American Journal of Energy Research, 2022, Vol. 10, No. 1, 22-28
Available online at http://pubs.sciepub.com/ajer/10/1/3
Published by Science and Education Publishing
DOI:10.12691/ajer-10-1-3

Study of the Capacity of a Photo Pile Based on CIGS in Frequency Dynamic Regime Under Lighting Monochromatic in Frequency Modulation: Effect of the Wavelength and Angular Frequency

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Received November 13, 2022; Revised December 16, 2022; Accepted December 25, 2022

Abstract This article presents the effect of wavelength and angular frequency on the capacity of a CIGS- based solar cell subjected to monochromatic illumination in frequency modulation. From the expression of the density of the minority charge carriers, phototension and capacitance are studied. A gap of 1.34 eV corresponding to a gallium proportion of 0.28 is chosen. The results found show that the efficiency of the capacity decreases with the increase of the wavelength.

Keywords: *capacity, CIGS, wavelength, monofacial photopile, dynamic frequency regime*

Cite This Article: Jean Jude Domingo, Demba Diallo, Alain Kassine Ehemba, and Moustapha Dieng, "Study of the Capacity of a Photo Pile Based on CIGS in Frequency Dynamic Regime Under Lighting Monochromatic in Frequency Modulation: Effect of the Wavelength and Angular Frequency." *American Journal of Energy Research*, vol. 10, no. 1 (2022): 22-28. doi: 10.12691/ajer-10-1-3.

1. Introduction

During this decade we are witnessing a development of research on renewable energies more precisely on solar cells in thin layers.

The development of photovoltaic solar power is marked by the diversity of these technologies. Of these, the solar cells in thin layers especially based e nt CIGS has significant advantages with record performance 21.7 % obtained in the laboratory, 15.9% for large modules and 12-13% for commercial modules [1,2,3]. The understanding of a CIGS solar cell through the determination of certain properties, such as s those optics, structural and electrical [4,5,6].

The electrical properties are based es, in general, the determination of the photocurrent, the photovoltage, shunt and series resistors and the capacity of the solar cell. [3] The parameters usually put into play are: The diffusion length (L), the diffusion coefficient (D), the recombination rates at the front face (Sf) and the rear face (Sb), the reflection coefficient (R) and the absorption coefficient (α) [4].

In this paper, the capacity of a CI GS solar cell and its efficiency will be determined from the density of the minority charge carriers. The influence of the wavelength and that of the modulation frequency will be highlighted.

2. Theoretical Study

As part of our study we consider Figure 1 next:

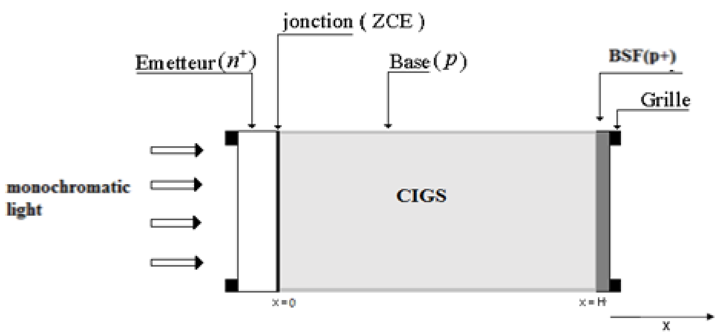

Figure 1. The solar cell (CIGS n + -p-p +) under illumination monochromatic to the front side

We neglect the contribution of the transmitter and we consider the quasi- neutral baseis (QNB)

When the solar cell is illuminated, electron-hole pairs are created in the active base. The density of the minority charge carriers generated follows the following continuity equation [4]:

$$\frac{\partial^2\delta(x,t)}{\partial x^2} - \frac{\delta(x,t)}{L(\omega)} = -\frac{G(x,t)}{D(\omega)} + \frac{\partial\delta(x,t)}{\partial t} \quad (1)$$

δ (x, t) and G (x, t) are respectively, the density and the generation rate of minority charge carriers in function of the thickness x and the time factor t. Their expressions are [4]:

$$\delta(x,t) = \delta(x)\cdot\exp(i\omega t) \quad (2)$$

$$G(x,t) = g(x)\cdot\exp(i\omega t) \quad (3)$$

$\delta(x)$ and $g(x)$ are the respective spatial components of the density and the generation rate. The generation rate of electron-hole pairs per the wavelength is equal to the photons rate of disappearance of the material [5].

$$g(x) = \varphi(\lambda)\cdot\alpha(\lambda)\cdot(1-R(\lambda))\cdot\exp(-\alpha(\lambda)\cdot x) \quad (4)$$

With:

$\varphi(\lambda)$ = the incidental monochromatic flux

$\alpha(\lambda)$ = the coefficient of monochromatic absorption

$R(\lambda)$ = the coefficient of monochromatic reflection

$L(\omega)$ and $D(\omega)$ respectively are the diffusion length and the diffusion coefficient, complex functions of the angular frequency, given by the following reports:

$$L(\omega) = \sqrt{\tau\cdot D_O}\cdot\sqrt{\frac{1-i\omega\tau}{1+(\omega\tau)^2}} \quad (5)$$

And

$$D(\omega) = D_0\left[\frac{1+\omega^2\tau^2}{(1-\omega^2\tau^2)^2+(2\omega\tau)^2}\times(1-i\omega\tau)\right] \quad (6)$$

L0 and D0 represent the intrinsic diffusion length and the intrinsic diffusion coefficient. The term D0 is given by the Einstein formula [7]:

$$D_0 = \mu\cdot\frac{K_b\cdot T}{q} \quad (7)$$

with μ which represents the mobility of the material, K_b the Boltzmann constant, T the temperature of the cell and q the elementary electron charge. The general solution of the continuity equation is the equation (8):

$$\delta(x,\lambda) = A\cdot\cos\left(\frac{x}{L(\omega)}\right) + B\cdot\sin\left(\frac{x}{L(\omega)}\right) - \frac{\alpha(\lambda)\cdot\phi(\lambda)\cdot(1-R(\lambda))\cdot L(\omega)^2}{D(\omega)\cdot\left(\alpha(\lambda)^2\cdot L(\omega)^2-1\right)}\cdot\exp(-\alpha(\lambda)\cdot x) \quad (8)$$

The coefficients A and B are obtained from the following boundary conditions: [4]

- At the junction at x = 0

$$\left.\frac{\partial\delta(x,\lambda)}{\partial x}\right|_{x=0} = \frac{S_f}{D(\omega)}\cdot\delta(x,\delta)\Big|_{x=0} \quad (9)$$

- At the rear side of the cell:

$$\left.\frac{\partial\delta(x,\lambda)}{\partial x}\right|_{x=H} = -\frac{S_b}{D(\omega)}\cdot\delta(x,\lambda)\Big|_{x=H} \quad (10)$$

S_f and S_b respectively represent the recombination speeds at the front side and the rear side of the absorber.

3. Results and Discussion

3.1. Absorption Coefficient

The CIGS can be used in photovoltaic devices because of its direct gap [8]. Thus, we represent the absorption coefficient of the CIGS as a function of the wavelength of the incident photons in Figure 2:

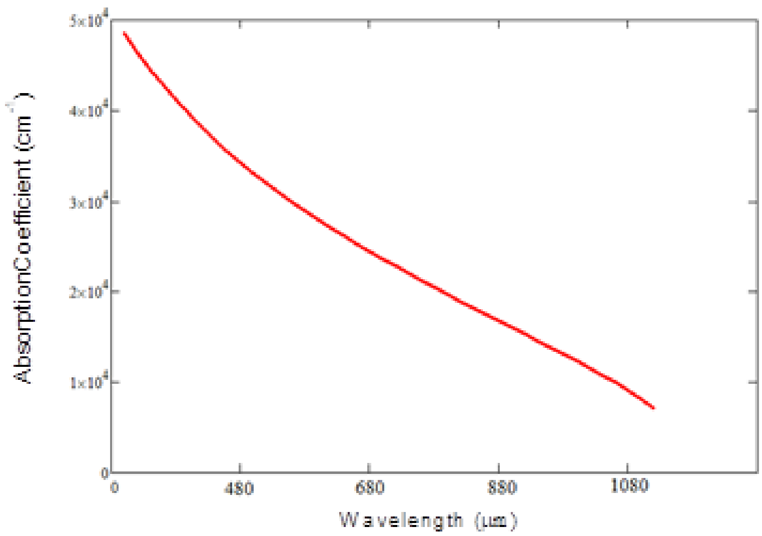

Figure 2. CIGS absorption coefficient as a function of the wavelength

This figure shows that the absorption coefficient decreases with increasing wavelength. Consequently the generation of electron-hole pairs increases with the increasing of the wavelength.

The magnitude of the CIGS absorption coefficient is of $10^4 cm^{-1}$, which explains its use in thin layer. Therefore, it takes some micrometer CIGS to absorb all of the incident light [9].

3.2. Density of Minority Charge Carriers

We present in the two following figures the density of the minority charge carriers as a function of the thickness x in the base for different angular frequencies and different wavelengths respectively in open circuit and in short circuit.

In Figure 3, all the curves start with a maximum then decrease gradually. Maximum this is the storage of minority carriers, so that e decay or the negative gradient corresponds to the recombination of minority carriers in the base [11].

In the Figure 4 for a given wavelength, we find two levels:

- at the first stage, the density of the minority carriers increases with the thickness of the base up to a maximum , this corresponds to the crossing of the minority charge carriers at the junction to participate in the generation of the photocurrent [12].
- at the second stage, the density of the minority carriers decreases with the thickness of the base, this corresponds to the surface and volume recombinations of the carriers which do not cross the junction [12].

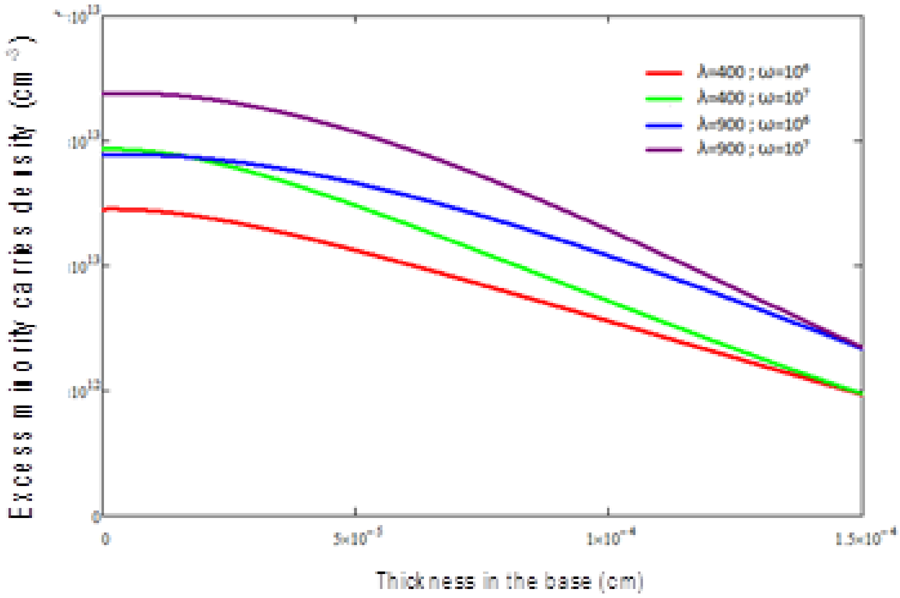

Figure 3. Profile density of the minority charge carriers as a function of the thickness in the base for different values of the wavelength (μm) and the frequency ($rad.s^{-1}$). Sf = 10 $cm.s^{-1}$ (Open circuit)

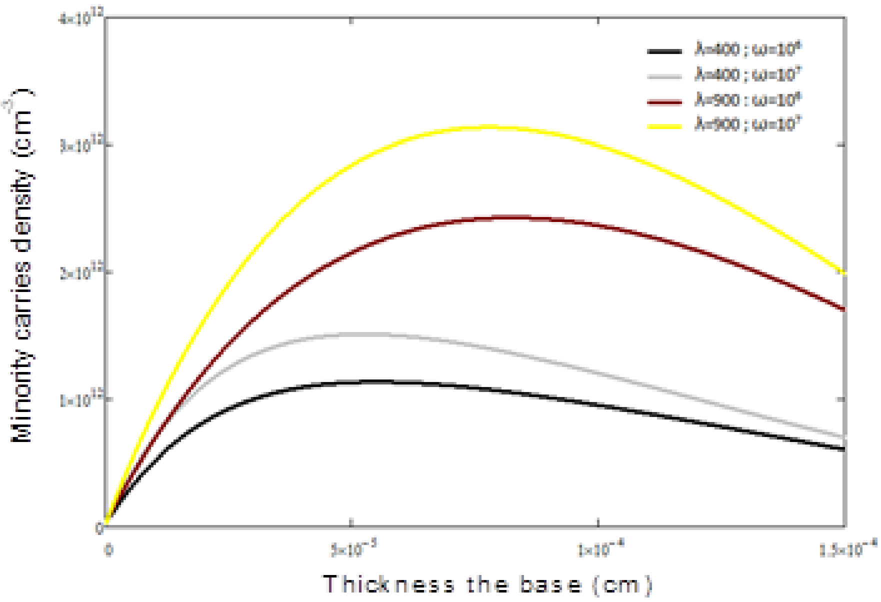

Figure 4. Profile density of the minority charge carriers as a function of the thickness in the base for different values of the wavelength (μm) and the frequency ($rad.s^{-1}$). Sf = 6.10^{6} $cm.s^{-1}$ (Short circuit)

The modulus of minority charge carrier density in both short-circuit and open-circuit increases with wavelength and for a given wavelength the modulus of density increases with frequency.

The increase of the modulus of the density with the wavelength corresponds to an increase of the carriers generated in the base since the absorption decreases when the wavelength increases [13].

For a given wavelength, the increase of NSITE with frequency is due to the fact that the frequency prevents undesired relaxation of carriers [14].

We can also see that for the low values of the wavelength (λ), the absorption is ready for the junction while for the large values of λ, the absorption moves in depth. The figures obtained in Figure 3 and Figure 4 are due to the fact that the CIGS has a reduced thickness of the order of a micrometer [4].

In Figure 5 and Figure 6, we represent the relative density of the minority charge carriers as a function of the thickness of the base for different frequencies and wavelengths:

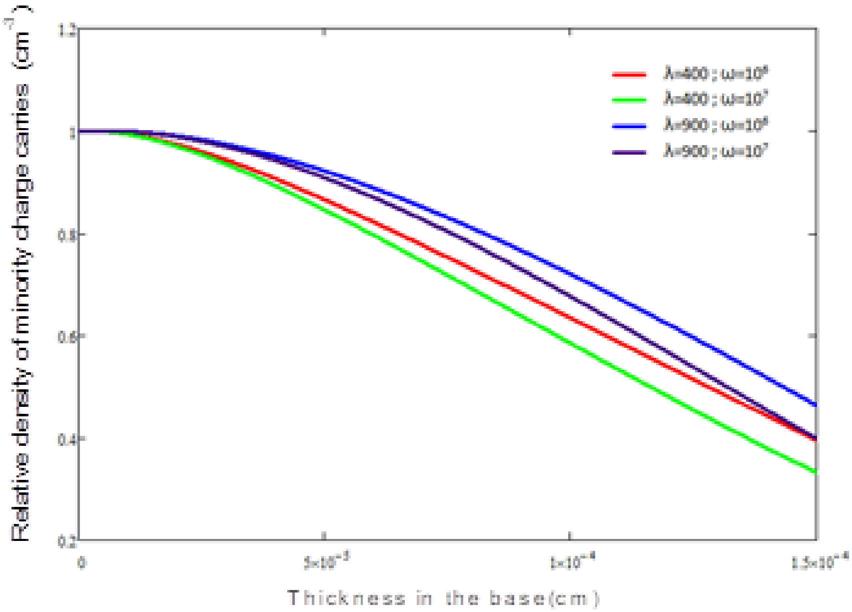

Figure 5. Density relative profile on minority charge carriers in function of the thickness in the base for different values of the wavelength(μm) and frequency (rad $^{-1}$). Sf = 10cm.s^{-1} (Open circuit)

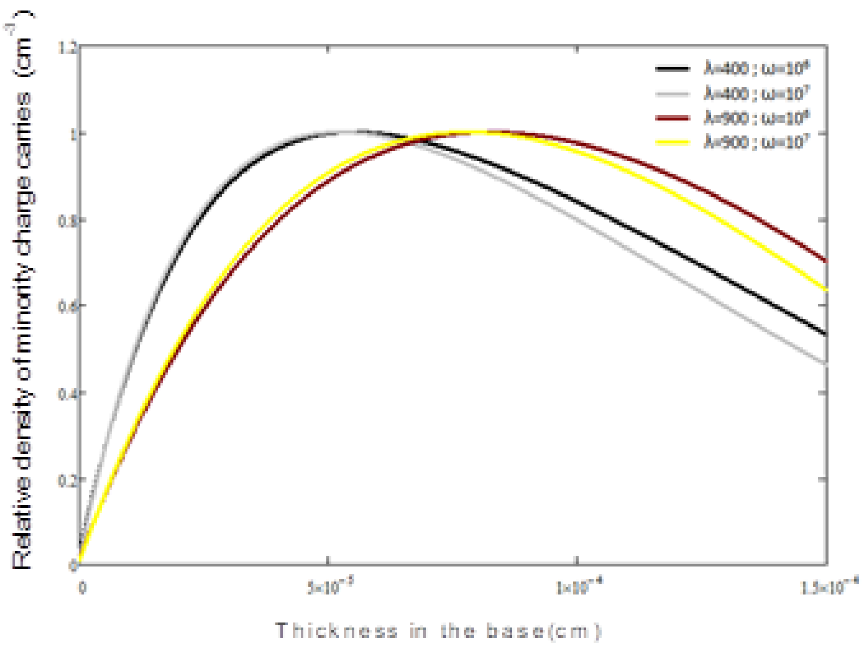

Figure 6. Density profile on minority charge carriers in function of the thickness in the base for different values of the wavelength (μm) and the frequency (rad $^{-1)}$ Sf = 6.10^{6}cm.s^{-1} (Short-circuit)

For a fixed value of S f near the short-circuit (Figure 6), the expansion of the space charge zone is greater with the large values of the wavelength. We can say that the small wavelengths offer a reduced space charge area thickness compared to long wavelengths.

For a given wavelength, there is a slight enlargement of the space charge area with the increase of the frequency. This means that the frequency of modulation does not contribute much to the expansion of the space charge area.

3.3. Photo Voltage

The photo voltage is given by the following Boltzmann equation [4]:

$$V_{ph} = V_T \ln\left[\frac{N_b}{n_i^2}\delta(0)+1\right] \qquad (11)$$

N_b and n_i are respectively the doping density and the intrinsic density of minority charge carriers is given by the following relationship [6]:

$$n_i^2 = N_C N_V \exp\left(\frac{-E_g}{K_b T}\right) \qquad (12)$$

N_C and N_V are respectively the densities of states in the conduction band and valence band. E_g is the energy gap of the material. Thermal stress is given by equation (13) [4]:

$$V_T = \frac{K_b T}{q} \qquad (13)$$

The photo voltage influences the diffusion capacity

3.4. Diffusion Capacity

When excess minority carriers diffuse into the base of a solar cell, they do not pass through all, the junction. Therefore they induce in the base equivalent capacity which is diffusing capacity whose expression is given as follows [5]:

$$C = \frac{dQ}{dV_{ph}} \qquad (14)$$

where: $Q = q\delta(0)$ is the number of carriers per unit area. By Q substituting its value is obtained:

$$C = q\frac{d\delta(0)}{dV_{ph}} \qquad (15)$$

$$C = q\frac{d\delta(0)}{dS_f}\frac{1}{\dfrac{dS_f}{dV_{ph}}} \qquad (16)$$

From the expression of the photo voltage, we finally get the following equation:

$$C = q\frac{n_i^2}{N_b V_T} + q\frac{\delta(0)}{V_T} \qquad (17)$$

C_O corresponds to the intrinsic capacity and C_d corresponds to the broadcast capacity.

The capacity decreases with the increase of Sf. It is maximum in open circuit and almost zero in short circuit. This can be explained on the one hand by the shape of the density of the minority charge carriers which is maximum in open circuit and on the other hand by the fact that the capacitance is proportional to the phototension. This last is maximum in open circuit and minimum in short circuit. If one refers to a plane capacitor, the capacitance is inversely proportional to the thickness of the capacitor. Now we have found that in an open circuit, the thickness of the space charge area is minimal in a short circuit where the thickness of the space charge area is maximum.

The capacitance increases with the wavelength and for a given wavelength the capacitance increases with the frequency. The increase of the capacity with the wavelength can be explained by the optical properties of the CIGS.

The increase of the capacity with the frequency can be explained by the fact that when the modulation frequency increases, the carriers of charges are more and more stored in the base of the solar cell.

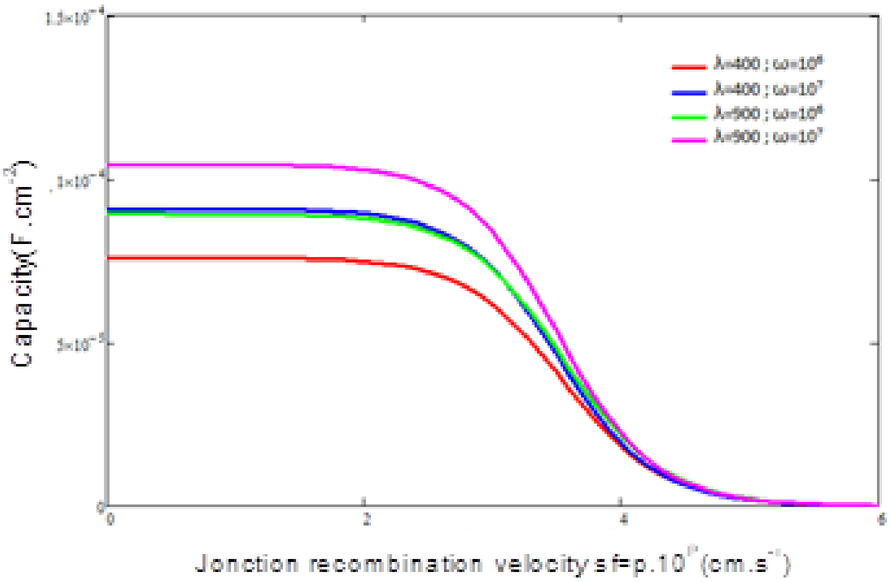

Figure 7. Capacity as a function of the recombination rate at the junction for different values of the wavelength(μm) and the frequency (rad.s $^{-1}$)

The The following figures illustrate the variation of the capacity as a function of the modulation frequency:

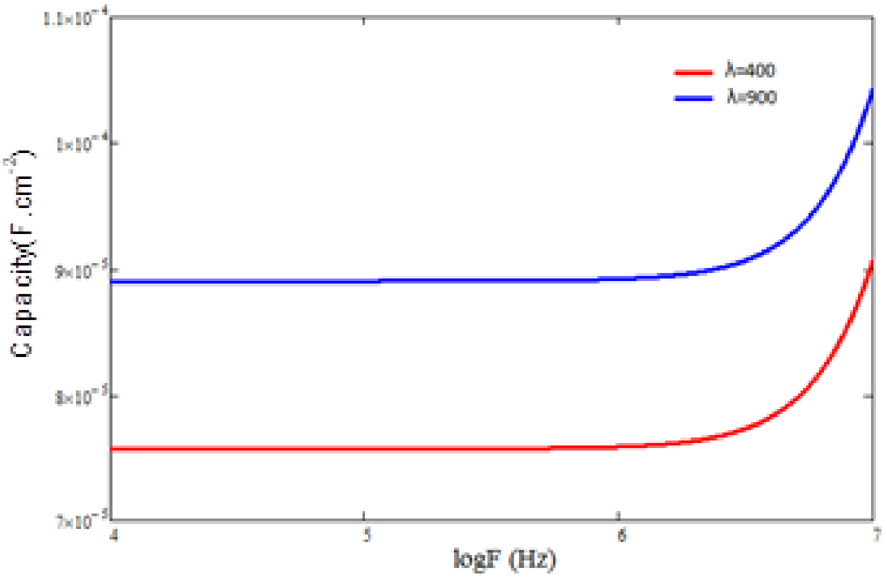

Figure 8. Ability as a function of the logarithm of the frequency for different values of the wavelength (µm). S f = 10cm.s $^{-1}$

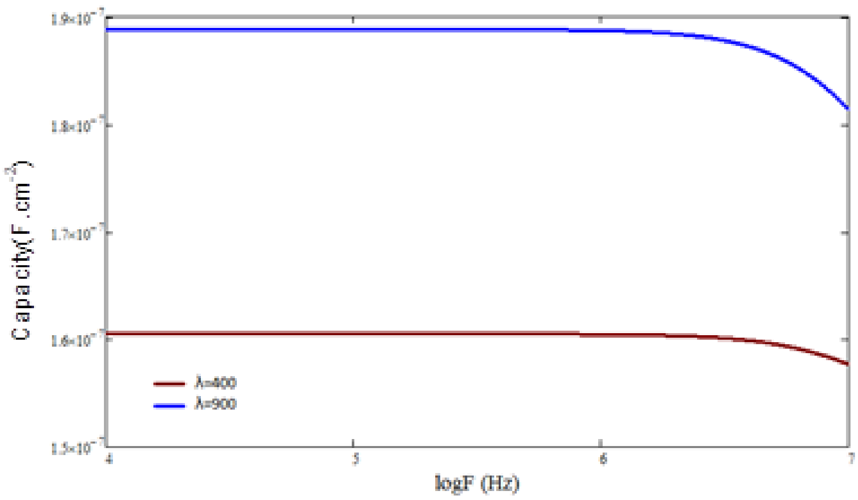

Figure 9. Ability as a function of the logarithm of the frequency for different values of the wavelength (µm). S f = 6.10 ^{6} cm s $^{-1}$

The Figure 8 and Figure 9 shows that the capacity remains constant up to a first frequency equal to 10 ^{6} Hz to increase (Figure 8) or decrease (Figure 9) then with the modulation frequency. The constancy of the capacitance shows that the regime is quasi-static up to 10 ^{6} Hz. It is at this value of the frequency that the dynamic frequency regime begins.

3.5. Efficiency of Capacity

The collection area of the minority load carriers corresponds to an extension of the space charge area which depends on the rate of recombination at junction. However, when the space charge area is considered a flat capacitor, one can write:

$$U_{cc} = \frac{X_{0,co}}{X_{0,cc}} U_{co} \tag{18}$$

U_{cc} and U_{co} are respectively the short-circuit and open-circuit energies $X_{0,co}$ and $X_{0,cc}$ are respectively the thickness of the space charge zon e in open circuit and in short circuit.

The capacity is written in this case:

$$C(\lambda,\omega) = \frac{\varepsilon.S}{X_o(\lambda,\omega)} \tag{19}$$

The efficiency of the capacity of the cell is given by the following relation:

$$\eta = \frac{\Delta U}{U_{oc}} \tag{20}$$

With the difference of energy in open circuit and in short circuit.

So the expression of efficiency becomes:

$$\eta(\lambda,\omega) = 1 - \frac{X_{o,co}(\lambda,\omega)}{X_{o,cc}(\lambda,\omega)} \tag{21}$$

Table 1. Summarizes the values of the maximum density of minority carriers, the thickness of the space gap zone and the capacity for different values of angular wave length and frequency

ω (rad.s^{-1})	λ (nm)	δmax,co (10^{13}cm^{-3})	δmax,cc (10^{13}cm^{-3})	Xo,co (10^{-2}.μm)	Xo,cc (10^{-2}.μm)	Cco (nf.cm^{-2})	Ccc (nF.cm^{-2})	η %
zsedççoqwwww10^6	400	1,2272	0,1136	1,9	55	63,34	21,88	96.5
10^6	910	1,4443	0,2428	5,08	82,37	23,69	14,61	93.8
10^7	400	1,4675	0,1511	1,9	51,98	63,34	23,15	96.3
10^7	910	1,6901	0,3136	5,08	76,89	23,69	15,65	93.4

We find that capacity efficiency is higher for small wavelength values. For these small wavelengths this high efficiency decreases with increasing angular frequency.

For large wavelength values the efficiency of the capacity decreases with the increase of the angular frequency.

It appears that for the same value of the frequency, the maximum density of the minority charge carriers and the thickness of the space charge area increase with the wavelength. On the other hand, open-circuit and short-circuit capacity decrease when the wavelength increases for the same value of the frequency. Note also that the thickness of the space charge area is substantially constant in open circuit whatever the value of the frequency for the same value of the wavelength.

4. Conclusion

In this work we conducted, we presented a simulation study of the wavelength and angular frequency on the capacity of a CIGS-based solar cell subjected to monochromatic illumination in frequency modulation.

The result obtained in this study is the decrease of the efficiency of the capacity of the cell with the increase of the wavelength for the same value of the frequency.

Therefore the diffusion capacity results from the variation of the minority charge carriers in the base of the photocell. In diffusion capacity studies, the parameter usually taken into account is the nature of the junction. Indeed the capacity is proportional to the density of the minority charge carriers which increases with the wavelength.

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