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Three-Dimensional Study of the Effect of the Angle of Incidence of a Magnetic Field on the Electrical Power and Conversion Efficiency of a Polycrystalline Silicon Solar Cell under Multispectral Illumination

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Abstract

A three-dimensional approach to the effect of magnetic field incidence angle on electrical power and conversion efficiency is performed on a front-illuminated polycrystalline silicon bifacial solar cell. A solution of the continuity equation allowed us to present the equations of photocurrent density, photovoltage and electric power. The influence of the angle of incidence of the magnetic field on the photocurrent density, the photovoltage and the electric power has been studied. The curves of electrical power versus dynamic junction velocity were used to extract the values of maximum electrical power and dynamic junction velocity and to calculate those of conversion efficiency. From this study, it is found that the conversion efficiency values increase with the angle of incidence of the magnetic field.

Keywords

Angle of Incidence, Magnetic Field, Electric Power, Bifacial Solar Cell, Conversion Efficiency

1. Introduction

Since the discovery of the photovoltaic solar cell in 1954 by the BELL laboratories, the photovoltaic sector has been presented as an alternative to other energy sectors. It is in this perspective that many researchers have studied the solar cell in order to make it sustainable. The studies were rather directed towards the quality control in company and the study of the performance of the monofacial or bifacial photopiles.

For quality control, John H. Wohlgemuth *et al.* [1] recommend the use of long-term accelerated testing to directly compare current designs with older designs that have achieved long outdoor exposure lifetimes.

Through experimental studies, several researchers have taken the lead. This is the case, for example, of Betser *et al.* [2] who experimentally measured the mobility of minority charge carriers in the base of the InP/GaInAs heterojunction bipolar transistors under a constant magnetic field. They assumed that the direction of the magnetic field was parallel to the surface of the emitter-base junction of the HTB.

As for the performances, some authors have investigated the electrical parameters of monocrystalline or polycrystalline silicon photocells exposed to external constraints. Indeed, several authors [3] [4] [5] [6] have shown the influence of the temperature (heat) on the solar cells. It appears from their study that the excess of light concentration decreases the electrical parameters of the solar cell.

Moreover researchers like Dioari Ulrich Combari *et al.* [7] and [8] [9] studied experimentally the impact of the magnetic field on the polycrystalline solar cells. It emerges from their study a negative influence of the magnetic field on the electrical parameters of the solar cell.

Among these parameters, we can quote the photocurrent density (JPh), the photovoltage (Vph), the electric power (Pél) and the conversion efficiency.

On the other hand, I. SOURABIE *et al.* [10] have shown the correction factor of the magnetic field on the short circuit current, the open circuit voltage and the electric power-voltage characteristics (P-V). Of all these works, no author was interested in the study of the effect of the angle of incidence of the magnetic field on the electrical parameters, such as the electrical power and the conversion efficiency of a bifacial solar cell illuminated with polycrystalline silicon by its front side with a multispectral light.

This is what motivated us as [10] to show theoretically the influence of the angle of incidence of a 3D magnetic field on the characteristics of the photocurrent density, the photovoltage and the electric power. From the characteristics, we will extract the values of the conversion efficiency of the photocell.

2. Theorical Background

The photopile grain used is of type n+-p-p+, it has the same electrical properties as a bifacial silicon photopile [2] [11] [12]. This bifacial cell has a base of type (p) of very great thickness, included between 200 and 400 µm and doped in acceptor atoms 10^{15} à 10^{17} cm^{-3} [2] [3] [6] which is the seat of generation, recombination and diffusion phenomena.

The bifacial photocell is shown in Figure 1 below.

- The crystalline field is zero in the base of the solar cell [3] [4] [6] [7] because we work in the theory of the quasi-neutral base.
- Light penetration occurs along the axis perpendicular to the junction (OZ) and the generation of excess minority charge carriers [4] [13].
- The contribution of the back side is not taken into account.
- The external magnetic field is constant and makes an angle with the axisOy [2] [3] [12].
- The surface area of the grain is square where gx = gy.

When the photocell is under multispectral illumination, the transport phenomena in the base of the photocell are governed by the continuity equation below [4]:

$$\frac{\partial^2 \delta(x,y,z)}{\partial x^2} + C_y \cdot \frac{\partial^2 \delta(x,y,z)}{\partial y^2} + \left[1+\left(\mu_n B_0 \sin\theta\right)^2\right] \frac{\partial^2 \delta(x,y,z)}{\partial z^2} - \frac{\delta(x,y,z)}{L_n^{*2}} = -\frac{G(z)}{D_n^*} \quad (1)$$

with $C_y = \left[1+\left(\mu_n B_0 \sin\theta\right)^2\right]$, $D_n^* = \frac{D_n}{1+\left(\mu_0 B_0\right)^2}$ and $L_n^* = \frac{L_n}{1+\left(\mu_0 B_0\right)^2}$ are respectively the diffusion coefficient and the diffusion length depending on the magnetic field.

A general solution of Equation (1) is in the form:

$$\delta(x,y,z) = \sum_j^{\infty}\sum_k^{\infty}\left[A_{j,k}\cosh\left(\frac{z}{L_{j,k}}\right) + B_{j,k}\sinh\left(\frac{z}{L_{j,k}}\right) - \sum_{i=1}^{3} K_i \cdot e^{-b_i z}\right] \quad (2)$$

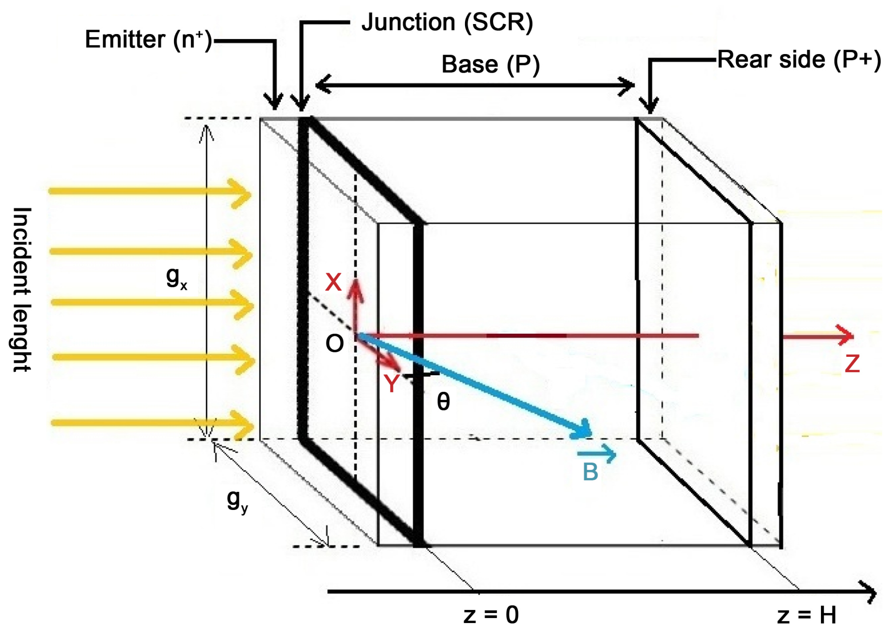

Figure 1. Photocell grain illuminated by the front face in the presence ofan external magnetic field.

with

$$K_i = \frac{n \cdot a_i \cdot L_{j,k}^2}{D_{j,k} \cdot \left[\left(b_i \cdot L_{j,k} \right)^2 - 1 \right]} \quad (3)$$

The coefficients $A_{j,k}$ and $B_{j,k}$ are determined using the boundary conditions at the junction and at the back side of the base below:

- At the junction ($z = 0$):

$$\left. \frac{\partial \delta(x,y,z)}{\partial z} \right|_{Z=0} = \frac{S_f}{D^*} \cdot \delta(x,y,0) \quad (4)$$

- On the back side ($z = H$):

$$\left. \frac{\partial \delta(x,y,z)}{\partial z} \right|_{Z=H} = -\frac{S_b}{D^*} \cdot \delta(x,y,H) \quad (5)$$

S_b is the recombination rate at the backside of the cell. Sf is the dynamic velocity at the junction. It reflects the quantity of carriers arriving at the junction [7] [8] [9]. Sf is the sum of two speeds such that $Sf = Sf_j + Sf_0$. Sf_0 is the intrinsic recombination rate induced by the shunt resistance. It will be taken equal to zero because solar cell is ideal.

Sf_j translates the current flow induced by the external load and defines the operating point of the solar cell [6].

The expression of the photocurrent density when the polycrystalline cell is illuminated from the front is given by Equation (6) [4]:

$$J_{Ph}(Sf, B, \theta) = \frac{q \cdot D_n(\theta)}{g_x \cdot g_y} \int_{-\frac{g_y}{2}}^{\frac{g_y}{2}} \int_{-\frac{g_x}{2}}^{\frac{g_x}{2}} \left[\frac{\partial \delta(x,y,z)}{\partial z} \right]_{z=0} \mathrm{d}x\mathrm{d}y \quad (6)$$

Also the expression of the hotovoltage is obtained by the Equation (7) which translates the Boltzmann relation:

$$V_{Ph}(Sf, B, \theta) = V_T \cdot \ln \left[1 + \frac{1}{n_0} \int_{-\frac{g_y}{2}}^{\frac{g_y}{2}} \int_{-\frac{g_x}{2}}^{\frac{g_x}{2}} \delta(x,y,0) \mathrm{d}x\mathrm{d}y \right] \quad (7)$$

V_T is the thermal voltage of value $V_T = 26\ \mathrm{mV}$ at absolute temperature $T = 300\ \mathrm{K}$.

n_0 represents the density of electrons at thermodynamic equilibrium. For silicon $n_0 = 10^4\ \mathrm{cm}^{-3}$.

The resolution of the Equation (7) allows to determine completely the photovoltage for an illumination in front of the solar cell. Its expression is:

$$V_{ph}(Sf, B, \theta) = V_T \cdot \ln \left[1 + \frac{1}{n_0} \sum_j \sum_k R_{jk} \cdot \left[A_{jk} - \sum_{i=1}^{3} K_i \right] \right] \quad (8)$$

with

$$R_{jk} = \frac{4 \cdot \sin\left(C_{xj} \cdot \frac{g_x}{2}\right) \cdot \sin\left(C_{yk} \cdot \frac{g_y}{2}\right)}{C_{xj} \cdot C_{yk}} \tag{9}$$

The equation of electrical power is given by [4]:

$$P(Sf, B, \theta) = V_{Ph}(Sf, B, \theta) \cdot J_{Ph}(Sf, B, \theta) \tag{10}$$

Thus, the conversion efficiency of a solar cell is the ratio of the maximum electrical power supplied by the solar cell to the external circuit and the incident light flux received by the solar cell [4]. His expression is:

$$\eta(Sf, B, \theta) = \frac{P_{el}(Sf, B, \theta)_{\max}}{P_{inc}} \tag{11}$$

3. Results and Discussion

3.1. Effect of the Angle of Incidence of the Magnetic Field on the Photocurrent Density

In **Figure 2**, we plot the photocurrent density versus dynamic velocity curves at the junction for different values of the magnetic field incidence angle.

It is noticed in **Figure 2** that the current produced by the polycrystalline cell increases when the value of the angle of incidence increases. The increase of the current with the angle of incidence shows that more carriers cross the junction. This behavior of the photocurrent density is due to the fact that the increase of the angle of incidence of the magnetic field intensity leads to a decrease of the Lorentz force and its effect until it is cancelled [4]. So many carriers migrate to

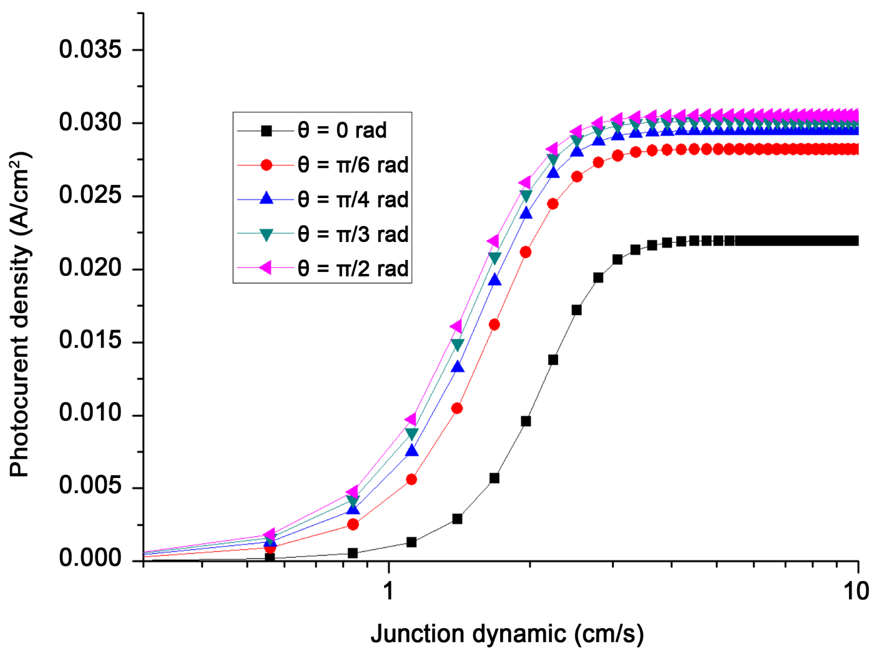

Figure 2. Photocurent density versus junction dynamic velocity for different values of incidence angle ($B = 7.5$ mT; $g_x = g_y = 0.003$ cm; $S_{gb} = 100$ cm/s; $S_b = 1000$ cm/s; $L = 0.015$ cm; $H = 0.03$ cm; $D_n = 26$ cm²/s; $\mu_n = 1000$ cm²/V·s).

the junction in order to cross it and participate in the external current. Thus, it can be seen that for small ($Sf \leq 1.581$ cm/s) and large ($Sf \leq 5000$ cm/s) values of the dynamic velocity at the junction the photocurrent density curves show plateaus that allow us to extract the values of the dynamic velocity initiating (Sf_{cc}) the short circuit and the open circuit (Sf_{co}). We record in **Table 1** the values of and for different values of the angle of incidence of the magnetic field.

It appears from this **Table 1** that the values of the dynamic velocity initiating the short circuit (Sf_{cc}) increase with the angle of incidence while those of the dynamic velocity initiating the open circuit (Sf_{co}) decrease.

The analysis of the values in the table shows that when the angle of incidence of the magnetic field increases from 0 rad to π/2 rad, the effect of the Lorentz force decreases until it is cancelled and the photocell returns to its operation without a magnetic field. But the effect of the disturbance caused by the magnetic field always remains, *i.e.* the precipitated effect of the establishment of the short circuit [10].

3.2. Effect of the Angle of Incidence of the Magnetic Field on the Photovoltage

We present in **Figure 3** the variations of the photovoltage as a function of the dynamic velocity at the junction for different values of the incident angle.

Table 1. Dynamic velocity at the junction initiating the short circuit and the open circuit for different values of the angle of incidence and for illumination from the front of the photopile.

θ (rad)	0	π/6	π/4	π/3	π/2
Sf_{cc} (cm/s)	5.072×10^3	6.584×10^3	8.5×10^3	11.07×10^3	14.33×10^3
Sf_{co} (cm/s)	13.848	3.508	1.581	1.005	0.599

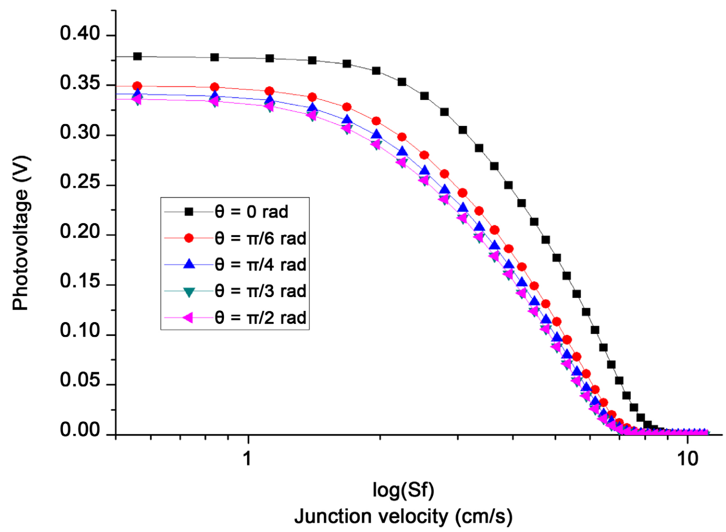

Figure 3. Photovoltage versus junction dynamic velocity for different values of incidence angle ($B = 7.5$ mT; $g_x = g_y = 0.003$ cm; $S_{gb} = 100$ cm/s; $S_b = 1000$ cm/s; $L = 0.015$ cm; $H = 0.03$ cm; $D_n = 26$ cm²/s; $\mu_n = 1000$ cm²/V·s).

Figure 3 shows that for a given value of the angle of incidence, the photovoltage has a plateau at low values of the dynamic speed at the junction (open circuit situation) and it cancels at high values of the dynamic speed at the junction (short circuit situation). The short circuit is the place where the photocell delivers a zero voltage and a maximum current. Also the figure shows that the photovoltage decreases as the angle of incidence increases. In addition studies [10] have shown that the increase in magnetic field leads to an increase in the storage of charge carriers near the junction.

However, the increase in the angle of incidence of the magnetic field from 0 of π/2 reduces the effect of the magnetic field on the charge carriers photogenerated in the base leading to the decrease in the concentration of minority carriers in the base. As the open circuit voltage is related to the concentration of carriers near the junction then increasing the angle of incidence of the magnetic field leads to the decrease of the open circuit voltage in the range [0, π/2 rad].

3.3. Effect of the Angle of Incidence on the Electrical Power

The variations of the electrical power versus dynamic velocity curves at the junction are shown in **Figure 4**.

The curves in **Figure 4** show that the electrical power delivered by the solar cell to the external load is zero in the open circuit and short circuit situation. Also it is noticed whatever the value of the angle of incidence of the magnetic field, the electrical power increases to reach its maximum at an intermediate operating point and then decreases until it is cancelled. It also appears that when the angle of incidence increases, the maximum power increases and the operating point towards the open circuit. These are due to the effect that the magnetic field has on the charge carriers. This is because it is able to deflect them from their trajectories and block them near the junction [3] [5] [8] [10]. So, the decrease of the effect of the magnetic field thanks to the increase of the angle of incidence results in a greater presence of the charge carriers in the base, a greater mobility of the carriers towards the junction, an increase of the current but a slight decrease of the voltage and consequently an increase of the electric power produced.

From the curves of **Figure 4**, we were able to extract the values of the maximum electrical power, and the dynamic speed at the point of maximum power and finally calculate the values of the conversion efficiency using Equation (11).

This **Table 2** shows an increase in power and conversion efficiency, a decrease in the dynamic speed at the junction with the increase of the angle of incidence. This observation is the consequence of the decrease of the effect of the magnetic field on the movement of the electrons. Indeed, the dynamic velocity at the junction characterizing the flow of carriers that diffuses per unit time through the junction, when the magnetic field decreases, the accumulation of carriers near the junction decreases and therefore the number of carriers that diffuse through the junction decreases. This phenomenon explains the decrease of the dynamic

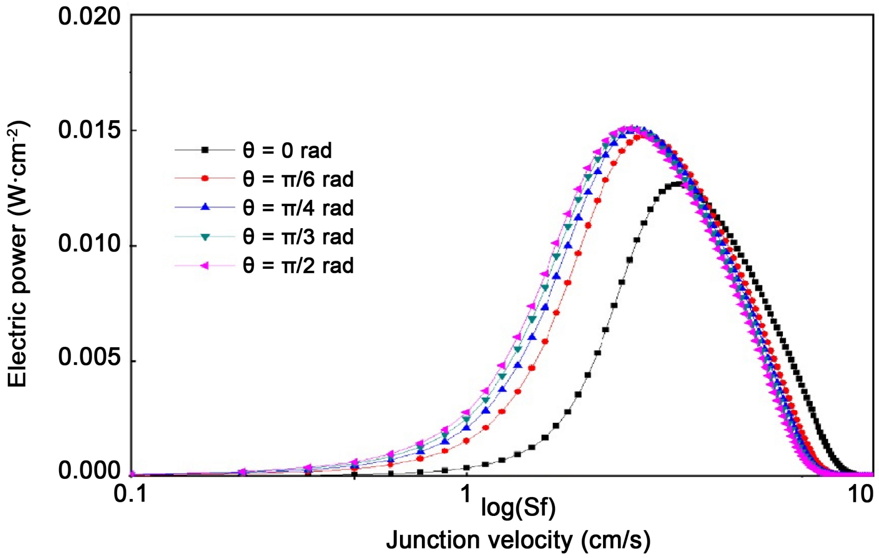

Figure 4. Electric power versus junction dynamic velocity for different values of incidence angle ($B = 7.5$ mT; $g_x = g_y = 0.003$ cm; $S_{gb} = 100$ cm/s; $S_b = 1000$ cm/s; $L = 0.015$ cm; $H = 0.03$ cm; $D_n = 26$ cm^2/s; $\mu_n = 1000$ cm^2/V·s).

Table 2. Maximum power, dynamic velocity at the junction at the point of maximum power and bifacial conversion efficiency for different values of the angle of incidence and for illumination from the front.

θ (rad)	0	π/6	π/4	π/3	π/2
P_{max} (mW/cm^2)	12.637	14.745	15.021	15.070	15.077
Sf_{MPP} (cm/s)	3000	602.853	458.910	348.677	348.677
η (%)	12.637	14.745	15.021	15.070	15.077

velocity at the junction with the increase of the angle of incidence.

4. Conclusions

In this paper, a three-dimensional modeling of the effect of the angle of incidence of the magnetic field on the electrical power and conversion efficiency of the photocell was analyzed.

The study showed that when the angle of incidence of the magnetic field increases from $\theta = 0$ rad to $\theta = \frac{\pi}{2}$ rad, the dynamic velocities initiating the open circuit (Sf_{co}) and the short circuit (Sf_{cc}) increase justifying the decrease of the Lorentz force until it is cancelled. Consequently, the voltage decreases and the current increases.

Also, the maximum power (P_{max}) and the dynamic speed at the junction at the point of maximum power (Sf_{MP}) were determined through the curve of electrical power versus dynamic speed at the junction for different values of the angle of incidence of the magnetic field. Thus, it appears that when the angle of incidence increases, the maximum power, the dynamic velocity at the junction and the conversion efficiency of the solar cell increase.

This analysis allows us to conclude that the harmful effect of the magnetic field can be corrected by arranging the photopile so that the field lines arrive perpendicular to the junction.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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