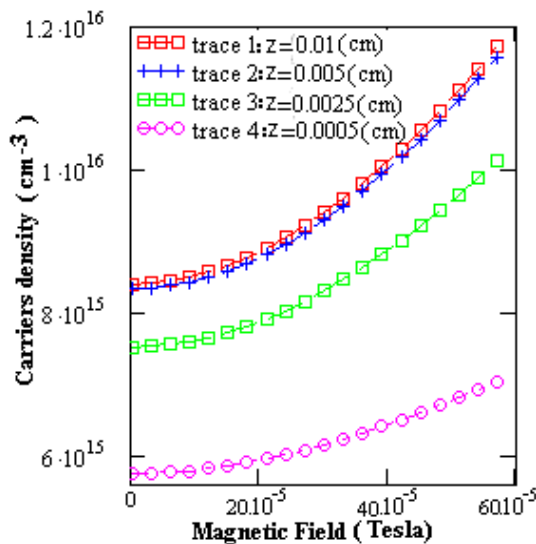


Figure 4 : Influence of magnetic field on the excess minority carriers density for various depths in the base: $z=0.01\text{cm}$, $z=0.005\text{cm}$, $z=0.0025\text{cm}$, $z=0.0005\text{cm}$.

Figures 3 and 4 show that for increasing magnetic field, the maximum of the excess minority carriers density increase also and are shifted left to the junction. This increasing of the maximum of the excess minority carriers density translate an increase of the carrier concentration near the junction. The displacement of the maximum of the excess minority carriers density shows that there is a decreasing carriers flow through the junction. These two consequences translate that there is an accumulation of carriers near the junction for increasing magnetic field.

These accumulated carriers enforce the space

charge region leading to an extension of the space charge region [14].

To exhibit the capacitive effect of the space charge region, let us replace the diode by a capacitor with capacitance C . The expression of C is inversely proportional to the space charge region width l : $C=S\cdot\epsilon/l$. S is the junction surface and ϵ is the silicon permittivity. In these conditions, a space charge region extension correspond to a decrease of the capacitance; the interpretation of this phenomenon leads us to add in series with C an extra capacitor with capacitance C_m depending of the applied magnetic field.

b) Shunt resistance variation under magnetic field

The photocurrent density J_{ph} is given by [11, 15].

$$J_{ph} = \frac{q \cdot D^*}{g_x \cdot g_y} \cdot \int_{-\frac{g_x}{2}}^{\frac{g_x}{2}} \int_{-\frac{g_y}{2}}^{\frac{g_y}{2}} \left[\frac{\partial \delta(x, y, z)}{\partial z} \right]_{z=0} dx dy \quad (12)$$

With

$$\delta(x, y, z) = \sum_j \sum_k Z_{j,k}(z) \cdot \cos(C_{xj}x) \cdot \cos(C_{yk}y)$$

Replacing $\delta(x, y, z)$ and equations (8), (9.1) and (9.2) into equation (12) we obtain:

$$J_{ph} = q \cdot D^* \cdot \sum_j \sum_k R_{jk} \cdot \left[\frac{B_{jk}}{L_{jk}} + \sum_{i=1}^3 K_i b_i \right] \quad (13)$$

with

$$R_{jk} = \frac{(1 + \mu_n^2 \cdot B^2) \cdot 4 \sin\left(C_{xj} \cdot \frac{g_x}{2}\right) \cdot \sin\left(C_{yk} \cdot \frac{g_y}{2}\right)}{g_y \cdot g_x \cdot C_j \cdot C_k}$$

Figures 5 and 6 illustrate the effect of magnetic field [10,16] on the photocurrent density.

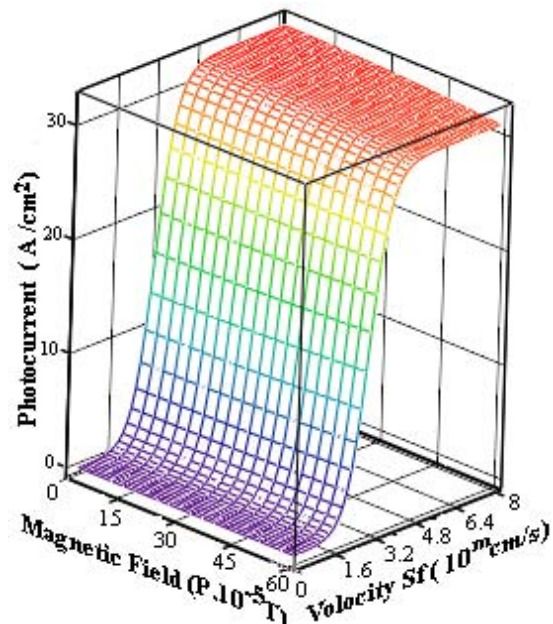


Figure 5 : Effect of magnetic field and junction recombination velocity on photocurrent: $g_x=g_y=3\cdot10^{-3}\text{cm}$, $S_{gb}=10^2\text{cm}\cdot\text{s}^{-1}$, $S_b=10^4\text{cm}\cdot\text{s}^{-1}$.

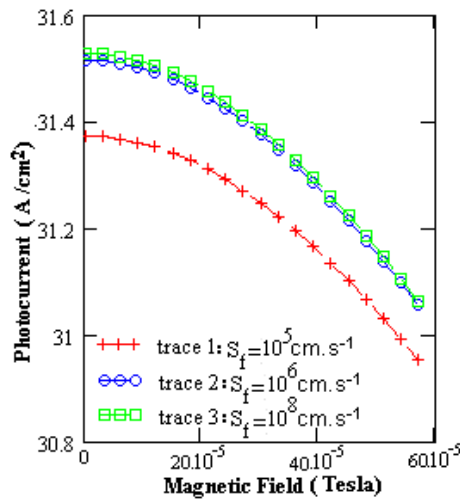


Figure 6 : Magnetic field effect on the photocurrent density closer to the short circuit: $S_f = 105 \text{ cm.s}^{-1}$, $S_f = 106 \text{ cm.s}^{-1}$, $S_f = 108 \text{ cm.s}^{-1}$.

We observe on figure 5 that near the open circuit ($S_r \rightarrow 0$), there is practically no influence of magnetic field on the photocurrent density, contrary to short circuit ($S_i \rightarrow \infty$) where the photocurrent density decreases drastically with increasing magnetic field (figures 5 and 6). This decrease of the photocurrent combined with the accumulation phenomenon depending on magnetic field mean that there is an increase of the leakage current (through the junction and the edges of the solar cell).

This leakage current can be represented by an extra resistance R_{shm} , depending on the magnetic field, in parallel with the shunt resistance R_{sh} .

c) Series resistance variation under magnetic field

The photovoltage can be expressed by means of the Boltzmann law [11, 15]:

$$V_{ph} = V_T \cdot \ln \left[1 + \frac{N_B}{n_i^2} \int_{-\frac{g_x}{2}}^{\frac{g_x}{2}} \int_{-\frac{g_y}{2}}^{\frac{g_y}{2}} \delta(x, y, 0) dx dy \right] \quad (14)$$

In this expression, V_T is the thermal voltage given by: $V_T = k_B \cdot T / q$, n_o is the carrier concentration at equilibrium: $n_o = n_i^2 / N_B$ (n_i represents the intrinsic carrier concentration : $n_i = 10^{10} \text{ cm}^{-3}$ for silicon, N_B is the base doping density : $N_B = 10^{16} \text{ cm}^{-3}$) and k_B is the Boltzmann's constant.

The resolution of the equation 14 leads to the following expression for V_{ph} :

$$V_{ph} = V_T \cdot \ln \left[1 + \frac{N_B}{n_i^2} \cdot \sum_j \sum_k R_{jk} \left[A_{jk} - \sum_{i=1}^3 K_i \right] \right] \quad (15)$$

We show on figures 7 and 8 the effect of the magnetic field on the photovoltage.

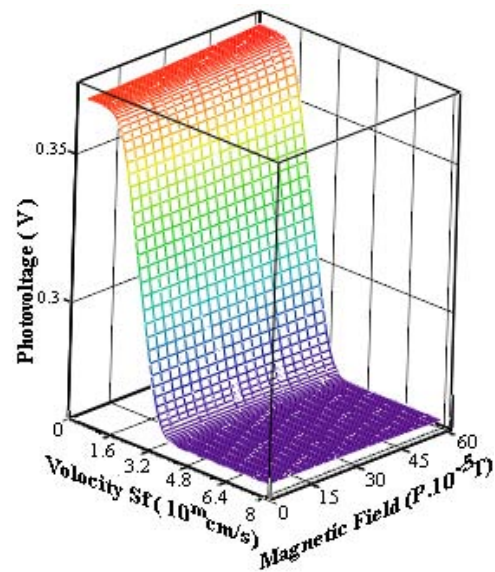


Figure 7 : Effect of magnetic field and junction recombination velocity on photovoltage: $g_x = g_y = 3 \cdot 10^{-3} \text{ cm}$, $S_{gb} = 10^2 \text{ cm.s}^{-1}$, $S_b = 104 \text{ cm.s}^{-1}$.

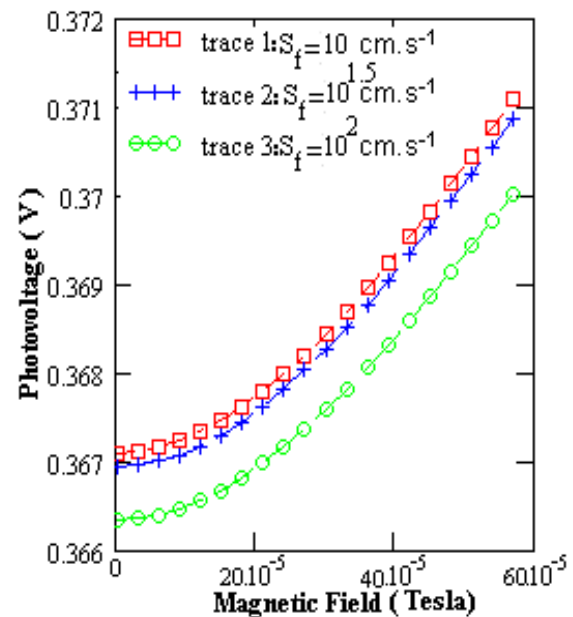


Figure 8 : Magnetic field effect on the photovoltage near open circuit. $S_f = 10 \text{ cm.s}^{-1}$, $S_f = 101.5 \text{ cm.s}^{-1}$, $S_f = 102 \text{ cm.s}^{-1}$.

We observe on these figures that the photovoltage which means an accumulation of charges across the junction present a maximum for very low S_i values (open circuit); this open circuit voltage increases with increasing magnetic field. This is a consequence of charge accumulation in the base and diminution of junction recombination with increasing magnetic field; this phenomenon is accompanied by an increase of recombination in the bulk and at the grain boundaries [8, 15].

The behavior of the photovoltage under magnetic field characterizes an increase of resistive losses in the base (due to material structure and electrical grids); this increase of resistive losses leads to a decrease in the output voltage. We characterize this behavior by adding an extra resistance R_{sm} (depending on magnetic field) in series with R_s .

From our previous results, we propose below an equivalent electrical model for the solar cell under intense light and external magnetic field.

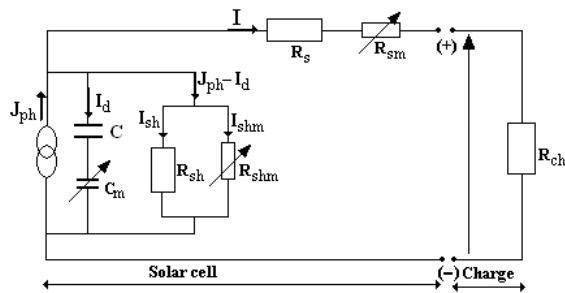


Figure 9 : Equivalent electrical model for the solar cell under intense light and external magnetic field

Given the series and parallel associations in the figure 9 above, we can write the following equations:

$$I(V) = J_{ph} - I_d(V) - I_{sh}(V) = I_{ph} - I_s \left[\exp\left(\frac{q \cdot \{V + I \cdot R_{sem}\}}{n \cdot k_B \cdot T}\right) - 1 \right] - \frac{V + I \cdot R_{sem}}{R_{shem}} \quad (19)$$

I_s is the diode saturation current and n is the ideality factor.

The $I(V)$ curve of the solar cell is then presented below based on the set of equations 10, 11, 13 and 19.

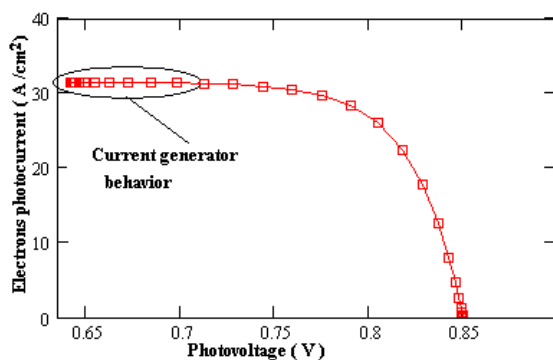


Figure 10 : Circled part show a current generator behavior for the solar cell.

It appears on this I - V curve that near the short circuit, the solar cell behaves like a non-ideal current generator, that is an ideal current generator associated with a shunt resistance [18, 19]. We determine the shunt resistance through the equivalent electrical model of the solar cell in short circuit (figure 11). The short circuit is

$$R_{sem}(B) = R_s + R_{sm}(B) \quad (16)$$

$$\frac{1}{R_{shem}(B)} = \frac{1}{R_{shm}(B)} + \frac{1}{R_{sh}} \quad (17)$$

$$\frac{1}{C_{em}(B)} = \frac{1}{C_m(B)} + \frac{1}{C} \quad (18)$$

$R_{sem}(B)$, $R_{shem}(B)$ and $C_{em}(B)$ represent electrical parameters under magnetic field, R_s , R_{sh} and C correspond to the same electrical parameters without magnetic field.

V. MAGNETIC FIELD EFFECT ON ELECTRICAL PARAMETERS

a) Magnetic field effect on shunt resistance

When an external load (with non-zero or non-infinite resistance) is connected to a solar cell, the solar cell will operate at a given operating point between open circuit and short circuit. The current I that flow through that load is given by [17]:

characterized by a maximum carrier flow through the junction, thus this situation exhibit very well the losses at the junction and then the shunt resistance.

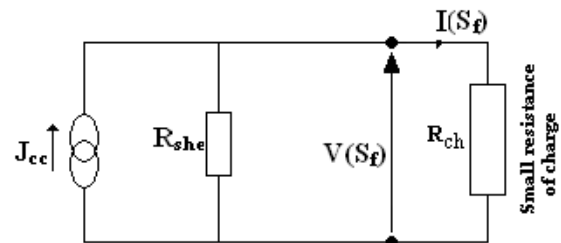


Figure 11 : Equivalent electrical model of the solar cell in short circuit.

A little analysis of figure 11 lead to the following expression:

$$V(S_f) = R_{she} \cdot (J_{cc} - I(S_f)) \quad (20)$$

We then have:

$$R_{she} = \frac{V(S_f)}{(J_{cc} - I(S_f))} \quad (21)$$

J_{cc} is the short circuit current density given by:

$$J_{cc} = \lim_{S_f \rightarrow \infty} J_{ph}$$

$$J_{sc} = qD^* \sum_j \sum_k \frac{R_{jk}}{L_{jk}} \sum_{i=1}^3 K_i \left[\frac{(S_0 - D^* \cdot b_i) e^{-b_i H}}{D^* \beta_{j,k}} - \frac{\alpha_{j,k}}{\beta_{j,k}} + L_{j,k} b_i \right] \quad (22)$$

The load resistance R_{ch} is taken very low to keep the solar cell close to the short circuit, given that R_{ch} and S_f varies inversely. [20]

The figure 12 below shows the effect of the magnetic field on the shunt resistance.

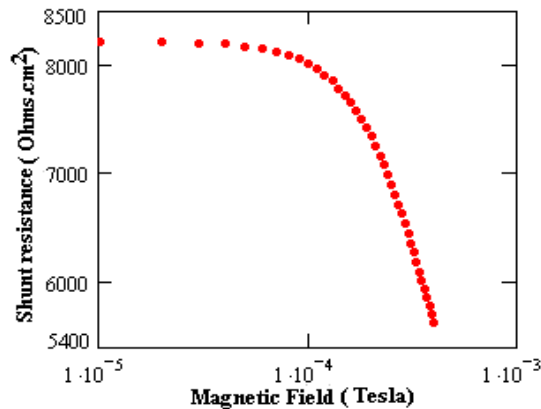


Figure 12 : Magnetic field effect on the shunt resistance.

We observe on this figure that the shunt resistance decrease with the increase of magnetic field [21]. This behavior means that intrinsic recombination in the solar cell increase and then the output current decrease. This phenomenon means that the shunt resistance derives a part of the generated photocurrent.

b) Magnetic field effect on series resistance

To determine the series resistance, let us take a look on the I - V curve near the open circuit (figure 13) particularly the circled part of the figure.

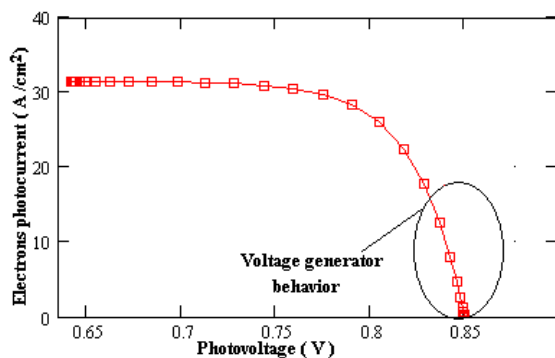


Figure 13 : Behavior of the solar cell near the short circuit

Near open circuit, the solar cell operate like a real voltage generator, that is an association of an ideal voltage generator and an internal series resistance R_{se} which causes a voltage drop and thus decreasing the output voltage. The determination of this series resistance is made near the open circuit. Near this

operating point there is a charge accumulation in the cell so that any losses are due to the cell structure and electrical grids.

Near this open circuit, the solar cell can be represented by the following electrical model

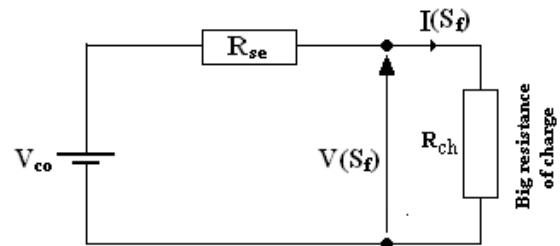


Figure 14 : Electrical model of the solar cell near open circuit.

Based on the figure 14 above we obtain:

$$V(S_f) = V_{co} - R_{se} \cdot I(S_f) \quad (23)$$

We then deduce the series resistance as:

$$R_{se} = \frac{V_{co} - V(S_f)}{I(S_f)} \quad (24)$$

V_{co} is the open circuit voltage and can be obtained from the Boltzmann relation when $S_f = S_{fo}$ [7, 11].

$$V_{co} = V_T \cdot \ln \left[1 + \frac{N_B}{n_i^2} \cdot \sum_j \sum_k R_{jk} \cdot \left[A'_{jk} - \sum_{i=1}^3 K_i \right] \right] \quad (25)$$

with:

$$A'_{jk} = \sum_{i=1}^3 K_i \cdot \frac{\frac{1}{L_{j,k}} \cdot \left(\frac{S_{fo}}{D^*} - bi \right) \cdot \exp(-bi \cdot H) + \beta_{j,k} \cdot \left(\frac{S_{fo}}{D^*} + bi \right)}{\frac{S_{fo}}{D^*} \cdot \beta_{j,k} + \frac{1}{L_{j,k}} \cdot \alpha_{j,k}}$$

Figure 15 below present the series resistance versus magnetic field:

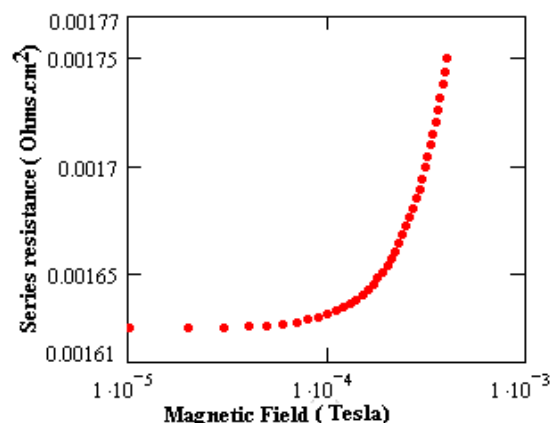


Figure 15 : Series resistance versus magnetic field.

It can be observed that for magnetic field values less than 7.10^5 Tesla there is no change on the series resistance; for values greater than 7.10^5 Tesla the series resistance increases with increasing magnetic field.

This series resistance must be kept as low as possible to minimize losses in the solar cell.

c) Magnetic field effect on the space charge region

The solar cell junction behaves like a capacitor with capacitance C [3, 22] depending on the space charge region width.

Based on the carrier density in the base, one can evaluate the amount Q of charge accumulated near the junction by: $Q=q.\delta(0)$ [20,23]. The associated capacitance is given by [23]: $C= Q/V_j$, where V_j is the voltage across the junction.

Figure 16 presents the effect of the magnetic field on the equivalent capacitance:

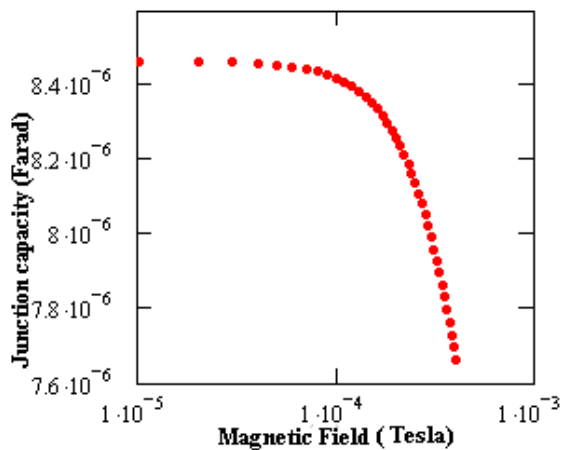


Figure 16 : Magnetic field effect on the equivalent capacitance.

As noted for the series resistance, the equivalent capacitance seems to not depend on magnetic field for values less than $B < 7.10^5$ Tesla. But for more intense magnetic field the equivalent capacitance decrease very rapidly.

This behavior of the equivalent capacitance is directly related to the space charge region widening with magnetic field.

V. CONCLUSION

This study of magnetic field effect on solar cell lead us to put in evidence new analytical expressions of carrier density in the base of the solar cell and electrical parameters such as J_{ph} , V_{ph} , P_{el} , R_s , R_{sh} and C . It was shown that magnetic field causes charge accumulation across the junction, increase the junction recombination and open circuit voltage but decrease in the same time the short circuit current density.

The analysis of the magnetic field effect on

carrier density, photocurrent and photovoltage show that there is a variation of electrical parameters such as shunt resistance, series resistance and space charge capacitance; we then proposed an equivalent electrical model describing the behavior of the solar cell under magnetic field.

Based on this model, the expressions of the series and shunt resistances, space charge capacitance have been determined, and the effects of the magnetic field on these parameters have been shown. It seems that magnetic field less than 7.10^5 Tesla has no effect on electrical parameters; for magnetic field greater than 7.10^5 Tesla, the shunt resistance and the capacitance decrease contrary to the series resistance.

These results also show that the terrestrial magnetic field (5.10^5 Tesla) and the electromagnetic waves (*AM antenna*, $B \leq 1.29.10^7 T$; *FM antenna*, $4.10^7 T \leq B \leq 2.58.10^6 T$) have no effects on solar cells.

REFERENCES RÉFÉRENCES REFERENCIAS

1. B. Equer, Energie solaire photovoltaïque, volume 1, 1993, Ellipses.
2. A. Rocher ; "Origine structurale et chimique de l'activité des joints de grain dans le silicium" *Revue de Physique Appliqué*, 22, (1987), 591-595.
3. J.P Charles, A. Haddi, A. Maouad, H. Bakhtiar, A Zerga, A Hoffmann, P Mialhe ; "La Jonction du Solaire à la Microélectronique" *Rev. Energ. Ren.* ,3 2000, 1-16
4. Zouma B, Maiga A S, Dieng M, Zougmore F and Sissoko G, " 3D approach of spectral response for a bifacial silicon solar cell under a constant magnetic field" *Global journal of pure and applied sciences* , 15.(1), (2009),117-124.
5. U. Freyer Nachrichten-Uebertragungstechnik, 1994 Edition Carl Hanser (Munich)
6. F. Pelanchon, C. Sudre, Y. Moreau "Solar Cells Under Intense Light Concentration: *Numerical and Analytical Approaches*" *Proc. 11th European Photovoltaic Solar Energy Conference*.Monteux. 12-16 October,1992.
7. B. Ba, M. Kane and J. Sarr. "Modeling recombination current in polysilicon solar cell grain boundaries", *Solar Energy Materials & Solar Cells*, 80, 2003, 143-154.
8. M. Zougrana, I. Ly, B. Zouma, F. I. Barro, G. Sissoko; " Effect of magnetic field and base depth on excess minority carrier generation". *Journal des Sciences*, 7 (4), 2007, 73-81.
9. S. N. Mohammad,an alternative method for the performance analysis of silicon solar cells" *Journal of Appl. Phys.*, 61(2), 1987, 767-772.
10. Y. Betser, D. Ritter, G. Bahir, S. Cohen and J. Sperling, "Measurement of the minority carrier mobility in the base of heterojunction bipolar

- transistor using magneto-transport method". *App. Phys. Lett.*, 67(13), 1995, 1883-84.
11. J. Dugas, "3D modelling of a reverse cell made with improved multicrystalline silicon wafers" *Solar Energy Materials and Solar cells*, 32, 1994, 71-88.
12. B. Thuillier, "Caractérisation structurale des contacts ohmiques réalisés à partir d'encre éalliques sur cellules photovoltaïques en silicium multicristallin", Thèse: Institut National des sciences Appliquées de Lyon, (2004 <http://docinsa.insalyon.fr/these/pont.php?id=thuillir>).
13. J.M Asensi, C Voz, J Merten and J Andreu, "Short-circuit resistance a-Si:HP-I-N solar cells: the link with the electronic properties of the active layer", *Proc. 2nd World conference and exhibition on photovoltaic solar energy conversion*, 1, 1998, 906-909.
14. G. Sissoko, B.Dieng, A.Corréa, M.Adj, D.Azilion, "Silicon solar cell space charge region width determination by a study in modelling" *Proc. World Renewable Energy Congress*, 1998, 1852-1855.
15. Dieng A, Zerbo I, Wade M, Maiga A S and Sissoko G "three dimensional study of polycrystalline silicon solar cell: the influence of the applied magnetic field on the electric parameters" *IOP: Semicond. Sci. Technol*/26, 2011, 095023.
16. S.Erel, "The effect of electric and magnetic fields on the operation of a photovoltaic cell" *Solar Energy Materials & Solar Cells*, 71, 2002, 273-280.
17. K.Kotsovos and K. Misiakos, "Evaluation of series resistance losses in the base of single and double junction rear point contact silicon solar cells through simulation and experiment", *Proc. 21st European Photovoltaic Solar Energy Conference*, 4-8 September, 2006, 328-331.
18. G. Sissoko, A. Corr  a, E. Nan  ma, M.N. Diarra, A.L. Ndiaye, M.Adj, "Recombination parameters measurement in silicon double sided surface field solar cell", *Proc. World Renewable Energy Congress*, 1998, 1856-1859.
19. C. L Garrido, D. Stolik, J.Rodriguez, A.Morales, "Influence of carrier recombination in the space charge region on minority carrier life time in the base region of solar cell", *Solar Energy Materials & Solar Cells*, 57 1999, 239-247.
20. G. Sissoko, E. Nan  ma, A. Corr  a, P.M. Biteye, M.Adj, A.L. Ndiaye, "Silicon solar cell recombination parameters determination using the illuminated I-V characteristic", *Proc. World Renewable Energy Congress*, 1998, 1847-1851.
21. S. A. Correia, J. Lossen, M. B  hr, "Eliminating shunts from industrial silicon solar cells by spatially resolved analysis", *Proc. 21st European Photovoltaic Solar Energy Conference*, 2006, 1297-1300.
22. N. V Philips, "Practical electronics", *gloeilampenfabrieken*, 1966.
23. G. Sissoko, B. Dieng, A. Corr  a, M. Adj, M.Adj, D. Azilion, "Silicon solar cell space charge width determination by study in modelling ", *Proc. World Renewable Energy Congress*, 1998, 1852-1855.

