



(RESEARCH ARTICLE)



TECHNIQUE FOR DETERMINING THE RECOMBINATION VELOCITY OF EXCESS MINORITY CARRIERS AT THE JUNCTION SFCC INITIATE A SHORT CIRCUIT USING MATLAB SOFTWARE

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ABSTRACT

The short-circuit photocurrent density is obtained when the carrier recombinassions velocity at the junction is at its maximum ($S_f \geq 10^6 \text{ cm} \cdot \text{s}^{-1}$). It corresponds to the maximum current that the photovoltaic cell can deliver. It is expressed by the following equation: $J_{phcc} = \lim_{S_f \rightarrow +\infty} J_{ph}$. We are interested in the point where the photocurrent density reaches its limiting value and becomes constant. This point corresponds to the point at which the short circuit begins. The orthogonal projection of this point onto the y-axis gives the short-circuit current, and its projection onto the x-axis gives the recombination rate of the minority carriers initiating the short circuit, S_{fcc} , for a given value of the magnetic field B.

Keywords: Wavelength, Photovoltage, Magnetic Field, Recombination Velocity, Photovoltaic Cell

1 INTRODUCTION

Photovoltaic conversion is carried out by a solar cell whose conversion efficiency depends on the nature of the semiconductor structure, its design, and its manufacturing processes [1]. A change in the charge in the base causes a corresponding change in the photovoltage across the junction, resulting in an associated capacitance. These studies [2–4] have shown that the diffusion capacitance decreases with the magnetic field and the doping concentration in the base. The various recombination processes of excess photo-generated minority carriers in the photovoltaic cell are essentially the main causes of low efficiencies; these include Shockley-Read-Hall bulk recombination [5,6], radiative Auger recombination [7,8], and surface recombination linked to crystal lattice imperfections. Previous studies have been conducted under steady-state [9–11], transient [12–13], and frequency-modulated [14–16] conditions. In this

article, we focus primarily on the recombination rate at the junction for a vertical-junction series device under a magnetic field and monochromatic illumination.

2 MATHEMATICAL MODELING

In this section, we will describe the method for calculating the following parameters:

A series vertical junction silicon solar cell of type n⁺-p-p⁺ under an applied magnetic field, is shown in figure 1.

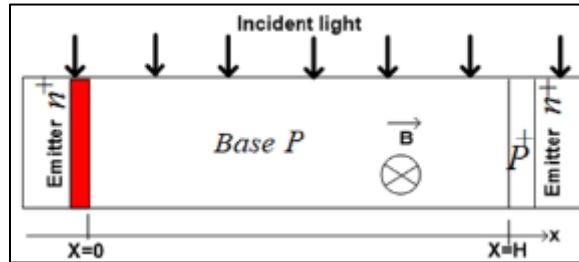


Figure 1: A single structure of a vertical junction solar cell with an applied magnetic field.

$$\text{We have : } D^*(B, \omega) = \frac{D_0[1 + \tau^2(\omega_C B^2 - \omega^2) + i\omega\tau(\tau^2(\omega_C B^2 - \omega^2) - 1)]}{4\omega^2\tau^2 + [1 + \tau^2(\omega_C B^2 - \omega^2)]^2} \quad (1)$$

Where D_0 is the diffusion coefficient in the absence of an applied magnetic field.

$$D^*(\omega, B) \cdot \frac{\partial^2 \delta(x, z, t)}{\partial x^2} - \frac{\delta(x, z, t)}{\tau} e^{i\omega t} = g(z) \cdot e^{i\omega t} + \frac{\partial \delta(x, z, t)}{\partial t} \cdot e^{i\omega t} \quad (2)$$

This continuity equation describes these physical phenomena: generation, diffusion, and recombination.

$D^*(\omega, B) \cdot \frac{\partial^2 \delta(x, z, t)}{\partial x^2}$ Describes the diffusion of charge carriers. Diffusion is the movement of charge carriers when densities are not uniform.

$\frac{\delta(x, z, t)}{\tau}$ Describes recombination

$g(z) \cdot e^{i\omega t} + \frac{\partial \delta(x, z, t)}{\partial t} \cdot e^{i\omega t}$ Describes the net generation rate

$$g(z) = \phi_\lambda \cdot \alpha_\lambda \cdot (1 - R_\lambda) e^{-\alpha_\lambda \cdot z} \quad (3)$$

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

$$\text{we have: } L^{*2}(\omega, B) = \tau \cdot D^*(B, \omega) \quad (5)$$

The continuity equation takes the following form:

$$\frac{\partial^2 \delta(x, z, \lambda, \omega, B)}{\partial x^2} - \frac{\delta(x, z, \lambda, \omega, B)}{L^{*2}(\omega, B)} = - \frac{g(z)}{D^*(B, \omega)} \quad (6)$$

It is a second-order differential equation with a right-hand side.

$$G(z, t) = g(z) \cdot e^{i\omega t} \quad \text{Avec } g(z) = \phi_\lambda \cdot \alpha_\lambda \cdot (1 - R_\lambda) e^{-\alpha_\lambda \cdot z} \quad (6)$$

We have :

$$\delta_1(x, z, \lambda, \omega, B) = \frac{L^{*2}(\omega, B)}{D^*(B, \omega)} \cdot g(z) \quad (7)$$

$$\delta_1(x, z, \lambda, \omega, B) = \frac{L^{*2}(\omega, B)}{D^*(B, \omega)} \cdot \phi_\lambda \cdot \alpha_\lambda \cdot (1 - R_\lambda) e^{-\alpha_\lambda \cdot z} \quad (8)$$

The general solution $\delta(x, z, \lambda, \omega, B)$ of the continuity equation is:

$$\delta(x, z, \lambda, \omega, B) = a. e^{\frac{x}{L^*(\omega, B)}} + b. e^{-\frac{x}{L^*(\omega, B)}} + \frac{L^{*2}(\omega, B)}{D^*(B, \omega)} \cdot \phi_{\lambda} \cdot \alpha_{\lambda} \cdot (1 - R_{\lambda}) e^{-\alpha_{\lambda} \cdot z} \quad (9)$$

ϕ_{λ} : is the incident monochromatic light flux at wavelength λ ; α_{λ} : the monochromatic absorption coefficient of the material at wavelength λ ; R_{λ} : the monochromatic reflection coefficient of the material at wavelength λ . To find the coefficients a and b , we must determine the boundary conditions.

At the junction at $x=0$

$$D^*(B, \omega) \cdot \frac{\partial \delta(x, z, \lambda, \omega, B)}{\partial x} \Big|_{x=0} = S_f \delta(x, z, \lambda, \omega, B) \Big|_{x=0} \quad (10)$$

In the middle of the base at $x = H/2$

$$\frac{\partial \delta(x, z, \lambda, \omega, B)}{\partial x} \Big|_{x=H} = -\frac{S_b}{D(\omega, B)} \delta(x, z, \lambda, \omega, B) \Big|_{x=H} \quad (11)$$

We have :

$$S_f \delta(x, z, \lambda, \omega, B) \Big|_{x=0} = S_f \cdot \left(a. e^{\frac{H}{2L^*(\omega, B)}} + b. e^{-\frac{H}{2L^*(\omega, B)}} + \phi_{\lambda} \cdot \alpha_{\lambda} \cdot (1 - R_{\lambda}) e^{-\alpha_{\lambda} \cdot z} \right) \quad (12)$$

$$S_f \delta(x, z, \lambda, \omega, B) \Big|_{x=0} = S_f \cdot \left(2. a. \cosh\left(\frac{H}{2L^*(\omega, B)}\right) + \phi_{\lambda} \cdot \alpha_{\lambda} \cdot (1 - R_{\lambda}) e^{-\alpha_{\lambda} \cdot z} \right) \quad (13)$$

$$2a. \frac{D^*(B, \omega)}{L^*(\omega, B)} \sinh\left(\frac{H}{2L^*(\omega, B)}\right) = S_f \cdot \left(2. a. \cosh\left(\frac{H}{2L^*(\omega, B)}\right) + \phi_{\lambda} \cdot \alpha_{\lambda} \cdot (1 - R_{\lambda}) e^{-\alpha_{\lambda} \cdot z} \right) \quad (14)$$

$$\delta(x, z, \lambda, \omega, B) = 2. \cosh\left(\frac{x}{L^*(\omega, B)}\right) \cdot \left(\frac{\frac{L^{*2}(\omega, B)}{D^*(B, \omega)} \phi_{\lambda} \cdot \alpha_{\lambda} \cdot (1 - R_{\lambda}) e^{-\alpha_{\lambda} \cdot z}}{2. \left(\frac{D^*(B, \omega)}{L^*(\omega, B)} \sinh\left(\frac{H}{2L^*(\omega, B)}\right) - S_f \cosh\left(\frac{H}{2L^*(\omega, B)}\right) \right)} \right) + \frac{L^{*2}(\omega, B)}{D^*(B, \omega)} \cdot \phi_{\lambda} \cdot \alpha_{\lambda} \cdot (1 - R_{\lambda}) e^{-\alpha_{\lambda} \cdot z} \quad (15)$$

$$\delta(x, z, \lambda, \omega, B) = \left\{ \frac{S_f \cosh\left(\frac{x}{L^*(\omega, B)}\right) + \frac{D^*(B, \omega)}{L^*(\omega, B)} \sinh\left(\frac{H}{2L^*(\omega, B)}\right) - S_f \cosh\left(\frac{H}{2L^*(\omega, B)}\right) \cdot \frac{L^{*2}(\omega, B)}{D^*(B, \omega)}}{\left(\frac{D^*(B, \omega)}{L^*(\omega, B)} \sinh\left(\frac{H}{2L^*(\omega, B)}\right) - S_f \cosh\left(\frac{H}{2L^*(\omega, B)}\right) \right)} \right\} \times \phi_{\lambda} \cdot \alpha_{\lambda} \cdot (1 - R_{\lambda}) e^{-\alpha_{\lambda} \cdot z} \quad (16)$$

The final expression for the photocurrent density is given by the equation

$$J_{ph}(x, z, \lambda, \omega, B) = q. \frac{L^{*2}(\omega, B) \cdot \phi_{\lambda} \cdot \alpha_{\lambda} \cdot (1 - R_{\lambda}) e^{-\alpha_{\lambda} \cdot z} \cdot \sinh\left(\frac{H}{2L^*(\omega, B)}\right)}{D^*(B, \omega) \cdot \sinh\left(\frac{H}{2L^*(\omega, B)}\right) - L^*(\omega, B) \cdot S_f \cosh\left(\frac{H}{2L^*(\omega, B)}\right)} \quad (17)$$

3 RESULTS AND DISCUSSION

Determination of the recombination rate of excess minority charge carriers at the Sfcj junction limiting the open-circuit current

The photocurrent results from the diffusion of minority carriers at the junction. Using the expression for the density of these carriers, we can determine the photocurrent density using Fick's law.

$$J_{ph}(x, z, \lambda, \omega, B) = q. D^*(B, \omega) \frac{\partial \delta(x, z, \lambda, \omega, B)}{\partial x} \Big|_{x=0} \quad (18)$$

It is observed that an increase in wavelength causes a rise in photocurrent density in the short-wavelength range, while the opposite effect occurs at long wavelengths. These variations can be explained by the dependence of the generation rate on different spectral ranges. Furthermore, the influence of wavelength on the photocurrent density is significantly more pronounced under short-circuit conditions than under open-circuit conditions. This observation justifies studying how the short-circuit photocurrent magnitude varies with wavelength.

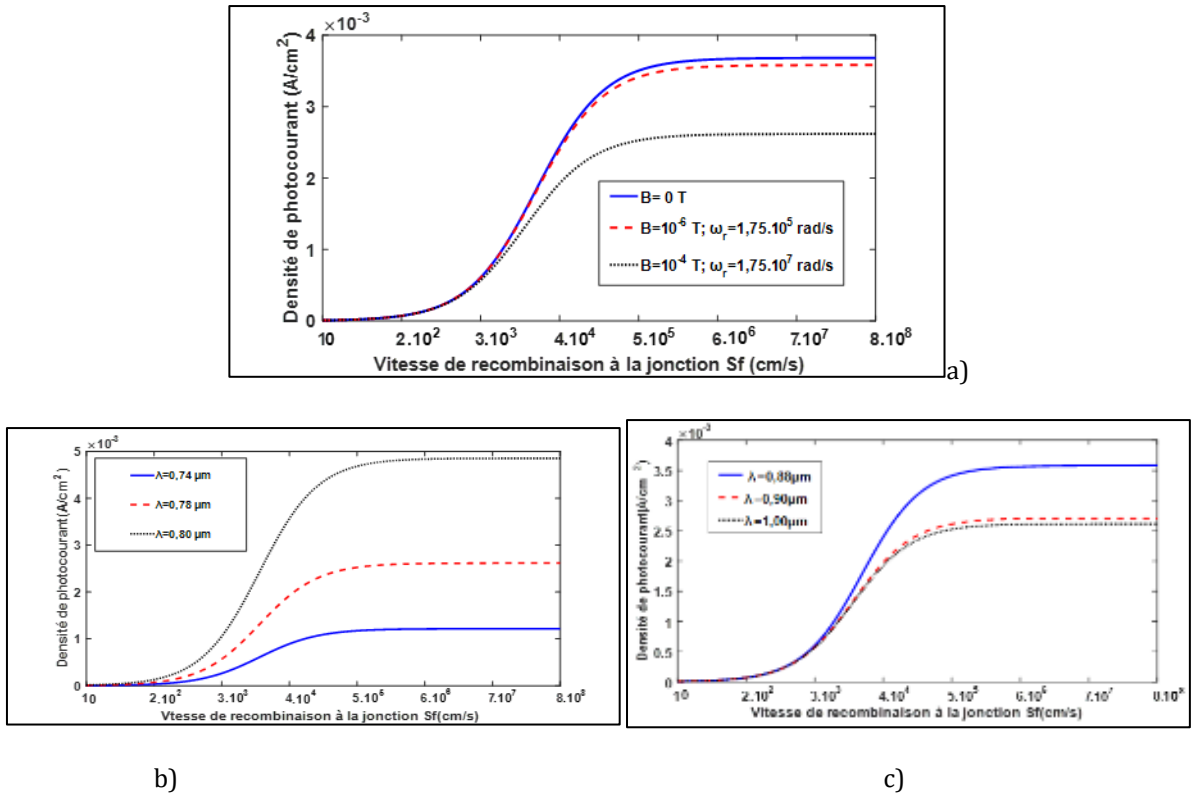


Figure 2: illustrates the technique for determining the recombination rate of minority carriers at the junction that limits the open-circuit current S_{fco} .

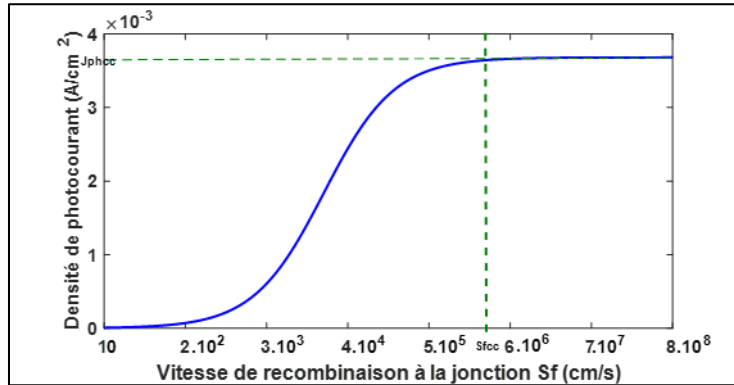


Figure 3: Photocurrent density profile as a function of the recombination rate at the S_f junction. $z = 0.002$ cm; $B = 10^{-4}$ T; $\omega_r = 1.75 \times 10^7$ rad/s

The short-circuit current is the current measured when the voltage applied to the cell is zero. It represents the maximum current that the cell can deliver. It is obtained from the expression for the photocurrent (Equation 17) by letting the recombination rate at the junction S_f approach a very high limit.

The curves showing the photocurrent density as a function of the recombination rate at the junction for different magnetic field values allowed us to present Table 1:

Table 1: Selected values of the recombination rate at the junction that initiates the short circuit (Sfcc) and the short-circuit current (Jphcc)

		Sfcc(cm/s)	Jphcc(A. cm ⁻²)
B= 0 T	ω_r (rad/s) = 0 rad/s	5,8.10 ^{5,8}	3,7.10 ⁻³
B=10 ⁻⁶ T	ω_r (rad/s) = 1.75 × 10 ⁵ rad/s	5,5.10 ^{5,5}	3,5.10 ⁻³
B=10 ⁻⁴ T	ω_r (rad/s)= 1.75 × 10 ⁷ rad/s	5,2.10 ^{5,2}	2,6.10 ⁻³

Table 1 highlights the quantitative variation in photocurrent density. The magnetic field inhibits photogenerated minority carriers from contributing to photocurrent generation. Similarly, we present some values of Sfcc and Jphcc for different wavelengths in Table 2.

Table 2: Selected values of Sfcc and Jph for different wavelengths

	$\lambda(\mu\text{m})$	Sfcc(cm/s)	Jphcc(A. cm ⁻²)
Courtes longueurs d'onde $\lambda < 0,86 \mu\text{m}$	0,74	4,8.10 ^{4,8}	0,9.10 ⁻³
	0,78	5,1.10 ^{5,1}	2.10 ⁻³
	0,80	5,3.10 ^{5,3}	4,8.10 ⁻³
Grandes longueurs d'onde $\lambda > 0,86 \mu\text{m}$	0,88	5,5.10 ^{5,5}	3,5.10 ⁻³
	0,90	5.10 ⁵	2,5.10 ⁻³
	1,00	4,4.10 ^{4,4}	2,3.10 ⁻³

Table 2 shows the variation in the values of the recombination velocity at the junction that initiates the short circuit (Sfcc) and the photocurrent density (Jphcc). Jphcc varies in parallel with Sfcc. In the short-wavelength range, Jphccexp increases along with Sfcc as the wavelength increases. The opposite phenomenon is observed in the long-wavelength range.

4 CONCLUSION

In this article, we examined the effects of the magnetic field and the resonance frequency on the electrical parameters of a series vertical-junction silicon photovoltaic cell under monochromatic illumination.

The density of minority carriers (in both short-circuit and open-circuit conditions) increases as the magnetic field and the resonance frequency become significant.

- As the magnetic field and the resonance frequency increase, the photovoltage and the diffusion capacity decrease.
- We were able to obtain two wavelength ranges: the short-wavelength range ($\lambda < 0.86 \mu\text{m}$) and the long-wavelength range ($\lambda > 0.86 \mu\text{m}$).
- A specific illumination wavelength of $\lambda = 0.86 \mu\text{m}$

In the short-wavelength range, as the illumination wavelength increases, the minority carrier density, photocurrent density, photovoltage, and diffusion capacity all increase. The opposite phenomenon is observed in the long-wavelength range.

Based on these various studies, we have established that the magnetic field and the resonance frequency promote the presence of photogenerated electrons in the base by inhibiting their diffusion and conduction. According to our model, the short-wavelength range ($\lambda < 0.86 \mu\text{m}$) generates more charge carriers in the base.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

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

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