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# Effect of both magnetic field and doping density on series and shunt resistances under frequency modulation

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Solar cells are aggregated in series and parallel combination into an array to produce desired voltage and power levels. In the present study, a new method has been investigated to study the electrical parameters of solar cell. Both the photocurrent density and photovoltage have been derived from continuity equation. The effects of both applied magnetic field and doping density on these electrical parameters have been studied.

Keywords: Magnetic field, Doping density, Solar cells, Resistance, Photocurrent

# **1** Introduction

Solar cells are connected in series and parallel combinations in an array to produce desired voltage and power levels. The solar cells are non-identical in their parameters and the parameters dispersions affect the performance in such a way that the power output is lower than that for cells with identical parameters. Therefore, measures of the cell quality are important for design and analysis of photovoltaic systems.

In the present work, firstly the continuity equation has been solved by taking into account the magnetic field to more accurately describe the dependence between parameters. Secondly, the I-V method is used to determine electrical parameters such as series resistance and shunt resistance for various magnetic fields based on the electrical equivalent circuit of the solar cell in frequency modulation under polychromatic illumination.

## 2 Theory

This study is based on a 1D modeling of a polycrystalline silicon solar cell; we made the following assumptions:

- The space charge region and the emitter thicknesses are very small as compared to that of the base; their contributions are then neglected so that only the contribution of the base is taken into account<sup>1</sup>.
- The emitter and the base regions are quasi-neutrals<sup>2</sup>; there is no internal electric field without the space charge region.
- The electrical and optical properties are identical at any point in the base; this enables us to use the Cartesian coordinates. The reflection on the silicon material has also been taken into account.

- The temperature effect on the performance of the photovoltaic cell is not taken into account.
- The excitation is done with a monochromatic frequency modulated light. The incident photons flux  $\phi(\lambda)$  is taken for AM 1.5 solar spectrum<sup>3</sup>. This case is characteristic of the whole terrestrial applications independently of the processing site.
- The illumination is carried out according to axis ox. The magnetic field *B* is represented perpendicularly to the plan (xoz) as shown in Fig. 1

## 2.1 Excess minority carrier density

 $D^*(P \leftrightarrow Nb) = D(Nb)$ 

Taking into account generation, diffusion and recombination phenomena in the base, the equation governing the variation of the minority carrier's density  $\delta(x, y, z, t)$  under frequency modulation<sup>4</sup> is:

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

 $\delta$  is the excess minority carrier density, *L* is their diffusion length and *D* their diffusion coefficient.

The diffusion coefficient can be written as<sup>5</sup>:

$$\begin{bmatrix} \frac{1 + (\omega n(B)^2 + \omega^2) \cdot \tau(Nb)^2}{\left[1 + (\omega n(B)^2 - \omega^2) \cdot \tau(Nb)^2\right]^2} + \\ + (2 \cdot \omega \cdot \tau(Nb))^2 \\ \omega \cdot \tau(Nb) \cdot \frac{(\omega n(B)^2 - \omega^2) \cdot \tau(Nb)^2 - 1}{\left[1 + (\omega n(B)^2 - \omega^2) \cdot \tau(Nb)^2\right]^2} \\ + (2 \cdot \omega \cdot \tau(Nb))^2 \end{bmatrix} \dots (2)$$



Fig. 1 — Theoretical model with an external magnetic field

with

$$D(Nb) = \frac{1350 \cdot Vt}{\sqrt{1 + \frac{81 \cdot Nb}{(Nb + 3, 2 \cdot 10^{18})}}} \qquad \dots (3)$$

With Nb is the base doping density.

The associated excess minority carrier lifetime is given by Lion & Wang<sup>5</sup>

$$\tau(Nb) = \frac{12}{1 + \frac{Nb}{5 \cdot 10^{16}}} \quad (\text{in } \mu \text{s}) \qquad \dots (4)$$

The diffusion length is then:

$$L_{c}^{*}(B,\omega,Nb) = \frac{L^{*}(B,\omega,Nb)}{\sqrt{1+i\cdot\omega\cdot\tau(Nb)}}$$
$$L^{*}(B,\omega,Nb) = \sqrt{D^{*}(B,\omega,Nb)\cdot\tau(Nb)} \qquad \dots (5)$$

Carriers generation rate G(x) at the depth x in the base is written in the form<sup>6,7</sup>:

$$G_{\alpha}(x) = n \sum_{i=1}^{3} \left[ \xi \exp(-b_i \cdot x) + \right] \qquad \dots (6)$$
$$\gamma \exp(-b_i \cdot (H-x))$$

n indicates illumination level; coefficients  $a_i$  and  $b_i$  are tabulated values obtained from solar irradiance and the dependence of the absorption coefficient on the illumination wavelength<sup>8</sup>.

The values of  $\alpha$ ,  $\xi$ ,  $\gamma$  of light mode are given in Table 1.  $a_i$  and  $b_i$  ray tabulated coefficients under AM 1.5 are given in Table 2:

Table 1 — Constants values			
Light	α	ξ	γ
Front face	1	1	Ó
Back face	2	0	1
Simultaneous	3	1	1
Table 2 — Coefficients tabulation			
i	1	2	3
$a_{i}(\text{cm}^{-3}.\text{s}^{-1})$	$6.13.10^{20}$	$5.4.10^{19}$	9.91.10 <sup>18</sup>
$b_{\rm i}({\rm cm}^{-3}.{\rm s}^{-1})$	6630	1000	130

The general solution of Eq. (1) is given by:

$$\delta_{\alpha}(x,t,B,\omega,p,m,Nb) = E_{\alpha} \cdot \cosh\left(\frac{x}{L_{c}^{*}(B,\omega,Nb)}\right) + F_{\alpha} \cdot \sinh\left(\frac{x}{L_{c}^{*}(B,\omega,Nb)}\right) + \sum_{i=1}^{3} k_{i} \cdot \left[\xi \cdot \exp\left(-b_{i} \cdot x\right) + \gamma \cdot \exp\left(-b_{i} \cdot (H-x)\right)\right] \dots (7)$$

where

$$k_i = -\frac{n \cdot a_i \cdot L^{*2}(\omega)}{D^*(\omega) \cdot (b_i^2 \cdot L^{*2}(\omega) - 1)} \qquad \dots (8)$$

The two arbitrary constant  $E_{\alpha}$  and  $F_{\alpha}$  can be evaluated if we consider the two following boundary conditions:

- at the junction (x=0):

$$\frac{\partial \delta_{\alpha}(\mathbf{x})}{\partial \mathbf{x}}\Big|_{\mathbf{x}=\mathbf{0}} = \frac{\mathrm{Sf}_{\alpha}}{\mathrm{D}} \cdot \delta_{\alpha}(\mathbf{0}) \qquad \dots(9)$$

- at the backside (x = H):

$$\frac{\partial \delta_{\alpha}(\mathbf{x})}{\partial \mathbf{x}}\Big|_{\mathbf{x}=H} = -\frac{\mathbf{Sb}_{\alpha}}{\mathbf{D}} \cdot \delta_{\alpha}(\mathbf{H}) \qquad \dots (10)$$

Sb is the back surface recombination velocity and Sf is the junction dynamic velocity; the more carrier flow through the junction the more  $S_f$  is. That is  $S_f$  traduces the carrier flow through the junction and is then directly related to the external load conditions<sup>9</sup>.

### 2.2 Photocurrent

The photocurrent density is given by the following relation:

$$J_{ph} = q \cdot D \cdot \frac{\partial \delta(x)}{\partial x} \Big|_{x=0} \qquad \dots (11)$$

where q is the elementary charge.

## 2.3 Photovoltage

Since the excess minority carrier density is known from Boltzmann relation, we can derive the photovoltage across the junction as:

$$V_{\rm ph} = \frac{k.T}{q} \cdot \ln\left(\frac{N_B.\delta(0)}{n_i^2} + 1\right) \qquad \dots (12)$$

 $V_{\rm T}$  is the thermal voltage and  $n_{\rm i}$  is the intrinsic carrier concentration.

# 2.4 Series Resistance

Based on previous works<sup>10</sup>, the equations giving series resistance is expressed as:

$$Rs_{\alpha}(t, B, \omega, Sf, m, Nb) = \frac{Vco_{\alpha}(t, B, \omega, m, Nb) - Vph_{\alpha}(t, B, \omega, Sf, m, Nb)}{Jph_{\alpha}(t, B, \omega, Sf, m, Nb)} \dots (13)$$

## 2.5 Shunt Resistance

Based on previous works<sup>10</sup>, the equations giving shunt and resistance is expressed as:

$$Rsh_{\alpha}(t, B, \omega, Sf, m, Nb) = \frac{Vph_{\alpha}(t, B, \omega, Sf, m, Nb)}{Jcc_{\alpha}(t, B, \omega, m, Nb) - Jph_{\alpha}(t, B, \omega, Sf, m, Nb)} \dots (14)$$

# **3 Results and Discussion**

### 3.1 Diffusion coefficient

Diffusion constant  $D^*$  is represented versus frequency modulation (semi logarithmicscale) as shown in Fig. 2.

The diffusion coefficient remain practically independent of modulation frequency: It is the quasistatic operation of the photovoltaic cell. The diffusion coefficient decrease quickly, which shows a strong dependence as compared to the modulation frequency. Indeed, more the photovoltaic cell is excited in frequency and less the carriers have time to release. This has direct consequence on their difficulty in diffusing through material. It is this difficulty of diffusing which we observe through the reduction in the diffusion coefficient.

The application of a magnetic field reveals a zone where we obtain a resonance peak. This resonance phenomenon is obtained when the modulation



Fig. 2 — Diffusion coefficient versus modulation frequency

frequency is equal to the cyclotron frequency. The magnetic field applied to the photovoltaic cell tends to slow down the electrons coming from the base toward the junction making them deviate from their original paths.

The diffusion coefficient decrease with increasing doping density.

Therefore, we have a reduction of the effective diffusion of the photo generated carriers in the semiconductor. Consequently, to carry out the study under frequency modulation, it is necessary to choose correct defined values of the magnetic field for the optimal answer of the photovoltaiccell.

## 3.2 Photocurrent-Photovoltage

Being given that the photocurrent density and the photovoltage are all junction dynamic velocity Sf function, we can represent them, one versus the other (for example the photocurrent density according to the

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Fig. 3 — Photocurrent-photovoltage curves

photovoltage) and we obtain the photocurrentphotovoltage characteristic of the solar cell (Fig. 3).

In a general way, each one of these characteristics is in concord with the traditional photocurrentphotovoltage characteristic of the solar cell (Fig. 4). The magnetic field reduces strongly the short circuit photocurrent but it is almost without effect on opencircuit photovoltage.

By considering the operating of the solar cell, either in situation of short-circuit or in situation of open circuit, certain parameters like series resistance Rsand shunt resistance Rsh can be deduced.

## 3.3 Series Resistance

The series resistance  $Rs^{10,11}$  is caused by the movement of electrons through the emitter and base of the cell, the contact resistance between the metal



Fig. 4 — Solar cell equivalent circuit near open circuit

contact and the silicon and the resistance of metal grids at the front and the rear of solar cell. For determining the series resistance  $R_s$ , we propose the equivalent electrical model of the solar cell in open circuit (low values of  $S_f$ ) where the solar cell operates

as photovoltage generator associated to series resistance and the external load<sup>7,12-17</sup>  $R_{ch}$ .

The variations of series resistance versus magnetic field for various doping density values are shown in Fig. 5.

For the low values of *B* (0  $T < B < 10^{-5}T$ ), series resistance *Rs* is low and almost constant. The magnetic field causes to increase series resistance: it is the effect of magneto-resistance. This increase in series resistance when the magnetic field increases is



Fig. 5 — Series resistance versus magnetic field for various doping density

due to the fact that the blocking of the minority carriers within material becomes significant due to the presence of magnetic field which causes the reduction in photocurrent. When the base doping density Nb increases, the series resistance decreases and this decrease is more marked for lower magnetic field B values. Effectively, when the base doping density increases, impurities concentration increase also, leading to more and more recombination of excess minority carrier and then a decrease of the series resistance.

## 3.4 Shunt Resistance

resistance<sup>18</sup> shunt is derived from The recombination of the charge carriers by volume at surface and at the interfaces of a solar cell. It models the eddy currents crossing the cell and is also indicative of good or bad quality of a solar cell, because when it is large, the leakage current through the solar cell is low and vice versa. In the present study, for determining the shunt resistance  $R_{\rm sh}$ , it is proposed the equivalent electrical model of the solar cell in short circuit situation where the solar cell is presented as current generator in parallel with the shunt resistance and series with the external charge<sup>12</sup>  $R_{\rm ch}$ . The illustrative model of this device<sup>7,12-17</sup> is shown in Fig. 6.

The variations of shunt resistance versus magnetic field for various doping density values are shown in Fig. 7.

The shunt resistance increases with the magnetic field. Figure 7 shows that the magnetic field causes to increase shunt resistance, this increase is less significant when magnetic field B becomes high. This is explained by the fact that when the magnetic field increases, the number of the deflected and blocked carriers increases too. When the base doping density Nb increases, the shunt resistance decreases and this decrease is more marked for lower magnetic field B



Fig. 6 — Solar cell equivalent circuit near short circuit



Fig. 7 — Shunt resistance versus magnetic field for various doping density

values. Effectively, when the base doping density increases, impurities concentration increase also, leading to more and more recombination of excess minority carrier and then a decrease of the shunt resistance.

## **4** Conclusions

The bifacial solar cell lit by a white light and under magnetic field B external has been studied. From different studies, we could establish that the magnetic field favours the presence of photo generated electrons in the base by inhibiting their diffusion and their conduction. The influence of the magnetic field also has been established on series and shunt resistances resulting from the solar cell electric model. Two resistances increase each one at the same time with the magnetic field.

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