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Research Article

Performance Analysis of a Photovoltaic Cell Under a Magnetic Field Considering Thermal Effects Induced by Excess Charge Carrier Mobility

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Abstract

In this article, we present a theoretical study of the electrical performance of a photovoltaic cell subjected to a magnetic field, taking into account the thermal effects induced by the mobility of excess charge carriers within the cell. When a solar cell is illuminated, several phenomena occur, such as the generation, diffusion, and recombination of charge carriers. All these phenomena are governed by the charge conservation equation known as the continuity equation for the density of excess minority carriers. Solving the continuity equation for front-side illumination in the frequency regime allowed us to obtain analytical expressions for the photocurrent density and the photovoltaic voltage. These expressions were then used to evaluate the electrical performance of the proposed model. The results show that the maximum power (Pmax), open-circuit voltage (Voc), fill factor (FF), and conversion efficiency initially increase with the magnetic field strength, reaching a maximum value before decreasing. In contrast, the short-circuit current density (Jsc) exhibits an inverse trend. Furthermore, the diffusion coefficient remains constant for low values because the system is in steady state. It decreases with the logarithm of the magnetic field. This decrease is explained by the fact that an increasing magnetic field generates a force called the Lorentz force, which slows the movement of charge carriers and therefore prevents them from moving within the basis.

Keywords

Electrical Performance, Magnetic Field, Thermal Effect, Photovoltaic Cell

1. Introduction

The performance of photovoltaic cells depends on several factors, including electronic parameters such as carrier lifetime and diffusion length, as well as electrical parameters such as series and shunt resistances, photovoltage, photocurrent, and the current–voltage (I–V) and power–voltage (P–V) characteristics [1-3]. In addition to these intrinsic parameters, environmental conditions [4, 5] and external factors, such as magnetic fields [5] and electric fields [4], also play a significant role. In particular, these factors can affect the energy conversion process [6] and, consequently, the overall efficiency of the cell.

One of the major challenges in photovoltaic devices is the limited collection of minority charge carriers during their diffusion process. This limitation may be attributed to several factors, including the diffusion length, carrier mobility, and

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the recombination of photogenerated minority carriers, both at the surface and within the bulk of the semiconductor material [6, 7].

To gain a better understanding of these effects and improve the control of photovoltaic performance, this work presents a study of the electrical performance of a photovoltaic cell subjected to a magnetic field, taking into account the thermal effects induced by the mobility of excess charge carriers. The analysis is carried out by examining the influence of these thermal effects on the transport and collection mechanisms of charge carriers within the cell.

2. Theory

Consider a bifacial silicon photovoltaic cell subjected to a magnetic field and illuminated by monochromatic light on its front surface. Its structure is shown in Figure 1.

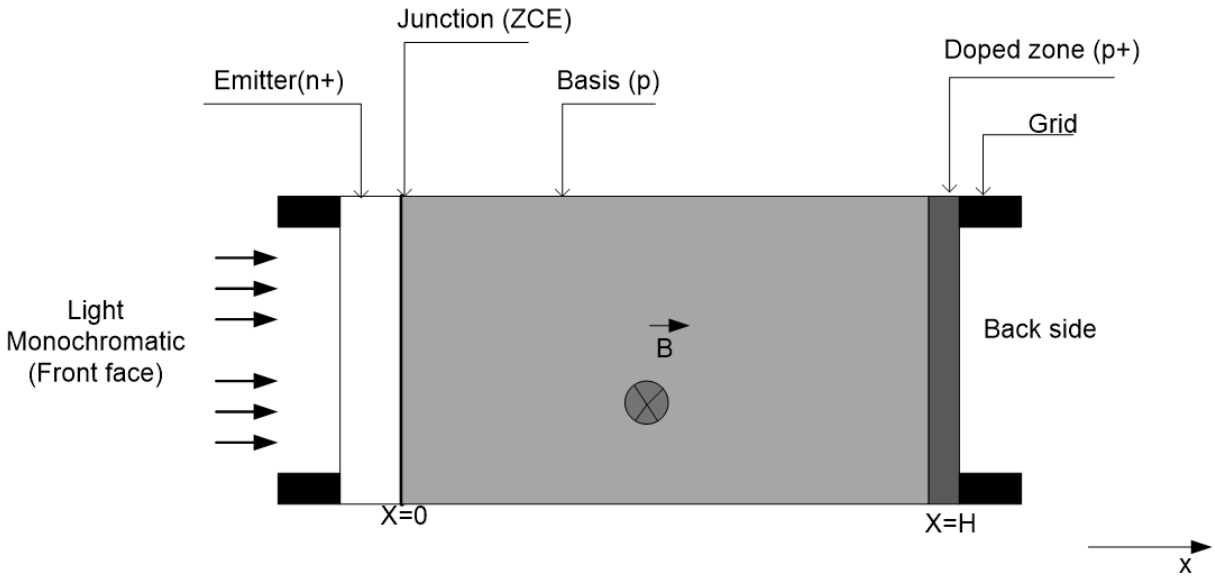

Figure 1. *Schematic structure of a bifacial silicon solar cell under the effect of a magnetic field.*

2.1. Continuity Equation

When a solar cell is illuminated, several phenomena occur within it, including the generation, diffusion, and recombination of charge carriers. These processes are governed by the charge conservation equation, also known as the continuity equation for the excess minority carrier density [8-11]:

$$D^*(B,w)\frac{\partial^2\delta(x,t,\omega,B)}{\partial x^2}-\frac{\delta(x,t,\omega,B)}{\tau}=-G(x,t)+\frac{\partial\delta(x,t,\omega,B)}{\delta t} \quad (1)$$

With:

$D^*(B,w)$ is called the complex diffusion coefficient as a function of the magnetic field. It is expressed by [8, 10]:

$$D^*(B,w)=\frac{D_O\left[\left(1+\tau^2\left(\omega_f^2(B)+\omega^2\right)\right)+i\omega\tau\left(\left(\omega_f^2(B)-\omega^2\right)-1\right)\right]}{4\tau^2\omega^2+\left(1+\tau^2\left(\omega_f^2-\omega^2\right)\right)} \quad (2)$$

et

$$\omega f=\frac{e.B}{m} \quad (3)$$

$D^*(B,w)$: complex diffusion coefficient as a function of frequency and magnetic field; ω: angular frequency in rad/s; ωf: cyclotron frequency in rad/s; τ: minority carrier lifetime in the base of the photovoltaic cell; D_0: diffusion coefficient of electrons generated in the base; e: electron charge; B: magnetic field and m: the mass of the electron [10, 11].

$\delta(x,t)$: is the density of minority carriers in the base which can be written in the form [9, 3]:

$$\delta(x,t)=\delta(x)e^{-i\omega t} \quad (4)$$

With

$\delta(x)$ as the spatial component and $e^{-i\omega t}$ as the temporal component.

$G(x,t)$: is the optical generation rate given by the following expression [9, 3]:

$$G(x,t)=G(x)e^{-i\omega t} \quad (5)$$

With $G(x)$ as the spatial component and $e^{-i\omega t}$ as the temporal component.

For front-facing illumination, we have [9, 3]:

$$G(x)=\alpha(\lambda)\phi(\lambda)(1-R(\lambda))e^{-\alpha(\lambda)x} \quad (6)$$

By substituting expressions (5), (6), and (7) into equation (1), we obtain the following equation:

$$\frac{\partial^2 \delta(x)}{\partial x^2} - \frac{(1+i\omega\tau)\delta(x)}{L^2} + \frac{G(x)}{D^*(B,w)} = 0 \quad (7)$$

yeah:

$$\frac{\partial^2 \delta(x,\omega,B,S_f)}{\partial x^2} - \frac{\delta(x,\omega,B,S_f)}{{L_\omega^*}^2} + \frac{G(x)}{D^*(B,w)} = 0 \quad (8)$$

with

$$\frac{1}{{L_\omega^*}^2} = \frac{(1+i\omega\tau)}{L^2} \quad (9)$$

et

$$L^{*2}(B,w,) = \tau D^*(B,w) \quad (10)$$

${L_\omega^*}^2$: complex diffusion length [14].

The expression for the charge carrier density is given by the following relation [8].

$$\delta(x,\omega,B,S_f) = A_1 \cosh\left(\frac{x}{L}\right) + A_2 sinh\left(\frac{x}{L}\right) + Ke^{-\alpha(\lambda)x} \quad (11)$$

With

$$K = \frac{-\alpha(\lambda)\phi(\lambda)(1-R(\lambda))L^2(\omega)}{D^*(B,w)(1-L^2(\omega))\alpha^2(\lambda))} \quad (12)$$

2.2. Conditions to the Limits

For the determination of the constants A_1 *and* A_2, we will use the boundary conditions below [9]:

On the front face of the junction, we have:

$$\left.\frac{\partial\delta(x,\omega,B,S_f)}{\partial x}\right|_{x=0} = \left.\frac{S_f\delta(x,\omega,B,S_f)}{D(\omega,B)}\right|_{x=0} \quad (13)$$

On the rear face of the photocell, we have:

$$\left.\frac{\partial\delta(x,\omega,B,S_f)}{\partial x}\right|_{x=H} = \left.\frac{-S_b\delta(x,\omega,B,S_f)}{D(\omega,B)}\right|_{x=H} \quad (14)$$

Where S_f and S_b are the recombination speeds at the junction and the back side, respectively.

2.3. Photocurrent Density

The photocurrent density is obtained by differentiating the expression for the minority carrier density, as given by the expression below [15]:

$$J_{ph}(T,\omega,B,S_f,S_b) = eD^* \left.\frac{\partial\delta(x,,\omega,B,S_f)}{\partial x}\right|_{x=0} \quad (15)$$

2.4. Photovoltage at the Junction

Boltzmann's law allows us to express the photovoltaic across the junction as a function of the density of minority charge carriers at the junction (x = 0) of the photovoltaic cell.

The expression of phototension is:

$$V_{ph} = V_T \ln\left(1 + \left.\frac{N_b\delta(x,,\omega,B,S_f)}{n_i^2}\right|_{x=0}\right) \quad (16)$$

With

N_b: the doping rate of the base (Nb=10^{16}cm^{-3}); n_i^2: the intrinsic density of minority shareholders n_i^2=10^{10}cm^{-3}; V_T: thermal tension; K: Boltzmann's constant; e: the charge of the electron; T: the absolute temperature at thermal equilibrium (T=300°K) [1].

2.5. Form Factor

The form factor is given by the following expression:

$$FF = \frac{P_{ph_{max}}}{Voc*Jsc} \quad (17)$$

V_{oc}: open circuit voltage; J_{sc}: short-circuit current; $P_{ph_{max}}$: maximum electrical power.

2.6. Electric Power

The electrical power of the photovoltaic cell through its front face is given by the following relationship:

$$P_{ph} = J_{ph} * V_{ph} \quad (18)$$

2.7. Yield

The yield of a cell is given by the following expression::

$$Rendement = \frac{P_{ph_{max}}}{P_{inc}} \quad (19)$$

P_{inc}: is the power of the incident luminous flux and is equal to 1000 W/m^2 under standard air mass conditions 1.5.

3. Results and Discussion

The profile of the maximum diffusion coefficient as a function of the magnetic field is shown in Figure 2 below.

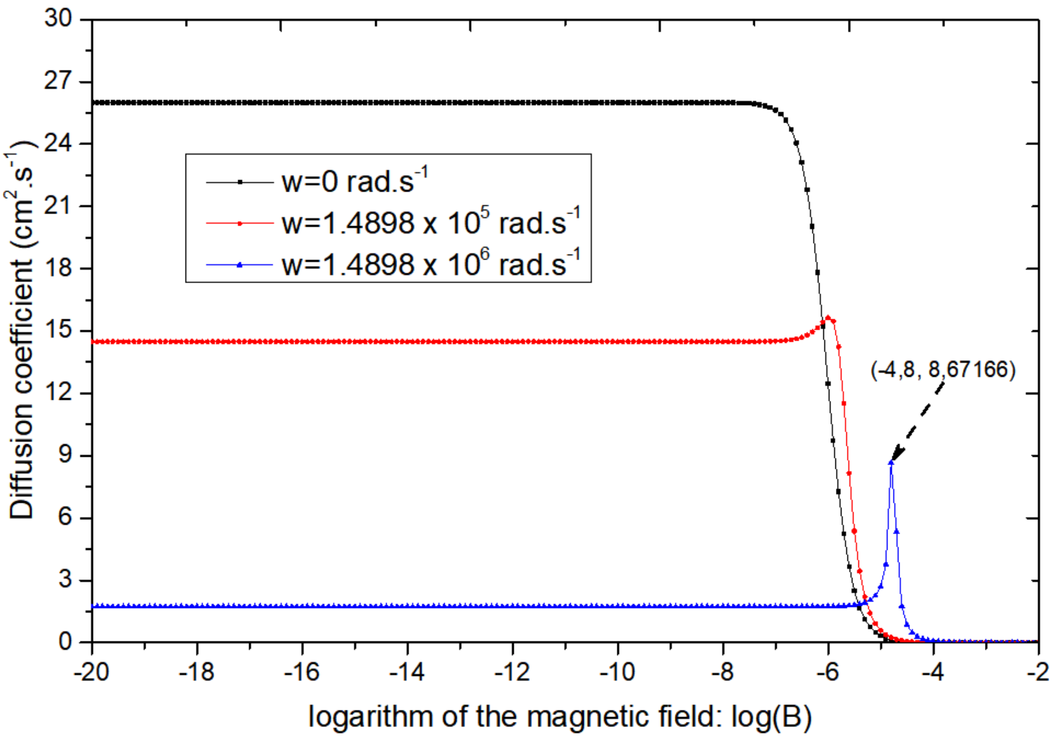

Figure 2. Maximum diffusion coefficient as a function of the magnetic field.

Figure 2 shows the diffusion coefficient profile as a function of the magnetic field. It is obtained after programming expression (2) in Matlab. For the curves where w=0 rad/s and w=1.4898 x 10^5 rad/s, the diffusion coefficient is constant for low values and decreases as a function of the logarithm of B.

For w=1.4898 x 10 ^{6} rad/s the constant diffusion coefficient for low values of B increases up to a maximum value and decreases as a function of log(B).

The nearly constant behavior observed at low magnetic field values for different frequencies can be explained by the fact that the cell operates under steady-state conditions. The subsequent decrease in the diffusion coefficient is attributed to the influence of the magnetic field, which exerts a Lorentz force on the charge carriers. As the magnetic field strength increases, carrier motion is increasingly hindered, reducing their mobility within the base region. This reduction in the diffusion coefficient degrades the intrinsic properties of the solar cell, particularly by affecting the carrier transport mechanisms and the energy band structure [12, 13].

Furthermore, the diffusion coefficient decreases as the angular frequency increases.

Table 1 is obtained after programming the above equations in the Matlab software. These values represent the maximum values of open circuit voltage (Voc), short circuit current (Jsc), maximum electrical power (Pmax), form factor (FF) and efficiency (Rend) for different magnetic fields.

Table 1. Electrical parameters as a function of the magnetic field.

B(T)	Voc (V)	Jsc (A/cm^2)	FF	Pmax (W/cm^2)	Rend
1.00E-06	0.5680	0.0421	0.8322	0.0199	0.1989
1.00E-05	0.5788	0.0421	0.8344	0.0203	0.2031
2.00E-05	0.5788	0.042	0.8344	0.0203	0.2030
2.50E-05	0.5781	0.042	0.8343	0.0203	0.2027
5.00E-05	0.6099	0.0407	0.8402	0.0209	0.2086
7.00E-05	0.5716	0.0419	0.8329	0.0200	0.1995

The profile of open-circuit voltage (Voc), short-circuit current (Jsc), maximum electrical power (Pmax), form factor (FF) and efficiency (Rend) as a function of different magnetic fields, is shown in Figure 3 below:

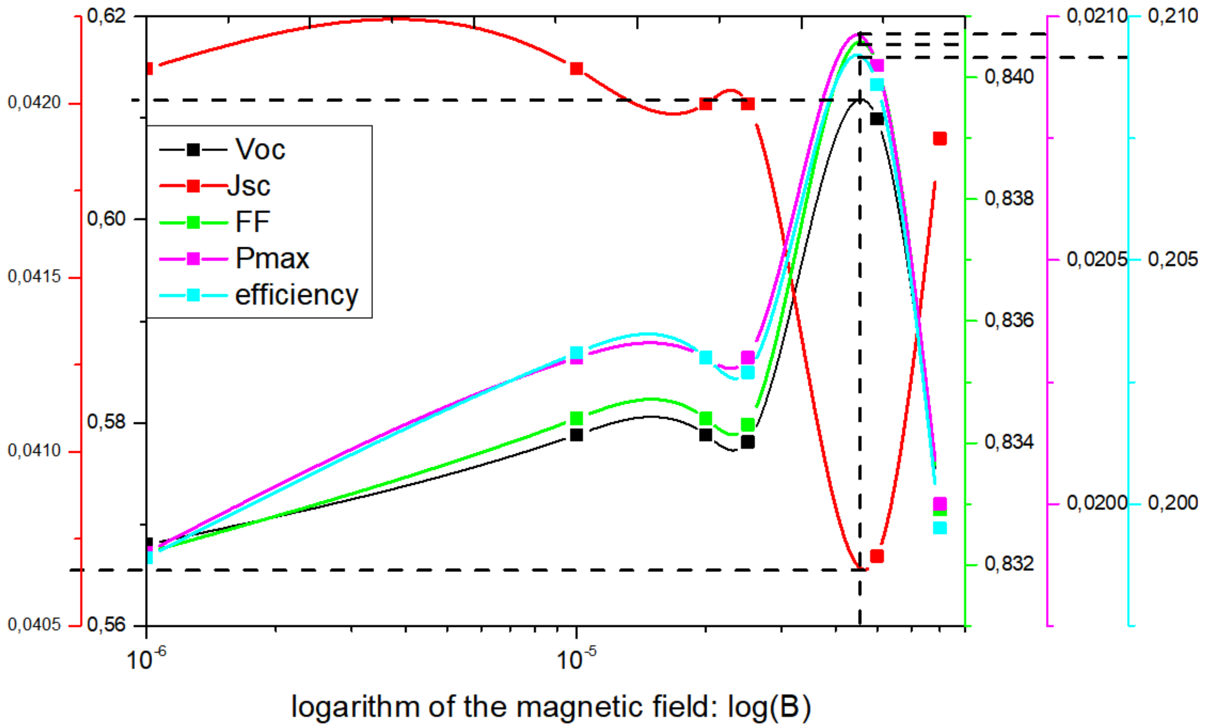

Figure 3. *Voc, Pmax, FF, efficiency, Jsc as a function of the magnetic field. B=5.0× 10-5 T.*

Figure 3 shows the profiles of open-circuit voltage (Voc), short-circuit current (Jsc), maximum electrical power (Pmax), form factor (FF), and efficiency (Rend) as a function of different magnetic fields. These curves show that Voc increases up to a maximum value corresponding to $B = 5.0 \times 10^{-5}$ T and then decreases as the magnetic field B increases, and conversely for Jsc. This is explained by the fact that the Lorentz force, perpendicular to the magnetic field, deflects the movement of minority charge carriers from their trajectory. The stronger the magnetic field, the slower the movement of the charge carriers becomes. This slowing leads to an increase in the storage of carriers near the junction, thus resulting in an increase in the open-circuit voltage (Voc) [16].

Maximum power (Pmax), form factor (FF) and efficiency decrease with increasing magnetic field strength. However, current intensities (Jsc and Jmax) decrease sharply, even for slight increases in the various voltages when the magnetic field strength increases [17, 18].

4. Conclusion

At the end of this work, we determined the electrical performance of a photovoltaic cell as a function of the magnetic field. This study allowed us to show that the open-circuit voltage increases until it reaches a maximum value before decreasing as the magnetic field intensifies, while the short-circuit current exhibits an inverse trend.

Furthermore, other electrical parameters, such as maximum power, form factor and efficiency, decrease as the magnetic field increases.

Abbreviations

ZCE	Space Charge Zone
J_{sc}	Short Circuit Current
V_{oc}	Open-circuit Voltage
FF	Form Factor
P_{max}	Maximum Electrical Power
ωf	Cyclotron Frequency
ω	Angular Frequency
Sf	Recombination Velocity at the Junction
Sb	Recombination Speed on the Rear Side
J_{ph}	Photocurrent Density
Rend	Efficiency
$D^*(B,w)$	Complex Diffusion Coefficient as a Function of the Magnetic
Jmax	Maximum Current
B	Magnetic Field
N_b	The Doping Rate of the Base (Nb=10^{16}cm^{-3})
n_i^2	The Intrinsic Density of Minority Shareholders n_i^2=10^{10}cm^{-3}
V_T	Thermal Tension
K	Boltzmann's Constant
e	The Charge of the Electron
T	The Absolute Temperature at Thermal Equilibrium (T=300 °K)
V_{ph}	Photovoltage
x	Base Depth
$\alpha(\lambda)$	Optical Absorption Coefficient as a Function of Wavelength

$\phi(\lambda)$	Incident Photon Flux
$R(\lambda)$	Reflection Coefficient as a Function of Wavelength
L(ω)	Broadcast Length
H	Base Thickness

Author Contributions

Ousmane Thiam: Conceptualization, Resources, Methodology

Mor Ndiaye: Conceptualization, Validation, Supervision

Gaye Kharma: Visualization

Pape Gueye Ndiaye: Software

Issa Diagne: Writing – original draft

Conflicts of Interest

The authors declare that they did not receive any financial assistance from any company or organization for the publication of this article. They confirm that there are no conflicts of interest related to the preparation of this study. The study was conducted independently.

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