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Research Article

Optimization of a Highly Doped Silicon Vertical Junction Silicon Solar Cell: Cross-effects of Base Thickness and Magnetic Field Inclination Angle

Landing Diatta[1], Moustapha Thiame[1, *], Sada Traore[1, 2], Moussa Camara[1, 3]

[1]Laboratory of Chemical and Physics of Materials, Assane Seck University, Ziguinchor, Senegal
[2]Laboratory of Semiconductor and Solar Energy, Cheikh Anta Diop University, Dakar, Senegal
[3]Faculty of Science, Gamal Abdel Nasser University, Conakry, Guinea

Abstract

In a context marked by the integration of silicon photovoltaic cells into environments subjected to magnetic fields, such as specialized or industrial systems, several key questions persist regarding their operational efficiency. This study is therefore designed to explore the performance optimization of a silicon solar cell under an applied magnetic field by analyzing the coupled effects of two critical parameters: the base thickness and the magnetic field inclination angle. The proposed model is founded on the one-dimensional, steady-state equations governing the generation, diffusion, and recombination of minority charge carriers, specifically aiming to determine the optimum base thickness and the most favorable field orientation. To achieve this objective, we developed a comprehensive analytical model that accurately describes the electrical behavior of a highly-doped $N^+/P^+/N^+$ vertical-junction solar cell under steady-state operation. The model assumes vertical monochromatic photo-generation, lateral carrier collection, and a static magnetic field applied at a variable inclination angle (θ) relative to the x-axis. Through rigorous numerical simulations, the influence of the base thickness (Wp) and the magnetic field inclination angle (θ) on fundamental photovoltaic parameters namely the short-circuit current density (Jsc), the open-circuit voltage (Voc), and the conversion efficiency (η) is systematically evaluated. This approach offers a pertinent strategy for developing highly efficient silicon solar cells designed for operational environments subject to significant electromagnetic perturbation. The findings demonstrate that the synergistic combination of a precisely engineered base thickness (approximately Wp=0.025cm) and an optimal magnetic field orientation (θ≈90°) is paramount for maximizing the performance of the silicon solar cells.

Keywords

Solar Cell, Optimization, Magnetic Field Inclination Angle, Base Thickness, Highly-doped Base

1. Introduction

The photovoltaic conversion of solar energy is strongly dependent on the optimization of solar cell structures, particularly for devices based on silicon, a material that is abundant and industrially well-mastered. Among the various architectures, the highly-doped $N^+/P^+/N^+$ vertical-junction solar cell, featuring vertical carrier generation and lateral collection,

*Corresponding author: mthiame@univ-zig.sn (Moustapha Thiame)

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constitutes a promising configuration for enhancing efficiency under complex irradiation conditions. This is especially true in high magnetic field environments [1-8], a factor often considered alongside its inherently low manufacturing cost (Marwa S. Salem et al.).

Previous studies by G. Sissoko and collaborators have demonstrated the significance of investigating thermal and magnetic effects on the electrical characteristics (specifically the open-circuit voltage and short-circuit current) of highly-doped double-junction cells [5-9]. Nevertheless, the coupled influence of two fundamental parameters one structural and one physical namely the base thickness (Wp) [6, 10, 11] and the inclination angle of the applied magnetic field [12-14], remains under-explored. These two variables can substantially alter the behavior of minority carriers within the base, simultaneously affecting diffusion, the spatial distribution of the photogenerated current, and the carrier collection efficiency at the lateral junctions.

The application of an inclined magnetic field modifies carrier trajectories via the Lorentz force, thereby either elongating or shortening the average path carriers must travel before collection, depending on the field's orientation. The base thickness, on the other hand, governs the diffusion distance and dictates the rates of bulk and surface recombination, directly impacting the current density and voltage developed at the $N^+/P^+/N^+$ interfaces. The simultaneous investigation of these two cross-effects is thus crucial for identifying the optimal solar cell configuration, ensuring the maximization of delivered power and overall conversion efficiency.

In this paper, we develop a rigorous analytical model describing the electrical performance of a highly-doped $N^+/P^+/N^+$ solar cell under steady-state conditions. The model incorporates vertical monochromatic photo-generation, lateral carrier collection, and a static magnetic field applied at a variable inclination angle (θ) relative to the horizontal x-axis. We analyze the resulting dependence of the short-circuit current density (Jsc), the open-circuit voltage (Voc), and the efficiency (η) on both the base. The "z y O" at the end, representing a coordinate system, is typically omitted or replaced by a formal Figure reference in an academic publication).

2. Theoretical Study

2.1. Structure Description

The solar cell under investigation is a highly-doped $N^+/P^+/N^+$ silicon vertical-junction structure. It is subjected to monochromatic illumination and an oriented magnetic field, as schematically illustrated in Figure 1.

The magnetic field, which is assumed to be static (constant), is applied within the base region along the (O,x,y) plane at an inclination angle of θ with respect to the (Oy) axis: $\theta=\left(\widehat{\vec{B},\vec{e_y}}\right)$.

A major problem with silicon-based solar cells is the poor collection of minority carriers due to short diffusion lengths. One approach to overcoming this problem is to manufacture vertical junction cells. The advantage of these new cells is the short distance between the site of minority carrier generation in the base and the emitter. This facilitates their collection.

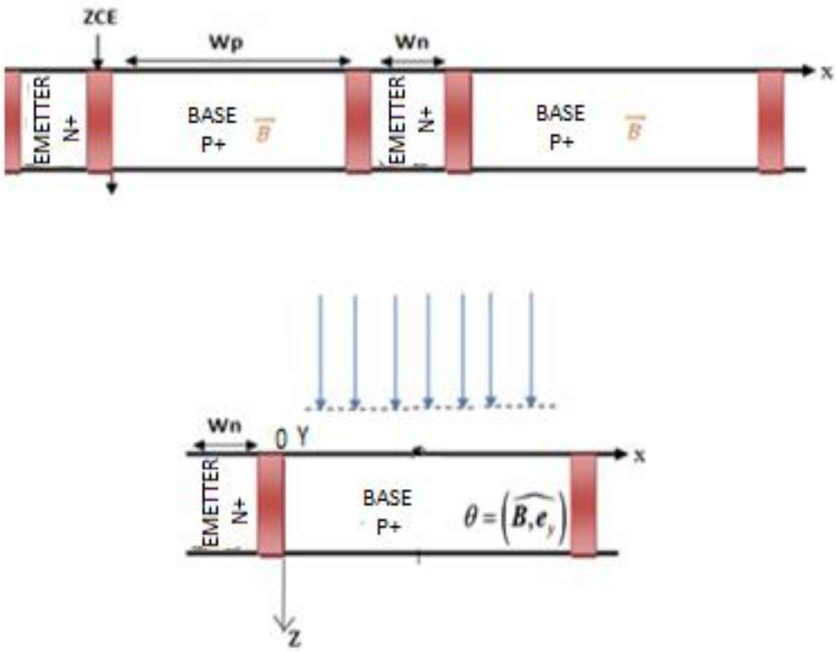

Figure 1. Structure of the N^+ /P^+/N^+ Vertical-Junction Solar Cell.

2.2. Continuity Equation

The magneto-transport equation governing the excess minority charge carrier density $\delta n(z, Wp, \theta, B, x)$ in the base region is given by the following relation [15, 16]:

$$\frac{\partial^2 \delta_n(x,Wp,\theta,B)}{\partial^2(x)} - \frac{\delta_n(x,Wp,\theta,B)}{L_n(\theta)} = -\frac{G(z)}{D_n^*(\theta)} \quad (1)$$

G(z) is the generation rate of the excess minority carriers as a function of the depth z, the expression of which [17, 18] is given by the following equation:

$$G(z) = \alpha_\lambda . F_\lambda . (1 - R_\lambda) . e^{-\alpha_\lambda . z} \quad (2)$$

Where $\alpha_\lambda, F_\lambda$ *et* R_λ are respectively absorption coefficient of silicon, the incident flux (or incident fluence) and the reflection coefficient of silicon [5].

$$D_n^*(\theta) = \frac{D(T)[1+{\mu_n}^2.B^2.\sin^2\theta]}{[(1+{\mu_n}^2(T).B^2)]} \quad (3)$$

$D_n(\theta, B)$: is the diffusion coefficient of the excess minority charge carriers in the base in the presence of magnetic field $B = 7.5mT$, of the field's inclination angle θ, of the minority carrier mobility in the base μ_n [16] at T=300 K.

The diffusion length $L_n(\theta, B)$ at T=300 K of the minority charge carriers in the base in the presence of the magnetic field's orientation is given by relation (4):

$$L_n((\theta) = \sqrt{\tau_n . D_n^*(\theta)} \quad (4)$$

τ_n is the lifetime of the photogenerated minority charge carriers in the base of the solar cell.

The general solution of equation (1) is given by the following relation (5):

$$\delta_n(z, x, Wp, \theta) = A(z, Wp, \theta, B) cosh\left(\frac{x}{L_n(\theta)}\right) + E(z, Wp, \theta, B) sinh\left(\frac{x}{L_n(\theta)}\right) + \frac{L_n^2(\theta,B).\alpha_\lambda.F\lambda.(1-R_t).e^{-\alpha_\lambda z}}{D_n^*(\theta)} \quad (5)$$

Where the expressions $A(z, Wp, \theta, B)$ and $E(z, Wp, \theta, B)$ are given by the following boundary conditions [19]:

1) At the Junction: x=0

$$D_n^*(\theta).\frac{\partial \delta_n(z,x,Wp,\theta)}{\partial x}/_{X=0} = Sf . \delta_n(z, 0, Wp, \theta) \quad (6)$$

Where Sf is the recombination velocity at the junction.

2) In the middle of the base: $x = \frac{Wp}{2}$

$$D_n^*(\theta).\frac{\partial \delta_n(z,x,Wp,\theta)}{\partial x}/_{X=\frac{Wp}{2}} = 0 \quad (7)$$

$$E(z, Wp, \theta) = \frac{L_n^3(\theta).Sf\alpha_\lambda.F_\lambda(1-R_\lambda).e^{-\sigma_\lambda . z}}{Sf.D_n^*(\theta).L_n(\theta) + D_n^2(\theta).\tanh\left(\frac{Wp}{2.L_n(\theta)}\right)} \quad (8)$$

$$A(z, Wp, \theta) = Sf.\frac{L_n(\theta)}{D_n^*(\theta)}.E(z, Wp, \theta) + Sf.\frac{L_n^2(\theta)}{D_n^2(\theta)} \times \alpha_\lambda . F_\lambda(1 - R_\lambda) . e^{-\alpha_\lambda . z} \quad (9)$$

2.3. Photocurrent Density

The diffusion of minority carriers across the junction allows for the determination of the photocurrent density. Indeed, the gradient of the density of these carriers leads to the expression for the photocurret density [20, 21] as follows:

$$Jph(z, Sf, Wp, \theta, B) = 2.q.D_n^*(\theta).\frac{\partial \delta_n(z,x,Wp,\theta)}{\partial x}/_{X=0} \quad (10)$$

2.4. Photovoltage

The photovoltage is obtained from the BOLTZMANN relation, created by the accumulation of minority charge carriers at the junction level [16, 21].

$$\mathrm{Vph}(z, Sf, Wp, \theta, B) = \frac{K.T}{q}.\left[1 + \frac{N_b.\delta_n(z,x=0,Wp,\theta,B)}{ni^2}\right] \quad (11)$$

2.5. Efficiency

The efficiency, as a function of the magnetic field inclination angle and the base thickness Wp, is obtained by the formula:

⍰ $= \frac{Pmax}{Pin}$ (12)

Where Pmax represents the maximum power of the cell and Pin the incident power, under standard conditions A.M 1.5 Pin=100 mW/cm^2 [5].

3. Results and Discussion

3.1. Short-circuit Current (Jsc), Open-circuit Voltage (Voc), and Efficiency Without Magnetic Field

In this section, we analyze the influence of the base thickness (Wp) on the performance parameters of a silicon solar cell with parallel vertical $N^+/P^+/N^+$ junctions: the short-circuit current (Jsc), the open-circuit voltage (Voc), and the photoconversion efficiency (η) (Figure 2). The simulations presented here are performed in the absence of a magnetic field, for a penetration depth Z=0.0004cm, and a wavelength λ=0.64 µm.

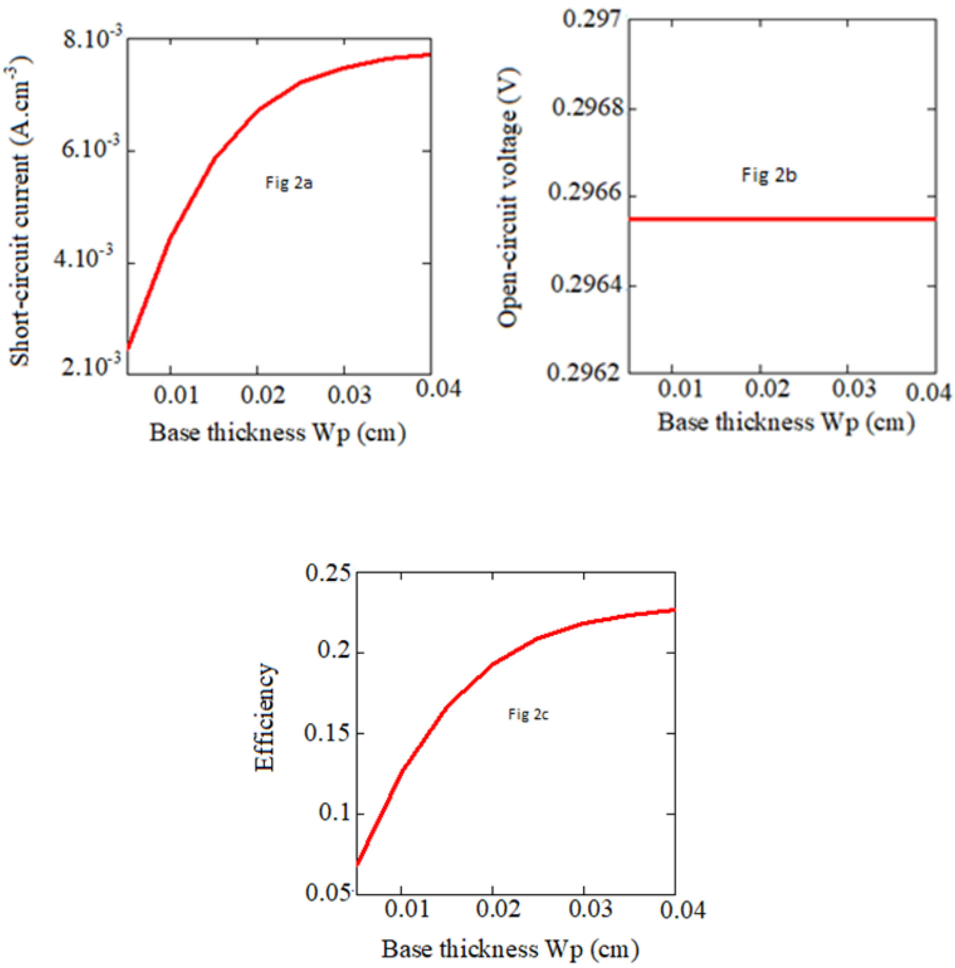

Figure 2. *The Short-circuit current Jsc (Figure 2a), the open-circuit voltage Voc (Figure 2b), and the efficiency η (Figure 2c) as a function of the base thickness, z = 0.0004cm, λ=0.64 µm.*

We first observe that the short-circuit current density (Jsc) increases rapidly with the base thickness (Figure 2a), before tending towards saturation for Wp≈0.02cm. This growth is due to the increased photonic absorption as the base is thickened, which favors the generation of supplementary electron-hole pairs. Beyond this critical thickness, recombination's become predominant because the carriers must travel longer distances to be collected, an effect amplified by the high doping level."

In contrast, the open-circuit voltage (Voc) (Figure 2b) remains practically constant (Wp ≈ 0.02cm), which shows that it primarily depends on the doping level and the overall generation/recombination ratio, and much less directly on the base thickness. Furthermore, the efficiency (η) follows the evolution of Jsc, reaching a maximum close to 20.5% for thicknesses between 0.03 and 0.04cm (Figure 2c). This trend confirms the existence of an optimal base thickness, where the balance between increased photonic absorption and losses due to recombination makes it possible to maximize the performance of the highly doped silicon solar cell.

To better understand the effect of thickness, Table 1 summarizes the values of Jsc, Voc, and η obtained in the absence of a magnetic field.

Table 1. *Values of Jsc, Voc, and η as a function of thickness without a magnetic field.*

Wp (µm)	Jsc ($mA.cm^{-2}$)	Voc (mV)	η (%)
50	2.432	296.548	6.8
100	4.433	296.548	12.6
150	5.830	296.548	16.6
200	6.698	296.548	19.1
250	7.199	296548	20.9

In this table, it is clearly observed that the increase in Wp mainly improves Jsc and therefore the efficiency, while Voc remains almost constant.

In the next section, we will analyze the influence of the inclined magnetic field, highlighting the cross-effects with the base thickness.

3.2. Short-circuit Current (Jsc), Open-circuit Voltage (Voc), and Efficiency with Magnetic Field

Figure 3 illustrates the evolution of the short-circuit current density (Jsc) (Figure 3a), the open-circuit voltage (Voc) (Figure 3b), and the efficiency as a function of the base thickness, for different magnetic field inclination angles (θ). The result shows that in (Figure 3c) Jsc increases with the base thickness (Wp), but its magnitude strongly depends on the angle θ. The higher the angle (θ=π/2), the greater the current generated. Conversely, for small inclinations (θ≈0), Jsc remains limited.

This behavior is explained by the fact that the magnetic field's inclination modifies the trajectories of the charge carriers (cyclotron curvature effect). A larger angle favors the prolongation of the carriers' effective lifetime and improves their collection probability, which increases Jsc.

The voltage Voc (Figure 3b) remains almost constant (≈0.2967 V) for all angles and all thicknesses. This confirms that Voc is primarily determined by the doping and the overall generation/recombination ratio, independently of the magnetic field's orientation. The efficiency (η) (Figure 3c) follows the trend of Jsc: it increases with thickness and is directly dependent on the magnetic field inclination.

For θ=π/2, the highest efficiency (above 20.9%) is obtained, while for θ=0, the performance remains low. This observation is consistent with the work of Combari et al. [13]. From this, we conclude that the magnetic field's inclination acts as an additional confinement factor, reducing recombination losses and improving the collection of photogenerated carriers.

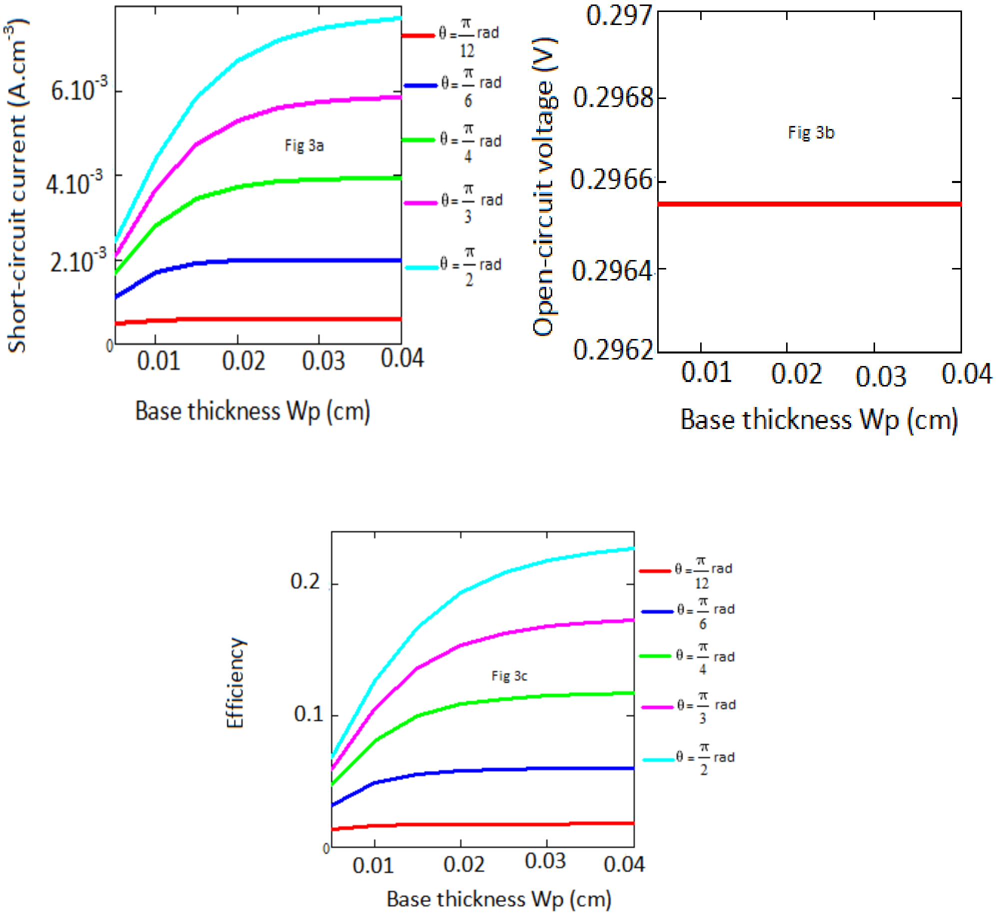

__Figure 3.__ Short-circuit current density Jsc (Figure 3a), open-circuit voltage Voc (Figure 3b), and the efficiency η (Figure 3c) as a function of the base thickness for Z=0.0004cm, λ=0.64 µm, and B = 0.0075 T.

To better understand the combined impact of the base thickness (Wp) and the magnetic field inclination angle (θ),

Table 2 compares the values of the short-circuit current density (Jsc), the open-circuit voltage (Voc), and the efficiency (η) obtained both without a magnetic field and under the action of an inclined field for different angles.

Table 2. Comparative effect of the base thickness (Wp) and the magnetic field angle (θ) on the photovoltaic parameters.

Wp (μm)	Magnetic field B (mT)	$\theta(rad)$	Jsc (mA cm^{-2})	Voc (mV)	η (%)
50	B = 0	–	2.432	296.548	6.8
	B = 7.5	$\theta = \pi/12$	0.483	296.548	1.8
		$\theta = \pi/6$	1.125	296.548	3.2
		$\theta = \pi/4$	1.673	296.548	4.7
		$\theta = \pi/3$	2.087	296.548	5.9
		$\theta = \pi/2$	2.432	296.548	6.8
100	B = 0	–	4.433	296.548	12.7
	B = 7.5	$\theta = \pi/12$	0.573	296.548	1.7
		$\theta = \pi/6$	1.708	296.548	4.9
		$\theta = \pi/4$	2.833	296.548	8.1
		$\theta = \pi/3$	3.704	296.548	10.6
		$\theta = \pi/2$	4.433	296.548	12.7
150	B = 0	–	5.830	296.548	16.8
	B = 7.5	$\theta = \pi/12$	0.582	296.548	1.7
		$\theta = \pi/6$	1.912	296.548	5.6
		$\theta = \pi/4$	3.447	296.548	10.0
		$\theta = \pi/3$	4.727	296.548	13.6
		$\theta = \pi/2$	5.830	296.548	16.8
200	B = 0	–	6.698	296.548	19.4
	B = 7.5	$\theta = \pi/12$	0.583	296.548	1.7
		$\theta = \pi/6$	1.973	296.548	5.8
		$\theta = \pi/4$	3.728	296.548	10.9
		$\theta = \pi/3$	5.294	296.548	15.4
		$\theta = \pi/2$	6.698	296.548	19.4
250	B = 0	–	7.199	296.548	20.9
	B = 7.5	$\theta = \pi/12$	0.583	296.548	1.8
		$\theta = \pi/6$	1.991	296.548	5.9
		$\theta = \pi/4$	3.847	296.548	11.3
		$\theta = \pi/3$	5.585	296.548	16.3
		$\theta = \pi/2$	7.199	296.548	20.9

The examination of Table 2 reveals several major trends:

1) Variation with Base Thickness Without Magnetic Field:

When the magnetic field is absent, increasing Wp leads to a significant rise in the current density Jsc and the efficiency η.

These quantities reach a near-saturation value for Wp≥200 μm, with a maximum efficiency of 20.9% for Wp=250 μm.

2) Effect of the Magnetic Field Angle:

The application of an inclined magnetic field shows an effect that is strongly dependent on θ. For small angles ($\pi/12$, $\pi/6$), the efficiency drops drastically (<6%), indicating a limitation in carrier transport. Conversely, starting from $/4$, the efficiency increases progressively, reaching notable values for $\pi/3$. Finally, for $\pi/2$, the performance becomes equal to that obtained without a magnetic field, indicating that the losses are totally compensated by the magnetic confinement effect. Consequently, the action of the Lorentz force is nullified.

3) Joint Optimization of Wp & θ:

The combination of the two parameters shows that thin configurations (Wp ≤ 100 μm) and low angles should be avoided, as they lead to limited efficiency. The optimal range is achieved for a relatively thick base (200 ≤ Wp ≤ 250), combined with a high angle θ ≈ π/2, allowing maximum efficiency of around 20 to 21% to be achieved.

4. Conclusion

This study shows that the design of a highly doped vertical junction solar cell must aim for a base thickness that maximizes carrier generation and minimizes recombination losses in order to increase the collected carriers, the short-circuit current, and its efficiency.

Similarly, it revealed a strong recombination loss of charge carriers for small angles due to the Hall effect, when subjected to a magnetic field of variable inclination, which reduces the short-circuit current and thus the efficiency.

The optimal efficiency of the solar cell is obtained at large angle values, demonstrating the beneficial nature of the θ charge carrier collection contributing to the short-circuit current density and allowing the efficiency to increase.

These results demonstrate that the efficiency of a highly doped silicon solar cell does not depend solely on the base thickness, but also on the orientation of the applied magnetic field. The joint optimization of the two parameters suggests that the best operating range is obtained for a base thickness Wp such that $(200 \leq W_p \leq 250)$ and a magnetic field with an angle of incidence $(\theta \approx \pi/2)$, conditions that guarantee efficient carrier collection.

In summary, the study shows the importance of the orientation of a magnetic field and the choice of an adequate thickness, critical factors to consider for the design of solar cells intended for environments where a magnetic field is present.

Abbreviations

θ	Magnetic Field Inclination Angle [rad]
Wp	Base Thickness [cm]
Jsc	Short-circuit Current Density [A.cm^{-2}],
Voc	Open-circuit Voltage [V],
η	Conversion Efficiency [-]
δ_n	Excess Minority Charge Carrier Density [cm^{-3}]
Jph	Photocurrent Density [A.cm^{-2}]
Vph	Photovoltage [V]
B	Magnetic field [mT]

Author Contributions

Landing Diatta: Conceptualization, Formal Analysis, Software, Writing – original draft, Visualization.

Moustapha Thiame: Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Sada Traore: Conceptualization, Formal Analysis, Investigation, Software, Writing, Visualization.

Moussa Camara: Software, Supervision, Validation.

Conflicts of Interest

The authors declare no conflicts of interest.

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Research Field

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