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Research Article

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Incidence angle and diffusion length effects on Shunt resistance of a parallel vertical junction silicon solar cell under monochromatic illumination and under irradiation

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Abstract In this paper, we made a theoretical study of a parallel vertical junction solar cell under monochromatic illumination, in static mode and under irradiation.

The resolution of the continuity equation that governs the generation, the recombinations and the process of diffusion of the electrons in the base, helped us to establish the expression of the electrons density in the base and deduce expressions of the photocurrent density and the phototension depending on the wavelength λ, the recombination velocity at the junction Sf and the diffusion length.

The expression of Shunt resistance has been established from those of phototension and photocurrent density.

We studied the influence of diffusion length and incidence angle variations on the minority carriers density in the base, the photocurrent density, the phototension and finally on the Shunt resistance.

Keywords silicon solar cell, diffusion length, incidence angle, solar radiation, shunt resistance

1. Introduction

We will perform, through this paper a theoretical study of a parallel vertical junction solar cell under monochromatic illumination, in static mode and under irradiation.

The resolution of the continuity equation will enable us to establish the expression of the minority density charge carriers in the base and deduce those of the photocurrent density and the phototension.

The expression of the Shunt resistance will be subsequently obtained.

We will study, in this article, the impact of the change in diffusion length and the incidence angle on the density of the minority carriers in the base, the photocurrent density , the phototension and finally on the Shunt resistance.

2. Theory

We consider a n^+-p-p parallel vertical junction solar cell whose structure can be represented in figure 1.

When the solar cell is illuminated, there isa creation of electron-hole pairs in the base.

The behaviour of the minority carriers in the base (the electrons) is governed by the continuity equation which integrates all the phenomena causing the variation of the density of the electrons according to the width x of the base, its depth z, the recombination velocity at the junction, of the wavelength , incidence angle and diffusion length.

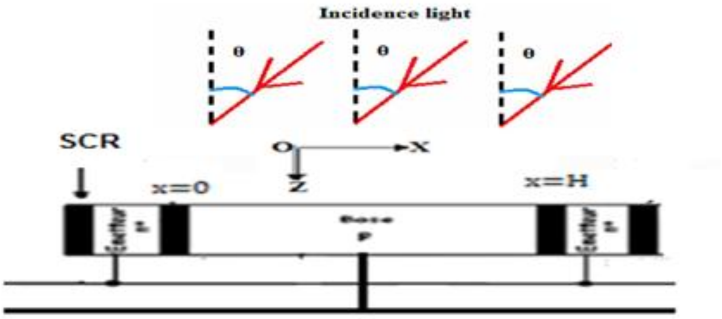

Figure 1: Parallel vertical junctions of a solar cell

The resolution of this equation will enable us afterwards to express on the one hand the density minority charge carriers from the base and deduce those of the quantitiesand other solar cell electrical parameters.

The continuity equation in static mode is presented in the form below:

$$D \cdot \frac{\partial^2 \delta(x)}{\partial x^2} - \frac{\delta(x)}{\tau} = -G(z, \lambda, \theta) \qquad (1)$$

$\delta(x)$describes the density of minority carriers in photo-generated charge.

. D is the coefficient diffusion. τis the average lifetime of carriers.

. G (z, λ,θ) is the overall generation rate of the minority charge carriers according to the depth z of the base, the wavelength and incidence angle.

The continuity equation can be written again as follows:

$$\frac{\partial^2 \delta(x)}{\partial x^2} - \frac{\delta(x)}{L^2} + \frac{G(z,\lambda)}{D} = 0 \qquad (2)$$

$L(kl,\phi) = \dfrac{1}{\sqrt{kl.\phi + \dfrac{1}{L_o^2}}}$ is the diffusion length [1]. L_O is the diffusion length with the absence of irradiation; kl and φ indicate the coefficient of damage and the irradiation energy.

The expression of the overall generation of minority charge carriers' rate is of the form: [2]

$$G(z, \lambda, \theta) = \alpha(\lambda)(1 - R(\lambda)) \cdot F \cdot \exp(-\alpha_t \cdot z).\cos(\theta) \qquad (3)$$

R (λ) is the monochromatic reflection coefficient; F is the flux of incident photons resulting from a monochromatic radiation.α is the coefficient of monochromatic absorption and θ the incidence angle.

$$\frac{\partial^2 \delta(x)}{\partial x^2} - \frac{\delta(x)}{L^2} = -\frac{G(z,\lambda)}{D} \qquad (4)$$

2.1. Solution of the continuity equation

- Special solution:

$$\delta_1(x) = \frac{L^2}{D}\alpha(\lambda)(1 - R(\lambda)).F.\exp(-\alpha_t.z).\cos(\theta) \qquad (5)$$

-solution of the second member equation:

$$\delta_2(x) = A\cosh\left(\frac{x}{L}\right) + B\sinh\left(\frac{x}{L}\right) \qquad (6)$$

-thus the general solution is:

$$\delta(x, z, \lambda, Sf, L, \theta) = \left[\begin{array}{l} A\cosh\left(\dfrac{x}{L(kl,\phi))}\right) + B\sinh\left(\dfrac{x}{L(kl,\phi)}\right) \\ + \dfrac{L^2(kl,\phi)}{D} \cdot \alpha(\lambda)(1 - R(\lambda)).F.\exp(-\alpha_t z).\cos(\theta) \end{array}\right] \qquad (7)$$

2.2. Find the coefficients A and B:

- The boundary conditions:

-Therefore, in the junction (x = 0) we have:

$$D \cdot \left.\frac{\partial \delta(x_t, z_t, \lambda, L, \theta)}{\partial x}\right|_{x=0} = Sf \cdot \delta(x_t, z_t, \lambda_t, L, \theta)\Big|_{x=0} \tag{8}$$

Sf is the recombination velocity at the junction. This is a phenomenological parameter that describes how the base minority carriers go through the junction. It can be divided into two terms [3].

We have $Sf = Sf_O + Sf_j$

Sf_O induced by the shunt resistance, is the intrinsic recombination velocity. It depends only on the intrinsic parameters of the solar cell.

Sf_j reflects the current which is imposed by an external charge and thus defining the operating point of the solar cell

-At The middle of the base $(x = \frac{H}{2})$. The structure of the solar cell, with two similar junctions on either side of the base, portends the equation **(9)** below:

$$D \cdot \left.\frac{\partial \delta(x, z, \lambda, L, \theta)}{\partial x}\right|_{x=H/2} = 0 \tag{9}$$

H is the thickness of the solar cell's base.

3. Results and Discussion

3.1. Density profile minority charge carriers in the base

Figure 2 below shows the profile of the electron density in the base according to the diffusion length for different values of the incidence angle.

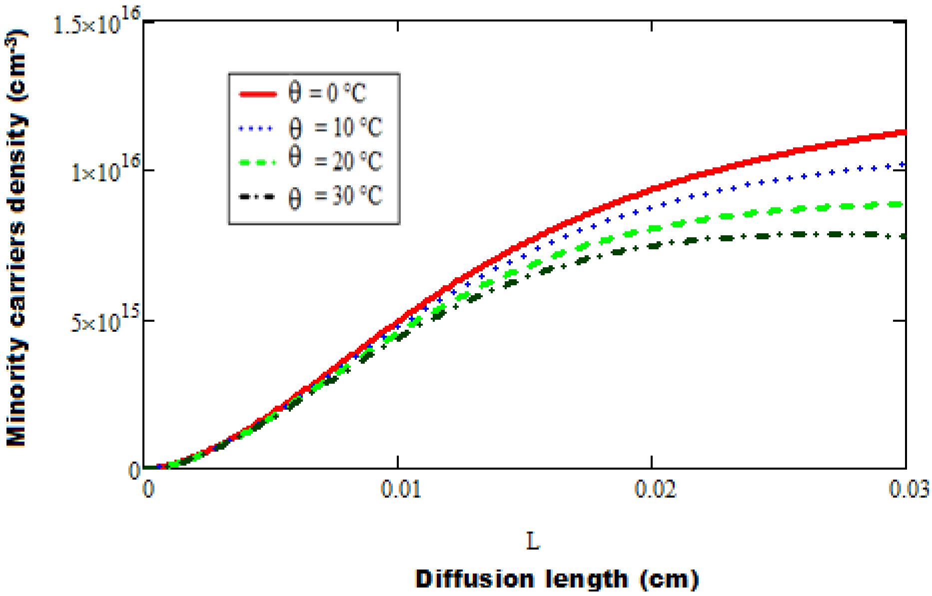

Figure 2: Variation of the minority carrier's density according to the diffusion length for different values of the incidence angle. H = 0, 03 cm, Z = 0, 0001 cm, λ = 0, 5 µm

The analysis of the curves shows that the minority carriers charge density in the base increases progressively according to the diffusion length.

However, it decreases when the incidence angle of solar radiation increases.

The diffusion length represents the average distance travelled by a charge carrier before recombining.

The more important is the diffusion length, the longer charge carriers live.

Low incidence angles of solar radiation allow a better generation rate of charge carriers.

A better illumination of solar cell surface associated with a higher lifetime of the carriers limiting the recombinations makes the minority carriers charges density increases according to the diffusion length.

When the incidence angle of solar radiation increases, the generation rate of carriers with the shadow effect (less absorbed photons) and the recombinations reduce the density carriers near the junctions.

3.2. Photocurrent density profile

The expression of the photocurrent density of the solar cell is obtained from the gradient of the minority carriers density in the base according to Fick's law. We have:

$$J_{Ph} = 2q \cdot D \cdot \left. \frac{\partial \delta(x, z, Sf, \lambda, L, \theta)}{\partial x} \right|_{x=0} \quad (10)$$

Where q is the elementary charge of electricity. From where:

$$J_{ph} = 2q \frac{S_f L^3 . \alpha(\lambda)(1 - R(\lambda)).F.\exp(-\alpha_t .z)\cos(\theta).\tanh(\frac{H}{2L})}{S_f .L + D\tanh(\frac{H}{2L})} \quad (11)$$

Figure 3 below shows the profile of the photocurrent density according to the diffusion length for different values of the incidence angle.

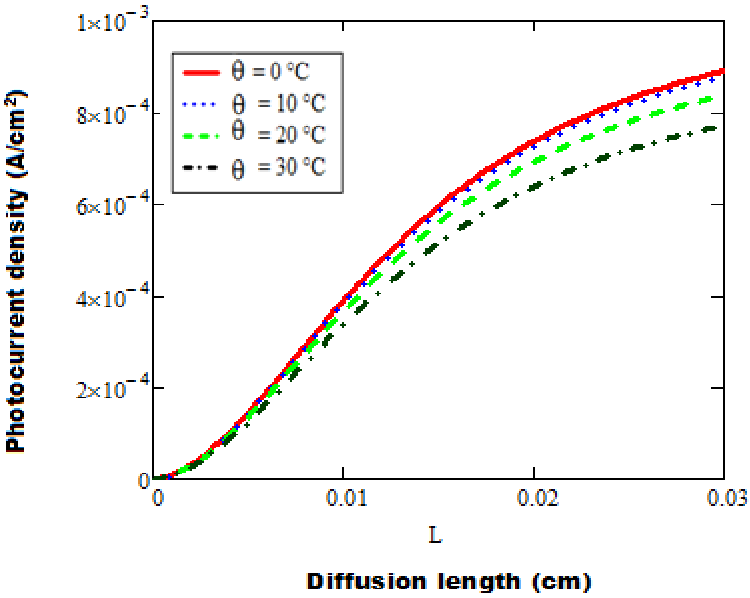

Figure 3: Variation of the photocurrent density according to the diffusion length for different values of the incidence angle. H = 0, 03 cm, Z = 0, 0001 cm, λ = 0, 5 µm

The analysis of the curves shows that the photocurrent density increases according to the diffusion length of the minority charge carriers.

However, it decreases when the incidence angle of solar radiation increases.

The increase of the lifetime of the minority charge carriers in the base makes grow their contribution in the delivered current by the solar cell.

Umber effect that increases according to the incidence angle makes decrease the minority charge carriers which result in a reduction of the photocurrent density when the incidence angle increases.

3.3. Phototension profile

The phototension created by accumulation of charge carriers at the junction is obtained from Boltzmann's relationship:

$$V = V_T \cdot \ln\left[1 + \frac{N_b}{n_0^2} \cdot \delta(0, z, \lambda, L, Sf, \theta)\right] \tag{12}$$

$V_T = \frac{KT}{e}$ is the thermal tension

Nb: doping rate of acceptor atoms in the base

n0: intrinsic density of carriers at thermal equilibrium. From where:

$$V_{Ph} = \frac{KT}{q}\ln\left\{1 + \frac{N_b}{n_0^2}\left[\frac{D\tanh(\frac{H}{2L})}{S_f L + D\tanh(\frac{H}{2L})}\right] \cdot \frac{L^2}{D} \cdot \alpha(\lambda)(1 - R(\lambda)) \cdot F \cdot \exp(-\alpha_t \cdot z).\cos(\theta)\right\}$$

Figure 4 below shows the profile of the phototension according to the diffusion length for different values of the incidence angle.

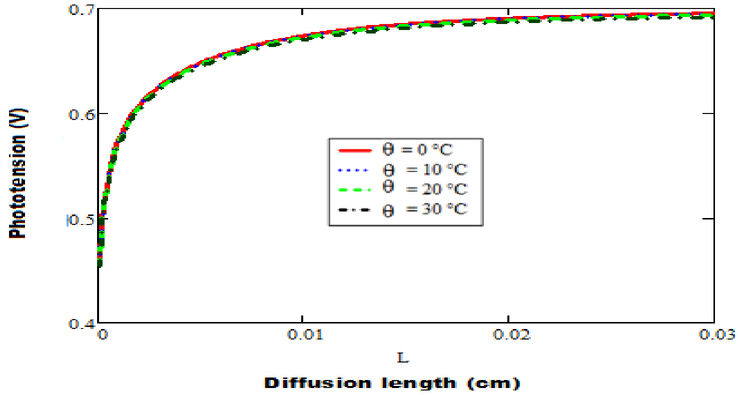

Figure 4: Variation of the phototension according to the diffusion length for different values of the incidence angle. H = 0, 03 cm, Z = 0, 0001 cm, λ = 0, 5 µm

The analysis of the curves shows that the phototension increases progressively according to the diffusion length. However, it decreases when the incidence angle of solar radiation increases.

The increase of the charge carriers lifetime results in an increase of the quantities of charges stored of both sides of the junctions.

The decrease of the carriers' generation rate reduces their density at the neighbourhood of the junctions, hence the reduction of the phototension when the incidence angle of solar radiation increases.

3.4. Current-voltage characteristic:

Figure 5 below shows the profile of photocurrent density according to the phototension.

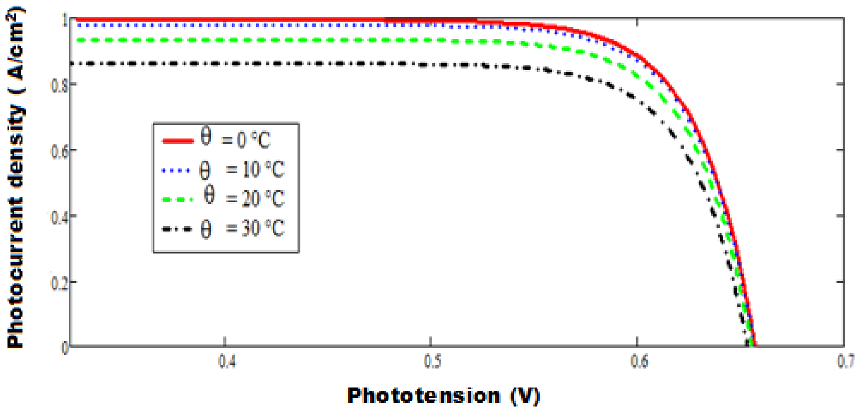

Figure 5: I-V characteristic of the solar cell

The characteristic analysis shows that the phototension is not independent of the photocurrent.
The solar cell operates as a real voltage generator in the vicinity of the open circuit and as a real current generator in the vicinity of the short circuit.
For each mode of operation, an electrical circuit equivalent to the solar cell is proposed.

3.6. Shunt Resistance

Below is the electric model which is equivalent to the solar cell and operating as a real current generator:

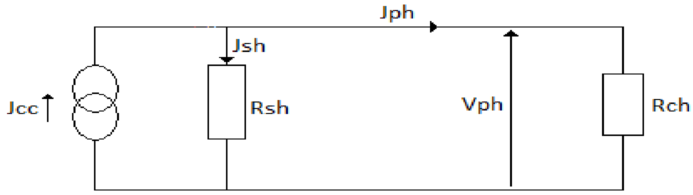

Figure 5: Equivalent circuit of the solar cell (real current generator)

From the study of this electrical circuit, the expression of the shunt resistance is deduced:

$$R_{SH}\left(S_f,\lambda,z,L,\theta\right)=\frac{V_{PH}\left(S_f,\lambda,z,L,\theta\right)}{J_{CC}(\lambda,z,L,\theta)-J_{PH}\left(S_f,\lambda,z,L,\theta\right)} \qquad (11)$$

The volume, surface and interface recombinations (base-emitter, base-contact, and contact-emitter) create the Shunt resistor which models the leakage currents in the solar cell.
Figure 6 below represent the profile of the Shunt resistance according to the diffusion length for different values of the incidence angle.

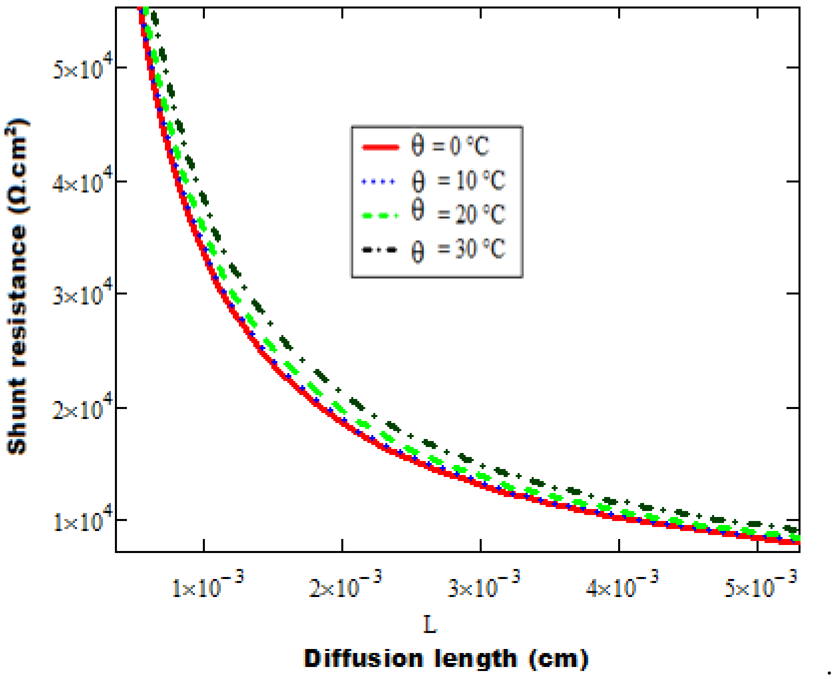

Figure 6: Variation of the Shunt resistance according to the diffusion length for different values of the incidence angle. H=0, 03cm, Z =0, 0001cm, λ = 0, 5 µm

The analysis of the curves shows that the Shunt resistance decreases according to the diffusion length and increases according to the incidence angle of the solar radiation.
The increase of the lifetime of the charge carriers, linked to that of the diffusion length, limits the recombinations; which decreases the Shunt resistance.
The increase of the Shunt resistance according to the incidence angle of solar radiation can be explained by the fact that photocurrent density decreases when the incidence angle increases; which reduces the leakage currents.

Conclusion

The resolution of the continuity equation allowed us to obtain the expression the electrons density in the base and we deduced those of the photocurrent density and the phototension.

From the electric model equivalent to the solar cell when operating in the vicinity of the short circuit, we have established the expression of the Shunt resistance.

We studied, in this paper, the impacts of diffusion length and incidence angle variations on the minority carriers density in the base, the photocurrent density, the phototension and finally on the Shunt resistance. .

The study showed that diffusion length and incidence angle variations affect the Shunt resistance.

The increase of the diffusion length which induces a growth in the lifetime of the carriers results in an increase of the photocurrent density, phototension and a decrease of the Shunt resistance.

Finally the increase of the incidence angle cause a decrease of the charge carriers' generation rate because of shadow effect, which result in a reduction of the minority charge carriers density, photocurrent density, phototension and an increase of the Shunt resistance because they are a fewer leakage currents.

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