Current Trends in Technology and Science
www.ctts.in, ISSN: 2279-0535, July 2022, Volume: 11, Issue: 4

Effect of the irradiation dose on monofacial silicon solar cell parameters in static mode

Idrissa GAYE[1], Doudou GAYE[3], Abdourahmane DIALLO[1], Adam SAYOUDI BOUZOU[2], Mamadou WADE[2]

[1] UFR-Sciences and Technologies, Iba Der Thiam University of Thiès – SENEGAL
[2] Electromechanical Engineering Department, Polytechnic School of Thies – SENEGAL
[3] Electromechanical Engineering Department, Polytechnic Institute of Saint-Louis – SENEGAL

Abstract:- *This work introduces a study of a monofacial silicon solar cell under multispectral illumination and irradiation dose of particles (heavy particles) effects. The continuity equation resolution leads to the minority carrier's density determination, with permits us to deduce electrical parameters. This study shows how irradiation dose variations influence phenomenological and electrical parameters of the silicon solar cell under static mode. Diffusion length, minority carriers' density, photocurrent, photovoltage, serial and shunt resistances are presented, and we show how they depend on the irradiation dose of energetic particles.*

Keywords: 1- Silicon solar cell, 2- Linear Transfer Energy (LET), 3- Irradiation dose

I. INTRODUCTION

Solar cells convert solar radiation energy into electrical energy. When a fraction of incident light is absorbed by a solar cell, excess minority carriers charge is generated, directed towards the contacts and then passes into the external charging circuit [1]. Indeed, semiconductor materials are continuously exposed to a natural and artificial radiative environment, so they are constantly submitted to a particle flow that transmits energy. This energy contribution by charged particles (protons, electrons and heavy ions) affects their stability, performance and reliability in part [2]. In this work, we study the effects of the irradiation dose on the monofacial solar cell under static conditions for polychromatic illumination. After a theoretical study on the solar cell, we study how irradiation dose influences phenomenological and electrical parameters of the silicon solar cell under static conditions for polychromatic illumination: Diffusion length, excess minority carrier density, photocurrent density, photovoltage, series and shunt resistance [3, 4].

II. THEORETICAL STUDY

2.1 Solar cell presentation

Considering that a monofacial silicon solar cell is the contribution of the base is more important, and the analyses will be conducted only in the base region. The silicon solar cell structure is presented below [4, 5].

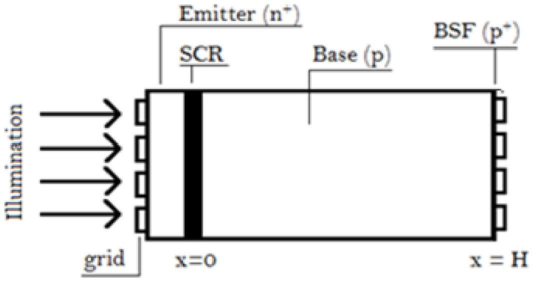

Figure I- 1: Silicon solar cell

It has four essential parts: The Emitter (n) with a doping level (10^{17} to 10^{19} cm^{-3}) and a thickness less than 1 µm. The base (p) with a doping level (10^{15} to 10^{17} cm^{-3}) has a thickness up to 4 µm. We have the Space Charge Region (SCR) between these two zones. The electric field E that reigns allows the separation of the electron-hole pair. Finally, an overdoped zone (p+) is located at the backside, and this region is the origin of an electric Back Surface Field (BSF), which allows photogenerated carriers near the back side to be returned towards the junction. The electrical contacts provided by the metal grid allow electrons to recover from their participation in the current at the external circuit.

2.2 Continuity equation of minority carriers' density in the base

The continuity equation of the minority carrier's density δ (x) in the static regime is given by the following relationship:

$$D\times\frac{\partial^2\delta(x)}{\partial x^2}-\frac{\delta(x)}{\tau}+G(x)=0 \qquad (1)$$

Where δ(x): denotes excess minority carriers' density; it depends on the base depth, τ: the lifetime of minority carriers in the base. D: diffusion coefficient of the minority carriers in the base. G (x): minority carriers generation rate in the base. It's expressed as a function of the absorption depth of light, and under polychromatic illumination, it can be written in the following form [6,7, 8]:

$$G(x) = n \cdot \sum_{i=1}^{3} a_i \times e^{-b_i x} \quad (2)$$

With ai and bi are the tabulated values of radiation:

Table I-1: Tabulated Values ai and bi

i	**ai**	**bi**
1	**6,13.10^{20} cm^{-3}.s^{-1}**	**6630 cm^{-1}**
2	**0,54.10^{20} cm^{-3}.s^{-1}**	**10^{3} cm^{-1}**
3	**0,0991.10^{20} cm^{-3}.s^{-1}**	**130^{-1}**

Here, n is related to the illuminance: it is the ratio between the real operating power and the reference power for AM1.5 (100 mW / cm2); when a material is exposed to a beam of energetic particles, it absorbs a radiation dose that creates defects in the material. The diffusion length L is related by the relationship below [9, 10]:

$$L(Kl,\phi) = \frac{1}{\sqrt{\frac{1}{L_0^2} + Kl.\phi}} \quad (3)$$

Where L_0: the diffusion length of minority carriers without irradiation by particles energy, Kl: damage coefficient. Φ: fluence at x depth, According to the irradiation dose absorbed d expressed by the following relationship [11]:

$$d = \phi \times \frac{1}{\rho}\frac{dE}{dx} = \phi \times LET \quad (4)$$

Where, d: the absorbed dose at this depth x, LET (Linear Transfer Energy): linear stopping power of the irradiated material can be expressed by Mass Stopping Power.

$$LET = \frac{1}{\rho}\frac{dE}{dx} \ (\text{MeV.cm}^{2}.\text{g}^{-1}) \quad (5)$$

Where ρ: silicon density

2.3. Expression of the diffusion length under the irradiation dose effect.

These relations taking into account the diffusion length under an irradiation dose effect can be expressed as follows:

$$L(Kl,d) = \frac{1}{\sqrt{\frac{1}{L_0^2} + Kl.\frac{d}{LET}}} \ (cm) \quad (6)$$

Equation 6 shows that diffusion length depends strongly on the irradiation dose. The behaviour of the solar cell will also be influenced by irradiation dose.

2. 4. Resolution of the continuity equation under the irradiation dose influence.

The following relation gives the solution of the continuity equation [12].

$$\delta(x) = A \times ch\left(\frac{x}{L}\right) + B \times sh\left(\frac{x}{L}\right) - \sum_{i=1}^{3} k_i e^{-b_i x} \quad (7)$$

With

$$k_i = \frac{-n \times L(d)^2 \times a_i}{D\left(b_i^2 \times L^2(d) - 1\right)} \quad (8)$$

The boundary conditions determine Coefficients A and B. At the junction x = 0,

$$\frac{\partial \delta(x)}{\partial x}\Big|_{x=0} = \frac{S_f}{D} \times \delta(0) \quad (9)$$

On the back side, x = H

$$\frac{\partial \delta(x)}{\partial x}\Big|_{x=H} = -\frac{S_b}{D} \times \delta(H) \quad (10)$$

Sf: Junction recombination velocity indicates passage velocity of minority charges carriers through the junction, towards the Emitter [13]. Sb: base recombination velocity indicates the recombination rate at the rear surface of the excess charge minority carriers [25; 26; 28], at x = H, where there is a rear electric field (p/p+, low-high junction), which pushes back the electric charges, towards the junction (ZCE), to collect them [14]. The following relationships express coefficients A and B:

$$A(Kl,d,p) = \sum_{i}^{3} k_i \times \frac{\left(b_i D - S_b(Kl,d)\right) \times \frac{D}{L(Kl,d)} \times e^{-b_i H} - \left(b_i D + S_f(Kl,d)\right) \times Y1(Kl,d)}{\frac{D}{L(Kl,d)} \times X1 + S_f(Kl,d) \times Y1(Kl,d)} \quad (11)$$

$$B(Kl,d,p) = \sum_{i}^{3} k_i \times \frac{\left(b_i D - S_b(Kl,d)\right) \times \frac{D}{L(Kl,d)} \times e^{-b_i H} + \left(b_i D + S_f(Kl,d)\right) \times X1(Kl,d)}{\frac{D}{L(Kl,d)} \times X1 + S_f(Kl,d) \times Y1(Kl,d)} \quad (12)$$

$$\delta(x,Kl,d,p) = A(Kl,d,p) \cdot \cosh\left(\frac{x}{L(Kl,d)}\right) + B(Kl,d,p) \cdot \sinh\left(\frac{x}{L(Kl,d)}\right) + \sum k_i \cdot e^{-b_i x} \quad (13)$$

III. RESULTS AND DISCUSSIONS

In this part, the obtained results are presented and discussed. The profile of diffusion length versus irradiation dose is given. But also, the profile of the minority carrier's density variation and the electric parameters are given for different irradiation values.

3.1. Diffusion length versus irradiation dose

Figure 3.1 show diffusion length versus irradiation dose for LET = 19 Mev.cm^2.g^{-1}.

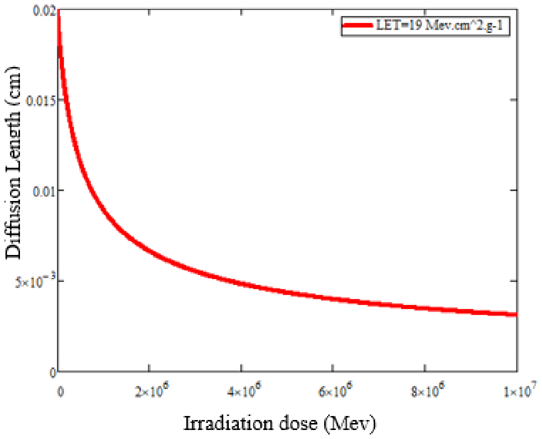

Figure 3. 1 : Diffusion length versus irradiation dose for LET = 19 Mev.cm2.g-1

The diffusion length decreases as the irradiation dose values increases. The decrease is more marked for higher irradiation energy. Since the diffusion length is strongly influenced by irradiation dose, it is clear that irradiation dose values will also influence the behaviour of the solar cell.

3.2. Density of minority carriers under the irradiation dose influence

Figure 3.2 shows the profile of the density of the minority carriers versus depth for different values of irradiation dose.

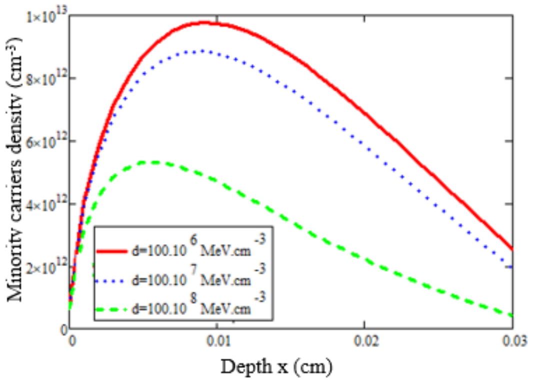

Figure 3.2: Minority carriers Density versus depth for different values of irradiation dose.

Figure III.3 shows that in the base, the minority carrier's density decreases, and also for increasing values of irradiation dose from a depth threshold (approximately x = 0.01 cm). The minority carrier's density loses its energy drastically in the base for higher irradiation dose, and they recombine.

3.4. photocurrent Density under the irradiation dose influence.

Crossing the junction, the generated charge carriers, under the action of light excitation, produce a photocurrent. The photocurrent density Jph is expressed by [15, 16]:

$$j_{ph} = q.D.\frac{\partial\delta(x)}{\partial x} \qquad (14)$$

Where $\delta(x)$: excess minority carriers' density photogenerated, q: electric charge q = 1.6.10^{-19} C.

Figure 3.3 the photocurrent density versus junction recombination velocity under the irradiation dose.

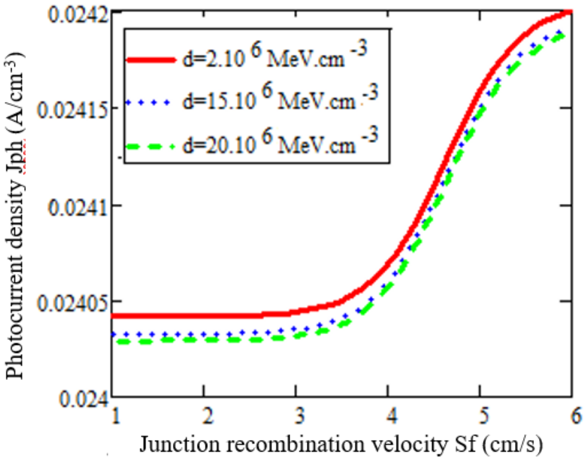

Figure 3.3: Photocurrent Density versus junction recombination velocity for different values of irradiation dose.

This photocurrent density profile shows that for high junction recombination velocity values (Sf reaching 6.10^6 cm/s), the profile of photocurrent density Jph versus Sf is a horizontal line, which gives the short circuit current density Jphsc. For low junction recombination velocity values (sf < 4.10^4 cm/s), the photocurrent density is almost zero and confirms that any carrier charge crosses the junction, and we have an open circuit situation. In both situations, we note a low amplitude of the photocurrent density, which is explained by a decrease in the minority carrier's density when the irradiation dose increases.

3.5. Photovoltage under the irradiation dose influence.

The photovoltage is given by the following Boltzmann relationship [15, 16]:

$$v_{ph} = V_T.\ln\left(\frac{N_b}{n_i^2}.\delta(0)+1\right) \qquad (15)$$

With

$$V_T = \frac{k_B.T}{q} \qquad (16)$$

And Vph can be rewritten as follows

$$v_{ph} = \frac{k_B \cdot T}{q}.\ln\left(\frac{N_b}{n_i^2}.\delta(0)+1\right) \qquad (17)$$

Where, V_T: Thermal tension, n_i: denotes the intrinsic density of the carriers at thermal equilibrium: ni = $10.^{10}$cm^{-3}, N_b is the base doping rate, Nb = 10^{16} cm-3, kB: Boltzmann constant (k_B = $1.381.10^{-23}$JK^{-1}), T: absolute temperature at thermal equilibrium (T = 300 ° K) and q: electric charge q = $1.6.10^{-19}$ C.

Figure 3.4 shows photovoltage versus junction recombination velocity under the influence of irradiation.

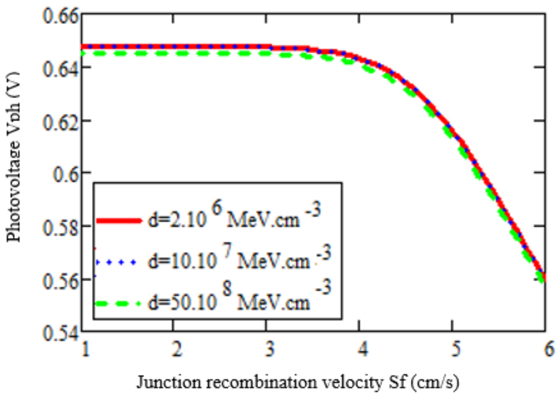

Figure3.4: Photovoltage versus junction recombination velocity for different values of irradiation dose.

This figure above shows us that for a given irradiation dose value, the photovoltage is maximum at the low values of junction recombination velocity (sf < 4.10^4 cm / s), which leads us to an open circuit situation. On the other hand, for high values of (sf > 4.10^4 cm / s), the photovoltage decreases and tends towards zero.

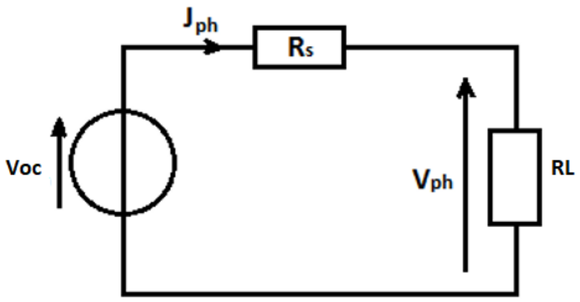

Figure III- 5: Equivalent electrical circuit of a solar cell operating in an open circuit

The photovoltage amplitude decreases with the irradiation dose increasing. These zero voltages characterize a solar cell operating in a short-circuit situation to which it delivers a maximum current.

3.6. Serial resistance under the irradiation dose influence.

The series resistance of a solar cell depends on the combined effects of the resistivity of the semiconductor material, the metallic contacts constituting the electrodes and the grid for collecting the minority charge carriers [12].

According to the Kirchhoff law:

$$R_s \times J_{ph} = V_{co} - V_{ph} \qquad (18)$$

From where

$$R_s = \frac{V_{co} - V_{ph}}{J_{ph}} \qquad (19)$$

Where V_{OC}: open circuit photovoltage, R_s: series resistance, V_{ph}: photovoltage, J_{ph}: photocurrent density, R_L: variable load resistance.

Under the influence of the dose, here is his profile shown in figure 3.6.

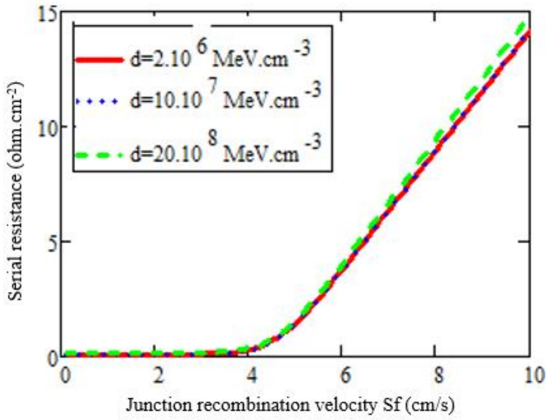

Figure 3.6: serial resistance versus junction recombination velocity for different values of irradiation dose.

This figure shows that the variation of serial resistance has two parts according to Sf values; for Sf < 4.10^4 cm/s, the series resistance is constant, and for Sf > 4.10^4cm/s, serial resistance increases with the junction recombination velocity. We note that when the irradiation dose increases, the degradations are greater, resulting in increased series resistance and a short-circuit current limitation.

3.7. shunt resistance

The shunt resistance comes from a solar cell's recombination charge carriers in volume at the surface and the interfaces (emitter-base, contact-emitter, contact-based). The equivalent model of the solar cell that operates in a short-circuit situation is given by [17].

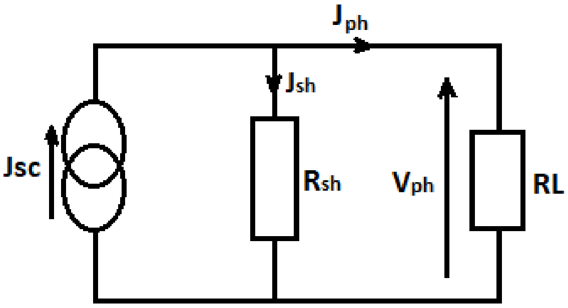

Figure 3.7: Equivalent electrical circuit of a solar cell in a short circuit situation

According to the second Kirchhoff law

$$R_{sh}\times\left(J_{cc}-J_{ph}\right)=V_{ph} \qquad (20)$$

Where

$$R_{sh}=\frac{V_{ph}}{J_{cc}-J_{ph}} \qquad (21)$$

Where Rsh: shunt resistance; Vph: photovoltage; Jph: the photocurrent density; Jcc: the short-circuit current; RL: the variable load resistance.

Under the irradiation dose influence, we obtain the following shunt resistance profile.

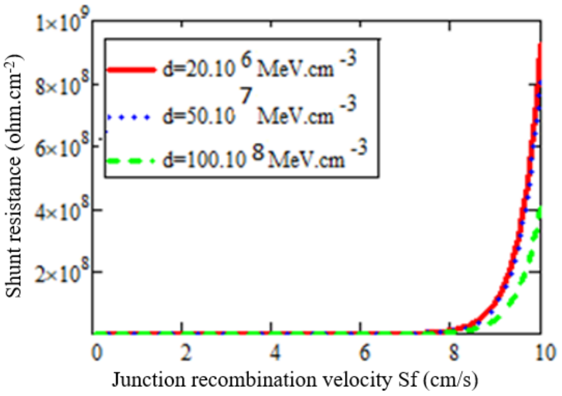

Figure3.8: shunt resistance versus junction recombination velocity for different values of irradiation dose.

This figure shows that for a given irradiation dose value, the shunt resistance is low for junction recombination velocity between 0 and 8.10^8 cm/s and then increases exponentially for junction recombination velocity between 8.10^8 and 10.10^{10} cm/s. Large irradiation doses cause degradation of the solar cell, which increases the leakage currents with the decrease in the shunt resistance.

CONCLUSION

We presented in this paper a bibliographic study which gave us the notions of the effects of irradiation dose on the solar cell and some electronic components. The work allowed the possibility to establish from the continuity equation in a static regime a new expression of the diffusion length, the minority carrier density, the photocurrent density, the photovoltage, the series and shunt resistance under the irradiation dose effect. Thus, from an analytical resolution of the continuity equation and the plotted curves, we have shown the influence of the irradiation dose on the electrical parameters. It emerges from our work that the irradiation dose has a negative effect on the phenomenological and electrical parameters of the solar cell and especially on the diffusion length. It may be possible to make this study on a bifacial solar cell in dynamic frequency and transient and to do this same study on a vertical junction solar cell.

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