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Research Article

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Incidence Angle Effect on the Diffusion Capacitance of a Parallel Vertical Junction Silicon Solar Cell under Static Regime and Monochromatic Illumination

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Abstract In this article, 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 allowed us to establish the expression of the electrons density in the base and thereby deduce the expression diffusion capacitance depending on the wavelength λ, the recombination velocity at the junction Sf, the incidence angle of the solar radiation and the irradiation parameters.

We studied the influence of the incidence angle variation on the diffusion capacitance, the short-circuit diffusion capacitance, the open-circuit diffusion capacitance and the efficiency of the capacitance.

Keywords silicon solar cell, vertical junction, incidence angle, diffusion capacitance, efficiency

1. Introduction

We will make, 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 allow us to establish the expression of the density of minority charge carriers in the base and deduce the expression of the diffusion capacitance.

The expressions of short-circuit and open-circuit capacitances will be subsequently deduced.

In this article, we will study the impact of the change in incidence angle on the diffusion capacitance and the efficiency of the diffusion capacitance.

2. Theory

We consider a n^+-p-p parallel vertical junction solar cell whose structure can be represented as follows:

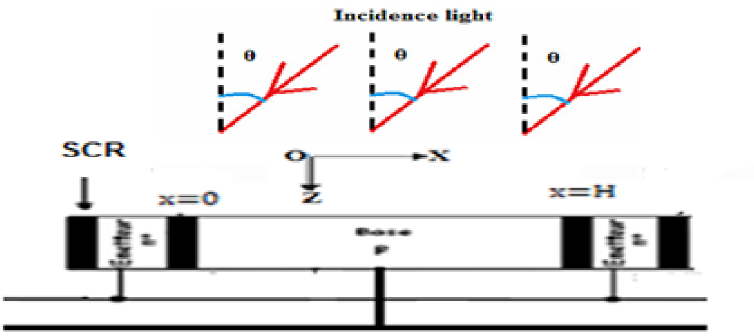

Figure 1: Parallel vertical junctions of a solar cell

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 irradiation parameters.
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 quantities and other solar cell electrical parameters.
The continuity equation in static mode is presented in the form below:

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

$\delta(x)$ describes the density of minority carriers in photo-generated charge.
D is the coefficient diffusion. $\tau$is 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:

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

$L(kl, \phi) = \dfrac{1}{\sqrt{kl.\phi + \dfrac{1}{L_o^2}}}$ 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]

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

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.

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

2.1. Solution of the continuity equation
- Special solution:

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

-solution of the second member equation:

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

-thus the general solution is:

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

2.2. Find the coefficients A and B:
- The boundary conditions:
-Therefore, in the junction (x = 0) we have:

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

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:

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

H is the thickness of the solar cell's base

3.1. Expression of the diffusion capacitance

The diffusion capacitance of the solar cell is considered as the capacitance resulting from the variation of the charge during the process of diffusion within the solar cell.

The storage charge on both sides of the base-emitter junction transforms the space charge area in a plane capacitor whose capacitance depends on the intrinsic and extrinsic parameters of the solar cell.

The expression capacitance of this capacitor is given by the following relationship [4]:

$$C(\lambda, kl, \phi, z, Sf, \theta) = \frac{dQ}{dV} = q\frac{d\delta(x=0, \lambda, kl, \phi, z, Sf, \theta)}{dV} = q\frac{d\delta(x=0, \lambda, kl, \phi, z, Sf, \theta)}{dSf} \times \frac{1}{\frac{dV}{dSf}} \qquad (10)$$

From where:

$$C(\lambda, kl, \phi, z, Sf, \theta) = q\frac{n_o^2}{V_T.N_B} + q\frac{\delta(x=0, \lambda, kl, \phi, z, Sf, \theta)}{V_T} \qquad (11)$$

The first term refers to the darkness capacitance C_0; it depends on the nature of the material (substrate) through (n_0), doping through (Nb) and temperature through (V_T) which is thermal voltage.

Whereas the second term depends on the temperature (V_T), the illumination, the operating point Sf, the depth z of the solar cell , incidence angle and irradiation parameters.

3.2. Diffusion capacitance profile

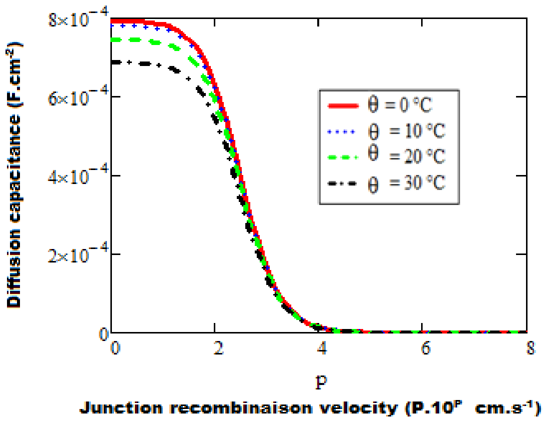

Figure 2: Variation of the diffusion capacitance according to the recombination velocity at the junction for different values of the incidence angle.

H = 0, 03 cm, z = 0, 0001 cm, L_o=0,01cm, λ = 0, 5 µm,kl = 5 cm²/s,ϕ = 50 MeV

Figure 2 show the profile of the diffusion capacitance according to the recombination velocity at the junction for respectively different values of the incidence angle.
Figure 2 show us that the diffusion capacitance is constant and maximum for the low values of the recombination velocity at the junction corresponding to the operation of the solar cellin the vicinity of open circuit.
It is almost zero for large values of Sf corresponding to the state of short circuit.
Open-circuit and short-circuit diffusion capacitance decrease when the incidence angle of solar radiation increases.
For a flat solar cell, the amount of photons absorbed depends on the incidence angle of solar radiation. The more the incidence angle increases, fewer energy is absorbed, which decreases the charge carriers generation.
The quantity of photogenic carriers, which diffuse towards the junction, therefore depends on the incidence angle of the solar radiation, which result in a decrease of the amount of charges stored on both sides of the junction when the incidence angle increases.
In these two operation modes of the solar cell, the decrease of the diffusion capacitance corresponds to an enlargement of the space charge zone since:

$$C(\lambda, kl, \phi, z, Sf, \theta) = \frac{\varepsilon S}{X(\lambda, kl, \phi, z, Sf, \theta)} \quad (12),$$

with X the width of the space charge zone.

3.3. Profile of short-circuit capacitance:
Figures 3 shows the profile of the short-circuit capacitance according to the incidence angle.

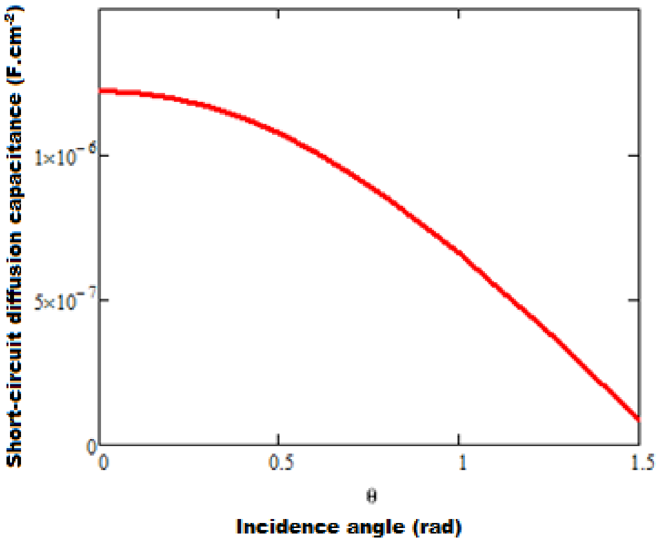

Figure 3: Variation of the short-circuit capacitance according to incidence angle.
H=0,03cm, z=0,0001cm, Sf=6.10^6 cm/s, L$_o$=0,01cm, λ= 0,6 µm,kl = 5cm^2/s,ϕ = 50 MeV

In the vicinity of the short circuit, the diffusion capacitance decreases when the incidence angle of the solar radiation increases.
In a short-circuit situation, there is a massive transfer of the electrons which arrive at the junction toward the emitter.
Since the generation of charge carriers decreases when the incidence angle increases, the amount of charges stored at the junction decreases consequently.

3.4. Profile of open circuit capacitance:
Figure 4 shows the profile of the open circuit capacitance according to the incidence angle of solar radiation.

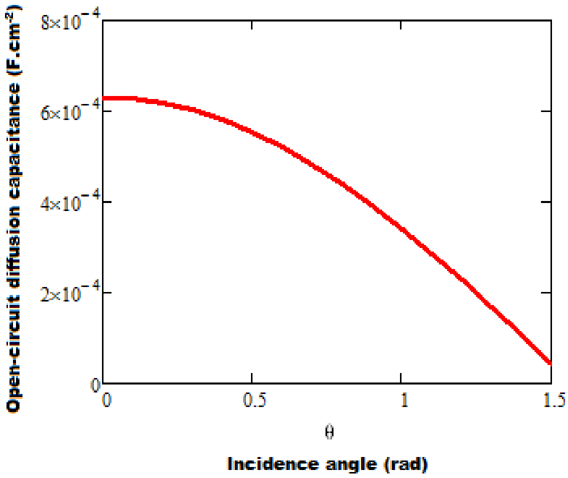

Figure 4: Variation of the open circuit capacitance according to incidence angle
$H = 0, 03$ cm, $Z=0, 0001$cm, $Sf = 10$ cm/s, $L_o=0,01$cm, $\lambda= 0, 6$ µm, $kl = 5cm^2/s$, $\phi = 50$ MeV

Owing to the low values of the recombination velocity of the charge carriers at the junction, there are in the vicinity of the open circuit a block of the charges at the junction.

Yet, the amounts of charges blocked at the junction decrease when the incidence angle of the radiation increases because of the decrease of the generation rate of the carriers.

3.5. Efficiency Capacitance

3.5.1. Expression

The efficiency of the diffusion capacitance represents the rate of charge transfer when the solar cell passes in the vicinity of the open circuit to in the vicinity of the short circuit. It has for expression [5]:

$$\eta(\lambda,kl,\phi,z,\theta)=1-\frac{C_{CC}(\lambda,kl,\phi,z,\theta)}{C_{CO}(\lambda,kl,\phi,z,\theta)} \qquad (13)$$

Where C_{CC} is the short-circuit capacitance and C_{CO} open circuit capacitance.

This expression of efficiency will allow us to study its variation according to incidence angle.

3.5.2. Efficiency profile

Figures 5 show the efficiency capacitance profiles according to incidence angle.

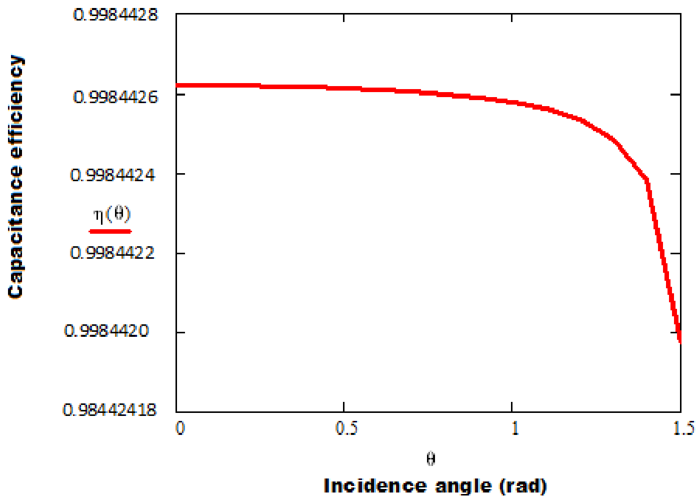

Figure 5: Variation of the diffusion capacitance efficiency according to incidence angle
$H = 0, 03$ cm, $Z=0,0001$cm $L_o=0,01$cm, $\lambda= 0, 6$ µm, $kl = 5cm^2/s$, $\phi = 50$ MeV

The efficiency capacitance determines the percentage of charges transferred to the emitter when the solar cell passes of the open circuit neighbourhood to the short circuit vicinity or the enlargement variation of the depletion zone.

For low values of the incidence angle of solar radiation, the efficiency capacitance varies not much.

When the angle of incidence tends to $\frac{\pi}{2}$, the efficiency capacitance decreases strongly according to the incidence angle.

Indeed, the generation rate decrease of the minority charge carriers in the base has more impact on the open-circuit diffusion capacitance than that in the vicinity of the short circuit.

The reduction of the efficiency also corresponds to an enlargement decrease of the space charge zone when the solar cell passes of the open circuit neighbourhood in the vicinity of the short circuit since:

$$C_{CC}(\lambda,\phi,kl,z,\theta)=\frac{\varepsilon S}{X_{CC}(\lambda,\phi,kl,z,\theta)} \tag{14}$$

and

$$C_{CO}(\lambda,\phi,kl,z,\theta)=\frac{\varepsilon S}{X_{CO}(\lambda,\phi,kl,z,\theta)} \tag{15}$$

Conclusion

The resolution of the continuity equation allowed us to obtain the expression of the electrons' density in the base and we deduced therefore that of the diffusion capacitance.

We studied in this paper the impact of the incidence angle variation on the diffusion capacitance, the open-circuit diffusion capacitance, the short-circuit diffusion capacitance and the efficiency of the diffusion capacitance.

The diffusion capacitance decreases according to the incidence angle of the radiation for two operating modes studied because of the decrease of the generation rate of the minority carriers in the base.

The efficiency capacitance, which measures the rate of charge transferred between two operation modes studied, depends on the incidence angle; it decreases according to this one.

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