World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(RESEARCH ARTICLE)

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STUDY AND OPTIMIZATION OF THE EFFICIENCY OF A VERTICAL-JUNCTION SILICON SOLAR CELL IN SERIES UNDER A MAGNETIC FIELD IN STEADY STATE

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World Journal of Advanced Research and Reviews, 2026, 31(02), 1191–1199

Publication history: Received on 14 July 2026; revised on 20 August 2026; accepted on 22 August 2026

Article DOI: https://doi.org/10.30574/wjarr.2026.31.2.2196

ABSTRACT

This article presents a theoretical study of a vertical-junction silicon solar cell in steady state under polychromatic illumination and subjected to an external magnetic field. After solving the magnetotransport equation for minority charge carriers in the base using the boundary conditions applied at the junctions and in the rear region, the expressions for the photovoltage, electrical power, and conversion efficiency of the photovoltaic cell are determined as functions of the magnetic field and the optimal thickness of the base. The current-voltage and power-voltage characteristics are studied for several values of the applied magnetic field. Finally, the photovoltaic cell's efficiency is studied as a function of the optimal base thickness obtained based on the applied magnetic field. This study shows a linear correlation between these two parameters.

Keywords: Silicon photovoltaic cell, Vertical series junctions, Steady state, Magnetic field, Optimal thickness, Conversion efficiency.

1 INTRODUCTION

To improve the photovoltaic conversion efficiency of series vertical junction solar cells, it is important to characterize the semiconductor material used.

Measuring the phenomenological parameters [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], namely lifetime (τ), diffusion coefficient (D), and diffusion length (L), as well as surface recombination (Sf and Sb) under slight optical [11] or electrical [12] excitation, allows for the definition and optimization of the solar cells in order to improve photovoltaic conversion efficiency.

In this study, the power output of a series vertical-junction photovoltaic cell subjected to a magnetic field under polychromatic illumination in a steady-state condition is determined for each value of the optimal base thickness, which is determined by the value of the applied magnetic field. Finally, the variation in the cell's efficiency as a function of the optimal base thickness is examined.

2 THEORETICAL MODELING

2.1 Description of the Structure

Vertical multi-junction solar cells, also known as edge-illuminated solar cells, consist of a number of non-monolithic junctions illuminated from the edges and connected in series [13], [14], [15].

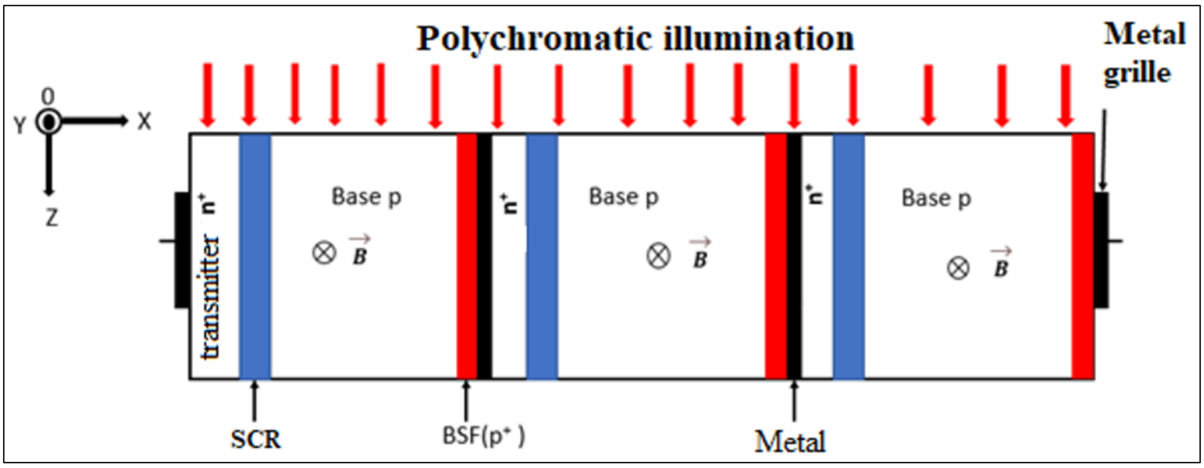

Figure 1: Schematic diagram of a vertical-junction solar cell in series under polychromatic illumination and in a magnetic field.

Figure 2 shows a schematic diagram of a vertical-junction series photovoltaic cell placed in a magnetic field and exposed to polychromatic illumination.

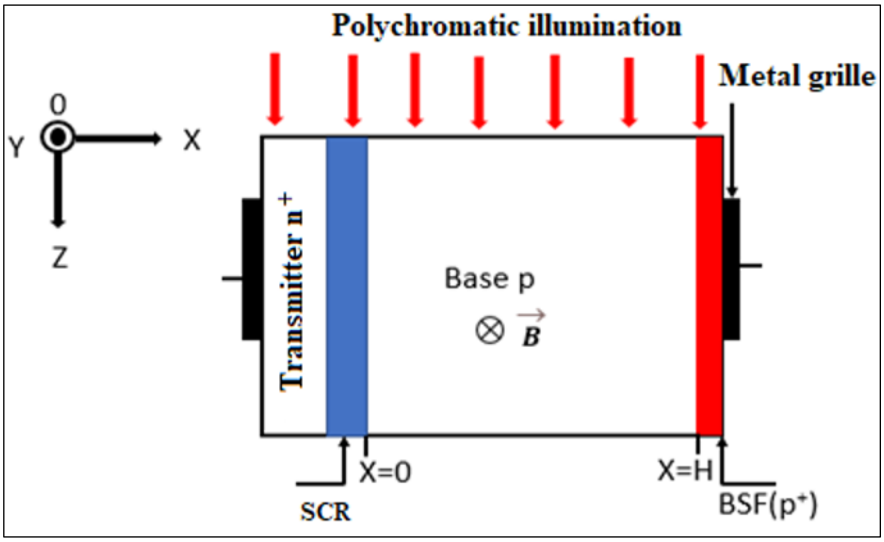

Figure 2: Schematic of a vertical-junction series photovoltaic cell placed in a magnetic field and under polychromatic illumination.

These different parts are:

The emitter (n+ region): It is heavily doped with donor atoms, with an impurity concentration ranging from 10^{17} to 10^{19} atoms/cm^3, and has a very small thickness.

The base (p-region): This region is lightly doped with acceptor atoms, with an impurity concentration ranging from 10^{15} to 10^{17} atoms/cm^3, but its thickness is much greater than that of the emitter. Being p-type, this part of the structure exhibits an electron deficiency (minority carriers). The characteristic analysis of the cell will focus primarily on this region, where absorption, generation, recombination, and diffusion phenomena predominate.

The junction, or space charge region (SCR), which separates electron-hole pairs due to the electric field present there.

Finally, an overdoped region (p+ type) located behind the base creates an electric field that directs the photogenerated carriers near this rear surface back toward the junction (Back Surface Field: BSF).

2.2 Continuity Equation in a Magnetic Field

The processes of generation, diffusion, and recombination of excess minority charge carriers in the base under a magnetic field and under polychromatic illumination are described by an equation known as the continuity equation. It is defined by the expression below.

$$D(B).\frac{\partial^2 \delta(x)}{\partial x^2} - \frac{\delta(x)}{\tau} = -G(z) \qquad (1)$$

$\delta(x)$ is the density of excess photogenerated minority charge carriers in the base of the solar cell.

$D(B)$ is the electron diffusion coefficient in the base in the presence of a magnetic field.

τ is the lifetime of minority carriers in the base; it is defined by the following Einstein relation:

$$\tau = \frac{L^2(B)}{D(B)} \qquad (2)$$

$L(B)$ is the diffusion length of excess minority charge carriers in the base.

The diffusion coefficient $D(B)$of minority carriers in the base [11], [16], [17] is defined as:

$$D(B) = \frac{D_0}{1+(\mu.B)^2} \qquad (3)$$

The expression for the minority carrier generation rate at depth z in the base is given by the following equation:

$$G(z) = n \times \sum_{i=1}^{3}\left(a_i \times exp(-b_i \times z)\right) \qquad (4)$$

Where a_i and b_i are tabulated coefficients for solar radiation and depend on the absorption coefficient of silicon at a given wavelength [18]. This equation allows the experimental irradiance level to be correlated with the reference irradiance level measured under AM 1.5 conditions.

The expression for the continuity equation becomes

$$\frac{\partial^2 \delta(x,z,B)}{\partial x^2} - \frac{\delta(x,z,B)}{L^2(B)} + \frac{1}{D(B)} \times n \times \sum_{i=1}^{3}\left(a_i \times exp(-b_i \times z)\right) = 0 \qquad (5)$$

The solution to this equation is in the following form:

$$\delta(x,z,B) = A(Sf,Sb,z,B).cosh\left(\frac{x}{L(B)}\right) + C(Sf,Sb,z,B).sinh\left(\frac{x}{L(B)}\right) + \frac{L^2}{D} \times \sum_{i=1}^{3} a_i.exp(-b_i.z) \qquad (6)$$

The coefficients $A(Sf,Sb,z,B)$ and $C(Sf,Sb,z,B)$ are determined from the boundary conditions

2.3 Boundary Conditions

At the junction (x=0) : $\left.\frac{\partial \delta(x,z,B)}{\partial x}\right|_{x=0} = \left.\frac{Sf.\delta(x,z,B)}{D(B)}\right|_{x=0}$ (7)

Sf is the recombination velocity of charge carriers at the junction, which is determined by the external charge; it represents the flow of minority carriers across the junction [1], [4], [5], [9].

On the back (x=H) : $\left.\frac{\partial \delta(x,z,B)}{\partial x}\right|_{x=H} = -\left.\frac{Sb.\delta(x,z,B)}{D(B)}\right|_{x=H}$ (8)

Sb is the recombination velocity of excess minority charge carriers on the back surface of the photovoltaic cell [4], [5], [6], [9], [19]. It characterizes the loss of carriers at this back surface. The presence of the backside electric field (BSF) thus allows the photogenerated minority carriers from the back surface (p/p+ junction) to be returned to the emitter-base junction to contribute to the photocurrent.

The coefficients $A(Sf, Sb, z, B)$ and $C(Sf, Sb, z, B)$ are given by the following expressions

$$A(Sf,Sb,z,B) = \left\{\frac{Sf.D.cosh\left(\frac{H}{L}\right) + Sf.Sb.L.sinh\left(\frac{H}{L}\right) + D.Sb}{L.D[-Sf - Sb].cosh\left(\frac{H}{L}\right) - [Sf.Sb.L^2 + D^2].sinh\left(\frac{H}{L}\right)}\right\} \times \frac{L^3}{D} \times \sum_{i=1}^{3} a_i.exp(-b_i.z) \quad (9)$$

$$C(Sf,Sb,z,B) = \left\{\frac{L.Sb.\left[1 - cosh\left(\frac{H}{L}\right)\right] - D.sinh\left(\frac{H}{L}\right)}{L.D[-Sf - Sb].cosh\left(\frac{H}{L}\right) - [Sf.Sb.L^2 + D^2].sinh\left(\frac{H}{L}\right)}\right\} \times \frac{Sf.L^3}{D} \times \sum_{i=1}^{3} a_i.exp(-b_i.z) \quad (10)$$

2.4 Electrical Characteristics and Conversion Efficiency

The photocurrent density is determined from the minority charge carrier density using Fick's law. It is given by the following expression:

$$Jph(Sf,Sb,z,B) = q.D(B).\frac{\partial\delta(x,z,B)}{\partial x}\Big|_{x=0} \quad (11)$$

With q being the elementary electric charge.

The photovoltage across the photovoltaic cell under illumination is given by the following Boltzmann equation.

$$Vph(Sf,Sb,z,B) = \frac{Kb.T}{q} \times ln\left[\frac{Nb}{(n_i)^2}.\delta(0,Sf,Sb,z,B,Hop) + 1\right] \quad (12)$$

Kb is the Boltzmann constant, T is the absolute temperature, Nb is the doping concentration in the base, and n_i is the intrinsic electron concentration.

Power indicates the solar cell's ability to supply electricity to the external load connected to its terminals; the higher the quality of the solar cell, the greater the power. It is an essential parameter for characterizing a solar cell, and its expression is given below.

$$P(Sf,Sb,z,B,Hop) = \Big(\big(Jph(Sf,Sb,z,B,Hop) - Jd(Sf,Sb,z,B,Hop) \times Vph(Sf,Sb,z,B,Hop)\big)\Big) \quad (13)$$

Jd is the diode current; its expression is given below.

$$Jd(Sf,Sb,z,B,Hop) = q.Sf0.\frac{(n_i)^2}{Nb} \times \exp\left(\frac{Vph(Sf,Sb,z,B,Hop)}{V_T} - 1\right) \quad (14)$$

Sf0 is the recombination velocity associated with charge carrier losses due to the photodiode's shunt resistance. It describes the intrinsic quality of a photovoltaic cell.

$V_T = \frac{K \times T}{q}$ (15) is the thermal voltage.

The conversion efficiency of a photovoltaic cell is the ratio of the maximum power output of the cell to the incident light power absorbed; it is given by the following equation:

$$\eta(Sf,z,B,Hop) = \frac{Imax.Vmax}{Pin} = \frac{Pmax}{Pin} \quad (16)$$

Pin=100 mW/cm^2 is the incident power.

3 RESULTS AND DISCUSSION

3.1 Current-voltage characteristics (Jph (Sf, Sb, z, B, Hop) -Vph (Sf, Sb, z, B, Hop)) and power-voltage characteristics (P-Vph).

Figure 3 shows the Jph (Sf, Sb, z, B, Hop) -Vph (Sf, Sb, z, B, Hop) characteristic curve of the photovoltaic cell under polychromatic illumination for different values of the magnetic field and different values of the optimal thickness imposed by the magnetic field.

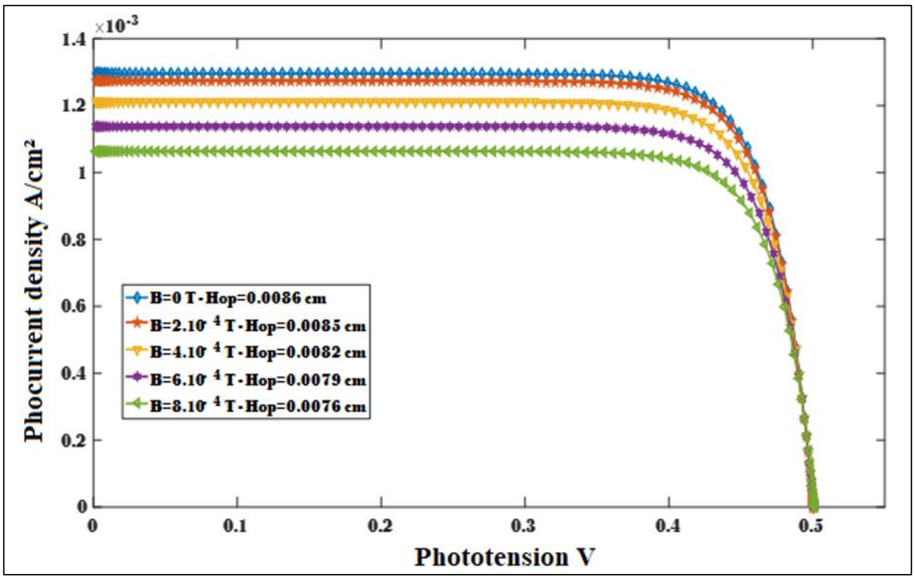

Figure 3: Jph-V characteristic of the photovoltaic cell for different magnetic field values ($\tau=10^{-5}$ s ; $\mu=1350$ cm^2 .V^{-1} s^{-1})

Figure 4 shows the power profile as a function of photovoltage for various magnetic field values and different values of the optimum thickness imposed by the magnetic field.

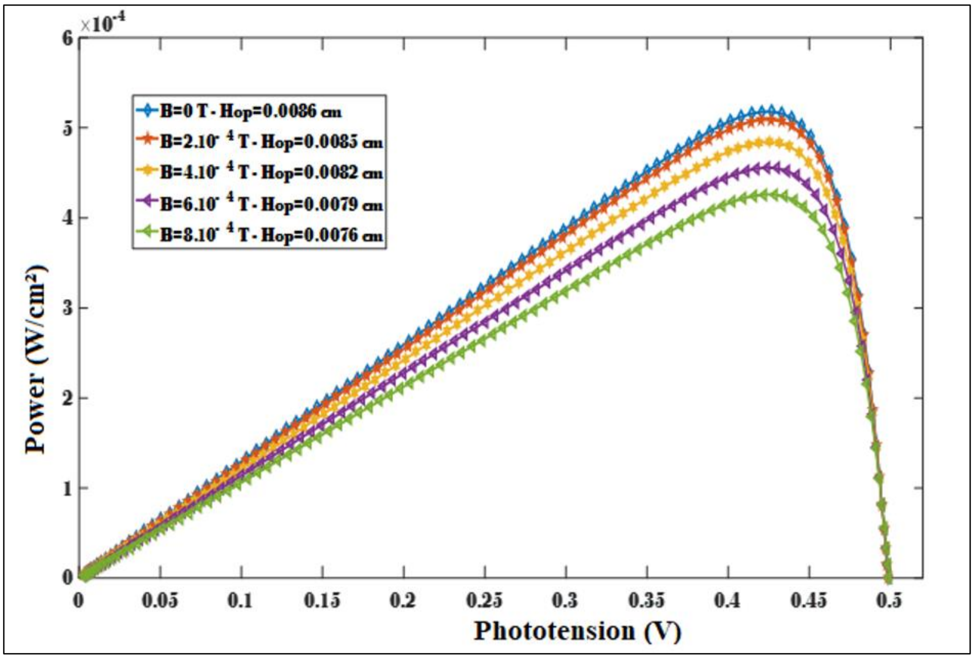

Figure 4: Power profile as a function of photovoltage for different magnetic field values ($\tau=10^{-5}$ s ; $\mu=1350$ cm^2 .V^{-1} s^{-1})

Power varies linearly with the photovoltage up to the limit value corresponding to the maximum power. As the photovoltage approaches its limit value corresponding to the open-circuit voltage (low values of Sf), the power decreases until it reaches zero.

Furthermore, as the intensity of the applied magnetic field increases, the power decreases and the photovoltage near the open-circuit condition increases slightly. This phenomenon can be explained physically by the Lorentz force acting on the minority charge carriers (electrons) moving in the base. Under the influence of the magnetic field applied to the diffusion current, the trajectories of the electrons are deflected, thereby increasing the distance they travel before reaching the junction. Theoretically, this mechanism results.

3.2 Evolution of Photovoltaic Conversion Efficiency

Table 1 below provides some numerical values for efficiency derived from Figure 4 and the efficiency expression for various values of the magnetic field and various values of the optimal thickness of the solar cell base imposed by the magnetic field.

Table 1: Efficiency values for different values of the optimum thickness

B (10^{-4}T)	**0**	**2**	**4**	**6**	**8**
Hop(cm)	0,0086	0,0085	0,0082	0,0079	0,0076
Pmax (10^{-4} W/cm^2)	5,179	5,092	4,844	4,552	4,259
η (%)	0,5179	0,5092	0 ,4844	0,4552	0,4259

Figure 5 shows how the conversion efficiency of the photovoltaic cell changes as a function of the applied external magnetic field.

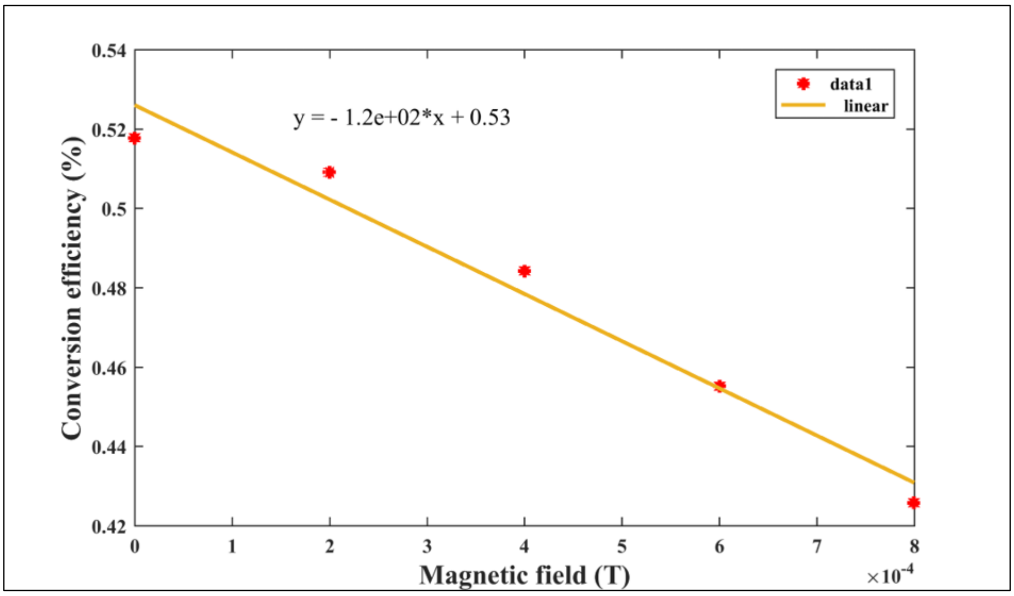

Figure 5: Conversion Efficiency Profile as a Function of Magnetic Field

Figure 6 shows how the photovoltaic cell's efficiency varies as a function of the optimal thickness of its base.

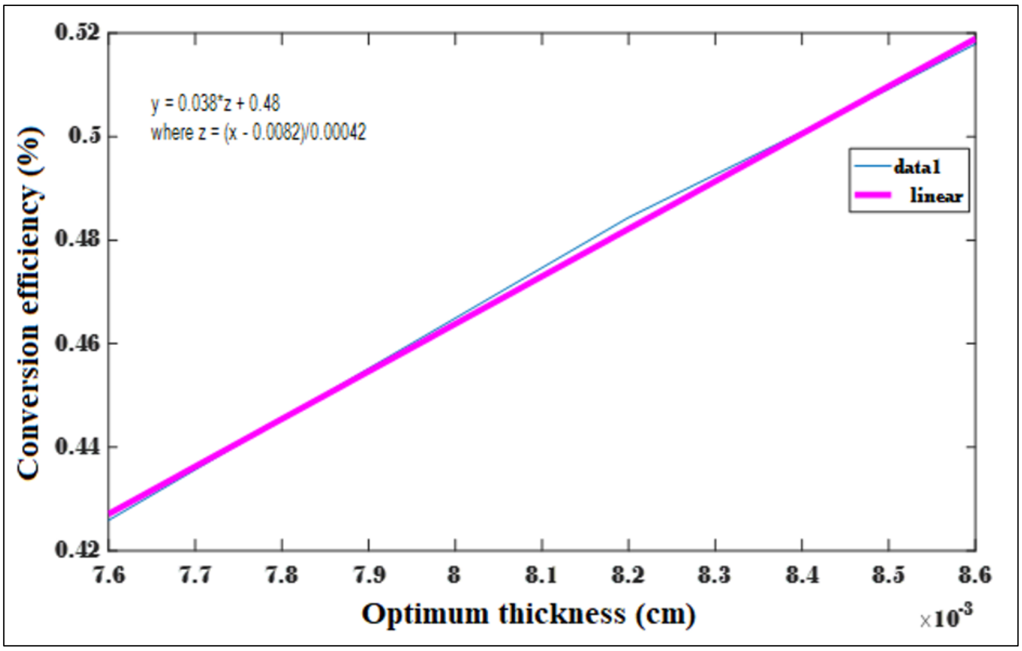

Figure 6: Performance Profile as a Function of the Optimal Base Thickness

Figure 6 shows that the photovoltaic conversion efficiency increases as the optimal thickness of the solar cell's base increases.

The mathematical correlation equation is given by:

$\eta = 0{,}038.Hop(B) + 0{,}48 \quad (17)$

The application of a magnetic field reduces the carrier diffusion length, which requires reducing the optimal thickness of the Hopt base to limit volume recombination. The linear relationship between the efficiency η and Hopt shows that a thicker base is beneficial only if the diffusion length remains sufficient.

The low calculated efficiencies (η ≅ 0.42% to 0.52%) are primarily explained by the fact that the study focuses on a single elementary unit, whereas the total voltage and power increase when connecting N junctions in series.

Finally, these modest values are also due to recombination losses at the interfaces (Sf and Sb), exacerbated by the presence of the magnetic field, as well as the diode current (Jd), which is not neglected in our study.

4 CONCLUSION

A study was conducted on the photovoltaic conversion efficiency of a series vertical-junction solar cell under polychromatic illumination in a steady-state condition for different values of the optimal thickness of the solar cell's base, as determined by the magnetic field.

We first determined the expressions for the photocurrent density, photovoltage, and power of the photovoltaic cell after solving the diffusion equation for excess minority charge carriers in the base. Next, we studied how its efficiency varies as a function of the optimal thickness of the photovoltaic cell's base, as determined by the magnetic field based on its expression (Equation 16) and Figure 4, which shows the power profile as a function of the photovoltage of the photovoltaic cell for different values of the optimal base thickness obtained from the values of the magnetic field applied to the photovoltaic cell. This study shows that the photodiode's efficiency increases as the optimal thickness of the base increases.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Funding Source

This article was funded by the authors themselves.

Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Statement of ethical approval

The authors declare that all applicable ethical standards have been followed during the conduct of this research.

Statement of informed consent

Informed consent was not applicable because this study did not involve human participants.

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