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Research Article

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Temperature Effect on the Depletion Zone Width of a Parallel Vertical Junction Silicon Solar Cell under Static Regime and Monochromatic Illumination

Alioune Badara Dieng[1], Fakoro Souleymane Dia[2], Senghane Mbodji[2], Birame Dieng[2]

[1]Faculty of Science and technology, University Cheickh Anta Diop, Dakar, Senegal
[2]Physics Department, Alioune Diop University, Bambey, Senegal

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, temperature and the irradiation parameters.

We studied the influence of the temperature variation on the diffusion capacitance, the depletion zone extension in short-circuit, the depletion zone extension in open circuit and the efficiency of the capacitance.

Keywords silicon solar cell, vertical junction, temperature, 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 depletion zone extension will be subsequently deduced.

In this article, we will study the impact of the change in temperature on the diffusion capacitance, the width of the depletion zone 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:

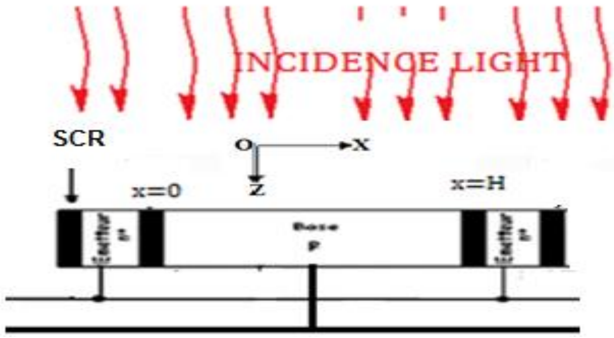

Figure 1: Parallel vertical junctions of a solar cell

When the solar cell is illuminated, there 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 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:

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

$\delta(x,kl,\phi,\lambda,z,T)$ 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.

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

$\tau(kl,\phi)$ is the average lifetime of carriers according to irradiation parameters.

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

where, 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]:

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

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 and θ the incidence angle.

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

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 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:

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

H is the thickness of the solar cell's base

3.1. 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]:

$$C(\lambda,kl,\phi,z,Sf,T) = \frac{dQ}{dV} = q\frac{d\delta(x=0,\lambda,kl,\phi,z,Sf,T)}{dV} = q\frac{d\delta(x=0,\lambda,kl,\phi,z,Sf,T)}{dSf} \times \frac{1}{\frac{dV}{dSf}} \quad (12)$$

V is the phototension obtained by Boltzmann relationship:

$$V = V_T \cdot \ln\left[1 + \frac{N_b}{n_i^2(T)} \cdot \delta(0,z,\lambda,kl,\phi,Sf,T)\right] \quad (13)$$

$V_T = \frac{KT}{e}$ 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: $A = 3{,}87.10^{16} cm^{-3} K^{\frac{-3}{2}}$ (14)

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:

$$C(\lambda, kl, \phi, z, Sf, T) = q\frac{n_i(T)^2}{V_T.N_B} + q\frac{\delta(x=0, \lambda, kl, \phi, z, Sf, T)}{V_T} \quad (15)$$

The first term refers to the darkness capacitance C_0; it depends on the nature of the material (substrate) through (n_i), doping through (Nb) and temperature through n_i and (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 and irradiation parameters.

3.2. Diffusion capacitance profile

Figure 2 show the profile of the diffusion capacitance according to the recombination velocity at the junction for different values of the temperature.

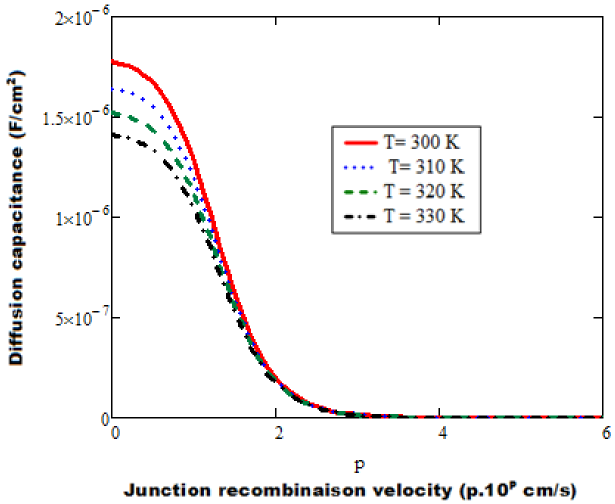

Figure 2: Variation of the diffusion capacitance according to the recombination velocity at the junction for different values of the temperature

H = 0.03 cm, z = 0.0001 cm, L_o=0.01cm, λ = 0.5 μm, kl = 5 cm^2/s, ϕ = 50 MeV

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 cell in 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 temperature increases.

The analysis of the curve shows that the temperature's increase induces an instability of the open circuit situation of the solar cell.

The interval of values of the junction recombination velocity for which a landing corresponding to the open-circuit diffusion capacitance is observed decreases considerably because of the temperature's increase.

The open circuit state, corresponding to a blockage of charges at the junction, becomes evanescent because the charges arriving at the junction have a thermal energy enabling them to overcome the potential barrier at the junction and to reach the emitter.

The increase of the temperature reduces the mobility of the charge carriers, which promotes recombination, therefore a decrease of the amount of charge arriving at the junction.

3.3. Profile of depletion zone extension in short-circuit:

Figure 3 shows the profile of the depletion zone extension in short-circuit according to the temperature.

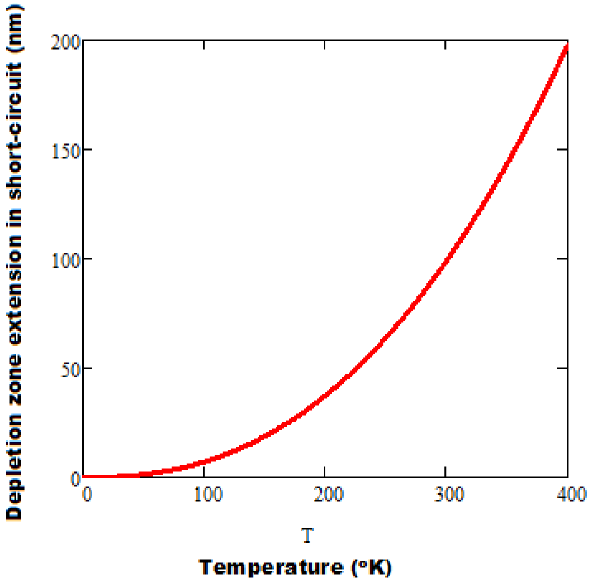

Figure 3: Variation of the depletion zone extension in short-circuit according to the temperature H=0.03cm, z=0.0001cm, Sf=6.10^{6} cm/s, L_o=0,.01cm, λ= 0.6 µm, kl = 5cm^{2}/s,ϕ = 50 MeV

In the vicinity of the short circuit, the width of the space charge zone increases when the temperature increases.
The diffusion of the majority carriers in the vicinity of the junction is favoured by the increase of the temperature because the carriers have a thermal energy allowing them to overcome the potential barrier in the depletion zone.
The internal electric field of the depletion zone separates the thermally generated carriers, which promotes recombination and expansion of the space charge zone.

3.4. Profile of open circuit capacitance:

Figure 4 shows the profile of the depletion zone extension in open circuit according to the temperature.

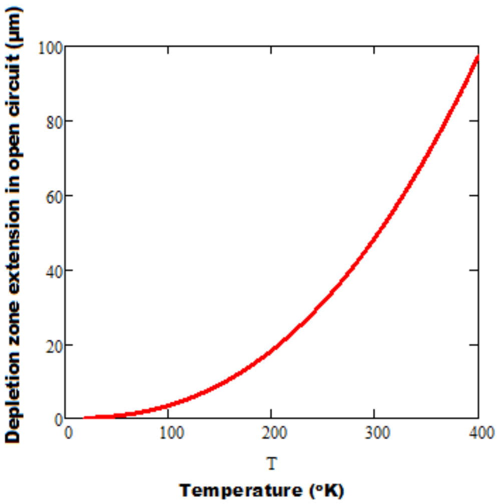

Figure 4: Variation of the open circuit capacitance according to incidence angle H = 0.03 cm, Z=0.0001cm, Sf = 10 cm/s, L_o=0.01cm, λ= 0.6 µm,kl = 5cm^{2}/s,ϕ = 50 MeV

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

The thermal generation in the depletion zone of the charge carriers promotes recombination with the blocked charges in the vicinity of the junction, which induces an expansion of the space charge zone.

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]:

$$\eta(\lambda, kl, \phi, z, T) = 1 - \frac{C_{CC}(\lambda, kl, \phi, z, T)}{C_{CO}(\lambda, kl, \phi, z, T)} \quad (16)$$

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

Since $C(\lambda, kl, \phi, z, Sf, T) = \frac{\varepsilon S}{X(\lambda, kl, \phi, z, Sf, T)}$, (17)

with X the width of the space charge zone.

The efficiency can also to express: $\eta(\lambda, kl, \phi, z, T) = 1 - \frac{X_{CO}(\lambda, kl, \phi, z, T)}{X_{CC}(\lambda, kl, \phi, z, T)}$ (18)

Thus, the capacitance efficiency also represents the rate of extension of the space charge zone when the solar cell passes from the neighborhood of the open circuit in the vicinity of the short circuit.

This expression of efficiency will allow us to study its variation according to the temperature.

3.5.2. Efficiency profile

Figures 5 show the efficiency capacitance profiles according to the temperature.

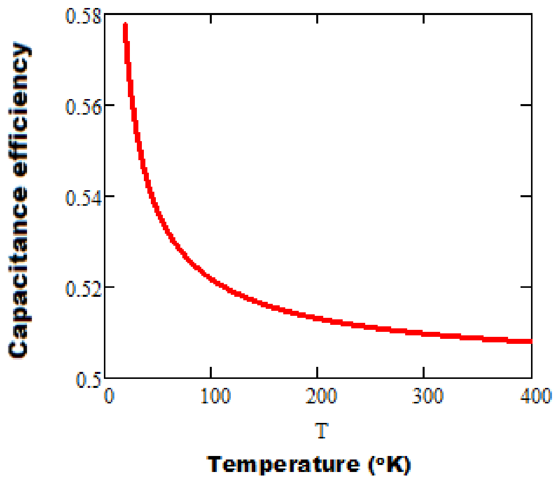

Figure 5: Variation of the diffusion capacitance efficiency according to the temperature

H = 0.03 cm, Z=0.0001cm L_o=0.01cm, λ= 0, 6 µm, kl = 5cm^2/s, ϕ = 50 MeV

The capacitance efficiency decreases when the temperature increases.

When the solar cell passes in the vicinity of the open circuit to the neighborhood of the short circuit, the temperature's increase is accompanied by a growth in the width of the depletion zone [6-12].

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 temperature variation on the diffusion capacitance, the depletion zone extension in open-circuit , the depletion zone extension in short-circuit and the efficiency of the diffusion capacitance.

The width of the space charge zone increases according to the temperature for two operating modes studied because of the thermal generation phenomenon and the recombination's in the vicinity of the junction.

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

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