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Research Article

Optimization of Base Thickness in Response to Magnetic Fields: Towards a Robust Design for Vertical Solar Cells

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Abstract

The article discusses the study of the impact of the magnetic field (B) on the performance of a series vertical junction solar cell operating in static conditions and under polychromatic illumination. These solar cells consist of several non-monolithic junctions connected in series and illuminated from the edges. The theoretical approach is based on solving the continuity equation for excess minority charge carriers in the base (p-zone). This equation explicitly incorporates the influence of the magnetic field via the diffusion coefficient (D (B)), which is inversely proportional to 1+(μ. B) 2 (magnetoresistance phenomenon). The solution to the continuity equation is used to derive expressions for photocurrent (Jph), photovoltage (Vph), power (Pmax), form factor (FF), and conversion efficiency (η). The results clearly show that maximum power (Pmax) and conversion efficiency (η) decrease as the magnetic field increases (B). This effect is attributed to the Lorentz force, which deflects the trajectory of photogenerated carriers, significantly increasing their recombination rate before they reach the junction, thereby reducing the photocurrent. The study mainly shows that the optimum thickness (Hopt) of the base offering maximum power decreases as the magnetic field increases. This decrease is due to the fact that the magnetic field deflects the trajectory of minority carriers (electrons) towards the lateral faces of the cell. Therefore, for better carrier collection, the thickness of the base must be much thinner. The form factor (FF) is only very slightly affected by the magnetic field.

Keywords

Magnetic Field, Solar Cell, Vertical Junction, Form Factor, Conversion Efficiency

1. Introduction

Faced with the depletion of fossil fuels and the pollution they cause, renewable energies, and more specifically solar energy, are becoming an essential alternative.

However, the use of solar energy is often limited by its low production efficiency. This low efficiency is often due to intrinsic parameters and/or parameters external to solar cells, such as magnetic fields, electric fields, temperature, illumination (or irradiation), etc. [1-7].

It is in this context that we wish to study the impact of the magnetic field on the form factor and conversion efficiency of a vertical junction solar cell in static conditions and under polychromatic illumination. [8-10].

2. Method and Theory

Vertical multi-junction solar cells, also known as edge-illuminated cells, consist of a number of non-monolithic junctions illuminated from the edges and connected together

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in series. [10-12].

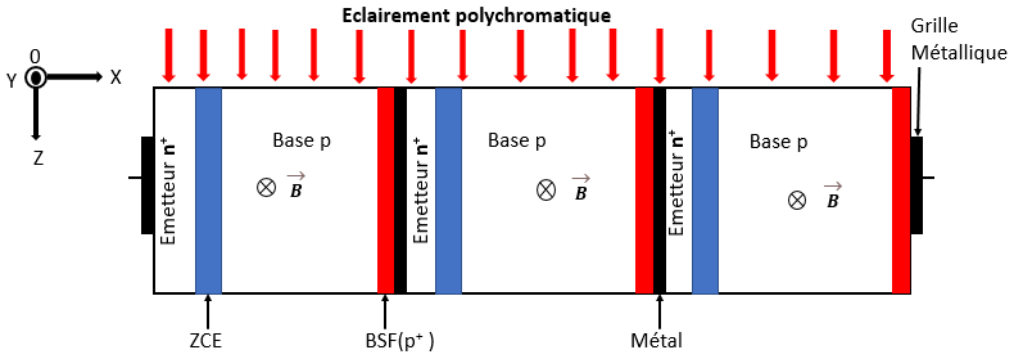

Figure 1. *Diagram of a Solar Cell with Vertical Series Junctions Under Polychromatic Illumination and Under a Magnetic Field.*

Figure 2 shows a diagram of a solar cell unit with vertical series junctions placed in a magnetic field and under polychromatic illumination.

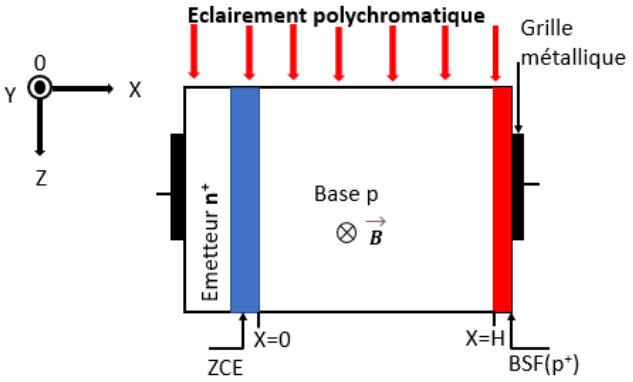

Figure 2. *Structure of a Vertical Junction Silicon Solar Cell.*

The different parts of a silicon solar cell are:

The emitter (n^+ zone): this zone is doped with donor atoms, with an impurity atom concentration ranging from 10^{17} to 10^{19} atoms/cm^3, and is very thin.

The base (p-zone): This part is slightly doped with acceptor atoms, with a concentration of atomic impurities between 10^{15} and 10^{17} atoms/cm^3. It is thicker than the emitter. The study of the cell's characteristics will focus mainly on this part, where absorption, generation, recombination, and diffusion phenomena predominate.

The junction or space charge region (SCR) that separates electron-hole pairs thanks to the electric field that prevails there.

Finally, an overdoped zone (p^+ type): this part creates an electric field that will send the photogenerated minority carriers near this rear surface back to the junction (Back Surface Field: BSF).

2.1. Continuity Equation

The minority carrier continuity equation is defined by the expression (1). This equation models the phenomena of diffusion, recombination, and generation of excess minority charge carriers in the base in static conditions, under a magnetic field, and under polychromatic illumination.

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

$\delta(x)$ defines the density of excess minority charge carriers.

$D(B)$ defines the diffusion coefficient of minority carriers (electrons) in the base under a magnetic field.

τ represents the lifetime of minority carriers in the base, its expression is given by the following Einstein relation.

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

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

The expression for the diffusion coefficient $D(B)$ [1, 5, 7], is given by the relationship (3).

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

D_0 represents the diffusion coefficient of minority carriers (electrons) in the material (silicon).

The rate of minority carrier generation depends on the depth z of the cell base. It is expressed by the equation (4).

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

a_i and b_i are solar radiation coefficients that depend on the absorption coefficient of silicon with wavelength [13]. These are used to establish the link between the experimental illuminance level and the reference illuminance level taken

under AM 1.5.

Solving the continuity equation

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

The general solution to this equation is given in the form:

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

Coefficients $A(Sf,Sb,z,B)$ and $C(Sf,Sb,z,B)$ are determined based on boundary conditions.

Boundary conditions

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

Sf is defined as the recombination velocity of minority charge carriers at the junction, imposed by the external load; it characterizes the flow of minority carriers through the junction. [14-17].

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

Sb is the recombination velocity of excess minority charge carriers on the rear surface of the solar cell [15-19]. It characterizes the loss of carriers at this rear surface. The existence of the back electric field (BSF) thus allows the photogenerated minority carriers from the rear surface (p/p+ junction) to be returned to the emitter-base junction to participate in the photocurrent.

2.2. Photocurrent Density, Photovoltage, and Power

Fick's law allows the expression of photocurrent density to be established based on the density of excess minority charge carriers.

$$Jph(Sf,Sb,z,B) = q.D(B).\frac{\partial\delta(x,z,B)}{\partial x}\Big|_{x=0} \quad (9)$$

q represents the elementary electric charge.

The Boltzmann relation allows us to establish the expression for phototension equation (10).

$$\mathrm{Vph(Sf,Sb,z,B)} = \frac{\mathrm{Kb.T}}{\mathrm{q}} \times \ln\left[\frac{\mathrm{Nb}}{(\mathrm{n_i})^2}.\delta(0,\mathrm{Sf,Sb,z,B,Hop}) + 1\right] \quad (10)$$

Kb, T, Nb and n_i represent Boltzmann's constant, absolute temperature, doping concentration, and intrinsic electron concentration, respectively.

Power characterizes the performance of a solar cell. The higher its value, the better the quality of the solar cell. It is expressed by the following equation:

$$\mathrm{P(Sf,Sb,z,B,Hop)} = \mathrm{I(Sf,Sb,z,B,Hop)} \times \mathrm{Vph(Sf,Sb,z,B,Hop)} \quad (11)$$

$$\mathrm{I(Sf,Sb,z,B,Hop)} = \mathrm{Jph(Sf,Sb,z,B,Hop)} - \mathrm{Jd(Sf,Sb,z,B,Hop)}$$

I is the current flowing through the load.

Jd is the diode current, whose expression is given below.

$$Jd(Sf,Sb,z,B,Hop) = q.Sf0.\frac{(n_i)^2}{Nb} \times \exp\left(\frac{Vph(Sf,Sb,z,B,Hop)}{V_T} - 1\right) \quad (12)$$

Sf0 represents the recombination velocity, which characterizes the loss of charge carriers due to the shunt resistance of the cell. It provides an insight into the intrinsic quality of the cell.

2.3. The Form Factor

The form factor is an important parameter for defining the quality of a solar cell. It is the ratio between the maximum power that the cell can deliver and the power formed by the rectangle Isc ×Vco equation (13). It indicates the quality of the p-n junction and the series or shunt resistances that operate in the solar cell. The form factor depends mainly on the cell design, the quality of the p-n junction and the material, and the resistivity of the metal contacts [20].

$$\mathrm{FF} = \frac{\mathrm{P_{max}}}{\mathrm{V_{oc}} \times \mathrm{I_{sc}}} \quad (13)$$

2.4. Conversion Efficiency

The conversion efficiency of a solar cell is calculated as the

ratio between the maximum power supplied by the cell and the incident light power absorbed. It is given by the following equation:

$$\eta(Sf, z, B, Hop) = \frac{Pmax}{Pin} \quad (14)$$

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

3. Results and Discussion

Figure 3 shows the variation in power as a function of cell base thickness for several magnetic field values.

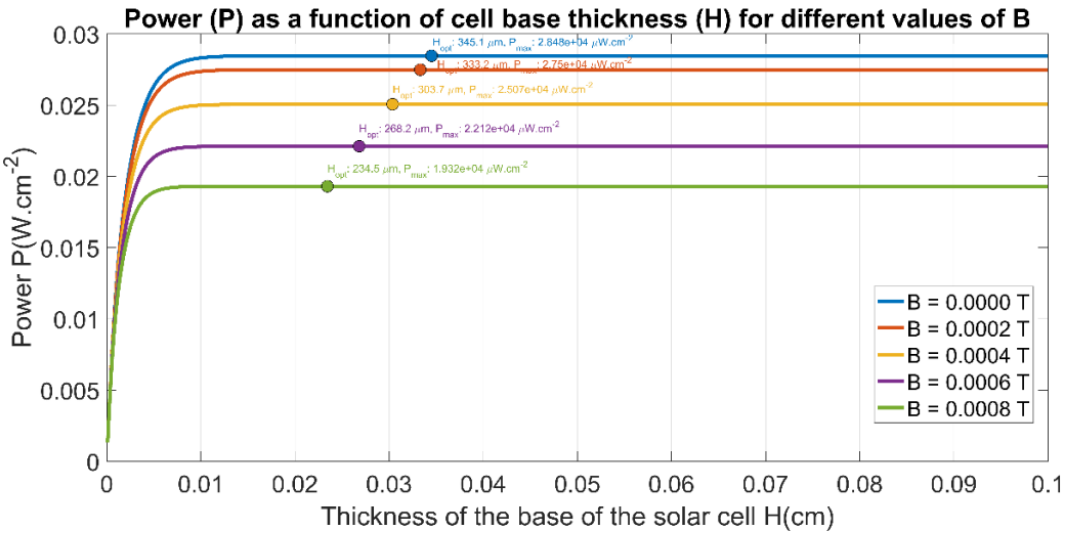

Figure 3. *Shows the Variation in Power as a Function of the Thickness of the Solar Cell Base for Several Values of the Magnetic Field.*

Figure 3 shows that as thickness H increases, the power generated increases. Greater silicon thickness allows for better absorption of incident photons, especially low-energy (longer wavelength) photons that penetrate deeper. Increased absorption means greater electron-hole pair generation, which translates into increased power. Light absorption reaches a point where almost all useful photons are captured. Beyond a certain critical thickness (optimum thickness), the increase in power becomes negligible or stagnates.

However, it has been observed that the power decreases as the magnetic field increases. This effect is due to the phenomenon of magnetoresistance, which influences the movement of charge carriers (electrons and holes) generated by light inside the semiconductor.

Table 1 shows the values for optimum thickness and maximum power obtained when the cell is applied to a magnetic field.

Table 1. *Optimum Thickness (Hopt) and Maximum Power (Pmax) Obtained for Different Magnetic Field Values (B).*

Magnetic field B (10^{-4}T)	**0**	**2**	**4**	**6**	**8**
Optimum thickness Hopt (µm)	345.12	333.18	303.71	268.20	234.48
Maximum power Pmax (10-2 W/cm2)	2.84761	2.74970	2.50653	2.21241	1.93160

Figure 4 shows the evolution of the optimum thickness as a function of the magnetic field.

Figure 4 shows that as the magnetic field increases, the optimum thickness of the base decreases. The application of a field reduces the effective diffusion length of charge carriers. Physically, the magnetic field curves the trajectories of the carriers (Lorentz force), increasing the actual distance they must travel to reach the junction, which is equivalent to shortening their effective "survival zone" before recombination. Therefore, to maintain high collection efficiency and maximize efficiency, it is necessary to reduce the thickness of the base so that the majority of the generated carriers are still

at a distance from the junction that is compatible with the new reduced effective diffusion length.

Figure 5 shows the variation in power as a function of the thickness of the solar cell base for several values of the magnetic field.

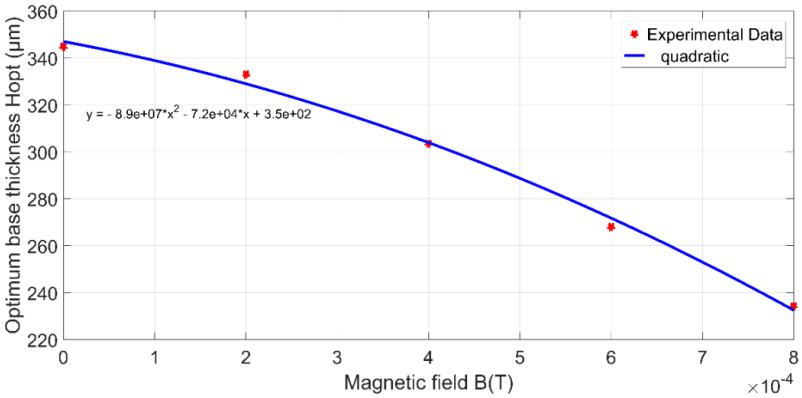

Figure 4. *Profile of the Optimum Thickness Hopt as a Function of the Magnetic Field.*

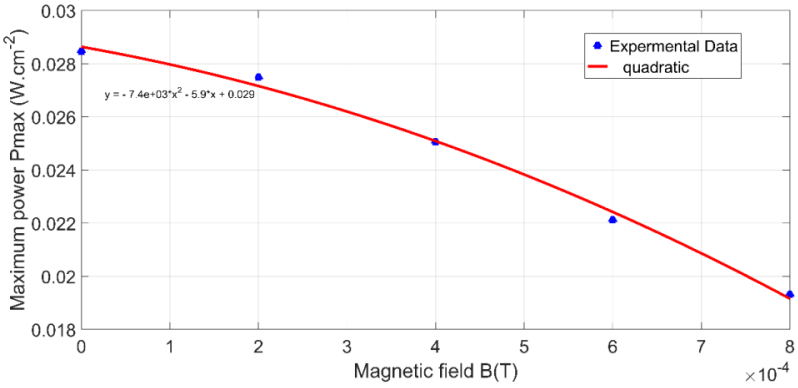

Figure 5. *Maximum Power Evolution as a Function of the Magnetic Field.*

Figure 6 shows the evolution of maximum power as a function of the optimal thickness of the solar cell base.

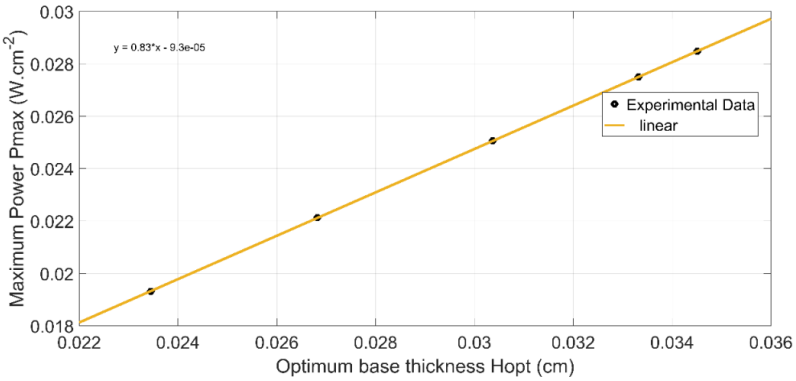

Figure 6. *Evolution of Maximum Power Pmax as a Function of Optimum Thickness Hopt.*

Figure 6 shows that the maximum power increases linearly with the optimum thickness of the cell base.

Figure 7 shows the photocurrent and power profiles as a function of photovoltage.

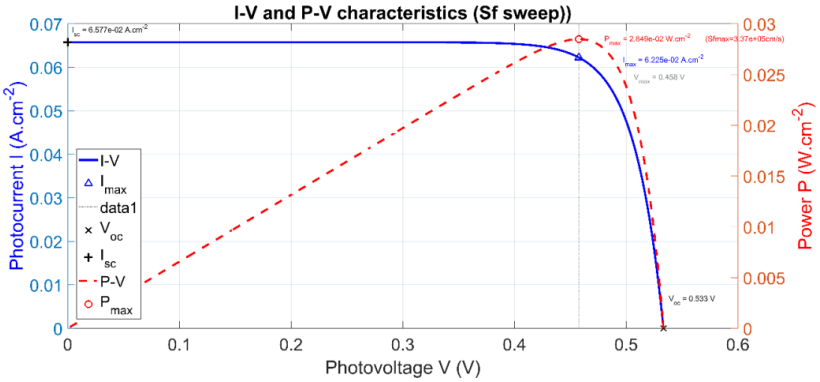

Figure 7. *Photocurrent and Power Profiles as a Function of Photovoltage.*

Table 2. *Shows the Form Factor Values Obtained from the Applied Magnetic Field Values.*

Magnetic field B (10^{-4} T)	**0**	**2**	**4**	**6**	**8**
Optimum thickness Hopt (µm)	345.12	333.18	303.71	268.20	234.48
Form Factor FF	0.8113	0.8118	0.8116	0.8117	0.8103

The form factor values recorded in Table 2 show that the magnetic field has a slight influence on the form factor. Table 3 shows the conversion efficiency values obtained from the applied magnetic field values.

Table 3. *Conversion Efficiency Values Obtained from the Applied Magnetic Field Values.*

Magnetic field B (10^{-4} T)	**0**	**2**	**4**	**6**	**8**
Optimum thickness Hopt (µm)	345.12	333.18	303.71	268.20	234.48
Conversion efficiency η (%)	28.4761	27.4970	25.0653	22.1241	19.3160

The conversion efficiency profile as a function of magnetic field is shown in Figure 8.

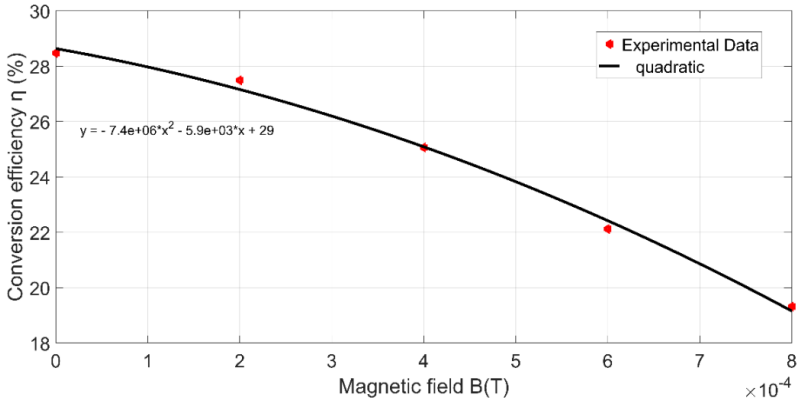

Figure 8. *Evolution of Conversion Efficiency as a Function of Magnetic Field.*

Figure 8 shows that the conversion efficiency decreases as the magnetic field increases. This decrease is due to the modification of the electrical parameters by the magnetic field.

Applying a magnetic field to a silicon solar cell causes a decrease in its conversion efficiency due to the Lorentz force acting on the charge carriers. Initially generated by incident photons, electron-hole pairs must move toward the contacts to form an electric current; however, under the effect of the magnetic field, the Lorentz force deflects the trajectory of these carriers. This deflection significantly increases the recombination rate of electrons and holes before they reach the collection terminals, reducing the number of carriers collected, thus leading to a decrease in photocurrent and, consequently, a drop in efficiency.

Figure 9 shows the evolution of conversion efficiency in relation to the optimum thickness of the solar cell base.

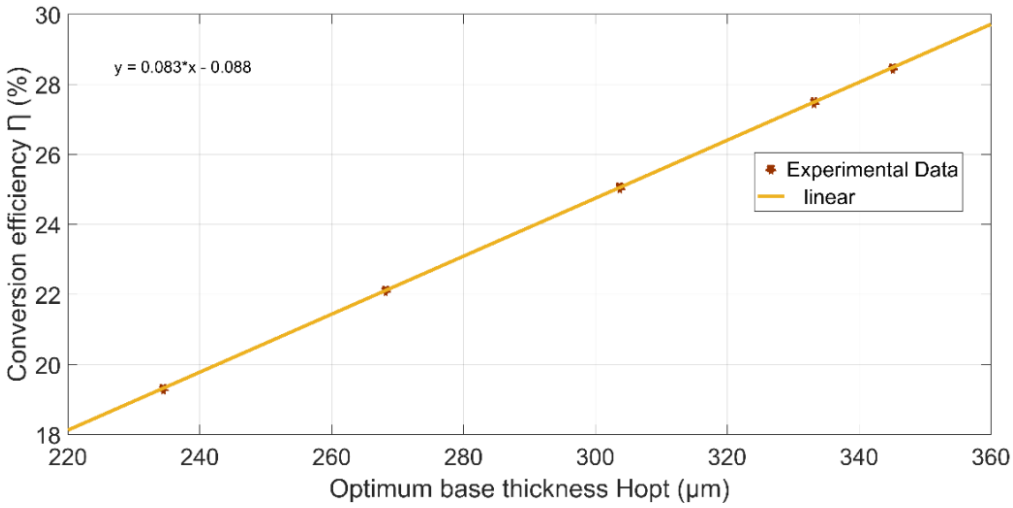

Figure 9. *Variation in Conversion Efficiency as a Function of Optimum Thickness Hopt.*

Figure 9 shows that the conversion efficiency increases linearly with the optimum thickness.

4. Conclusion

This study confirms, through analytical modeling of transport mechanisms, that the presence of a magnetic field has a significant degrading impact on the performance of vertical series junction solar cells, manifested by a decrease in conversion efficiency and maximum power.

The main physical mechanism is magnetoresistance, which, via the Lorentz force, curves the trajectories of electrons and holes in the semiconductor base, reducing their effective diffusion length. This reduction increases losses due to recombination of minority carriers before they are collected at the junction, thereby decreasing the photocurrent and, by extension, the efficiency.

A key technical finding is the need to reduce the optimum thickness of the base in the presence of a magnetic field. This highlights an avenue for optimization: in environments subject to magnetic fields, cell design should favor thinner base architectures to minimize the effect of increased recombination.

The article makes an important theoretical contribution to understanding the external parameters affecting solar cells, paving the way for future studies on mitigation solutions (e.g., shielding techniques or appropriate architectural modifications) to ensure the robustness of photovoltaic systems in magnetically active environments (such as space or certain industrial facilities).

Abbreviations

FF	Form Factor
SCR	Space Charge Region
BSF	Back Surface Field
AM	Air Mass
Isc	Short-Circuit Current
Voc	Open Circuit Voltage

Author Contributions

Dibor Faye: Conceptualization, Methodology, Writing – review & editing, Writing – original draft, Software

Mountaga Boiro: Conceptualization, Writing – original draft, Writing – review & editing

Babou Dione: Conceptualization, Validation, Writing – review & editing

Pape Diop: Writing – review & editing, Software

Conflicts of Interest

The authors declare no conflicts of interest.

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