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A SILICON SOLAR CELL ILLUMINATED BY LARGE Λ WAVES AT ITS EMITTER, AT TEMPERATURE AND IN A STATIC REGIME: XCO IS INVESTIGATED ON THE EXCESS MINORITY CHARGE CARRIERS' DENSITY BASIS AND THE CAPACITANCE

Ibrahima Diatta [1, 2, *], Marcel Sitor Diouf [1, 2], Oulimata Mballo [1, 2], Khady Loum [1] and Sega Gueye [1, 3]

[1] International Renewable Energy Research Group (GIRER). BP.15003, Dakar, Senegal.
[2] Semiconductor and Solar Energy Laboratory, Faculty of Science and Technology.
[3] Faculty of Education and Formation Sciences and Techniques, Cheikh Anta Diop University, Dakar, Senegal.
* Corresponding Author

ORCID details
Ibrahima DIATTA: https://orcid.org/0009-0000-7097-3586
Marcel Sitor DIOUF: https://orcid.org/0009-0006-2806-3128

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ABSTRACT

This work is carried out on the excess minority charge carriers density basis in the base, $\delta(x)$, obtained from the continuity equation solution. The latter involves modelling the phenomena that arise when long wavelengths λ Illumination is emitted from our n+/p/p+ type solar cell at temperature T, under static regime. Using the $\delta(x)$ expression, the excess minority charge carriers relative density in the base versus depth x in the base is plotted. The maximum of this relative density, projected onto the x-axis, is denoted by X. As we are considering the case where the solar cell is in an open-circuit condition, X is denoted by Xco. This is also referred to as the space charge region thickness or width when the solar cell is in an open-circuit condition. As the solar cell is at a high temperature and high λ, then Xco corresponds to Xco(T, λ_{high}). The solar cell capacitance expression is derived from those for $\delta(x)$ and the photovoltage Vph. Based on the neperien logarithm graph of capacitance against the temperature neperien logarithm, Xco(T, λ_{high}) is investigated.

Keywords: Silicon solar cell, Thickness Xco(T, λ_{high}), Temperature, Long wavelength, Static regime.

1 INTRODUCTION

The silicon solar cell manufacture involves the formation of an (n/p) junction between n-type and p-type silicon [1-2]. Other studies have proposed the manufacture of this solar cell with an n+/p junction [3-14]. This junction is established by the migration of electric charges between the two semiconductors [1–2] or within a single semiconductor [15–27], which take the form of fixed charges of opposite signs. This junction is also known as the space charge region (SCR) [28, 29]. The SCR is linked to the junction recombination velocity (Sf), which governs the solar cell operation [6–9]. When Sf is low, the solar cell is in open-circuit mode [7, 8, 28] and the SCR width becomes Xco [28, 29].

Using the minority charge carriers relative densit and the silicon solar cell capacitance in static regime when illuminated on its emitter, we will investigate the width Xco(T, λ_{high}). behaviour.

2 THEORETICAL STUDY

The solar cell under consideration is of the n^+-p-p^+ type, and its structure is shown in Figure 1. [26-29].

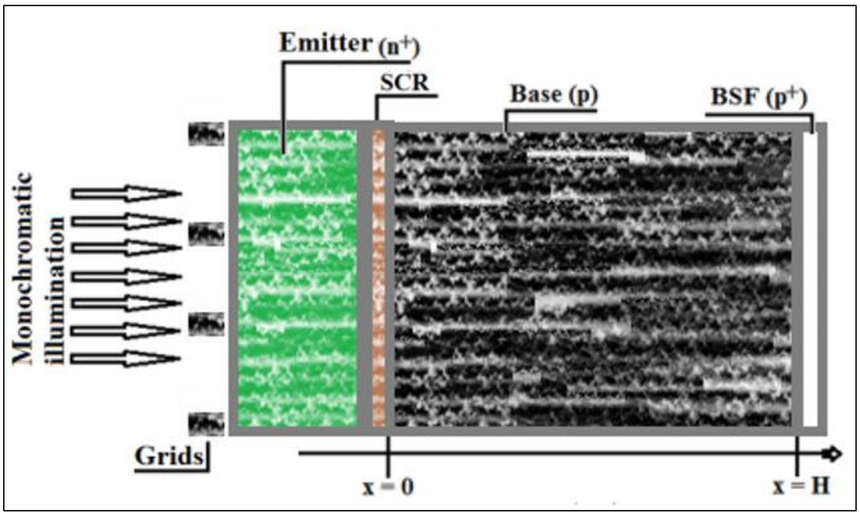

Figure 1: n^+-p-p^+ solar cell structure

The phenomena that occur when the solar cell is illuminated are described by the continuity equation. This equation is given by Equation 1.

$$D(T)\frac{\partial^2\delta(x,Sf,\lambda,T)}{\partial x^2}-\frac{\delta(x,Sf,\lambda,T)}{\tau}=-g(x) \tag{1}$$

Where: x, T and λ are, respectively, the depth into the base, the temperature and the wavelength.

and

δ (x, Sf, λ, T) is the excess minority charge carriers density in the base,

ϕ(λ), α(λ), R(λ) and g(x) are, respectively: the monochromatic incident light flux, the material monochromatic absorption coefficient, the material monochromatic reflectance coefficient and the minority charge carrier generation rate,

Où

$$g(x)=\phi(\lambda)\alpha(\lambda)(1-R(\lambda))e^{(-\alpha(\lambda)x)} \tag{2}$$

$$L(T)=\sqrt{D(T).\tau} \tag{3}$$

L(T), τ and D(T) are respectively: is the electrons diffusion length in the base, the electrons lifetime in the base, and the electrons diffusion coefficient in the base. The latter is given by the Einstein relation, which is

$$D(T) = \mu(T)\frac{k_b}{q}T \quad (4)$$

Où

$\mu(T)$, kb and q are respectively: the electron mobility coefficient [30], the Boltzmann constant and the electron elementary charge.

$$\mu(T) = 1,43.10^9 T^{-2,42} cm^2 V^{-1} s^{-1} \quad (5)$$

Thus, the general solution to Equation 1 is:

$$\delta(x,\lambda,T) = A\cosh\left(\frac{x}{L(T)}\right) + B\sinh\left(\frac{x}{L(T)}\right) - \frac{\phi(\lambda)\alpha(\lambda)(L(T))^2(1-R(\lambda))e^{(-\alpha(\lambda)x)}}{D(T)\left[(L(T))^2(\alpha(\lambda))^2-1\right]} \quad (6)$$

The expressions for A and B are determined from the following boundary conditions [6,7,8] :

A la jonction (x = 0)

$$\left.\frac{\partial\delta(x,\lambda,T)}{\partial x}\right|_{x=0} = \frac{S_f}{D(T)}\delta(x,\lambda,T)\Big|_{x=0} \quad (7)$$

j) A arrière (x = H)

$$\left.\frac{\partial\delta(x,\lambda,T)}{\partial x}\right|_{x=H} = -\frac{S_b}{D(T)}\delta(x,\lambda,T)\Big|_{x=H} \quad (8)$$

Sf is the junction recombination velocity of excess minority carriers, and also determines the solar cell operating point [6,7,8].

Sb is the back face recombination velocity of excess minority charge carriers [6,7,8].

3 EXCESS MINORITY CHARGE CARRIERS DENSITY

The minority charge carriers density expression is given by Equation 6. This equation can be used to plot the δ(x, Sf, λ, T) relative density curves. These curves are shown in Figures 2, 3, 4 and 5.

Figure 2 shows the excess minority charge carriers relative density profile versus depth x in the base, for a temperature T_1 and a long wavelength λ of the solar cell in an open-circuit (Sf = $1.5 \times 10^{1.5}$ cm/s).

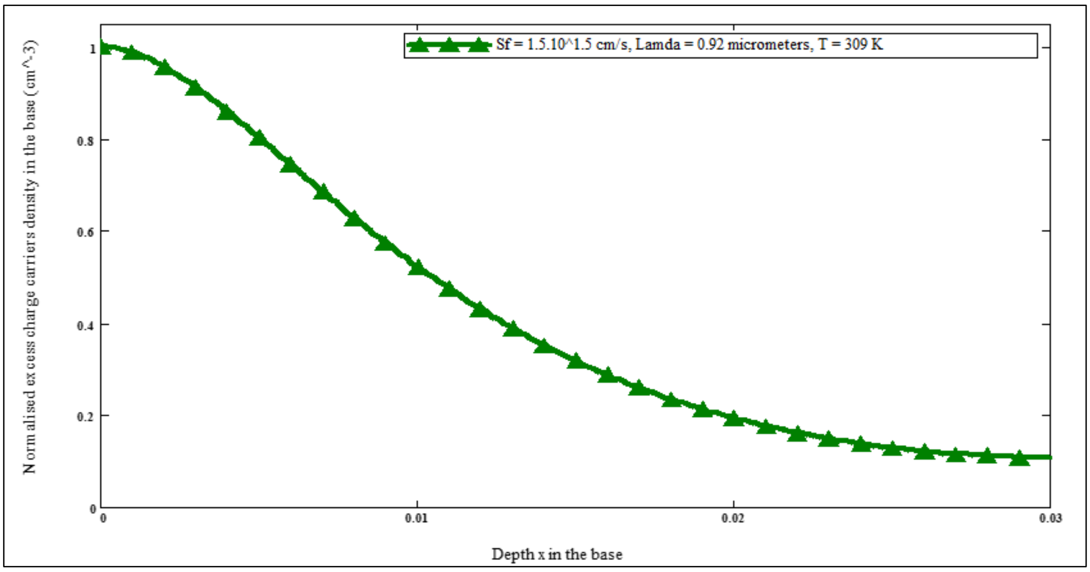

Figure 2: Minority charge carriers relative density versus x for λ= 0.92 µm and.T_1 = 309 K. (Sf = 1.5 × $10^{1.5}$ cm/s), Xco(309 K, 0.92 µm) = 0.0001 cm.

Figure 3 shows the excess minority charge carriers relative density profile versus depth x in the base, for a temperature T_2 and a long wavelength λ of the solar cell in an open-circuit (Sf = 1.5 × $10^{1.5}$ cm/s)

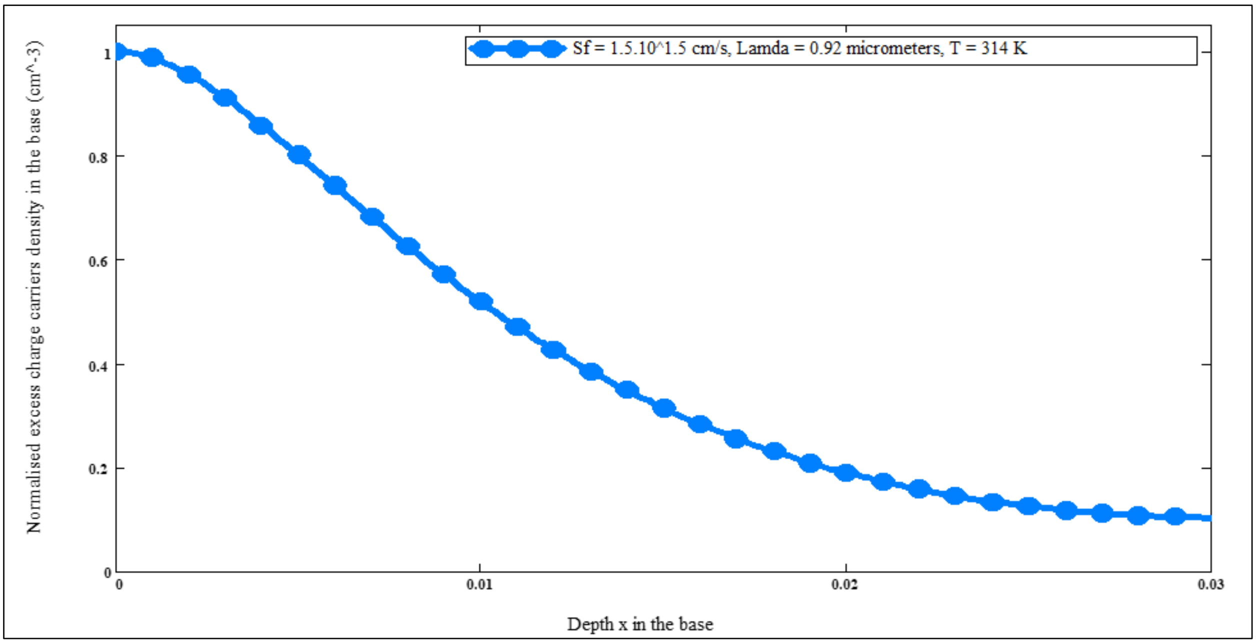

Figure 3: Minority charge carriers relative density versus x for λ= 0.92 µm and.T_2 = 314 K. (Sf = 1.5 × $10^{1.5}$ cm/s), Xco (314 K, 0.92 m) = 0 cm.

Figure 4 shows the minority charge carriers relative density profile versus the depth x in the base for a temperature T_2 and a large wavelength λ of the solar cell at the open circuit end (Sf = 3 × 103 cm/s).

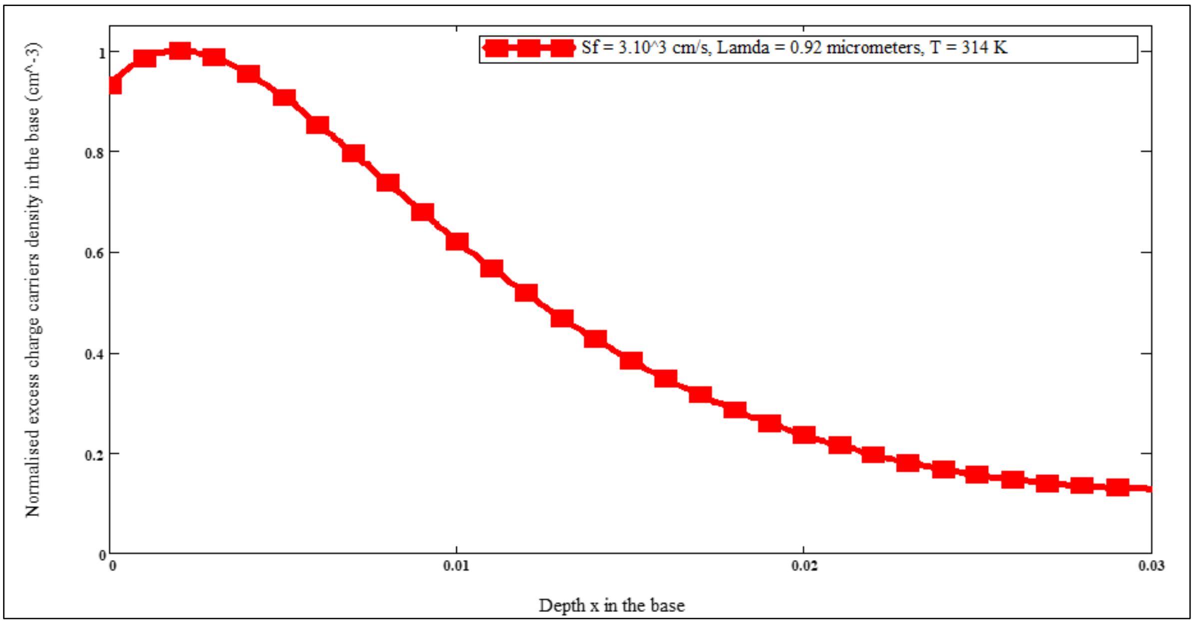

Figure 4: Minority charge carriers relative density versus x for λ= 0.92 µm and.T_2 = 314 K. (Sf = 3×10^3 cm/s), Xco(314 K, 0.92 µm) = 0.002 cm.

Figure 5 shows the excess minority charge carriers relative density profile versus the depth x in the base for long wavelengths λ and a temperature T1 of the solar cell at the open circuit end (Sf = 3×10^3 cm/s).

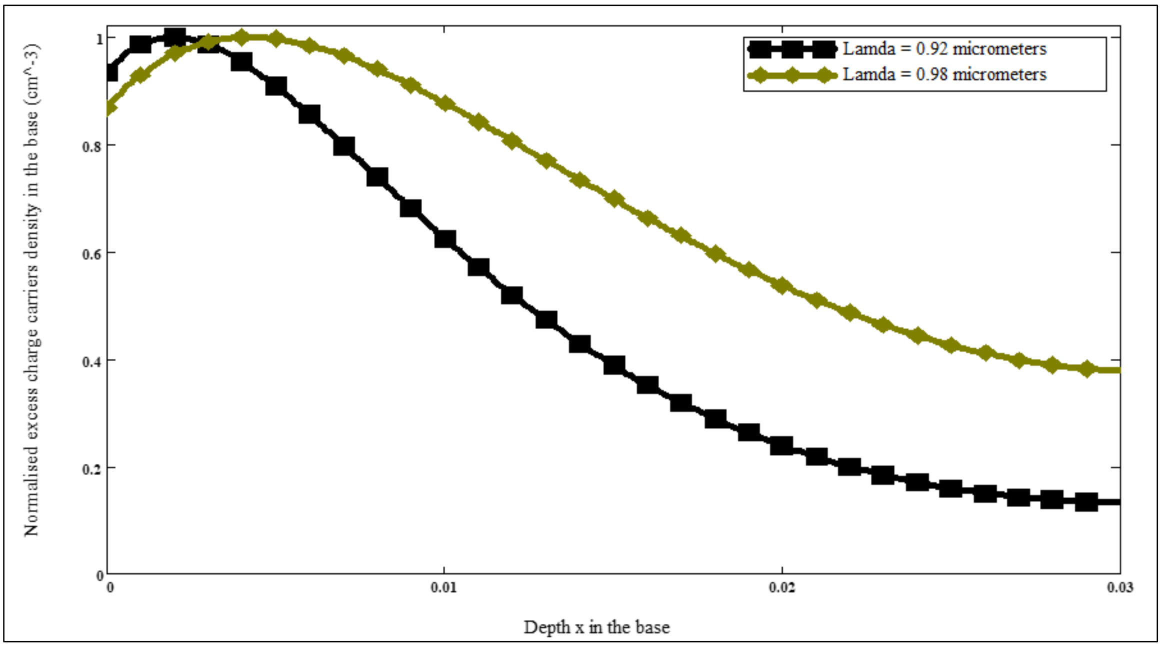

Figure 5: Minority charge carriers relative density versus x for different λ_{high}, T_1 = 309 K, (Sf = 3×10^3 cm/s), Xco (0.92 µm) = 0.002 cm et Xco (0.98 µm) = 0.0048 cm.

Two spatial variation rates are observed in Figures 2, 3, 4, and 5:

- The horizontal coordinate density Xco(T, λ_{high}) highest point corresponds to a zero spatial variation rate. This location presents a excess minority charge carriers barrier or storage.
- The excess minority charge carriers in the base are forced to remain there to avoid crossing the emitter-base junction, due to the change negative spatial rate presence. This leads to the minority charge carriers recombination both on the surface and within the volume.

We also observe that increasing the temperature leads to a decrease in Xco(T, λ_{high}) when the same open-circuit conditions (Sf = 3 × 10^3 cm/s) and wavelength (λ = 0.92 µm) are present. Then there is a open-circuit solar cell space width Xco(T, λ_{high}) narrowing. (figures 2 and 3).

We also note that increasing the recombination velocity, Sf, induces an increase in Xco(T, λ_{high}); this occurs when the wavelength (λ = 0.92 µm) and temperature (T = 314 K) remain the same. This results in a thickness widening, Xco(T, λ_{high}), (Figures 3 and 4).

Finally, we observe that under the solar cell same operating conditions (Sf = 3 × 10^3 cm/s) and at the same temperature (T = 309 K), increasing the wavelength leads to an increase in Xco(T, λ_{high}). Therefore, the bandwidth Xco(T, λ_{high}) is broadened. Figure 5.

4 PHOTOVOLTAGE

Boltzmann's relation, when applied to the minority charge carriers density, yields the following expression for the solar cell photovoltage.

$$V_{ph}\left(S_f,\lambda,T\right)=V_T\ln\left[\frac{N_b}{\left(n_i^2(T)\right)}\delta\left(0,S_f,\lambda,T\right)+1\right] \tag{9}$$

Where V_T is the thermal voltage, defined as follows:

$$V_T=\frac{k_b}{q}T \tag{10}$$

n_i is the minority carriers intrinsic density [31], expressed as follows

$$n_i(T)=A.T^{\frac{3}{2}}\exp\left(-\frac{E_g}{2.k_b.T}\right) \tag{11}$$

N_b is the doping concentration

The bandgap energy (Eg = 1.12 × 1.6 × 10^{-19} J) is the difference between the conduction band energy (Ec) and the valence band energy (Ev). A = 3,87.10^{16} cm^{-3} $K^{-3/2}$, is a constante.

5 CAPACITANCE

The solar cell capacitance crude expression, combined with that of the photovoltage, is:

$$C\left(S_f,\lambda,T\right)=\frac{dQ\left(S_f,\lambda,T\right)}{dV\left(S_f,\lambda,T\right)} \tag{12}$$

with $Q\left(S_f,\lambda,T\right)=q\delta\left(x=0,S_f,\lambda,T\right)$ (13)

$$C=q\frac{d\delta\left(x=0\right)}{dV} \tag{14}$$

Equation (12) can be rewritten as:

$$C=q\frac{d\delta\left(x=0\right)}{dS_f}\frac{1}{\frac{dV}{dS_f}} \tag{15}$$

The final, capacitance detailed expression is given by Equation 16:

$$C\left(S_f,\lambda,T\right)=\frac{q\left(n_i\left(T\right)\right)^2}{N_bV_T}+\frac{q\delta\left(x=0,S_f,\lambda,T\right)}{V_T} \tag{16}$$

$$C\left(S_f,\lambda,T\right)=C_0\left(T\right)+C_d\left(S_f,\lambda,T\right) \tag{17}$$

$$\text{Où } C_0\left(T\right)=\frac{q\left(n_i\left(T\right)\right)^2}{N_bV_T} \tag{18}$$

$$C_d\left(S_f,\lambda,T\right)=\frac{q\delta\left(x=0,S_f,\lambda,T\right)}{V_T} \tag{19}$$

$C_0(T)$ and $C_d(T,\lambda, Sf)$ are, respectively: the solar cell short-circuit capacitance [28, 29] and the solar cell diffusion capacitance [28].

With, V_T represents the thermal voltage, which is given by Equation 10:

Equation 16 can be used to represent Figure 6.

The open-circuit solar cell capacitance logarithm profile versus the temperature logarithm for long wavelengths λ is shown in Figure 6.

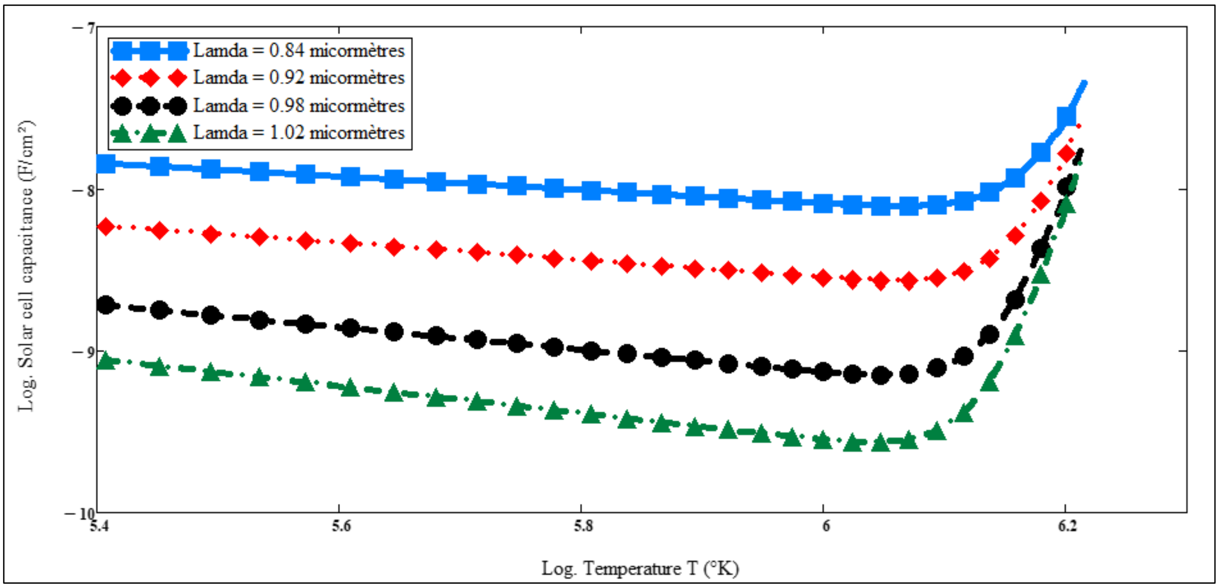

Figure 6: Solar cell capacitance logarithmic profile versus the logarithmic temperature for large wavelengths λ.(Sf = 10 cm/s).

From Figure 6:

On the one hand, an increase in temperature leads to a decrease in capacitance up to a reference temperature. Above this temperature, an increase in temperature causes an increase in capacitance. This reference temperature is called the optimum temperature (T_{opt}). The optimum temperature corresponds to an solar cell operating condition that provides high capacitance efficiency for the given wavelength [28, 29]. However, the T_{opt} temperature varies with long wavelengths, hence $T_{opt}(\lambda_{high})$.

Indeed, for $T < T_{opt}$, the decrease in capacitance is equivalent to the increase of $Xco(T, \lambda_{high})$ up to $T = T_{opt}$ corresponding to $Xco(T_{opt}, \lambda_{high})$. Thus, for $T > T_{opt}$, the increase in capacitance is equivalent to a decrease in $Xco(T, \lambda_{high})$. This leads us to the following inequality:

$[T < T_{opt}, Xco(T, \lambda_{high})] < Xco(T_{opt}, \lambda_{high}) < [T > T_{opt}, Xco(T, \lambda_{high})]$

On the other hand, increasing the wavelength leads to a decrease in capacitance. Therefore, $Xco(T, \lambda_{high})$ increases.

The decrease in $Xco(T, \lambda_{high})$ corresponds to a space charge zone narrowing, and its increase is equivalent to a space charge zone widening.

Figure 6 allows the solar cell capacitance to be modelled using Equation 20 [28]:

$$C_\lambda(T) = \chi_\lambda T^{\gamma_\lambda} \tag{20}$$

where,

χ_λ is proportional to the capacitance and is determined from the intercept. Thus, γ_λ is the slope.

The values of χ_λ **and** γ_λ derived from the plots in Figure 6 are given in Table 1.

Table 1: The values of χ_λ and γ_λ versus temperature for solar cell wavelength low values in open-circuit conditions.

Zone	**λhigh (µm)**	**χ_λ (F.cm-2)**	γ_λ
T < Topt(λhigh)	0,84	3,60.10-3	-0,41
	0,92	4,91.10-3	-0,54
	0,98	7,20.10-3	-0,70
	1,02	10,93.10-3	-0,84
T > Topt(λhigh)	0,84	1,80.10-52	18
	0,92	3,45.10-47	16
	0,98	4,75.10-58	20
	1,02	3,55.10-66	23

6 CONCLUSION

The work carried out on this subject involved studying the space charge zone thickness or width $Xco(T, \lambda_{high})$ of a solar cell in an open-circuit configuration illuminated at its emitter and in static regime. The study of this width was based on the excess minority charge carriers density in the basis $\delta(x, Sf, \lambda_{high})$ and the solar cell capacitance $C(Sf, \lambda_{high}, T)$. This revealed that:

- Regarding the density $\delta(x, Sf, \lambda, T)$, the excess minority charge carriers relative density profile in the basis versus the depth x in the basis showed that:
  - As the temperature increases, $Xco(T, \lambda_{high}$ decreases,
  - As the wavelength increases, $Xco(T, \lambda_{high})$ increases.
  - When the junction recombination velocity increases, $Xco(T, \lambda_{high})$ increases.
- Regarding the capacitance $C(Sf, \lambda_{high}, T)$, the solar cell capacitance neperien logarithm profile versus the temperature neperien logarithm showed that:
  - For $T < T_{opt}$, as the temperature increases, $Xco(T, \lambda_{high})$ increases up to a temperature $T = T_{opt}$ corresponding to $Xco(T_{opt}, \lambda_{high})$,
  - For $T > T_{opt}$, as the temperature increases, $Xco(T, \lambda_{high})$ decreases.
  - Increasing the wavelength induced an increase in $Xco(T, \lambda_{high})$.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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