Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2020, 7(1):88-94**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Evolution of the Capacitance According to the Recombination Velocity at the Junction and the Photovoltage of a CIGS Thin Film Solar Cell under Monochromatic Illumination at the Front Face

Ibrahima WADE*, Demba DIALLO, Djmba NIANE, Moustapha DIENG

* Laboratory of Semiconductors and Solar Energy, Physics Department, Faculty of Science and Technology, - University Cheikh Anta Diop – Dakar – Senegal

Abstract The aim of this article is to show the evolution of the capacitance (C) of a thin film photovoltaic CIGS according to the parameters such as the recombination velocity at the junction (Sf) and the photovoltage (Vph) for different incident wavelength values. The study of the capacitance efficiency according to wavelength values (η(λ)) is also made when the photovoltaic system is in short-circuit and in open-circuit under monochromatic illumination in static and one dimensional conditions. The expression of its parameters is obtained from the excess minority carriers density. The capacitance efficiency depends on the maximum of the relative minority carriers density according to the thickness of the base corresponding to the space charge area in the case of a short circuit (Xcc) and in the Open circuit (Xco). The study revealed that the capacitance performance increases implying a decrease in capacity from where a good generation rate of our solar photovoltaic.

Keywords CIGS- Recombination velocity at the junction (Sf) - photovoltage (Vph) - Capacitance -Wavelength (λ)

Introduction

$Cu(In,Ga)Se_2$ thin film solar cells are a realistic option for good efficiency conversion compared to silicon. The $Cu(In,Ga)Se_2$ chalcopyrite has unique physical properties such as an absorption coefficient greater than 20% [1-3], a direct bandgap adjustable according to the ratios between the materials of the layer CIGS. We used a copper-poor thin layer CIGS [4] with a gallium percentage of 30% which gives good conversion efficiency [5].

The aim of this work is to study the capacitance evolution according to the recombination velocity at the junction of a CIGS thin film solar cell under monochromatic illumination by the front face.

Theoretical study

The considered solar cell $\left(n^+/p/p^+\right)$ and its structure are represented in the following figure1:

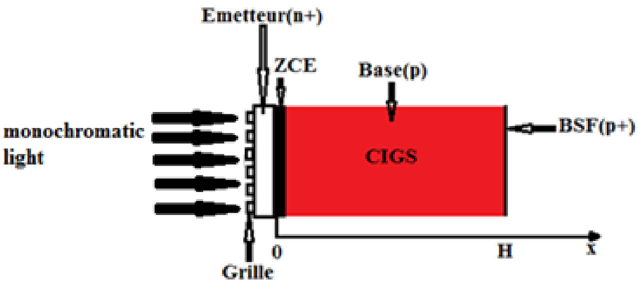

Figure 1: Solar cell $\left(n^+/p/p^+\right)$ containing CIGS under monochromatic illumination at the front surface

When the light source is illuminated, we can note the presence of three major phenomena: generation, recombination and diffusion of minority carriers charge. In our physical model which is a monofaciale solar cell based on CIGS thin layers in steady state; These phenomena are governed by a mathematical equation called the continuity equation:

$$\frac{\partial^2\delta(x,\lambda,Sf,Sb)}{\partial x^2}-\frac{\delta(x,\lambda,Sf,Sb)}{L^2}=-\frac{G(x,\lambda)}{D} \qquad (eq.1)$$

Where $\delta(x,\lambda,Sf,Sb)$ is electron density in the base.

The electron-hole pairs are created in the base. The distribution of the photocreated minority carriers (electrons) in the base is governed by the following continuity equation whose resolution makes it possible to determine the excess minority carriers density.

The carriers generation rate is expressed as:

$$G(x;\lambda)=\alpha(\lambda).\phi(\lambda).(1-R(\lambda)).e^{-\alpha(\lambda).x} \qquad (Eq.2)$$

Where α (λ) is the material monochromatic absorption coefficient; R (λ) is the material monochromatic reflection coefficient; $\phi(\lambda)$ is the incident carrier flux; H the thickness of the solar cell.

$$L^2=\tau.D \qquad (Eq.3)$$

L: is the diffusion length

$L=4.5\mu m$ for a 3 µm solar cells [5].

D: is the electron diffusion coefficient of the minority carriers density in the base

τ : Is the electron lifetime in the base.

The general solution of the continuity equation is like:

$$\delta(x,\lambda,Sf,Sb)=A.\cosh\left(\frac{x}{L}\right)+B.\sinh\left(\frac{x}{L}\right)+\beta(\lambda).\exp(-\alpha x) \qquad (Eq.4)$$

with $\beta(\lambda)=\dfrac{-L^2.\alpha(\lambda).\Phi(\lambda).(1-R(\lambda))}{D.(L^2.\alpha^2(\lambda)-1)}$ and $(L^2.\alpha^2(\lambda)-1)\neq 0$

Where A and B are coefficients determined from boundary conditions:

- At the junction (x = 0) **[6].**

$$\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=0}=\frac{Sf.\delta(x=0)}{D} \qquad (Eq.5)$$

- On the back surface of the base (x = H) [6].

$$\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=H}=\frac{-Sb.\delta(x=H)}{D} \qquad (Eq.6)$$

Sf and Sb are respectively the excess minority carriers recombination velocity at the junction and the excess minority carriers recombination velocity at the back side.

Sf: also characterizes the operating point of the solar cells.

Results & Discussion

Photovoltage

The expression of the photovoltage is obtained from the Boltzmann law given by the following relation:

$$Vph(x,\lambda,Sf,Sb)=V_T.\ln\left(1+\frac{N_b}{ni^2}.\delta(x,\lambda,Sf,Sb)\Big|_{x=0}\right) \qquad (Eq.7)$$

With $V_T = \frac{K.T}{q}$ $(Eq.8)$

$ni = 10^{13} cm^{-3}$

Where V_T is the thermal voltage ($V_T = 0,026V$); n_i the intrinsic carrier's density, K_B the Boltzmann constant ($K_B = 1,38.10^{-23} J.K^{-1}$), T the temperature (T = 300K) and N_b: base doping density.

Capacitance

The solar cell capacitance [7] in the base is given by:

$$C = \frac{dQ}{dV}$$

Q is the elementary charge

Or $Q = e.\delta(x=0)$ Then $C = e.\frac{d\delta(x=0)}{dV}$

Hence the above expression can be put in the form:

$$C = e.\frac{d\delta(x=0)}{dSf}.\frac{1}{\frac{dVph}{dSf}}$$

Taking into account the photovoltage expression (Boltzmann) and the minority carriers density, we get the following relation:

$$C = \frac{e.\frac{ni^2}{Nb}}{V_T} + \frac{e.\delta(x=0)}{V_T} = C0 + \frac{e.\delta(x=0)}{V_T} \qquad (Eq.9)$$

We present in the following figure 2 the profile of the capacitance according to the junction recombination velocity for various wavelength values :

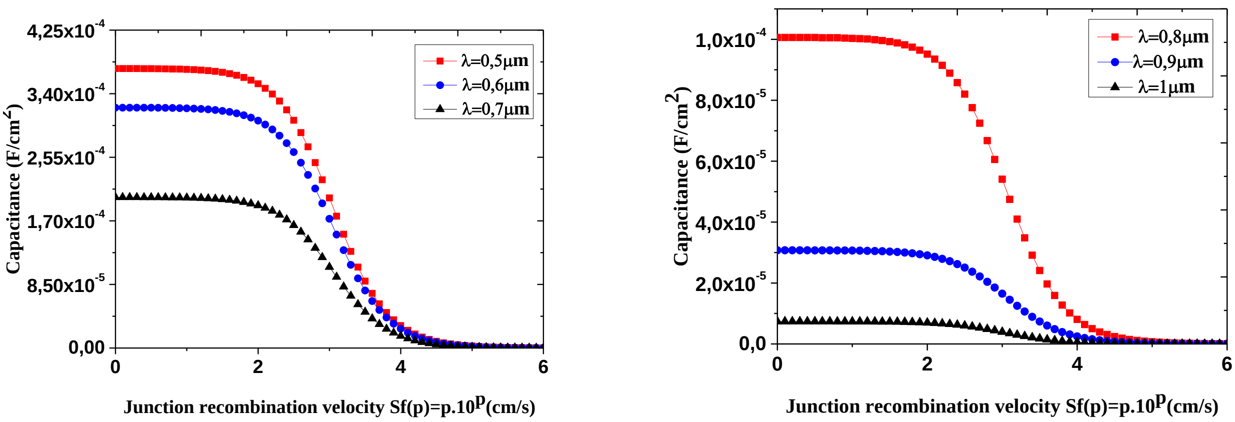

Figure 2: The variation of the Capacitance according to the junction recombination velocity for various wavelength values

We find that the capacitance decreases as the junction recombination velocity increases. This variation reflects an important storage of the excess minority carriers charges in the base in the range of 0 to $2,5.10^{2,5}$cm/s. The maximum value of the diffusion capacitance, corresponding to the solar cell under open circuit, is obtained when the junction recombination velocity tends towards null.

The capacitance also increases when the wavelength decreases because the wavelength is inversely proportional to the incident photon from which there is a strong generation of the excess minority carriers density in the base and consequently the carriers pass through the junction. We will then see the capacitance evolution under the darkness for our CIGS solar cell according to the photovoltage is represented in the following figure 3:

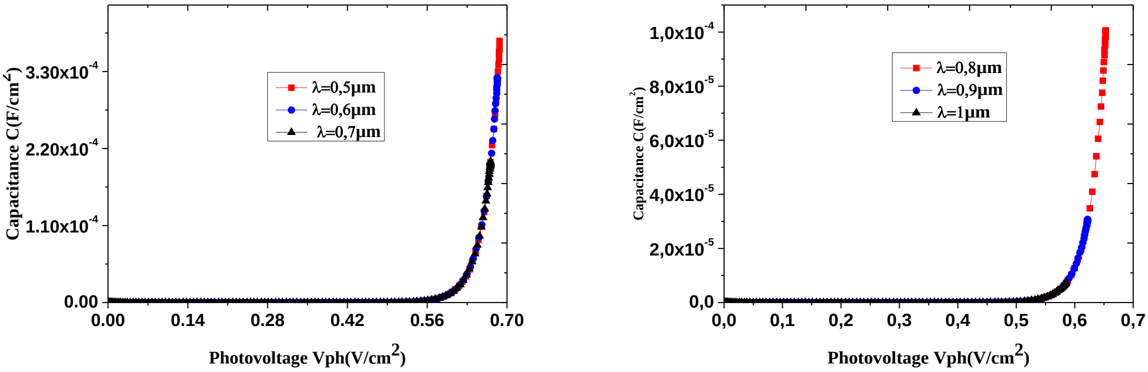

Figure 3: Variation of the capacitance according to the photovoltage for various wavelength values

We see that capacitance increases when the photovoltage grows. Thus, for the photovoltage values (Vph < 0.56V/cm^2) corresponding to an operation in situation of short-circuit, the capacitance is low or even zero; This is due to the massive crossing of the excess minority charge carriers at the junction, whereas for the values of the photovoltage (Vph > 0.56 V/cm^2), the capacitance increases as we note a storage of charge carriers at the junction level. When the capacity increases, the number of carriers stored at the junction increases, which increases the photovoltage. In this case, the photocurrent decreases because the number of the excess minority carriers collected is small.

Whatever the wavelength value, we observe the same values of the capacitance of the solar cell unit under the dark, so the wavelength has not effect on the variation of the capacitance under darkness according to the photovoltage.

The expression of the logarithm of the capacitance versus the photovoltage allows us to have an idea on the value of the capacitance of our solar cell. It's detailed in the following section:

The capacitance value of our solar cell

We use the expression of the photovoltage and we obtain after transformation the following relation:

$$\frac{C}{C0} = \left(1 + \frac{Nb}{ni^2}.\delta(0)\right) \qquad (Eq.10)$$

$$\frac{Vph}{V_T} = \ln\left(1 + \frac{Nb}{ni^2}.\delta(0)\right) \qquad (Eq.11)$$

From these two relations we have the following expression:

$$\frac{C}{C0} = \exp\left(\frac{Vph}{V_T}\right) \qquad (Eq.12)$$

$$\ln C - \ln C0 = \frac{Vph}{V_T} \qquad (Eq.13)$$

With Co the photovoltaic capacitance in the dark.

The profile of the logarithm according to the phototension is represented in the following figure:

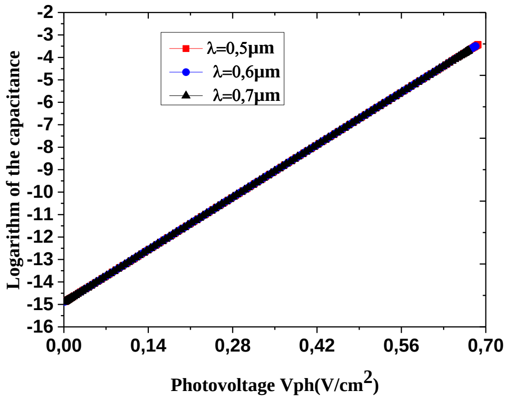

Figure 4: Variation of the logarithm of capacitance according to the photovoltage for different wavelength values

The curve of the logarithm of the capacitance as a function of the phototension is a straight line of slope 1 / VT whose ordinate at the origin is the value ln (Co).

We note that the curve of the logarithm of the capacitance as a function of the phototension is a line of slope 1 / VT whatever the value of the wavelength. We have a coincident curve for long wavelength values; and the logarithm of the capacity increases for the short lengths (and when the wavelength decreases).

So for long wavelengths the logarithm of the capacitance does not vary.

In all cases, we obtain about the same ordinate at the origin of value substantially equal to: ln (Co) = -15.

The value of Co after extrapolation on the ordinate axis is therefore: Co = 3.05 X 10^{-6} F/cm^2.

Relative density of the carriers as a function of the depth in the base of the photovoltaic cell

- **In a short-circuit situation**

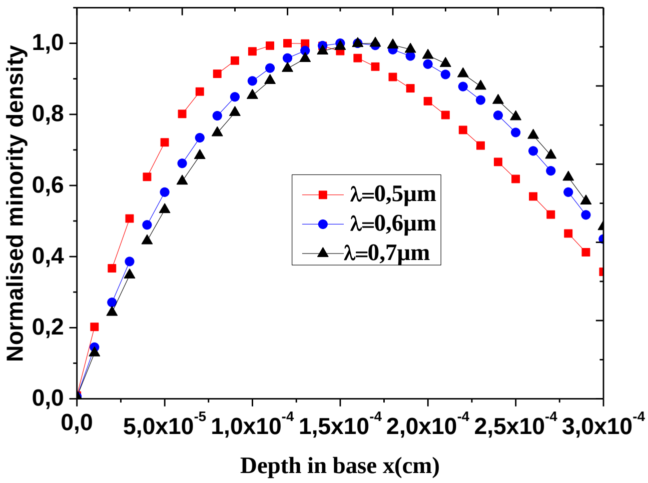

Figure 5: Normalised minority carriers density according to the base depth for various wavelengths in short circuit

We observe a displacement of the maxima of the relative minority charge carriers density which move away from the junction when the wavelength increases. This is due to a widening of the space charge area caused by a large crossing of excess minority charge carriers density at the junction. These maximums represent the width of the space charge area for various wavelength values when the solar cell is under short-circuit. They are noted $Xcc(\lambda)$.

- **In an open-circuit situation**

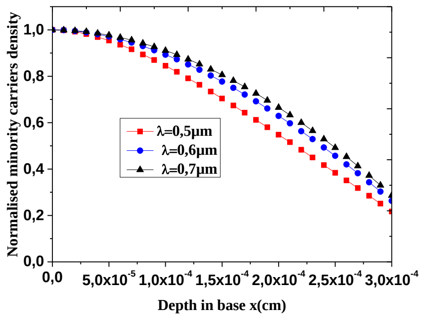

Figure 6: Normalised minority carriers density according to the base depth for various wavelengths in CIGS photovoltaic cell base of the open-circuit

The profiles of relative density minority carriers, according to the CIGS base depth when the solar cell operates under open circuit for different wavelength values, admit their maximums practically at the junction. This results in storage of the carriers at the junction caused by a narrowing of the space charge area. These maximums correspond to the width of the space charge area when the photovoltaic cell is under open-circuit. They are noted $Xco(\lambda)$. This last remains almost constant whatever the wavelength.

We also notice that $Xco(\lambda)$ is always less than $Xcc(\lambda)$.

Xco (λ) and Xcc (λ) are two parameters dependent of the solar cell capacitance efficiency; we will then see the variation of the capacitance efficiency η(λ) according to the wavelength in the rest of our study.

- **Capacitance efficiency**

The yield of the capacity is given by the expression [8, 9]:

$$\eta(\lambda) = 1 - \frac{Xco(\lambda)}{Xcc(\lambda)} \qquad (Eq.14)$$

Where Xco (λ) and Xcc (λ) are respectively the space charge ~~zone~~ thickness when the photovoltaic cell operate in open-circuit and in short-circuit.

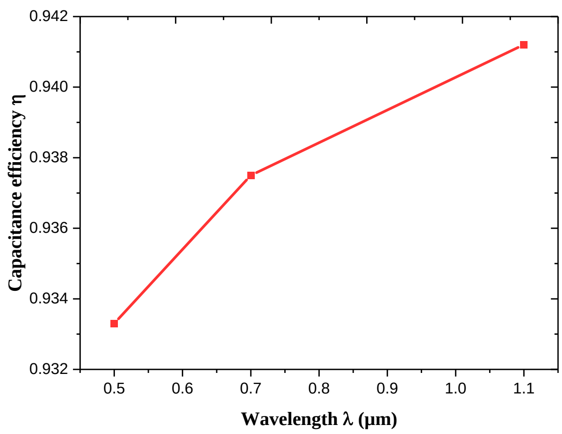

Figure 7: Variation of the Capacitance efficiency according to the wavelength

We see an increase in capacitance efficiency according to the wavelength. From the foregoing, the ratio $\frac{Xco(\lambda)}{Xcc(\lambda)}$ becomes increasingly less than unity. Hence the capacitance efficiency increases with the growth of the wavelength. We note that the higher is the capacitance efficiency; The more important is the capacitance of CIGS thin film and consequently the photocurrent becomes greater. So increasing the capacitance efficiency promotes a good generation of our solar cell.

Conclusion

The evolution of the capacitance according to the junction recombination velocity shows that the capacitance decreases for various wavelength values . More the wavelength is significant minus the capacitance is important; which is very favorable for a better generation of a direct-gap solar cell.

The capacitance also evolves increasingly with the photovoltage which is very normal. Its value is obtained with the profile of the logarithm of the capacitance as a function of thephototension. The value of the diffusion capacitance under darkness is obtained for approximately Co = 3.05 X 10^{-6} F/cm^2. The capacitance efficiency increases with the wavelength, which implies a reduction of the capacitance. This article allows us to see the variation of the capacitance with the parameters such as the junction recombination velocity, the photovoltage and for different wavelength values .

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