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Research Article

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Series Resistance of a Parallel Vertical Junction Silicon Solar Cell under Monochromatic Illumination and under Irradiation: Temperature and Irradiation Effects

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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 temperature.

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

We studied the influence of irradiation energy and temperature variations on the minority carriers density in the base, the photocurrent density, the phototension and finally on the series resistance.

Keywords silicon solar cell - vertical junction - wavelength - temperature - irradiation - Series 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 chargecarriers density in the base and deduce those of the photocurrent density and the phototension.

The expression of the series resistance will be subsequently obtained.

We will study, in this article, the impact ofthe change in irradiation energy and the temperature on the density of the minority carriers in the base, the photocurrent density, the phototension and finally on the series resistance.

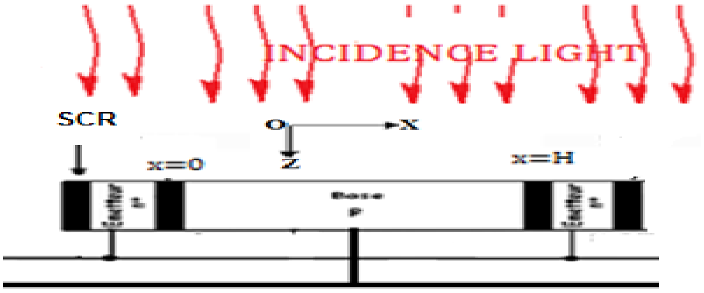

Figure 1: Parallel vertical junctions of a solar cell

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 is a 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 , temperature and irradiation parameters.
The resolution of this equation will enable us afterwards to express on the one hand the minority charge carriers density 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:

$$D(T)\cdot\frac{\partial^2\delta(x,kl,\phi,\lambda,z,T)}{\partial x^2}-\frac{\delta(x,kl,\phi,\lambda,z,T)}{\tau(kl,\phi)}=-G(z,\lambda) \quad (1)$$

$\delta(x,kl,\phi,\lambda,z,T)$ describes the density of minority carriers in photo-generated charge.

. $D(T)$ is the coefficient diffusion according to the temperature. It is obtained by Einstein relationship:

$$D(T)=\mu(T)\frac{k_b}{e}.T \quad (2)$$

μ (T) denotes the mobility of the charge carriers according to the temperature.

$$\mu(T)=1{,}43.10^9 T^{-2,42} cm^2.V^{-1}.S^{-1}$$

τ(kl,ϕ) is the average lifetime of carriers according to irradiation parameters.

We have the relationship: $$\frac{1}{\tau(kl,\phi)}=\frac{1}{\tau_0}+kl\phi$$ [1]

, k1 and φ respectively denote the damage coefficient and the irradiation energy. τ_o is the average lifetime of carriers with the absence of irradiation.

. G (z, λ) is the overall generation rate of the minority charge carriers according to the depth z of the base and wavelength.
The continuity equation can be written again as follows:

$$\frac{\partial^2\delta(x)}{\partial x^2}-\frac{\delta(x)}{L^2}+\frac{G(z,\lambda)}{D}=0 \quad (3)$$

$$L(kl,\phi,T)=\sqrt{D(T)\times\tau(kl,\phi)} \quad (4)$$

is the diffusion length.

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

$$G(z,\lambda)=\alpha_t(1-R(\lambda))\cdot F\cdot\exp(-\alpha_t\cdot z) \quad (5)$$

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.

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

2.1. Solution of the continuity equation

- Special solution:

$$\delta_1(x) = \frac{L^2}{D}\alpha(\lambda)(1-R(\lambda)).F.\exp(-\alpha_t.z) \quad (7)$$

-solution of the second member equation:

$$\delta_2(x) = A\cosh\left(\frac{x}{L}\right) + B\sinh\left(\frac{x}{L}\right) \quad (8)$$

-thus, the general solution is:

$$\delta(x,z,\lambda,Sf,kl,\phi,T) = \left[\begin{array}{l} A\cosh\left(\frac{x}{L(kl,\phi,T))}\right) + B\sinh\left(\frac{x}{L(kl,\phi,T)}\right) \\ +\frac{L^2(kl,\phi,T)}{D(T)}\cdot\alpha(\lambda)(1-R(\lambda)).F.\exp(-\alpha_t z). \end{array}\right] \quad (9)$$

2.2. Find the coefficients A and B:

- The boundary conditions:

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

$$D(T)\cdot\left.\frac{\partial\delta(x_t,z_t,\lambda,kl,\phi,T)}{\partial x}\right|_{x=0} = Sf\cdot\delta(x_t,z_t,\lambda_t,kl,\phi,T)\big|_{x=0} \quad (10)$$

Sf is the recombination velocity at the junction. This phenomenological parameter 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:

$$D(T)\cdot\left.\frac{\partial\delta(x,z,kl,\lambda,\phi,T)}{\partial x}\right|_{x=H/2} = 0 \quad (11)$$

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 temperature for different values of the irradiation energy.

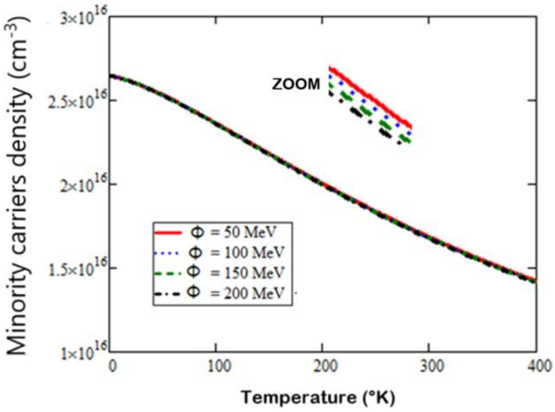

Figure 2: Variation of the minority carriers density according to the temperature for different values of the irradiation energy

H=0, 03cm, Z =0, 0001cm, L_o=0, 01cm, kl = 10 cm^2/s

The analysis of the curves shows that the minority charge carriers density decreases when the temperature increases as well as when the irradiation energy increases.

The increase in temperature reduces the mobility of the charge carriers, which favors recombinations; hence, the decrease in the minority charge carriers density.

Irradiation causes the multiplication of the recombination centers, which has the effect of reducing the density of minority carriers in the base.

Degradations caused by energetic particles in the material reduce the generation of charge carriers especially in the most irradiated areas.

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:

$$J_{Ph} = 2q\, D(T) \cdot \left. \frac{\partial \delta(x_t, z_t, \lambda, kl, \phi, T)}{\partial x} \right|_{x=0} \quad (12)$$

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

$$J_{ph} = 2q \frac{S_f L^3 . \alpha_t (1-R).F.\exp(-\alpha_t .z).\tanh(\frac{H}{2L})}{S_f .L + D \tanh(\frac{H}{2L})} \quad (13)$$

Figure 3 below shows the profile of the photocurrent density according to the temperature for different values of irradiation energy.

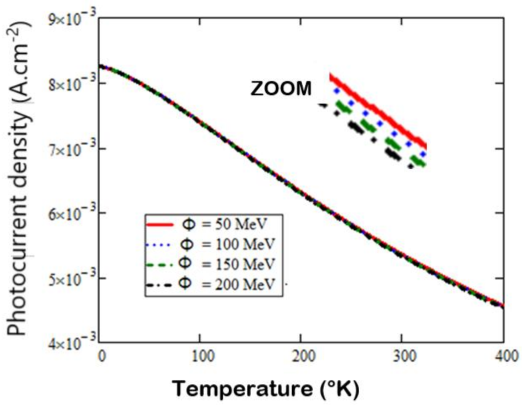

Figure 3: Variation of the photocurrent density according to the temperature for different values of the irradiation energy.

H=0, 03cm, Z =0, 0001cm, L_o=0, 01cm, kl = 10 cm^2/s

The analysis of the curves shows thatthe variations ofthe photocurrent density according to the temperature for different values of irradiation energy are similar to those of the minority charge carriers density in the base.
The contribution of the minority charges carriers in the current debited by the solar cell is related to variations in the density of these carriers according to Fick's law.

3.3. Phototension profile:

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

$$V = V_T \cdot \ln\left[1 + \frac{N_b}{n_i^2(T)} \cdot \delta(0, z, \lambda, kl, \phi, Sf, T)\right] \quad (14)$$

$V_T = \frac{KT}{e}$ is the thermal tension
Nb: doping rate of acceptor atoms in the base
$n_i(T)$: intrinsic minority carriers density according to the temperature.

$$n_i(T) = A.T^{\frac{3}{2}} \exp\left(\frac{-E_g}{2k_b.T}\right)$$; A is a coefficient t: $A = 3{,}87.10^{16} cm^{-3} K^{\frac{-3}{2}}$ (15)

E_g is the gap energy; It correspond at the energy between conduction and valence band. We are

$E_g = E_c - E_v$ = 1.12 eV

From where:

$$V_{Ph} = \frac{KT}{q} \ln\left\{1 + \frac{N_b}{n_i^2}\left[\frac{D \tanh(\frac{H}{2L})}{S_f L + D \tanh(\frac{H}{2L})}\right] \cdot \frac{L^2}{D} \cdot \alpha_i (1-R) \cdot F \cdot \exp(-\alpha_i \cdot z)\right\} \quad (16)$$

Figure 4 below shows the profile of the phototension according to the temperature for different values of the irradiation energy.

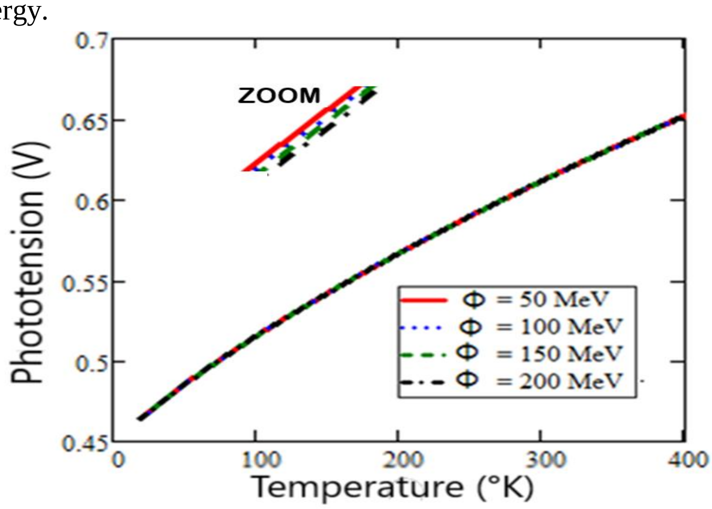

Figure 4: Variation of the phototension according to the temperature for different values of the irradiation energy.
H=0, 03cm, Z =0, 0001cm, L_o=0, 01cm, kl = 10 cm^2/s

The analysis of the curves shows that the phototension increases according to the temperature; however, it decreases when the irradiation energy increases.
Because of the increase in the recombinationrate, maintained by irradiation, the quantities of charges stored on either side of the junction decrease bringing the phototension.

The reduced mobility of the charge carriers combined with their thermal generation due to the increase in temperature creates an increase in the quantities of charge stored on either side of the junction creates a growth of the quantities of charges stored on either side of the junction.

3.4. Current-voltage characteristic:

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

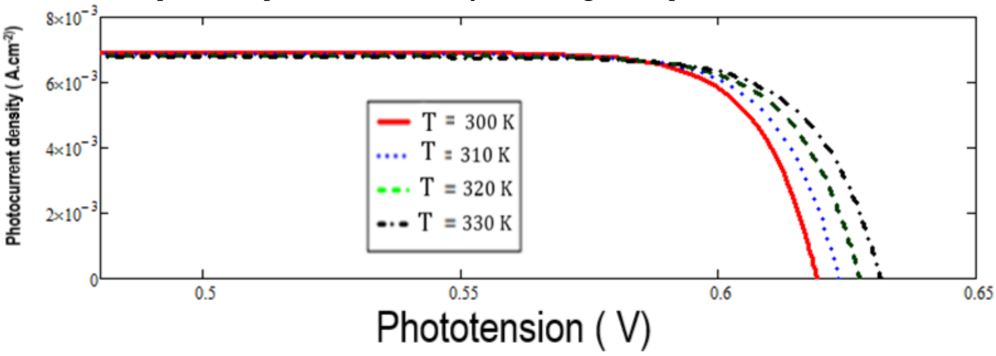

Figure 5: I-V characteristic of the solar cell

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 near the short circuit.

For each mode of operation, an electrical circuit equivalent to the solar cell is proposed.

3.5. Series resistance

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

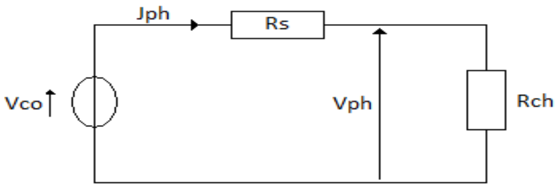

Figure 6: Equivalent circuit of the solar cell (real voltage generator)

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

$$R_S\left(S_f,\lambda,kl,\phi,z,\mathrm{T}\right)=\frac{V_{CO}\left(\lambda,kl,\phi,z,\theta\right)-V_{PH}\left(S_f,\lambda,kl,\phi,z,\mathrm{T}\right)}{J_{PH}\left(S_f,\lambda,kl,\phi,z,\mathrm{T}\right)}$$

Figure 7 below represent the profile of the Series resistance according to the temperature for different values of the irradiation energy.

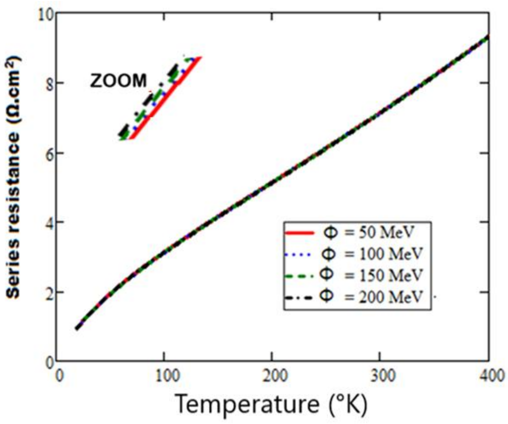

Figure 7: Variation of the series resistance according to the temperature for different values of the irradiation energy

H = 0, 03 cm, Z = 0, 0001 cm, L_o = 0, 01 cm,kl **=** *10 cm^2/s***,** *Sf = 10cm/s*

Series resistance characterizes the resistive effects of the material and contact device used.
The analysis of the curves shows that the series resistance increases with temperature but also according to the radiation energy.
When the temperature rises, the disordered movement of thermal agitation of the charge carriers increases and it hinders their overall movement towards the junctions, hence the increase in series resistance.
Irradiation creates recombination centers, which decreases extrinsic conductivity and increases series resistance.

Conclusion

The resolution of the continuity equation allowed us to obtain the expression of the density of the electrons in the base and we deduced those of photocurrent density and phototension.
From the electric model equivalent to the solar cell when it operates near the open circuit, we established the expression of the series resistance.
We studied in this article the impacts of variations in temperature and irradiation energy on the density of minority carriers in the base, photocurrent density, phototension and finally on series resistance.
The study showed that the density of minority carriers decreases when the temperature increases as well as photocurrent density while phototension and series resistance increase according to the temperature.
The density of minority carriers, photocurrent density and phototension decrease when irradiation energy increases. The series resistance increases according to the irradiation energy.
The increase in temperature results in a reduction in the mobility of the charge carriers and a disturbance of their overall movement, which reduces the density of minority carriers in the base as well as the density of photocurrent and this, leads to an increase in phototension and series resistance.
The increase in irradiation energy leads to a decrease in the charge carriers density, the photocurrent density and phototension due to the multiplication of recombination centers and degradations at the material level hence the increase in series resistance.

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