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STUDY OF THE CAPACITANCE OF A MONO FACIAL SOLAR CELL BASED ON SILICON UNDER HORIZONTAL MONOCHROMATIC ILLUMINATION IN A DYNAMIC FREQUENCY REGIME : THE EFFECT OF THE WAVELENGTH

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ABSTRACT

In this present work, this is a scientific contribution in the field of research on photovoltaic solar cells. The work is a theoretical study of the effect of wavelength on the capacity of a silicon-based solar cell subjected to horizontal monochromatic illumination in frequency modulation. With the same objectives as most of the authors who work in this field: how to help improve the performance of photovoltaic solar cells. Based on the expression of the density of minority charge carriers, we will study the photovoltage and the capacity. The influence of wavelength on capacity is achieved. The obtained results show that the capacitance efficiency decreases with increasing wavelength.

Keywords: Capacity, photovoltage, silicon, wavelength, Monofacial solar cell.

1. INTRODUCTION

Most of the world's energy production comes from fossil fuels. Greenhouse gas emissions come from CO2 emissions into the atmosphere. Fossil fuels contribute mainly to the emission of CO2 into the atmosphere [1], which is therefore largely responsible for the increase in global warming. To reduce such a problem, one of the solutions is photovoltaic solar energy. The development of photovoltaic solar energy is marked by the diversity of these technologies. Among the latter, silicon-based crystalline cells. Today this technology is the most widely used. Silicon-based cells have the particularity of presenting significant advantages with a record yield that exceeds 20% in industrial production and 26% in the laboratory. When the incident solar radiation is totally diffused in theoretical modeling of a single junction, the efficiency can exceed 30% for commercial modules [1], [2] and [3]. Understanding a solar cell requires the determination of certain properties, such as optical, structural and electrical [4], [5] and [6] and also the control of certain electrical parameters. The search to increase performance continues. Good performance is limited by the lack of control of certain electrical parameters and certain simplifying assumptions on its parameters such as: the band gap energy or the recombination velocity of the charge carriers

The electrical properties are based, in general, on the determination of the photocurrent, the photovoltage, the series and shunt resistances and the capacitance of the solar cell [3]. The parameters usually involved are: the diffusion length (L), the diffusion coefficient (D), The recombination velocity at the front face (Sf) and rear face (Sb), the reflection coefficient (R) and the absorption coefficient (α) [4].

In this article, the capacity of a solar cell and its efficiency will be determined from the density of the minority charge carriers. The influence of wavelength is highlighted.

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2. THEORY STUDY

II.1. Modeling of the solar cell

The solar cell considered is of type n+pp+, it is of length H, illuminated by the front face under monochromatic illumination. The solar cell is modeled in Figure 1.1:

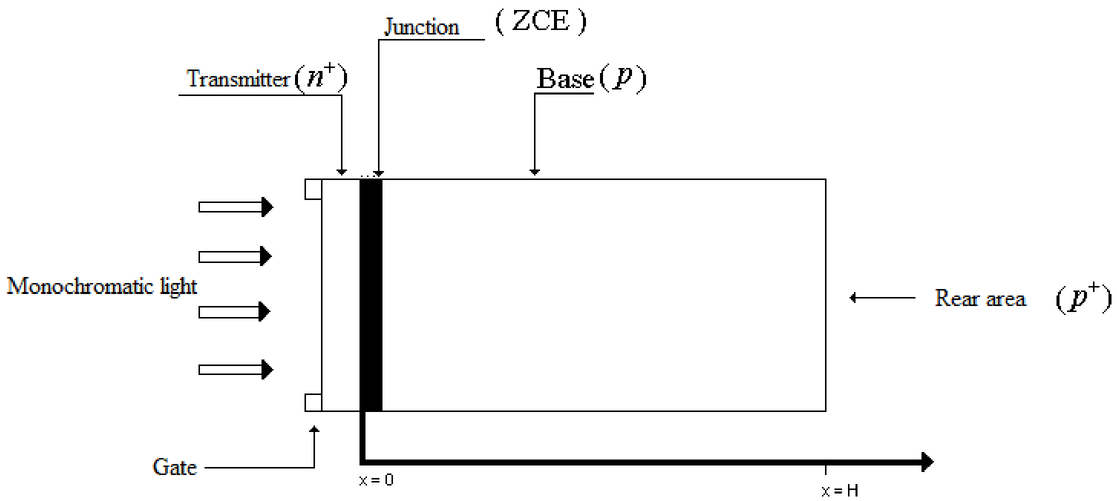

Figure 1.1 : Solar cell under monochromatic illumination on the front face.

II.2. Theory modeling

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

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

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

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

$$\delta(x,t) = \delta(x).\exp(i\omega t) \qquad (2)$$

$$G(x,t) = g(x).\exp(i\omega t) \qquad (3)$$

and are the respective spatial components of density and generation rate. The rate of generation of electron-hole pairs per wavelength is equal to the rate of disappearance of photons in the material [5]

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

With :

$\phi(\lambda)$: The monochromatic incident flux

$\alpha(\lambda)$: The monochromatic absorption coefficient

$R(\lambda)$: The monochromatic reflection coefficient

$L(\omega)$ and $D(\omega)$ are respectively the diffusion length and the diffusion coefficient. Their expressions as a function of the angular frequency are given by the following relations [6]:

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

And

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

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L_0 and D_0 represent the intrinsic diffusion length and the intrinsic diffusion coefficient respectively. The expression of D_0 is given by Einstein's formula [7]:

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

With μ representing the mobility of the material, K_b the Boltzmann constant, T the temperature of the cell and q the elementary charge of the electron.

The general solution of the continuity equation is the following equation (8):
The coefficients A and B are obtained from the following boundary conditions [4]:

- at the junction at x= 0 : $$\left.\frac{\partial \delta(x,\lambda)}{\partial x}\right|_{x=0} = \frac{S_f}{D(\omega)} \cdot \delta(x,\delta)\big|_{x=0} \quad (9)$$

- on the rear face of the cubicle: $$\left.\frac{\partial \delta(x,\lambda)}{\partial x}\right|_{x=H} = -\frac{S_b}{D(\omega)} \cdot \delta(x,\lambda)\bigg|_{x=H} \quad (10)$$

S_f and S_b respectively represent the recombination velocity at the front face and at the back face of the absorber.

3. RESULTS AND DISCUSSIONS

III .1. Absorption coefficient
When the solar cell is illuminated, it absorbs incident photons with an energy greater than or equal to that of the silicon gap, the energy threshold necessary for this mechanism will therefore give us a measure of the width of the forbidden band. Silicon can be used in devices
photovoltaic because of its direct gap [8].

δ(x,λ)=A ·cos(x/L(ω))+ B·sin(x/L(ω))-(α(λ)·ϕ(λ)·(1-R(λ))·L(⟦ω)⟧^2)/(D(ω)·(α(⟦λ)⟧^2 . L(⟦ω)⟧^2-1)) ·exp(-α(λ)·x) (8)

Thus, we represent the absorption coefficient of silicon as a function of the wavelength of the incident photons in Figure 2.1: [9]

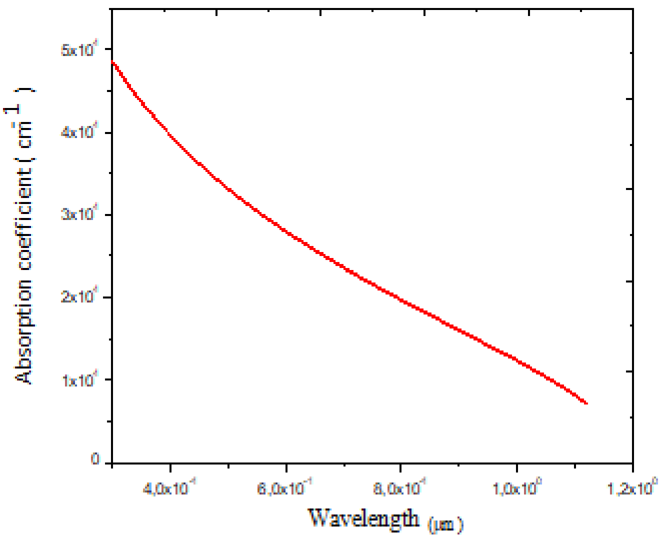

Figure 2.1 : Absorption coefficient of silicon as a function of wavelength

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The curve in Figure 2.1 shows that the absorption coefficient decreases with increasing wavelength. Consequently, the generation of electron-hole pairs increases with increasing wavelength.
The order of magnitude of the absorption coefficient of silicon is 104cm-1, which explains its use in thin layers. Therefore, it takes a few micrometers for silicon to absorb all of the incident light [9].

III.2. Study of the density of minority charge carriers
In figures 2.2, 2.3, 2.4 and 2.5 we present the density of minority charge carriers as a function of the thickness x in the base for visible and infrared wavelengths respectively in open circuit and in short-circuit.

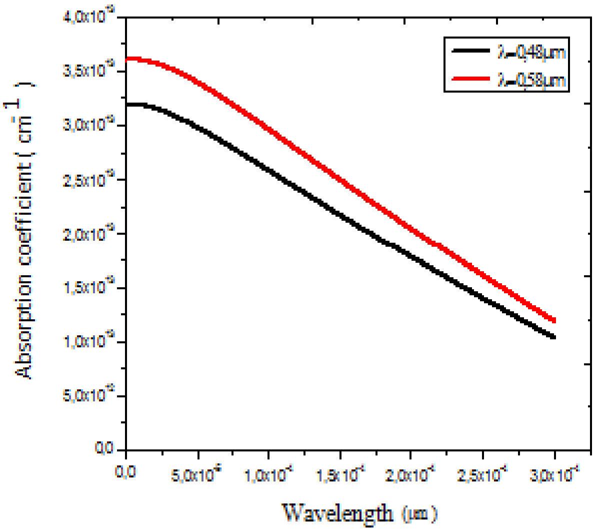

Figure 2. 2 : Profile of minority charge carrier density as a function of thickness in the base for different visible wavelength values. Sf =10cm.s-1 (Open circuit)

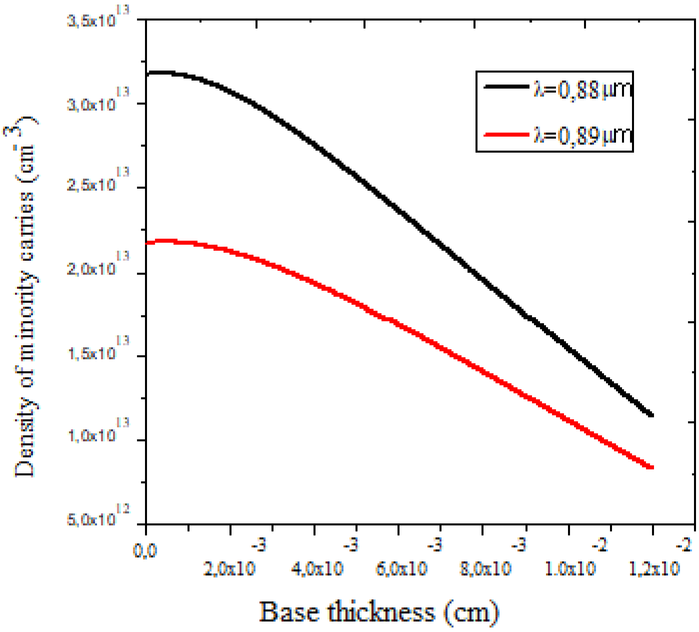

Figure 2.3 : Profile of the density of minority charge carriers as a function of the thickness in the base for different values of infrared wavelength Sf =10cm.s-1 (Open circuit)

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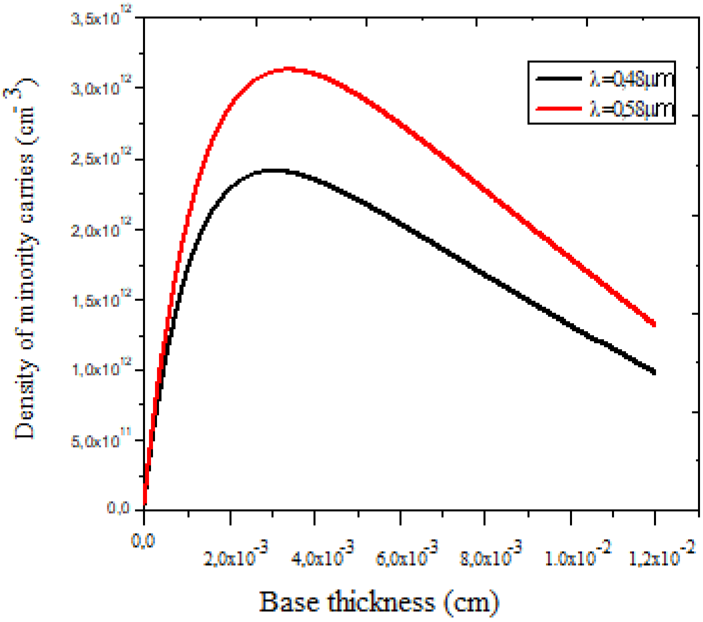

Figure 2.4 : Profile of minority charge carrier density as a function of base thickness for different visible wavelength values. Sf = 6.106cm.s-1 (Short circuit)

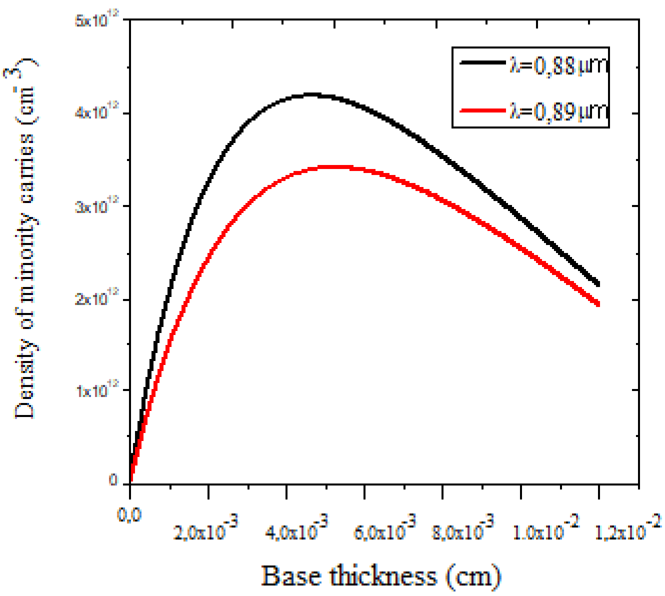

Figure 2.5 : Profile of the density of minority charge carriers as a function of the thickness in the base for different values of infrared wavelength. Sf = 6.106cm.s-1 (Short circuit)

In figures 2.2 and 2.3, all the curves start with a maximum and then gradually decrease. The maximum density corresponds to a zero carrier gradient. Then this density decreases with the depth x in the base. Because of this, carriers cannot cross the junction to produce a photocurrent. They will recombine. This decrease or even the negative gradient corresponds to the recombinations of minority carriers in the base [10].

In Figures 2.4 and 2.5 for a given wavelength in the infrared domain, we see two levels: at the first level, the density of minority carriers increases with the thickness in the base up to a maximum, this corresponds to the

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crossing of minority charge carriers at the junction to participate in the generation of the photocurrent [11]. at the second stage, the density of the minority carriers decreases with the thickness of the base, this corresponds to the recombinations in surface and in volume of the carriers which do not cross the junction [11].

The modulus of the density of minority charge carriers in short-circuit as in open-circuit increases with the wavelength.

The increase in the modulus of the density with the wavelength corresponds to an increase in the carriers generated in the base since the absorption decreases when the wavelength increases [12].

We also see that for low values of the wavelength (λ), the absorption takes place close to the junction while for large values of λ, the absorption moves in depth. The shapes obtained in figures 2.2, 2.3, 2.4 and 2.5 are due to the fact that silicon has a thickness reduced to one micrometer [4].

In figures 2.6 and 2.7, we represent the relative density of minority charge carriers as a function of the thickness in the base for different values of wavelength respectively in open circuit and in short circuit:

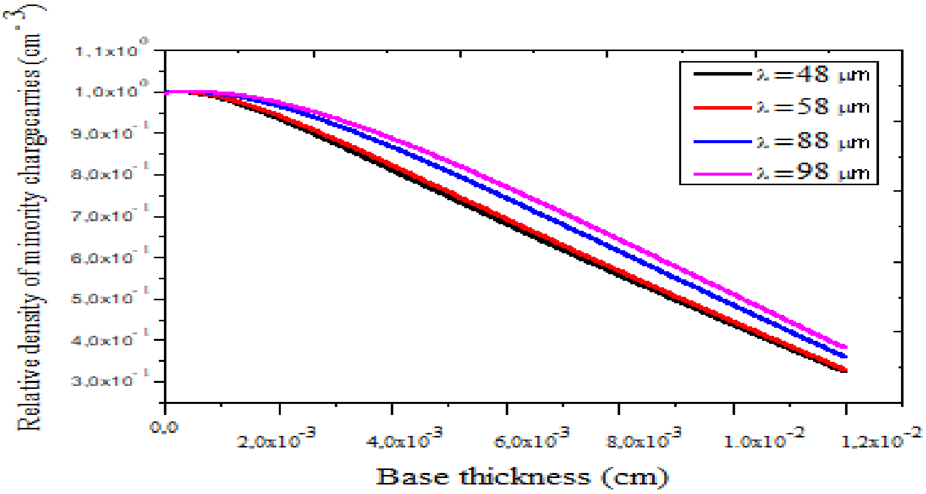

Figure 2.6 : Profile of the relative density of minority charge carriers as a function of the thickness in the base for different values of the wavelength. Sf=10cm.s-1(Open circuit)

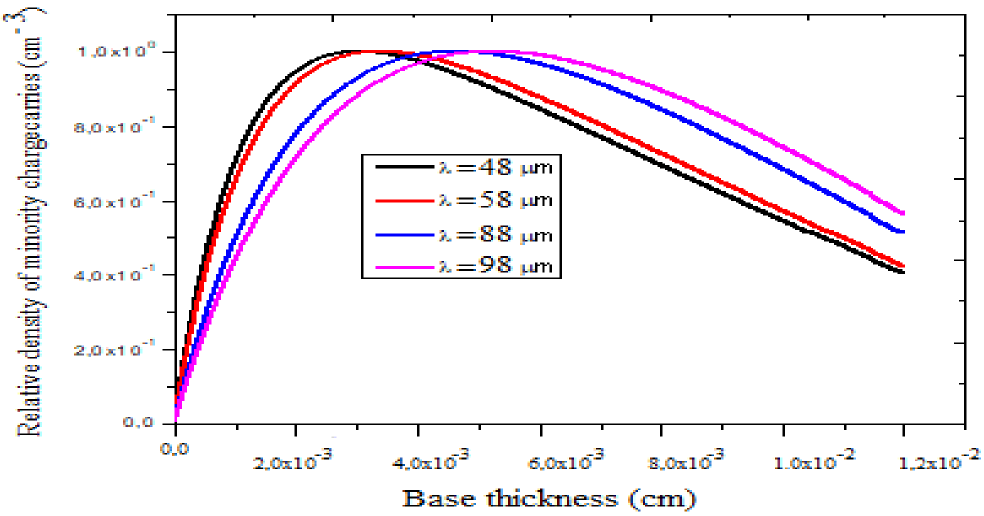

Figure 2.7 : Profile of the relative density of minority charge carriers as a function of the thickness in the base for different values of the wavelength.
Sf = 6.106cm.s-1 (Short circuit)

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In figures 2.8 and 2.9, the thickness of the cell where the modulus of the density of the minority carriers is maximum corresponds to the extension of the space charge zone. We note that the thickness of the latter widens with the increase in the recombination rate at the Sf junction. This is due to the fact that the carriers are stored more in open-circuit than in short-circuit [13].

For a recombination velocity value at the junction Sf fixed in the vicinity of the short-circuit figure 2.9 the widening of the space charge zone is greater with large values of the wavelength. We can say that short wavelengths offer a reduced space charge zone thickness compared to long wavelengths.

III-3-Phototension

A solar cell is properly lit, generates at these terminals a photovoltage V whose expression is given by the Boltzmann relationship. The photovoltage across the junction as a function of the charge carrier density at the junction (x = 0) of the solar cell is given by the following expression: [4]-[14]-[15]

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

With, N_b the density of the doping rate of the base (Nb = 10^{16} cm^{-3}) [14] - [15]
n_i the intrinsic density of minority charge carriers which is given by the following relation [15]:

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

N_c and N_v are the densities of the states respectively in the conduction band and in the valence band.

E_g is the gap energy of the material.

The thermal stress is given by equation (13) [4]:

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

Where K is the Boltzmann constant, q the charge of the electron and T the absolute temperature at thermal equilibrium (T = 300°K).

Diffusion capacitance can vary with photovoltage, so it is important to do a photovoltage study before studying capacitance.

III-4- Broadcast capacity

When excess minority carriers diffuse into the base of a solar cell, not all of them cross the junction. Consequently, they induce in the base an equivalent capacity which is the diffusion capacity whose expression is given as follows [5]:

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

Or : $Q = q\delta(0)$ (15)

Q is the number of carriers per unit area.

Substituting Q its value, we get:

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

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$$C = q\frac{d\delta(0)}{dS_f}\frac{1}{\frac{dS_f}{dV_{ph}}} \quad (17)$$

From the expression of the phototension, we finally obtain the following relation:

$$C = q\frac{n_i^2}{N_b V_T} + q\frac{\delta(0)}{V_T} \quad (18)$$

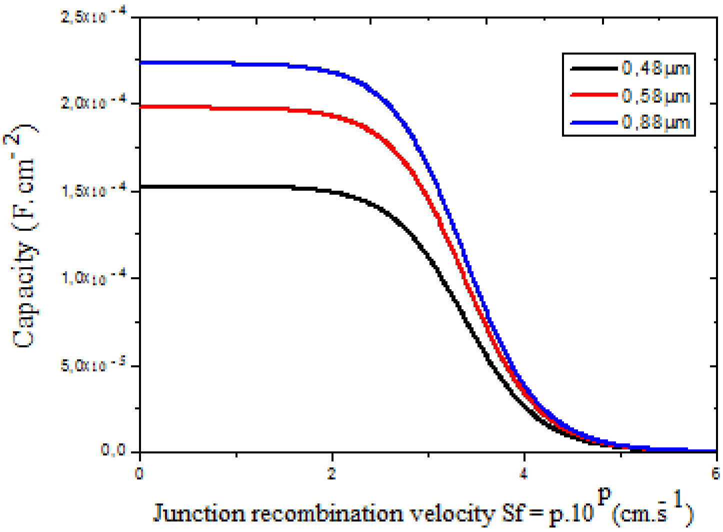

Figure 2. 8 : Capacity as a function of the recombination velocity at the junction for different values of the wavelength.

The capacity decreases with increasing recombination velocity at the junction. It is maximum in open circuit and almost zero in short circuit. This can be explained on the one hand by the form of the density of minority charge carriers which is maximum in open circuit and on the other hand by the fact that the capacity is proportional to the photovoltage. The latter is maximum in open circuit and minimum in short circuit. If we refer to a plane capacitor, the capacitance is inversely proportional to the thickness of the capacitor. However, we have found that in open circuit, the thickness of the space charge zone is minimal, unlike in short circuit where the thickness of the space charge zone is maximum.

Capacitance increases with wavelength. The increase in capacitance with wavelength can be explained by the optical properties of the e.g. wavelength and absorption coefficient.

III.5. Capacity Efficiency

The collection zone of minority charge carriers corresponds to an extension of the space charge zone X_0 which depends on the recombination rate at the junction. However, when the space charge area is considered as a plane capacitor, we can write:

$$U_{cc} = \frac{X_{0,co}}{X_{0,cc}} U_{co} \quad (19)$$

U_{CC} and U_{CO} are respectively the energies when the solar cell is short-circuited and open-circuited. $X_{0,co}$ and $X_{0,cc}$ are respectively the thickness of the space charge zone when the solar cell is in open circuit and in short circuit.

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The capacity is written in this case: $C(\lambda,\omega)=\dfrac{\varepsilon.S}{X_o(\lambda,\omega)}$ (20)

The efficiency of the solar cell capacity is given by the following relationship:

$$\eta=\frac{\Delta U}{U_{oc}} \quad (21)$$

With ΔU the difference of energy in open circuit and in short circuit.
Thus, the expression for the efficiency becomes:

$$\eta(\lambda,\omega)=1-\frac{X_{o,co}(\lambda,\omega)}{X_{o,cc}(\lambda,\omega)} \quad (22)$$

Table 1 summarizes the values of the maximum minority carrier density, the thickness of the space charge zone and the capacitance for different values of the wavelength.

Table 1 :

λ (nm)	δmax,co ($10^{13}cm^{-3}$)	δmax,cc ($10^{12}cm^{-3}$)	Xo,co (10^{-2}.µm)	Xo,cc (10^{-2}.µm)
480	3,19044931	2,4100749	4,13	75,64
580	3,60422911	3,1270275	4,94	84,24
880	3.17749864	4,187250	8,83	115,20
980	2.1797098	3,4194892	11,59	130,31

λ (nm)	Cco (mF.cm^{-2})	Ccc (µF. cm^{-2})	η %
480	2,14	117,00	94,54
580	1,79	105,06	94,34
880	1,00	76,82	92,33
980	0,76	67,91	91,10

Both open-circuit and short-circuit capacitance decrease as the wavelength increases. This capacitance is very low in short circuit. We also notice that the thickness of the space charge zone in open-circuit as well as in short-circuit increases when the wavelength increases. We also find that the efficiency of the capacitance for long wavelengths is higher than that of short wavelengths.

4. CONCLUSION

In the present work, we presented a simulation study using the effect of wavelength on the capacitance of a silicon-based solar cell subjected to horizontal monochromatic illumination in frequency modulation.

The result obtained in this study is the decrease in the efficiency of the capacity of the solar cell with the increase in wavelength. So the diffusion capacity results from the variation of the minority charge carriers in the base of the solar cell. In diffusion capacitance studies, the parameter usually taken into account is the nature of the junction.

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In the end we can affirm that the capacity is proportional to the density of the minority charge carriers which increases with the wavelength.

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