

Study of the Electrical Parameters of a Bifacial Polycrystalline Silicon Solar Cell under Multispectral Illumination in the Static Regime by Simulation Using MATHCAD Software

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Abstract

In this work, we present a theoretical study of the bifacial polycrystalline silicon solar cell in static regime under the effect of the illumination level using the Mathcad software, along with a comparative study with experimental results. Minority carrier density profiles accounting for the illumination level, recombination velocities at the junction and at the back surface have been plotted as a function of depth in the base. From these carrier densities, other parameters, photocurrent, photovoltage, I-V characteristic and power, were derived. Two operating modes of the solar cell (current or voltage generator) are described, corresponding to high and low recombination velocities at the junction, respectively. The theoretical results are in good agreement with the experimental results obtained in 2012 by Ly, Ibrahima *et al.* Furthermore, the power study showed that the power obtained from simultaneous illumination of both faces is greater than that obtained from the front or rear face alone.

Keywords

Bifacial Photocell, Carrier Density, Photocurrent, Photovoltage, Power, Static Regime, Recombination Velocity, Open Circuit, Short Circuit

1. Introduction

The direct conversion of sunlight into electricity is made possible by solar photo-

voltaic technology. This method is based on the use of photovoltaic cells called solar modules that capture photons present in sunlight and transform them into electric current [1].

Photovoltaic energy is considered a clean and renewable energy source because it does not generate greenhouse gases or air pollution during its operation. It has many advantages such as durability, reliability and ease of deployment. Solar modules can be installed on roofs, ground structures or integrated into portable devices [2].

In recent decades, photovoltaic technology has experienced considerable growth, characterized by constant improvements in the efficiency of solar cells, a reduction in production costs and an increase in global production capacity. Photovoltaic installations have become widespread both on a large scale in solar parks and on a small scale on rooftops, thus contributing to the energy transition [3].

Bifacial solar cells with polycrystalline silicon are particularly interesting because they can capture light from both sides (front and back), thus improving their overall energy production. This type of solar cell is subject to various types of illumination (white, monochromatic or multispectral light) depending on the conditions of use. Modeling and simulation are essential tools to understand and optimize the electrical parameters of these devices.

In this work, we carry out a theoretical study of the n^+p-p^+ polycrystalline silicon bifacial solar cell in static regime under multispectral illumination, using the Mathcad software. We analyze the influence of the level of illumination on minority carrier density profiles, photocurrent, photovoltage, current-voltage characteristic (I-V) and power, for three illumination modes: front face, back face and simultaneous illumination of both faces.

2. Materials and Methods

2.1. Presentation of the Silicon Bifacial Solar Cell

The solar cell under study is a bifacial polycrystalline silicon n^+p-p^+ solar cell, whose structure is shown in **Figure 1**. It consists of four distinct parts:

- **The n^+ type emitter (front face):** the most heavily doped region, which receives incident light and collects electrons.
- **The p -type base:** weakly doped with acceptor atoms; electrons are minority carriers.
- **The rear panel of type p^+ :** p^+ overdoping generating a back surface field (BSF) that repels minority carriers generated near the backside toward the junction.
- **The emitter-base junction (space charge region):** the internal electric field separates the electron-hole pairs generated by the absorption of photons.

The solar cell is subjected successively to three illumination modes. front face ($\alpha = 1$), back face ($\alpha = 2$), and simultaneous illumination of both faces ($\alpha = 3$). The study is conducted in a static regime, which means that all parameters are independent of time.

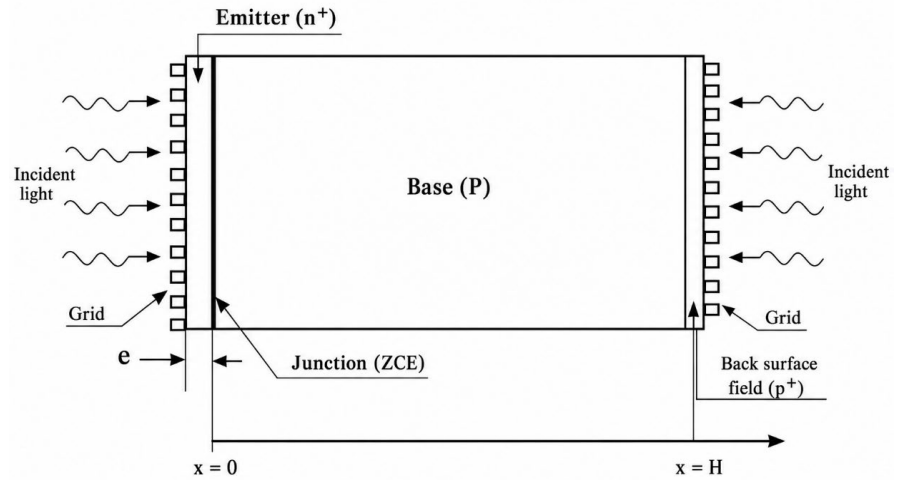


Figure 1. Structure of an $n^+ - p - p^+$ silicon bifacial solar cell [4].

2.2. Physical Model and Equations

The model is one-dimensional, with the junction ($x = 0$) and the base extending to $x = H$ as its origin [5]. The contribution of the emitter is neglected given its small thickness (about $1 \mu\text{m}$). In the static regime under multispectral illumination, the density of excess minority carriers in the base obeys the continuity equation.

$$\frac{\partial^2 \delta_\alpha(x)}{\partial x^2} - \frac{\delta_\alpha(x)}{L^2} = -\frac{G_\alpha(x)}{D} \quad (1)$$

where:

- $\delta_\alpha(x)$: Denotes the density of excess minority carriers as a function of depth x in the base according to the different illumination modes;
- L : Diffusion length of minority charge carriers in the base. It represents the average distance traveled by minority carriers before their recombination;
- D : Diffusion coefficient of minority carriers in the base;
- $G_\alpha(x)$: Rate of generation of minority carriers at a distance x from the solar cell junction.

The generation rate $G_\alpha(x)$ expressed as a function of the light absorption depth x in the base can be written as follows [6]:

$$G_\alpha(x) = n \cdot \sum_{i=1}^3 a_i \left[\xi_\alpha \cdot e^{-b_i x} + \chi_\alpha \cdot e^{-b_i (H-x)} \right] \quad (2)$$

where n is the illumination level. The absorption coefficients for the AM1.5 spectrum are:

$$a_1 = 6.13 \times 10^{20} \text{ cm}^{-3} \text{ s}^{-1}; a_2 = 0.54 \times 10^{20} \text{ cm}^{-3} \text{ s}^{-1}; a_3 = 0.0991 \times 10^{20} \text{ cm}^{-3} \text{ s}^{-1}$$

$$b_1 = 6630 \text{ cm}^{-1}; b_2 = 10^3 \text{ cm}^{-1}; b_3 = 130 \text{ cm}^{-1}$$

The ξ_α and χ_α parameters are defined according to the illumination mode (Table 1).

Table 1. Values of the parameters ξ_α and χ_α depending on the illumination mode [7] [8].

Illumination mode	ξ_α	χ_α
Front-facing lighting ($\alpha = 1$)	1	0
Backside illumination ($\alpha = 2$)	0	1
Simultaneous illumination ($\alpha = 3$)	1	1

Boundary conditions are written: at the junction ($x = 0$): $\partial\delta_\alpha/\partial x = (Sf_\alpha/D) \cdot \delta_\alpha(0)$; to the rear face ($x = H$). $\partial\delta_\alpha/\partial x = -(Sb_\alpha/D) \cdot \delta_\alpha(H)$, où Sf_α et Sb_α are the recombination speeds at the junction and on the rear face, respectively.

The parameter values used in the simulation are. $L = 0.015$ cm; $D = 26$ cm²/s; $H = 0.03$ cm; $N^b = 10^{16}$ cm⁻³; $n_i = 10^{10}$ cm⁻³; $T = 300$ K. These values are consistent with the reported experimental data for polycrystalline silicon under AM1.5.

2.3. Expressions of Photocurrent, Photovoltage, and Power

• Photocurrent density

The photocurrent density is deduced from Fick's law applied to the junction.

$$J_{pha} = q \cdot A_\alpha \cdot D \cdot \left. \frac{\partial \delta_\alpha(x)}{\partial x} \right|_{x=0} \quad (3)$$

For recombination speeds $Sf_\alpha \rightarrow \infty$, J_{pha} reaches a constant value corresponding to the short-circuit current J_{pha} .

A_α denotes the illuminated active area of the solar cell for illumination mode α (the front-face area for $\alpha = 1$, the rear-face area for $\alpha = 2$, and the sum of the front- and rear-face areas for the simultaneous mode $\alpha = 3$), used to convert the photocurrent density J_{pha} (mA/cm²) into the photocurrent $I_{pha} = A_\alpha J_{pha}$ (mA), and the power density P_α (mW/cm²) obtained from Equation (5) into the electrical power P_α (W) = $A_\alpha P_\alpha$ (mW), for a cell of a given physical surface area.

• Photovoltage

The photovoltage is deduced from the carrier density at the junction via the Boltzmann relation.

$$V_\alpha = V_T \ln \left(\frac{N_b}{n_i^2} \delta_\alpha(0) + 1 \right) \quad (4)$$

where $V_T = \frac{K \cdot T}{q}$ is the thermal voltage (~ 0.026 V à 300 K).

• Electrical power

Taking into account the diode current J_{pha} , the power per unit area is written.

$$P_\alpha = V_{pha} \cdot \left(J_{pha} - qSf_0 \left(1 + e^{\frac{V_{pha}}{V_T}} \right) \right) \quad (5)$$

All these expressions have been implemented in MATHCAD and evaluated as

a function of the recombination rate Sf_α at the junction, for the different illumination levels n and the three illumination modes.

The illumination level n used throughout Equation (2) is a dimensionless multiplicative factor applied to the AM1.5 reference spectral irradiance from which the absorption coefficients a_i and b_i were derived; $n = 1$ corresponds to one standard sun (AM1.5G, total irradiance $\approx 100 \text{ mW/cm}^2$), and the sub-unity values used in this study ($n = 0.065, 0.175$ and 0.375) correspond to fractions of this reference irradiance, consistent with the illumination conditions reported by Bernard (2006) and with the experimental levels used for validation against Ly *et al.* (2012).

For the simultaneous illumination mode ($\alpha = 3$), the same illumination level n is applied to the front and rear faces simultaneously ($\xi_3 = \chi_3 = 1$ in Equation (2)) rather than a fixed total irradiance being split between the two faces. Consequently, for a given n the total incident energy under simultaneous illumination is twice that received under single-face illumination, and part of the higher photocurrent, photovoltage and power obtained for this mode reflects this larger total input rather than a purely bifacial gain. A strictly energy-normalized comparison between modes would require halving n on each face for the simultaneous case, which is not done in the results presented here and is left for a dedicated bifacial-gain analysis in future work.

In Equation (5), Sf_0 denotes the recombination velocity associated with the diode dark (saturation) current; it is taken as a fixed, mode-independent parameter and is used, together with the thermal voltage V_T , to represent the reverse dark current $qSf_0 \left(1 + e^{\frac{V_{pha}}{V_T}} \right)$ that is subtracted from the illuminated photocurrent J_{pha} to obtain the net current used to compute the power P_α for each illumination mode.

All expressions for $\delta_{\alpha(x)}$, J_{pha} , V_α and P_α were implemented in Mathcad by solving the linear second-order ordinary differential Equation (1), together with its boundary conditions at $x = 0$ and $x = H$, in closed analytical form (a homogeneous cosh/sinh solution plus a particular solution driven by the exponential generation term $G_{\alpha(x)}$); the resulting closed-form expressions were then evaluated numerically over a logarithmic sweep of the junction recombination velocity, $Sf_\alpha = 10^p \text{ cm/s}$ with p varied from 0 to 6, for each illumination level n and each mode α . Unless stated otherwise in a figure caption, all other parameters (L , D , H , Nb , n_b , T and the back-surface recombination velocity Sb_α) were held fixed at the values given above.

For each illumination mode and level n , the current-voltage (I-V) characteristic shown in Section 3.4 was constructed parametrically. J_{pha} and V_α were both computed as functions of the same junction recombination velocity Sf_α over the sweep described above, and paired point-by-point at each value of Sf_α to trace the J_{pha} - V_α curve, using the dark-current assumption described for Equation (5) for all three illumination modes.

3. Results and Discussions

3.1. Density of Excess Minority Carriers as a Function of Depth in the Base

3.1.1. Illumination from the Front Face

The substitution of integration coefficients in the continuity equation makes it possible to obtain the expression of the density of excess minority carriers for an illumination by the front face of the solar cell. The density profiles are illustrated in **Figure 2** for different levels of illumination.

In the vicinity of the junction ($x = 0$), a carrier storage is observed, which corresponds to a maximum density of minority carriers when the recombination rate is low (open circuit). The carrier density decreases as one moves away from the junction towards the rear face. The increase in the level of illumination leads to an increase in the density of minority carriers, especially at the junction. This effect becomes negligible for a depth greater than 0.025 cm.

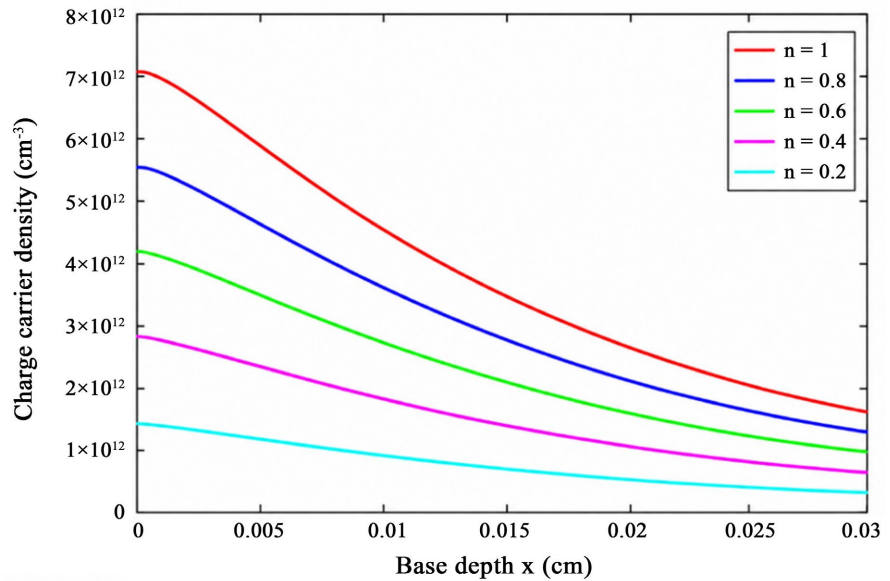


Figure 2. Charge carrier density as a function of depth x in the base and for different levels of illumination from the front face with $S_f = 1000$ cm/s; $D = 26$ cm²/s; $L = 0.015$ cm et $S_{b1} = 1000$ cm/s.

When the recombination rate at the junction increases significantly, the carrier density $\delta(x)$ decreases. This behavior illustrates the transition from open circuit mode ($S_f \rightarrow 0$, maximum density) to short-circuit mode (high S_f low density at the junction). **Figure 3** shows the influence of the recombination rate at the junction on the carrier density for a fixed illumination level $n = 0.2$.

According to the curve, the recombination rate at the junction increases, which leads to a decrease in the minority charge carrier density.

3.1.2. Illumination from the Rear Face

For backside illumination, the carrier density increases from the junction to a

maximum located at the backside of the base (positive gradient in this area). This behavior is the opposite of what was observed for front side illumination. **Figure 4** shows the profiles for different levels of illumination n .

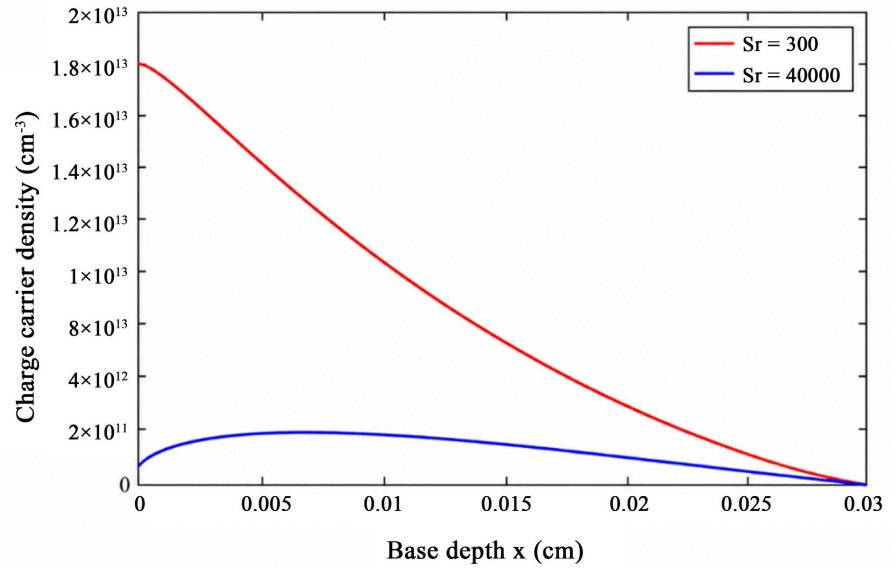


Figure 3. Carrier density as a function of depth x in the base for illumination from the front face and for different recombination speeds at the junction with $D = 26 \text{ cm}^2/\text{s}$; $n = 0.2$; $Sf = 300 \text{ cm/s}$ $L = 0.015 \text{ cm}$; $H = 0.03 \text{ cm}$; $Sb_1 = 4000 \text{ cm/s}$.

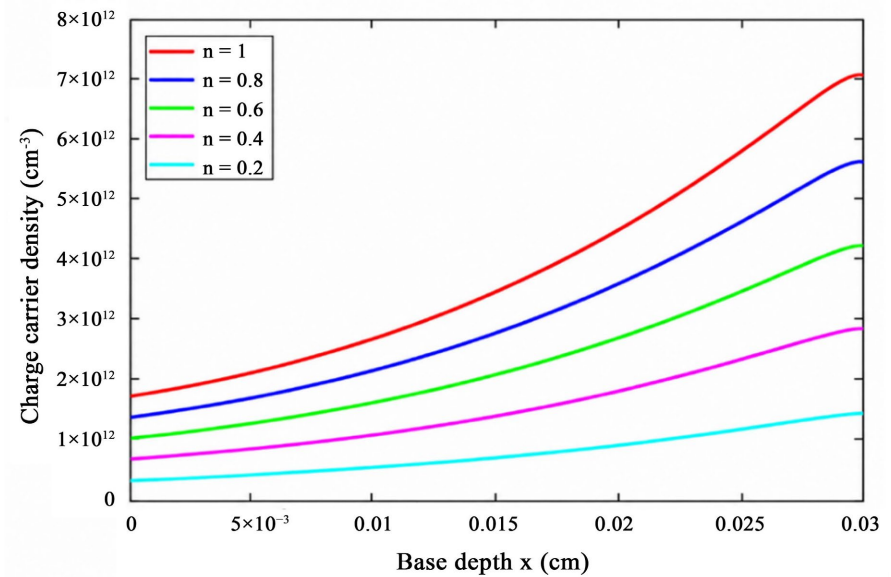


Figure 4. Charge carrier density as a function of depth x in the base and for different levels n of illumination through the rear face with $Sf_2 = 1000 \text{ cm/s}$; $D = 26 \text{ cm}^2/\text{s}$; $L = 0.015 \text{ cm}$; $H = 0.03 \text{ cm}$ et $Sb_2 = 1000 \text{ cm/s}$.

Figure 5 illustrates the influence of the recombination rate at junction Sf_2 for different values and for an illumination level $n = 0.2$. Whatever the recombination

rate at the Sf_2 junction, the carrier density increases with depth x up to a maximum, then decreases. In the decreasing zone, carriers can no longer cross the junction and recombine. When Sf_2 is very high (short circuit), the junction density is almost zero.

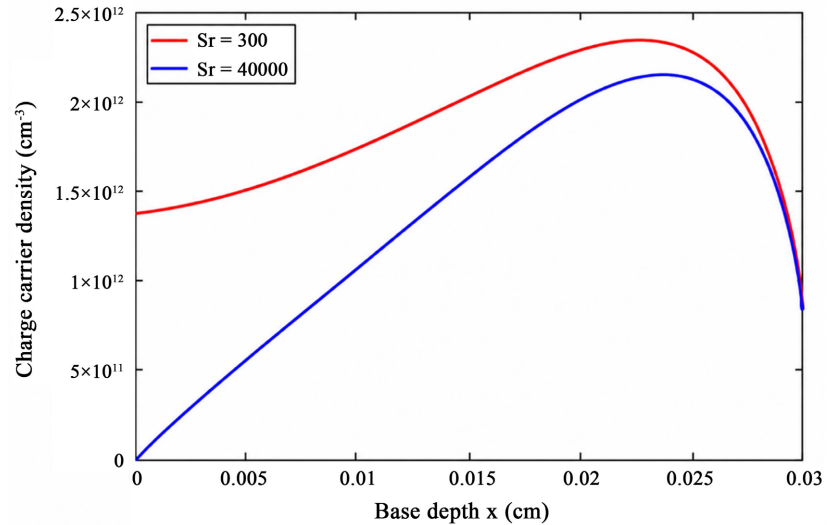


Figure 5. Carrier density as a function of depth x in the base for illumination from the rear face and for different recombination speeds at the junction with $D = 26 \text{ cm}^2/\text{s}$; $n = 0.2$; $Sf_2 = 300 \text{ cm/s}$; $L = 0.015 \text{ cm}$; $H = 0.03 \text{ cm}$; $Sb_2 = 40,000 \text{ cm/s}$.

3.1.3. Simultaneous Illumination of Both Sides

For simultaneous illumination, the carrier density has two maxima. one at the junction (influence of the front face) and the other at the rear face (influence of the rear face). **Figure 6** illustrates these profiles for different levels of illumination.

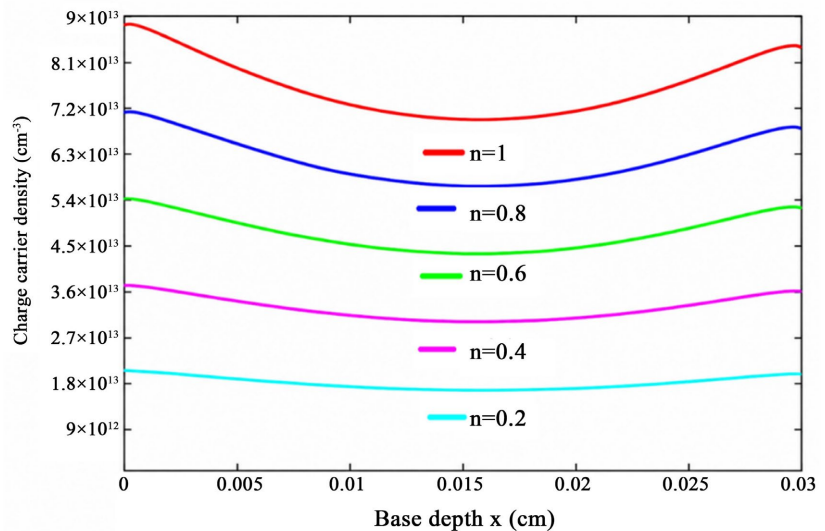


Figure 6. Density of charge carriers as a function of depth x in the base and for different levels n of simultaneous illumination with $Sf_2 = 1000 \text{ cm/s}$; $D = 26 \text{ cm}^2/\text{s}$; $L = 0.015 \text{ cm}$; $H = 0.03 \text{ cm}$ et $Sb_3 = 1000 \text{ cm/s}$.

Figure 7 shows the influence of the recombination rate at the Sf_3 junction for simultaneous illumination. The density decreases with the increase of Sf_3 ; this effect attenuates as we move away from the junction, to become almost zero at the end of the base (x between 0.028 and 0.03 cm).

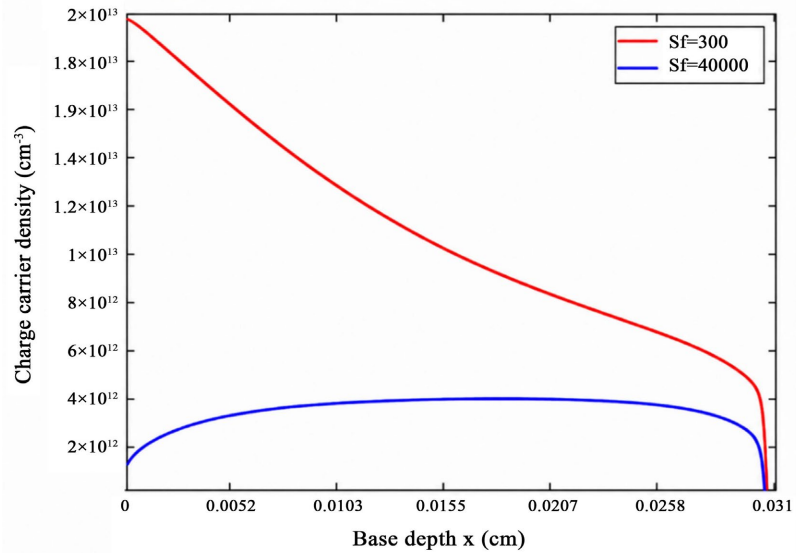


Figure 7. Carrier density as a function of depth x in the base for simultaneous illumination and for different recombination speeds at the junction Sf_3 with $D = 26 \text{ cm}^2/\text{s}$; $n = 0.2$; $L = 0.015 \text{ cm}$; $H = 0.03 \text{ cm}$ et $Sb_3 = 40,000 \text{ cm/s}$.

3.2. Study of the Current Density for Different Illumination Modes

3.2.1. Current Density for Illumination from the Front Face

Figure 8 illustrates the variation of the photocurrent density as a function of the recombination rate at junction Sf_1 for different illumination levels n , for illumination from the front face.

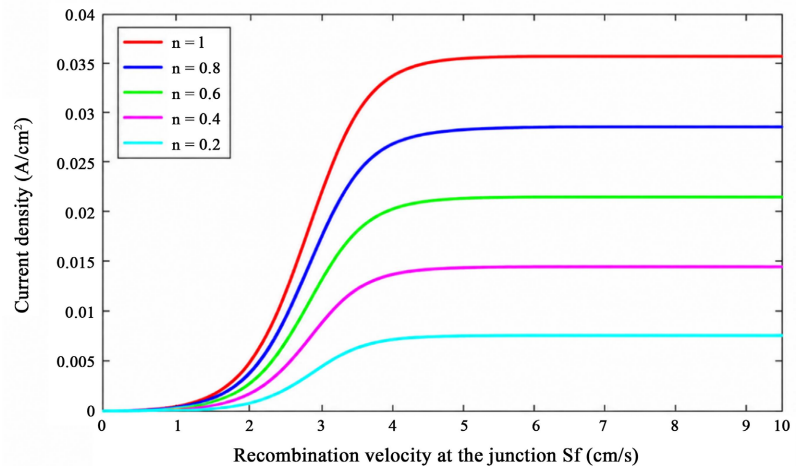


Figure 8. Current density as a function of the recombination rate at the junction Sf_1 for different values of n for illumination by the front face of the solar cell with $D = 26 \text{ cm}^2/\text{s}$; $L = 0.015 \text{ cm}$ et $Sb_1 = 1000 \text{ cm/s}$.

For low values of Sf_1 (open circuit), the photocurrent density is almost zero because the carriers are blocked at the junction. When Sf_1 increases, the current gradually increases until it reaches a constant value corresponding to the short-circuit current. The photocurrent density increases with the level of illumination n , which is explained by the increase in the density of minority carriers under more intense illumination [8].

3.2.2. Current Density for Backlighting

Figure 9 illustrates the variation of current density as a function of recombination rate at junction Sf_2 for different illumination levels n , for backside illumination.

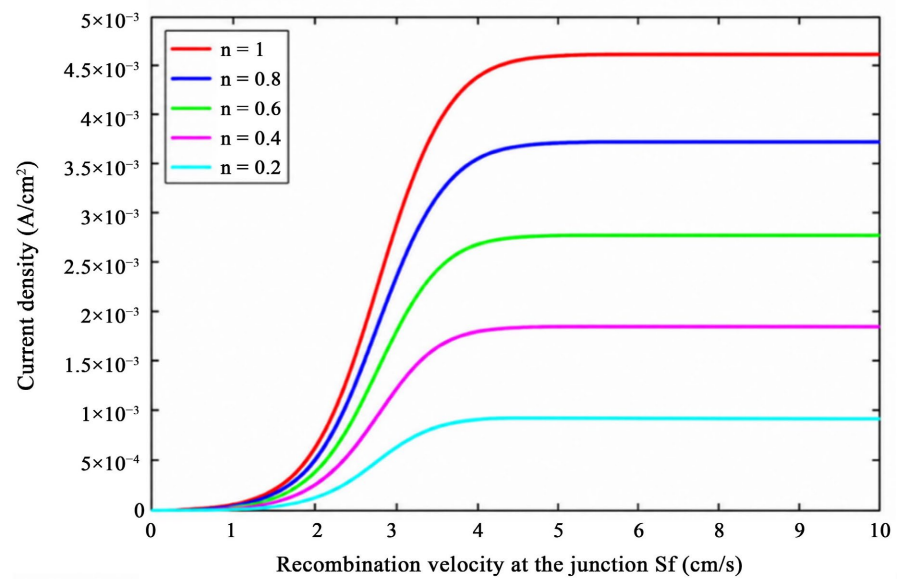


Figure 9. Current density as a function of the recombination rate at the Sf_2 for different values of n for illumination by the rear face of the solar cell with $D = 26 \text{ cm}^2/\text{s}$; $L = 0.015 \text{ cm}$ et $Sb_2 = 1000 \text{ cm/s}$.

The current density profiles present a similar pattern to those obtained for the front side illumination. However, the short-circuit photocurrent density for a front face illumination is higher than that obtained by the rear face [8]. The level of illumination leads to an increase in photocurrent density in both cases.

3.2.3. Current Density for Simultaneous Illumination of Both Sides

Figure 10 shows the variation profiles of photocurrent density J_{ph3} as a function of recombination rate at junction Sf_3 for different illumination levels n .

The photocurrent density for simultaneous illumination is higher than those obtained for front or rear face illuminations alone. The density of the currents increases according to the level of lighting.

3.2.4. Comparative Study of Current Densities for Different Illumination Modes

Figure 11 presents a comparison of the photocurrent curves for the three illumi-

nation modes (front face, rear face, simultaneous) at an illumination level $n = 1$.

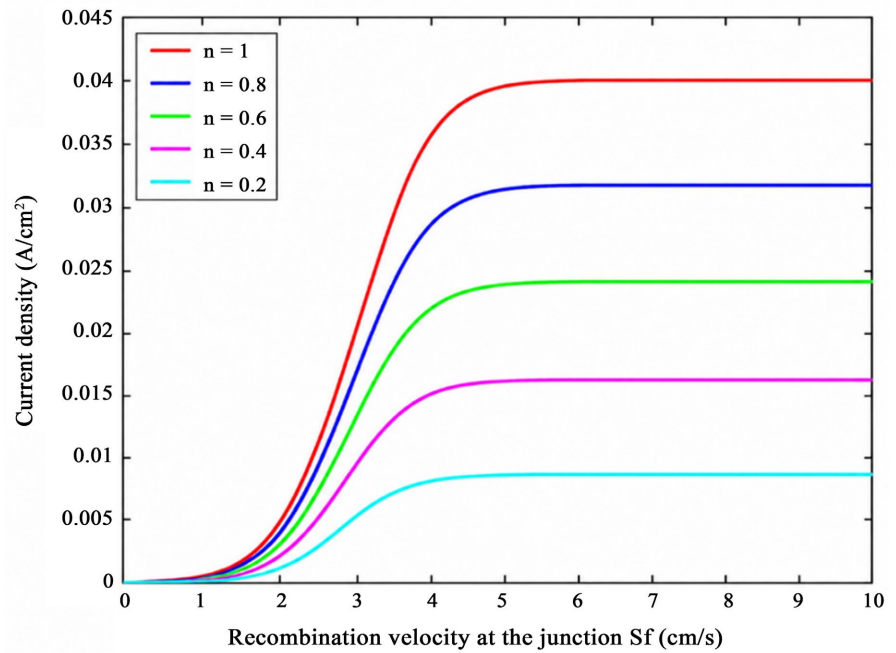


Figure 10. Current density as a function of the recombination rate at the junction S_f for different values of n for simultaneous illumination of both sides with $D = 26 \text{ cm}^2/\text{s}$; $L = 0.015 \text{ cm}$ et $S_b = 1000 \text{ cm/s}$.

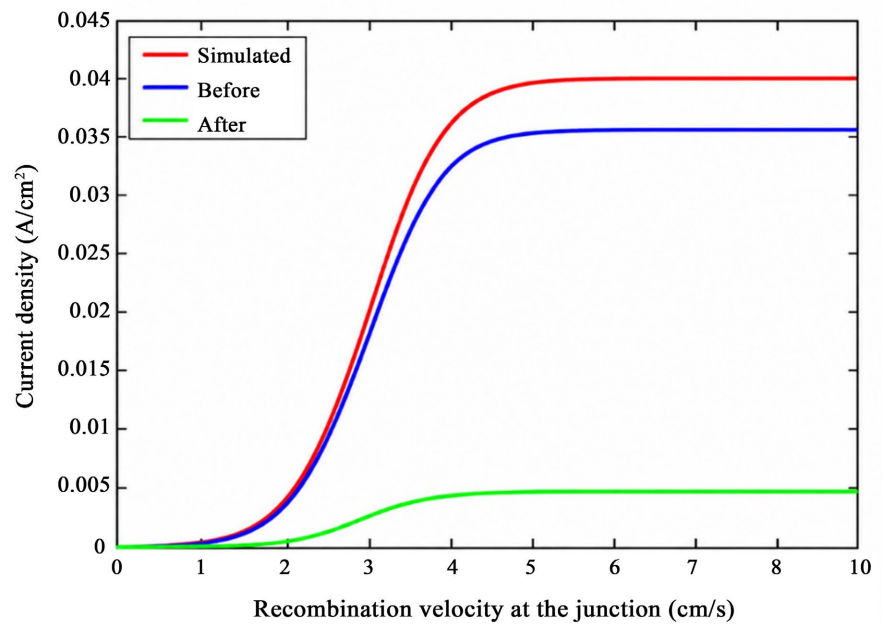


Figure 11. Current density as a function of the recombination rate S_f for different illumination modes with $n = 1$; $H = 0.03 \text{ cm}$; $S_b = 1000 \text{ cm/s}$; $D = 26 \text{ cm}^2/\text{s}$; $L = 0.015 \text{ cm}$.

For a given illumination level ($n = 1$), the theoretical short-circuit current of the front face is greater than that of the rear face, in accordance with the experi-

mental results presented in **Table 2**. The short-circuit current of simultaneous illumination is the highest of the three modes.

3.3. Study of the Photovoltage

3.3.1. Phototension for Illumination from the Front Face

Figure 12 shows the variation of the photovoltage as a function of the recombination rate at junction Sf_1 for front side illumination and for different illumination levels n .

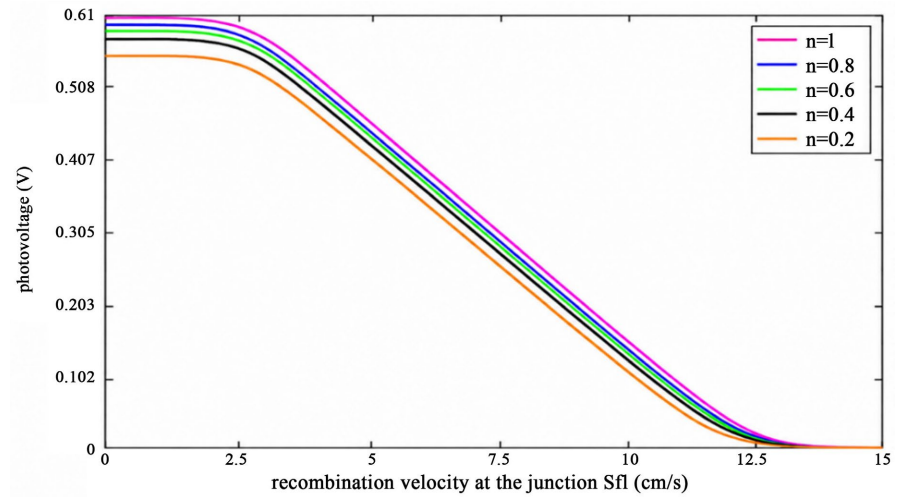


Figure 12. Photovoltage as a function of the recombination rate Sf_1 for different values of n for illumination from the front face with $D = 26 \text{ cm}^2/\text{s}$; $Sb_1 = 1000 \text{ cm/s}$; $H = 0.03 \text{ cm}$ et $Sf_1 = 10^p \text{ cm/s}$.

The photovoltage is maximum and constant for low values of Sf_1 (open circuit, storage of carriers at the junction). When Sf_1 reaches high values, the voltage decreases and tends to zero (short circuit). The photovoltage increases with the level of illumination, because the density of minority carriers, on which the photovoltage directly depends, is higher under intense illumination.

3.3.2. Photovoltage for Illumination from the Back Side

Figure 13 illustrates the profile of photovoltage V_2 as a function of recombination rate at the junction Sf_2 for different illumination levels n .

The rear side photovoltage profiles have the same overall appearance as those on the front side. However, for the same level of illumination, the photovoltage for a front side illumination is higher than that obtained by the rear side.

3.3.3. Photovoltage for Simultaneous Illumination of Both Sides

Figure 14 shows the profile of the photovoltage V_3 as a function of the recombination rate at the junction Sf_3 for different illumination levels n and for simultaneous illumination.

The photovoltage V_3 remains constant and maximum when Sf_3 is low (open circuit), then rapidly decreases to zero for high values of Sf_3 (short circuit). The

photovoltage increases with the level of illumination, in accordance with the trends observed for the other modes.

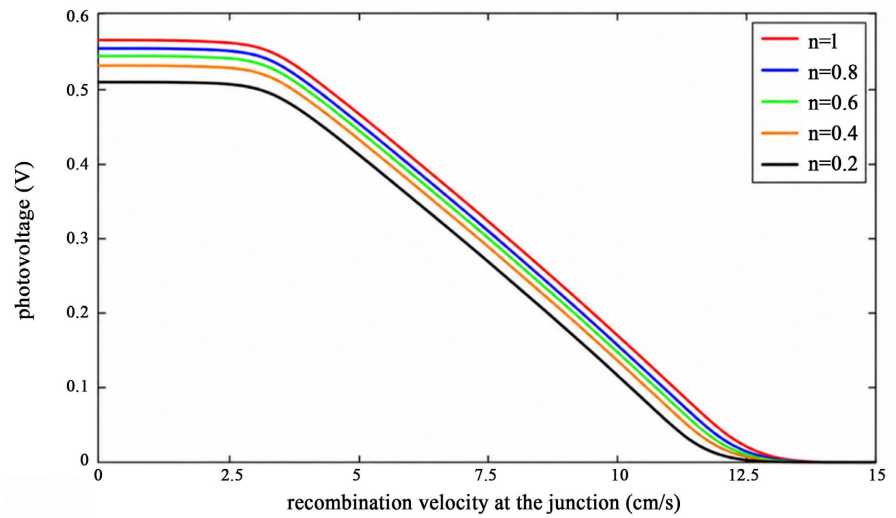


Figure 13. Photovoltage as a function of the recombination rate S_L for different values of n for illumination from the rear front with $D = 26 \text{ cm}^2/\text{s}$; $Sb_2 = 1000 \text{ cm/s}$; $H = 0.03 \text{ cm}$ et $S_L = 10^p \text{ cm/s}$.

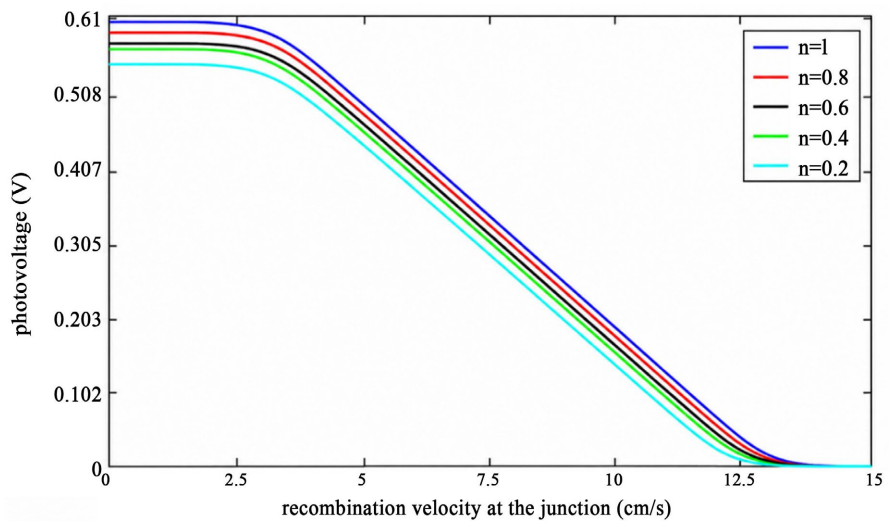


Figure 14. Photovoltage as a function of the recombination rate S_L for different values of n for simultaneous illumination with $D = 26 \text{ cm}^2/\text{s}$; $Sb_3 = 1000 \text{ cm/s}$; $H = 0.03 \text{ cm}$ et $S_L = 10^p \text{ cm/s}$.

3.3.4. Comparative Study of Photovoltages for Different Types of Illumination

Figure 15 compares the photovoltage as a function of the recombination rate at the junction for the three illumination modes at $n = 1$.

For a given illumination level ($n = 1$), the open-circuit voltage obtained by simultaneous illumination of both sides is higher than that of the front and rear faces, in accordance with the experimental result from **Table 3**.

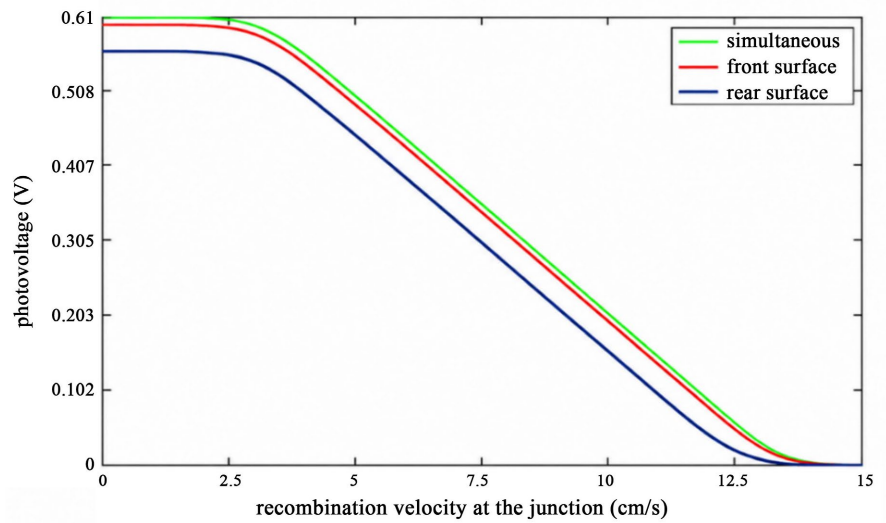


Figure 15. Photovoltage as a function of the recombination rate S_L for different types of illumination and for $n = 1$ with $D = 26 \text{ cm}^2/\text{s}$; $L = 0.015 \text{ cm}$; $H = 0.03 \text{ cm}$; $S_L = 1000 \text{ cm/s}$.

3.4. Study of the Current Density-Photovoltage (I-V) Characteristic

3.4.1. Characteristic I-V for Different Levels of Illumination from the Front Face

Figure 16 shows the current-voltage characteristic I-V obtained for illumination from the front face and for different levels of illumination n .

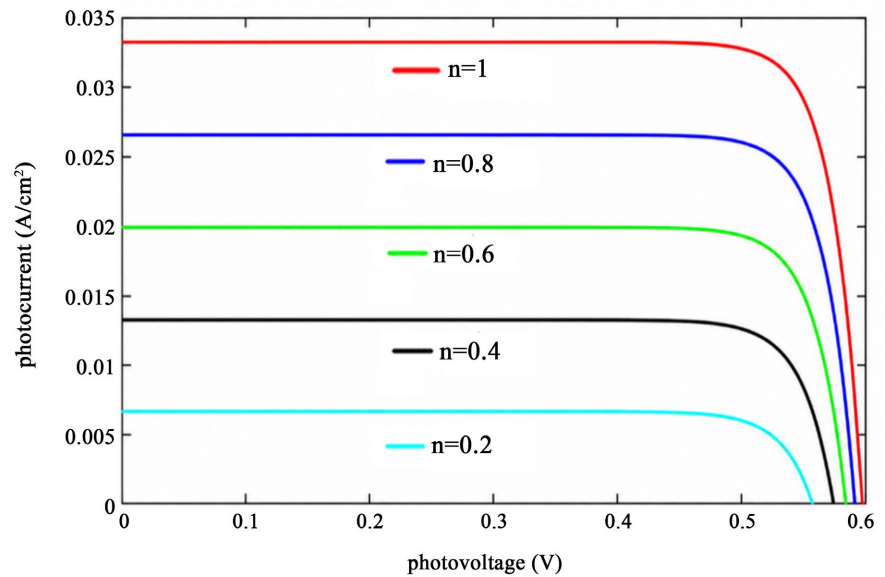


Figure 16. Characteristic I-V for different values of n for a front side illumination with $S_L = 1000 \text{ cm/s}$; $D = 26 \text{ cm}^2/\text{s}$; $H = 0.03 \text{ cm}$; $L = 0.015 \text{ cm}$.

For a voltage below 0.5 V, the current density remains practically constant, close to the short-circuit current. Above 0.5 V, it rapidly drops towards zero in the vicinity of the open circuit. The open-circuit voltage and the short-circuit current

increase with the level of illumination, the variation in current being much greater than that in voltage.

3.4.2. Characteristic I-V for Different Levels of Backlighting

Figure 17 shows the characteristic I-V for backlighting and for different levels of illumination n .

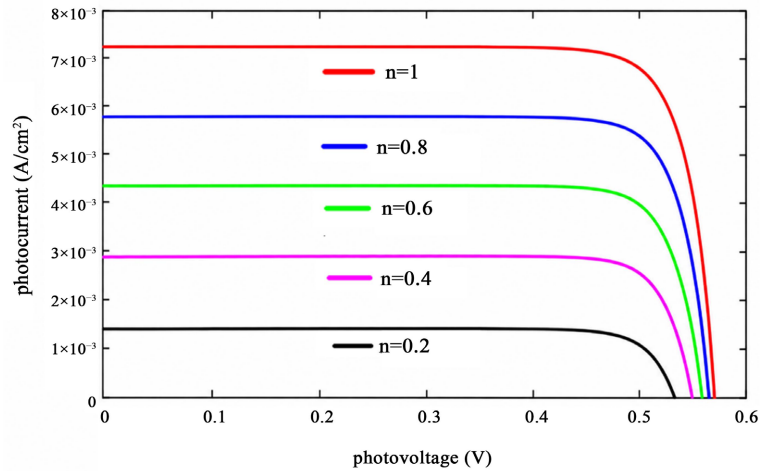


Figure 17. Characteristic I-V for different values of n for a rear side illumination with $Sb_2 = 1000 \text{ cm/s}$; $D = 26 \text{ cm}^2/\text{s}$; $H = 0.03 \text{ cm}$ et $L = 0.015 \text{ cm}$.

For a voltage below 0.45 V, the current density is practically constant and equal to the back side short-circuit current. The current density and open-circuit voltage increase with the level of illumination, the increase in current being much greater than that in voltage.

3.4.3. Characteristic I-V for Simultaneous Illumination

Figure 18 shows the variation in current density as a function of voltage for simultaneous illumination of both sides and different levels n .

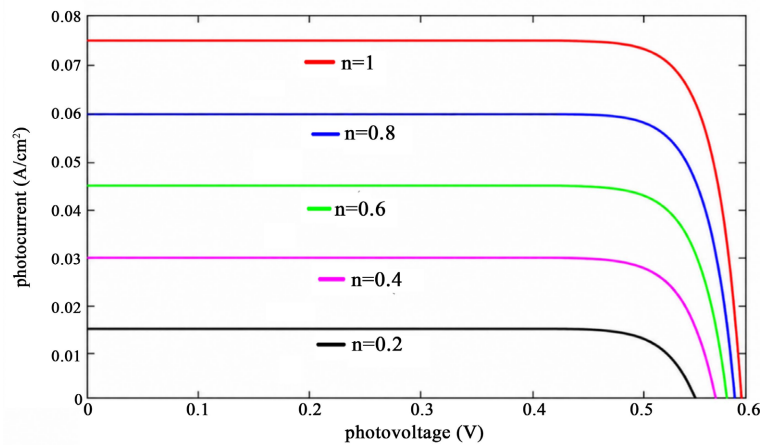


Figure 18. Characteristic I-V for different values of n for simultaneous illumination of both sides with $Sb_2 = 1000 \text{ cm/s}$; $D = 26 \text{ cm}^2/\text{s}$; $H = 0.03 \text{ cm}$ et $L = 0.015 \text{ cm}$.

For a voltage lower than 0.5 V, the current density is constant (short-circuit). It then decreases quickly to cancel itself at the open circuit point. The effect of the illuminance level is more pronounced in the vicinity of the short circuit.

3.4.4. Comparative Study of I-V Characteristics for Different Illumination Modes

Figure 19 compares the I-V characteristics of the three illumination modes for $n = 1$.

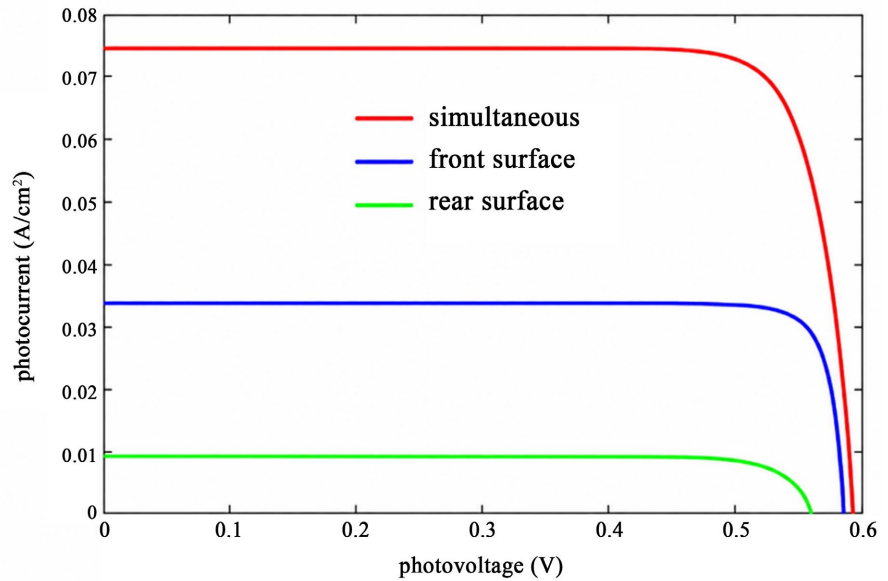


Figure 19. I-V characteristic for different illumination modes and for $n = 1$; $Sb_a = 1000$ cm/s; $D = 26$ cm²/s; $H = 0.03$ cm et $L = 0.015$ cm.

Simultaneous illumination of both sides produces the highest current density and open circuit voltage. The back side alone yields the lowest values. These results are consistent with experimental results from the literature [8].

3.5. Power of the Solar Cell for Different Lighting Modes and Levels

3.5.1. Power for Illumination from the Front Face

Figure 20 shows the variations of the electric power P_1 as a function of the recombination rate at junction S_f for different levels of illumination n .

There are four operating zones. 1) open circuit (low S_f , $P \approx 0$); 2) zone between open circuit and maximum power; 3) zone between maximum power and short circuit; 4) short circuit (high S_f , $P \approx 0$). The maximum power point is around $p \approx 3.85$. This point moves to the open circuit when the illumination level increases.

3.5.2. Power for Rear-Side Illumination

Figure 21 shows the variations in P_2 power as a function of S_{f_2} for backside illumination.

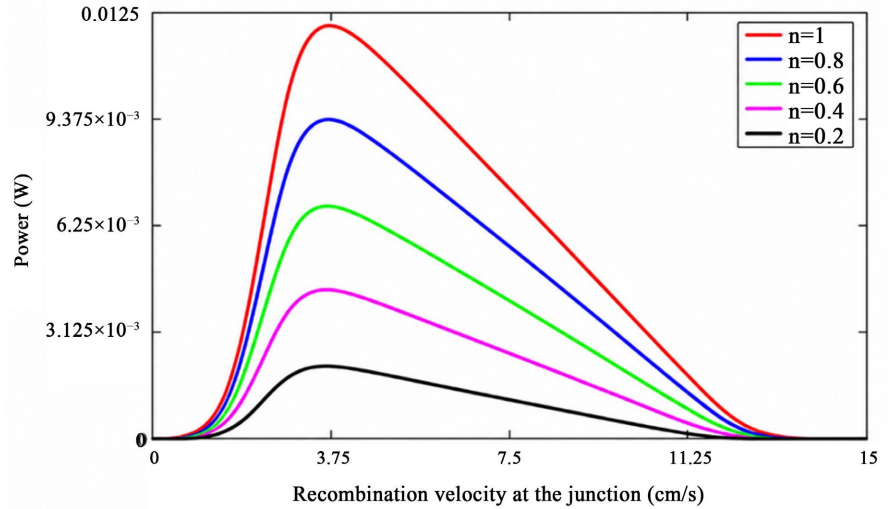


Figure 20. Power of the solar cell illuminated by its front face as a function of the recombination rate Sf_1 at the junction, for different illumination levels n of the solar cell, $Sb_1 = 3 \cdot 10^3$ cm/s; et $Sf_1 = 10^p$ cm/s.

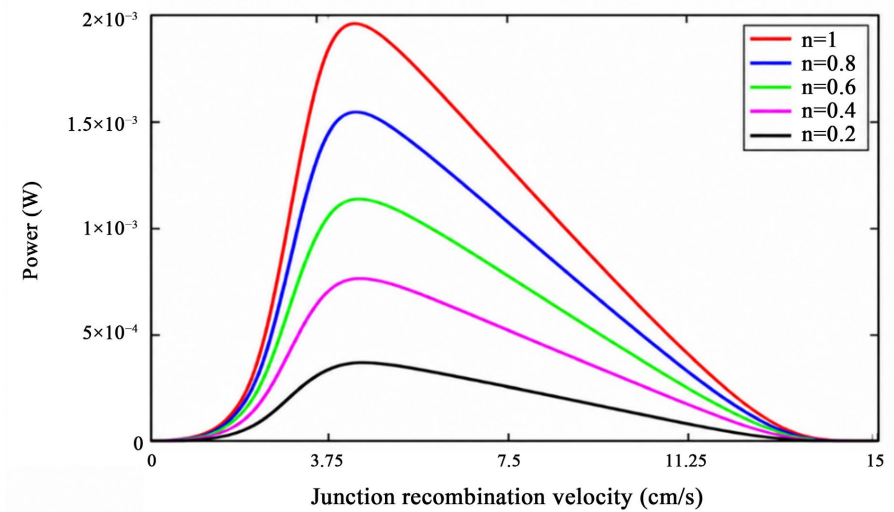


Figure 21. Power of the solar cell illuminated by its back surface as a function of the recombination rate Sf_2 at the junction, for different illumination levels n of the solar cell, $Sb_2 = 3 \cdot 10^3$ cm/s; et $Sf_2 = 10^p$ cm/s.

The same four areas of variation are observed. For the same level of illumination, the power obtained by backlighting is lower than that of the front side, but cannot be neglected.

3.5.3. Power for Simultaneous Illumination of Both Sides

Figure 22 shows the variations in P3 power as a function of Sf_3 for simultaneous illumination.

The influence of the recombination rate at the junction on the power is similar to the observations of previous modes. The maximum power is the highest for simultaneous illumination.

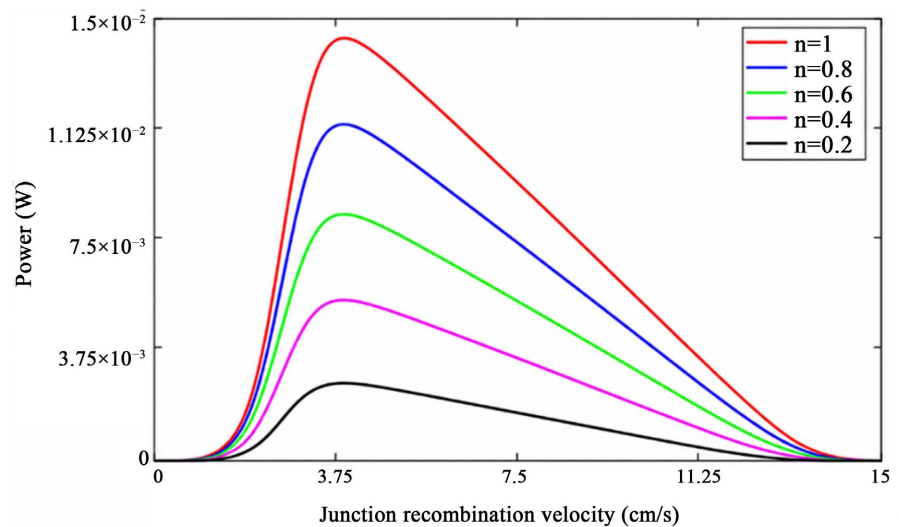


Figure 22. Power of the solar cell for simultaneous illumination of both sides as a function of the recombination rate S_b at the junction, for different illumination levels n of the solar cell with $S_b = 3 \cdot 10^3$ cm/s; et $S_a = 10^p$ cm/s.

3.5.4. Comparative Study of Power Characteristics for Different Illumination Modes

Figure 23 compares the power characteristics for the three illumination modes at $n = 1$.

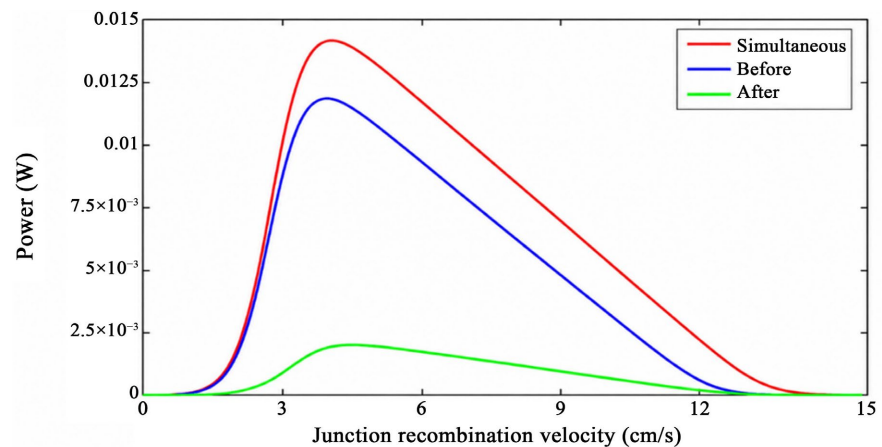


Figure 23. Power characteristics for different illumination modes and for $n = 1$; $S_b = 3 \cdot 10^3$ cm/s; et $S_a = 10^p$ cm/s.

For $n = 1$, the simultaneous illumination of both sides provides the highest power, followed by the front side and then the rear side. This result is consistent with the photocurrents and photovoltages obtained for each mode.

3.6. Comparison with Experimental Results

Table 2 presents a comparison of theoretical and experimental short-circuit currents for different levels of illumination, while **Table 3** compares open-circuit voltages.

Table 2. Comparison of the short-circuit currents J_{cc1} and J_{cc2} (front and rear face) for different levels of illumination—Theoretical and experimental results.

Illumination (n)	Theoretical J_{cc1} (mA)	Experimental J_{cc1} (mA)	Theoretical J_{cc2} (mA)	Experimental J_{cc2} (mA)
0.375	12	11.4	2.74	2.6
0.312	9.98	9.5	2.34	2.2
0.175	5.55	5.3	2.34	1.2
0.065	2.09	2	0.53	0.5
Reference		[8].		[8].

Table 3. Comparison of open circuit voltages V_{co1} , V_{co2} and V_{co3} for different levels of illumination—Theoretical and experimental results [8].

Illum. (n)	Theo. V_{co1} (mV)	Exp. V_{co1} (mV)	Dev. V_{co1} (%)	Theo. V_{co2} (mV)	Exp. V_{co2} (mV)	Dev. V_{co2} (%)	Theo. V_{co3} (mV)	Exp. V_{co3} (mV)	Dev. V_{co3} (%)
0.375	508	487	4.31	477	469	1.71	519	503	3.18
0.175	488	467	4.50	458	450	1.78	494	479	3.13
0.065	456	438	4.11	433	426	1.64	469	455	3.08
Reference		[8].			[8].			[8].	

Experimental J_{cc} values are taken from **Table 1** and experimental V_{co} values from Tab. 4 of reference [8]. The theoretical trends obtained (short-circuit current and open-circuit voltage both increasing with illumination level, and simultaneous illumination outperforming either single-face mode) are consistent with the experimental observations reported in reference [8]. Quantitatively, the theoretical short-circuit current densities deviate from the experimental values in reference [8] by about 4.5% to 6.4% for J_{cc1} (**Table 2**), and the theoretical open-circuit voltages deviate by about 1.6% to 4.5% (**Table 3**), which supports the concordance claimed above.

4. Conclusions

In this work, we carried out a theoretical study by simulation of the n+-p-p+ polycrystalline silicon bifacial solar cell under multispectral illumination in static regime, using the Mathcad software. The main objective was to analyze the influence of the level of illumination and recombination velocities on the electrical parameters of the solar cell. minority carrier density, photocurrent, photovoltage, I-V characteristic, and power, for three distinct modes of illumination (front, back and simultaneous).

The results showed that the minority carrier density, photocurrent, photovoltage and power all increase with the level of illumination. The simultaneous illumination of both sides systematically generates higher performances than those obtained by illuminating only one side. The theoretical results are in good agreement with experimental data from the literature [8], confirming the ob-

served trends.

This work confirms the potential of bifacial solar cells for better use of solar radiation. In perspective, it would be relevant to extend this study to the dynamic regime (transient and frequency) and to explore the effect of other parameters such as series resistance, shunt resistance and temperature on the performance of the bifacial solar cell.

Author Contributions

OYEDELE Sampson O. design and definition of the research problem, formulation of the methodology, development of the theoretical model of the bifacial photovoltaic cell, supervision of the study, analysis and interpretation of the results, as well as critical review of the manuscript. **SOUMAHORO Ibrahima.** contribution to the formulation of the physical and mathematical model, analysis of the electrical parameters of the photovoltaic cell, interpretation of the simulation results and revision of the manuscript. **KOUADJA Rika Justin.** contribution to modeling and simulation under Mathcad, processing and analysis of results related to carrier density, photocurrent, and photovoltage, as well as the revision of the manuscript. **OBUE Kouakou Sarfo Denis.** contribution to the analysis of the electrical characteristics of the cell, notably the current-voltage and power characteristics, participation in the interpretation of the results and the revision of the manuscript. **BAMBA Lanciné.** contribution to the implementation of numerical simulations under Mathcad, to the processing and presentation of results, to the comparative analysis of different illumination modes and to the revision of the manuscript. **MARIKO Mamadou.** contribution to the analysis of theoretical and experimental results, to the comparison of cell performance according to different illumination modes, as well as to the revision and finalization of the manuscript. **BOKO Aka.** Scientific supervision and contribution to the methodological orientation of the study, to the critical analysis of the results and to the revision of the manuscript.

Conflicts of Interest

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

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