



(RESEARCH ARTICLE)



TECHNIQUE FOR DETERMINING THE RECOMBINATION VELOCITY OF EXCESS MINORITY CHARGE CARRIERS AT THE JUNCTION SFCO LIMITING THE OPEN-CIRCUIT WITH MATLAB SOFTWARE

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ABSTRACT

The open-circuit photovoltage is obtained when the recombination velocity of carriers at the junction is very low ($S_f \rightarrow 0 \text{ cm/S}$). It corresponds to the maximum voltage that the photovoltaic cell can deliver. It is given by $V_{phco} = \lim_{S_f \rightarrow 0} V_{ph}$. When the recombination velocities of minority carriers at the junction are low, the photovoltage reaches its maximum and remains constant: the system is then in open-circuit operation. From this part of the curve, the orthogonal projection of the point marking the end of this regime onto the x-axis allows us to determine the value of the recombination velocity of minority carriers at the junction corresponding to the open-circuit limit, denoted S_{fco} .

Keywords: Solar Cell; Velocity Recombination; Wavelength; Magnetic Field

1 INTRODUCTION

The first monocrystalline and polycrystalline silicon solar cells achieved an energy conversion efficiency of 6% [1,2]. To significantly improve this efficiency, extensive research has led to the development of solar cells [3,4], whose conversion efficiency defined as the ratio of the electrical energy produced to the incident light energy is greater than or equal to 20% [1].

This quest for increased performance is based on a thorough understanding of charge carrier recombination mechanisms. These include Shockley-Read-Hall bulk recombination [2–5], as well as Auger, radiative, and surface

recombination [6]. These processes are quantified using key electronic parameters, such as carrier lifetime, diffusion length, and recombination velocity at interfaces and on the back surface, in addition to electrical parameters such as series and shunt resistances [7,8]. The techniques used to characterize these parameters whether in the static regime [9,10], the dynamic frequency regime [11,12], or the transient regime [13,14] are based on the measurement of optical [15] and electrical [16] effects. Their goal is to optimize the efficiency and overall performance of solar cells. We will theoretically study the recombination velocity at the junction that limits the open-circuit voltage of a silicon photovoltaic cell under a magnetic field and monochromatic illumination.

1.1 Mathematical Modeling of the Problem

The vertical-junction solar cell is designed such that the incident light rays are parallel to the junction plane. A series vertical-junction solar cell of the n+-p-p+ type [10] and a single cell of a series vertical junction solar cell under a magnetic field are shown in Figure 1.

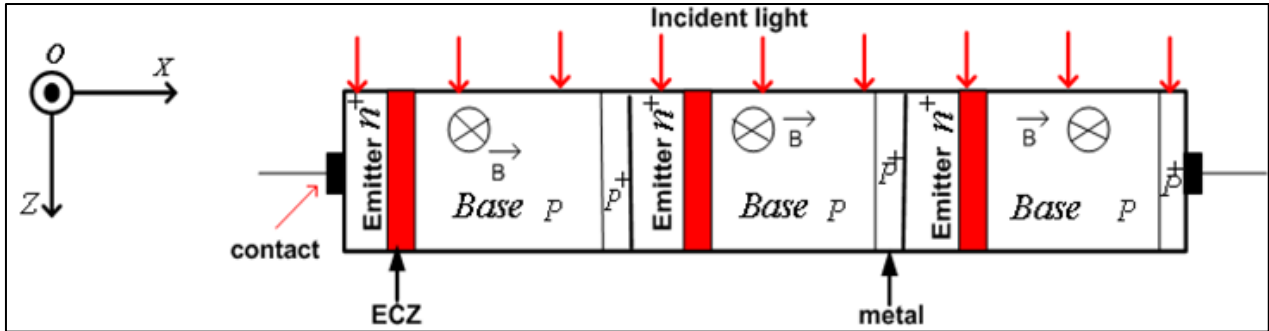


Figure 1: n+-p-p+ series vertical-junction solar cell

The diffusion coefficient of minority charge carriers in a photovoltaic cell under dynamic frequency conditions influenced by a magnetic field is given by the following equation [11].

$$D^* \cdot \frac{\partial^2 \delta(x,z,t)}{\partial x^2} - \frac{\delta(x,z,t)}{\tau} = -G(z,t) + \frac{\partial \delta(x,z,t)}{\partial t} \quad (1)$$

Where x and z are the spatial variables, along the (ox) and (oy) axes, respectively. D^* is the complex electron diffusion coefficient as a function of the magnetic field and the modulation frequency; t is time; τ is the average lifetime of minority carriers in the base; $\delta(x,z,t)$ is the density of minority carriers in the base; and $G(z,t)$ is the overall generation rate of minority carriers. We have the following equations :

$$G(z,t) = g(z) \cdot e^{i\omega t} \quad (2)$$

$$\delta(x,z,t) = \delta(x,z) \cdot e^{i\omega t} \quad (3)$$

$$g(z) = \alpha \phi (1 - R) \times e^{-\alpha z} \quad (4)$$

Physical phenomena are governed by the continuity equation:

$$\frac{\partial^2 \delta(x,z,\lambda,\omega,B)}{\partial x^2} - \frac{\delta(x,z,\lambda,\omega,B)}{L^2(\omega,B)} = -\frac{g(z)}{D(\omega,B)} \quad (5)$$

$L^* = L(\omega, B)$ represents the complex diffusion length. It depends on the excitation frequency and the magnetic field.

$$L^2(\omega, B) = \tau \cdot D(\omega, B) \quad (6)$$

A general solution to the continuity equation

$$\delta(x,z,\lambda,\omega,B) = K_1 \cdot e^{\frac{x}{L(\omega,B)}} + K_2 \cdot e^{-\frac{x}{L(\omega,B)}} + \frac{L^2(\omega,B)}{D(\omega,B)} \cdot \phi \cdot \alpha \cdot (1 - R) e^{-\alpha z} \quad (7)$$

Where the coefficients K_1 and K_2 are determined by the boundary conditions.

At the emitter-base junction ($x = 0$):

$$D(\omega, B) \cdot \left. \frac{\partial \delta(x, z, \lambda, \omega, B)}{\partial x} \right|_{x=0} = S_f \cdot \delta(x, z, \lambda, \omega, B)|_{x=0} \quad (8)$$

in the middle of the base at $x = H/2$:

$$\left. \frac{\partial \delta(x, z, \lambda, \omega, B)}{\partial x} \right|_{x=\frac{H}{2}} = 0 \quad (9)$$

The photovoltage (or photovoltaic voltage), according to Boltzmann's law, is given by:

$$V_{ph}(x, z, \omega, \lambda, B, S_f) = V_T \cdot \ln \left(1 + \frac{N_b}{n_i^2} \cdot \delta(x, z, \omega, \lambda, B, S_f)|_{x=0} \right) \quad (10)$$

2 RESULTS AND DISCUSSION

The incident light flux as a function of wavelength is given by the following figure

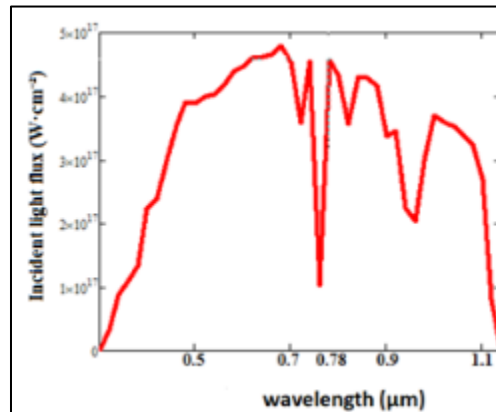


Figure 2: Incident light flux as a function of wavelength.

The first region, where the incident light flux generally increases. This corresponds to short wavelengths; at this wavelength, photon absorption is high. The second region, where the incident light flux generally decreases. This corresponds to long wavelengths; at this wavelength, photon absorption is low. Photovoltage as a function of the recombination velocity at the Junction is given by the following figures.

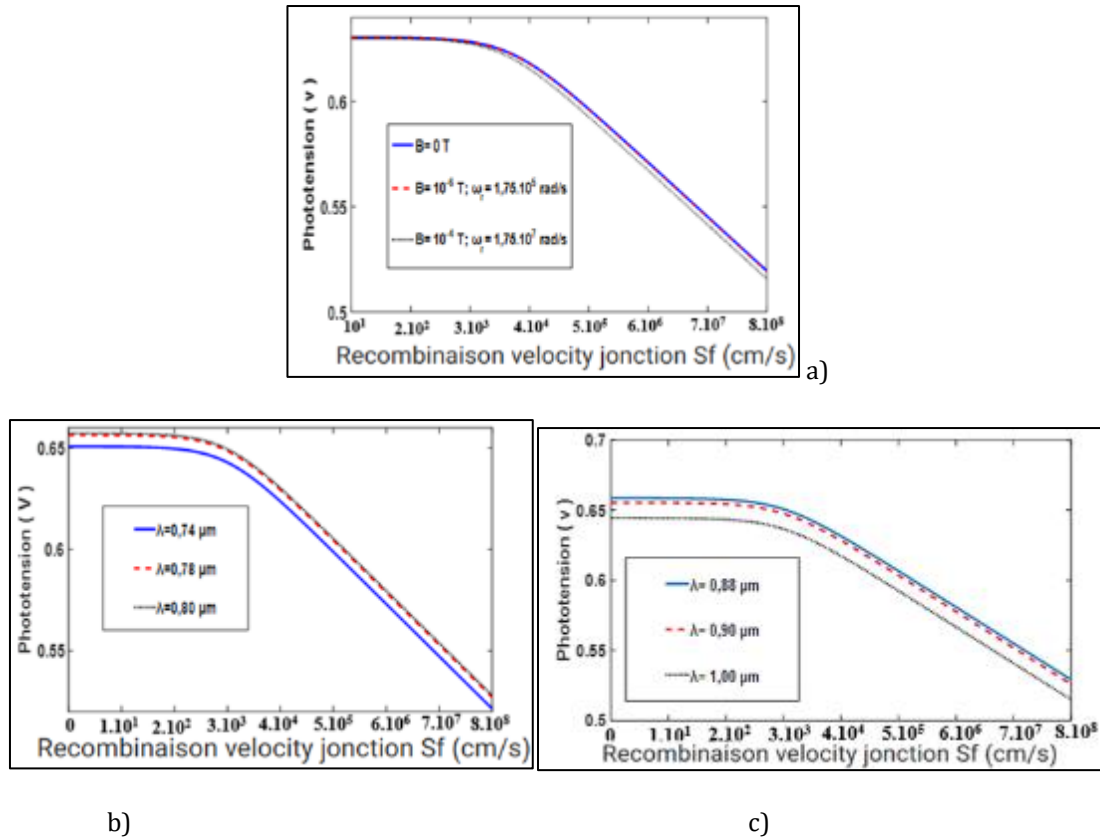


Figure 3: Photovoltage module as a function of the recombination velocity at the junction $z = 0.002$ cm; $B = 10^{-4}$ T; $\omega_r = 1.75 \times 10^7$ rad/s a) Magnetic field, b) Short wavelengths

2.1 Long wavelengths

We observe on this figure that the photovoltage reaches its maximum value and remains almost constant when the recombination velocities are low: this corresponds to the open-circuit regime. On the other hand, for high recombination velocities, it decreases progressively and tends towards zero. This behavior corresponds to the short-circuit operating point of the solar cell. The decrease in the amplitude of the short-circuit photovoltage is explained by intense recombination of the carriers at the emitter-base interface. The orthogonal projection used to determine the Sf_{co} is shown in the following figure .

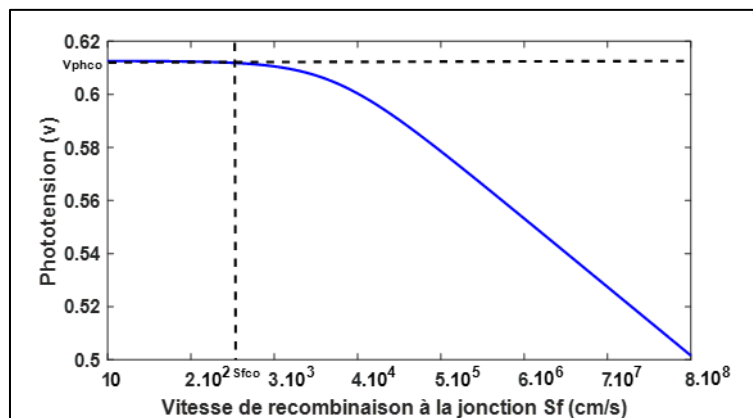


Figure 4: Photovoltage profile as a function of the recombination rate at the Sf junction. $z = 0.002$ cm; $B = 10^{-4}$ T; $\omega_r = 1.75 \times 10^7$ rad/s

The figure 4 illustrates the technique for determining the recombination velocity of minority carriers at the junction that limits the open-circuit current Sf_{co} .

At low values of the recombination velocity of minority carriers at the junction, the photovoltage is maximal and constant: this is the open-circuit photovoltage V_{phco} . Referring to this portion of the curve, the orthogonal projection

of the point defining the open-circuit condition onto the x-axis yields the value of the minority carrier recombination rate at the junction that limits the open-circuit condition, S_{fco} . Thus, we have the following correlation tables:

Table 1: Some values of S_{fco} and V_{phco} for different magnetic field values

Magnetic Field (T)	$S_{fco}(cm/s)$	$V_{phco}(V.cm^{-2})$
$B=0\text{ T}$	$2,6.10^{2,6}$	0,61
$B=10^{-6}\text{ T}$	$2,6.10^{2,6}$	0,61
$B=10^{-4}\text{ T}$	$2,8.10^{2,8}$	0,54

Table 2: Selected values of S_{fco} and $V_{phcoexp}$, along with their wavelengths

wavelength (86 μm)	$\lambda(\mu m)$	$S_{fco}(cm/s)$	$V_{phco}(V.cm^{-2})$
Courtes longueurs d'onde $\lambda < 0,86\text{ }\mu m$	0,74	2,034	0,649
	0,78	2,140	0,654
	0,80	2,047	0,657
Grandes longueurs d'onde $\lambda > 0,86\text{ }\mu m$	0,88	2,113	0,659
	0,90	2,626	0,654
	1,00	2,490	0,644

Table 1 shows several values of the recombination velocity at the junction limiting the open-circuit current (S_{fco}) and the open-circuit photovoltage. This qualitative variation in the photovoltage shows that the stronger the magnetic field, the lower the photovoltage.

Table 2 presents some values for the recombination velocity at the junction limiting the open-circuit current (S_{fco}) and the open-circuit photovoltage. Just like the short-circuit photocurrent density (J_{phcexp}), the open-circuit photovoltage varies in parallel with S_{fco} . At short wavelengths, V_{ph} and S_{fco} increase with wavelength. The opposite phenomenon is observed in the long-wavelength range. From the study of the effects of the magnetic field, angular frequency, and wavelength on the photovoltage, we can deduce the effect on the diffusion capacitance.

3 CONCLUSION

In this article, we conducted a theoretical study of a vertical-junction silicon solar cell under the influence of a magnetic field and wavelength. The magnetic field acts as a factor that inhibits the conversion process; we observe a slowing of the diffusion of excess minority charge carriers in the base relative to their generation. The concepts of minority carrier recombination rates at the junction that limit the open-circuit voltage were developed and studied. This study shows a decrease in the recombination velocity of minority carriers in the back region, as well as in the intrinsic recombination rate of minority carriers at the junction. The concept that the recombination rates of minority carriers at the junction limiting the open-circuit current vary depending on the design parameters, the magnetic field (and resonance frequency), and the illumination wavelength.

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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