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(RESEARCH ARTICLE)

SILICON MONOFACIAL SOLAR CELL, ILLUMINATED BY LONG WAVELENGTHS ON (N^+) AND UNDER TEMPERATURE, IN STATIC REGIME: SPACE CHARGE ZONE THROUGH CAPACITANCE AND SHORT-CIRCUIT CAPACITANCE DETERMINATION.

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ABSTRACT

The monofacial silicon solar cell, under temperature in a static regime, is illuminated on the (n^+) emitter by long wavelengths. From the continuity equation (which describes the phenomena established in the solar cell base (p) when the latter is illuminated), the excess minority carrier density expression in the base is established. The latter allows obtaining the photovoltage through the Boltzmann relation. The emitter-base junction (x = 0) minority carrier density expression and of the photovoltage allow establishing the solar cell capacitance expression. From the latter, the solar cell capacitance profilles the junction recombination velocity, for different temperatures, for different and long wavelengths are represented. From the latter, the space charge region behavior is studied. The space charge region (SCR) is planar capacitor modeled. The solar cell capacitance expression also allows representing the photovoltage versus solar cell capacitance natural logarithm profiles, for different temperatures, for different et long wavelengths. From these, the solar cell capacitance values when it is under short-circuit condition are extracted.

Keywords: Monofacial Solar Cell, Short-Circuit Capacitance, Temperature, Long Wavelengths, Space Charge Region.

1 INTRODUCTION

The space charge region (SCR) is an essential element in solar cells [1-5]. This SCR is the junction recombination velocity Sf related (which determines the solar cell operation point) [6, 7,8]. This solar cell SCR is planar capacitor modeled [9]. The diffusion of minority charge carriers creates a diffusion capacitance when the solar cell is illuminated [10]. The diffusion capacitance thickness is the SCR, which depends on Sf [7, 8, 11, 12]. The solar cell can be studied in regimes:

static, transient or dynamic frequency [13-18]. The SCR has been studied in a static three-dimensional regime [19] as well as in a one-dimensional solar cell under an external electric field [20], in a transient regime [21], and in a frequency-domain dynamic regime [22].

The solar cell capacitance is the short-circuit capacitance C0(T) sum and the diffusion capacitance C_d (Sf, λ, T) [2, 3]. This capacitance C0 (T) has been studied [3, 4, 22].

Our work will focus, based on the solar cell capacitance, on the space charge region (SCR) and the capacitance C0(T). The SCR and C0(T) studies will be carried out with long wavelengths and temperature.

2 THEORETICAL STUDY

The considered solar cell is of the $n^+/p/p^+$ type and its structure is presented in figure 1 [23-27].

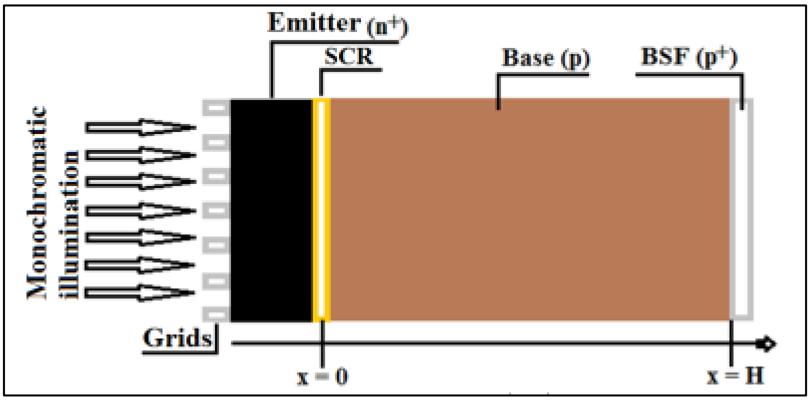

Figure 1: Silicon solar cell $n^+/p/p+$ type

When the solar cell is illuminated, electron-hole pairs are created in the base. The excess minority charge carriers density in the base is modeled by the following continuity equation :

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

With

□ (x) is the density of electron generated in the base at position x

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

$\delta(x)$ is the carrier generation rate,

$\phi(\lambda)$ is the monochromatic incident light flux,

$\alpha(\lambda)$ is the material's monochromatic absorption coefficient at the wavelength λ

$R(\lambda)$ is the material's monochromatic reflection coefficient at the wavelength λ.

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

L(T) is the carrier diffusion length in the base, it depends on temperature,

τ is the carrier lifetime in the base. D(T) is the electron diffusion coefficient in the base, given by the Einstein relation as follows :

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

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

$\mu(T)$ is the electron mobility coefficient [28],

k_b is the Boltzmann constant,

q is the elementary charge of an electron.

The general solution to equation (1) is

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

The expressions for A and B are determined from the following boundary conditions:

i) A the junction (x = 0)

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

ii) At the back surface (x = H)

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

S_f is the junction recombination velocity of excess minority charge carriers in the base, and determines the solar cell operating point [11,12].

S_b is the back surface recombination velocity of excess minority charge carriers in the base [12].

3 CAPACITANCE

Using the photovoltage expression, the solar cell capacitance is expressed as :

$$C(S_f,\lambda,T)=\frac{dQ(S_f,\lambda,T)}{dV(S_f,\lambda,T)} \tag{21}$$

with $Q(S_f,\lambda,T)=q\delta(x=0,S_f,\lambda,T)$ (22)

$$C=q\frac{d\delta(x=0)}{dV} \tag{23}$$

Equation (21) can be rewritten as follows :

$$C = q\frac{d\delta(x=0)}{dS_f}\frac{1}{\frac{dV}{dS_f}} \quad (24)$$

Taking into account the photovoltage expression and the excess minority charge carrier density in the base, we obtain the following expression :

$$C(S_f,\lambda,T) = \frac{q(n_i(T))^2}{N_b V_T} + \frac{q\delta(x=0,S_f,\lambda,T)}{V_T} \quad (25)$$

$$C(S_f,\lambda,T) = C_0(T) + C_d(S_f,\lambda,T) \quad (26)$$

Où $C_0(T) = \frac{q(n_i(T))^2}{N_b V_T}$ (27)

$$C_d(S_f,\lambda,T) = \frac{q\delta(x=0,S_f,\lambda,T)}{V_T} \quad (28)$$

$C_0(T)$ is the solar cell capacitance under short-circuit conditions,

$C_d(T,\lambda,Sf)$ is the solar cell diffusion capacitance at temperature T, under illumination λ at an operating point determined by Sf.

V_T is defined as the thermal voltage and its expression:

$$V_T = \frac{k_b T}{q} \quad (29)$$

N_b is the doping concentration and n_i is the minority carriers intrinsic density [29], expressed as follows:

$$n_i(T) = A.T^{\frac{3}{2}} e^{\left(-\frac{E_g}{2.k_b.T}\right)} \quad (30)$$

Eg is the band gap energy, and corresponds to the difference between the conduction band (Ec) energy and that of the valence band (Eg). Eg = 1.12 × 1.6 × 10^{-19} J.

Figure 2 presents the solar cell capacitance profile versus junction recombination velocity Sf, for various long wavelengths, at a temperature T.

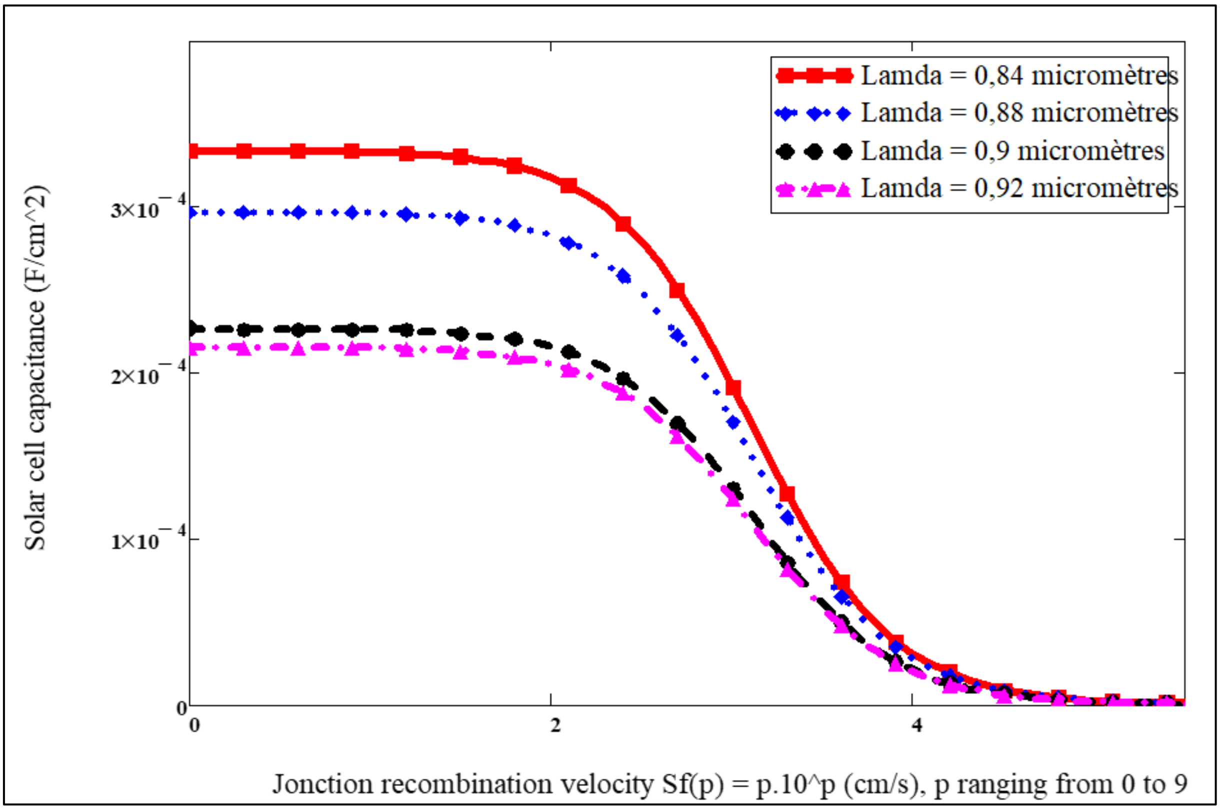

Figure 2: Solar cell capacitance versus junction recombination velocity for various long wavelengths (T = 330 K).

The figure 2 :

Taking into account the low junction recombination velocity Sf ($Sf \le 2.5*10^{2.5} cm/s$), the solar cell is in open-circuit condition. Minority charge carriers are accumulated at the junction n^+p. Consequently, there is a space charge region (SCR) narrowing. The charges are accumulated on the planar capacitor plates, because the SCR is considered as a planar capacitor [9]. Then the capacitor charges and store energy.

Taking into account the junction recombination velocities between ($2.5*10^{2.5} cm/s \le Sf \ge 5*10^{5} cm/s$), the solar cell is in open circuit and early short-circuit conditions. The minority charge carriers accumulated at the n^+p junction begin to cross it. This is the beginning of the gradual decrease in charge accumulation at the planar capacitor plates. Then the capacitor starts to discharge. The stored energy begins to be distributed.

Taking into account the high junction recombination velocities Sf ($Sf \ge 5*10^{5} cm/s$), the solar cell is in short-circuit conditions. All the minority charge carriers cross the junction n^+p. Consequently, the SCR total widening is established. Therefore, no charge is accumulated at the planar capacitor plates. Consequently, the energy stored in the capacitor is totally dissipated. Then the planar capacitor is completely discharged.

The solar cell capacitance decreases as the longer wavelengths increase..This leads to a space charge region widening. However, the larger wavelengths photogenerate excess minority charge carriers far from the junction n^+p and near the junction pp^+. Hence the capacitance decrease.

Figure 3 represents the solar cell capacitance natural logarithm profiles versus photovoltage, for various long wavelengths, at a temperature T.

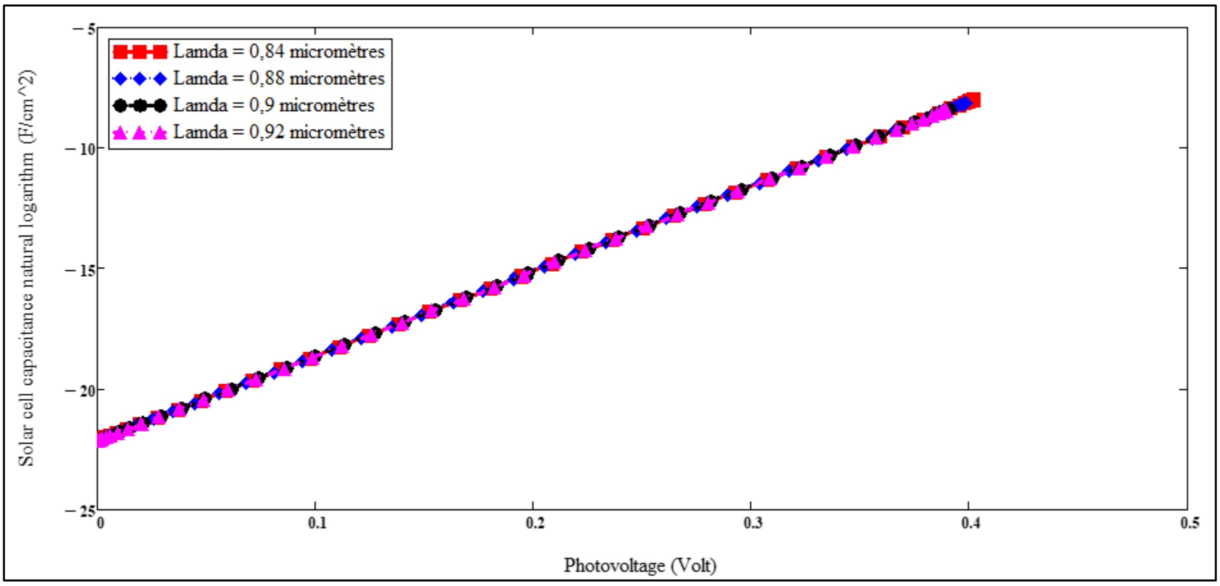

Figure 3: Solar cell capacitance natural logarithm versus photovoltage for various long wavelengths (T = 330 K).

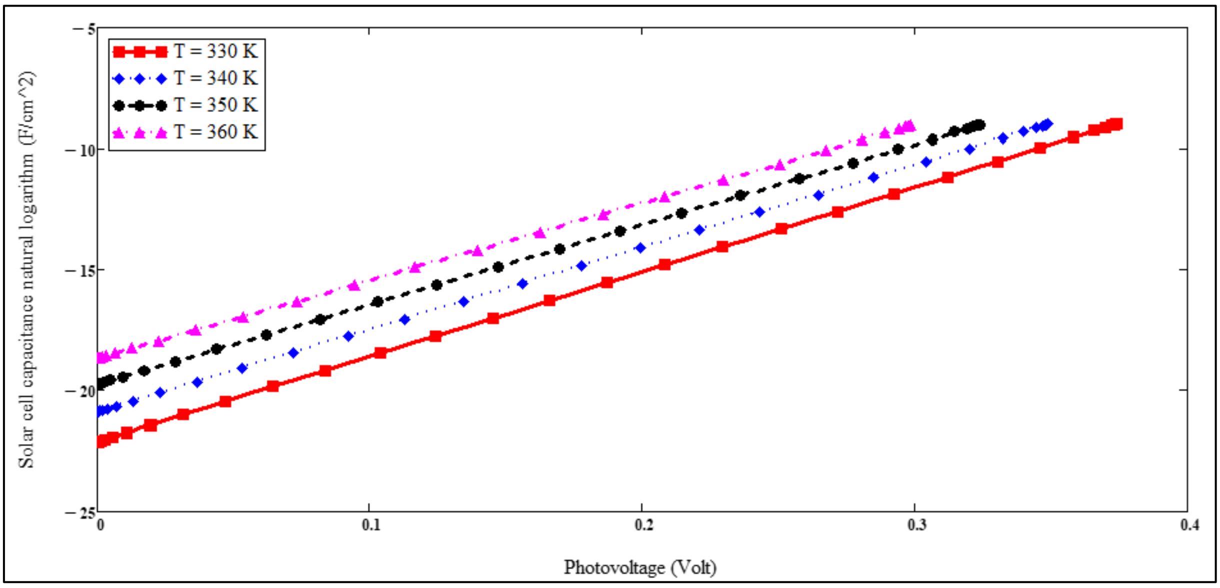

Figure 4: Solar cell capacitance natural logarithm versus photovoltage for various temperatures (λ = 0.98 µm).

The increase in photovoltage leads to that of capacitance (figures 3 and 4). When the solar cell is under short-circuit conditions, the photovoltage is zero. This corresponds to a capacitance value of C0. The latter is referred to as the solar cell capacitance under short-circuit conditions or short-circuit capacitance.

The wavelength effect λ isn't visible, regardless of its long values (figure 4). Hence, $C0 = 2.54*10^{-10}$ F/cm^2

The temperature effect on capacitance C0 is visible (la figure 5). Then C0 becomes C0(T).

From figure 4, the capacitance C0(T) is determined for each temperature value T. Table 1 presents its values.

Table 1: C0(T) Values with their respective temperatures

T(K)	C0(T) (F.cm^{-2})	λ(μm)
330	$2.50*10^{-10}$	0.98
340	$8.31*10^{-10}$	0.98
350	$2.62*10^{-9}$	0.98
360	$7.81*10^{-9}$	0.98

From table 1, we obtain figure 5, which represents the solar cell short-circuit capacitance versus temperature.

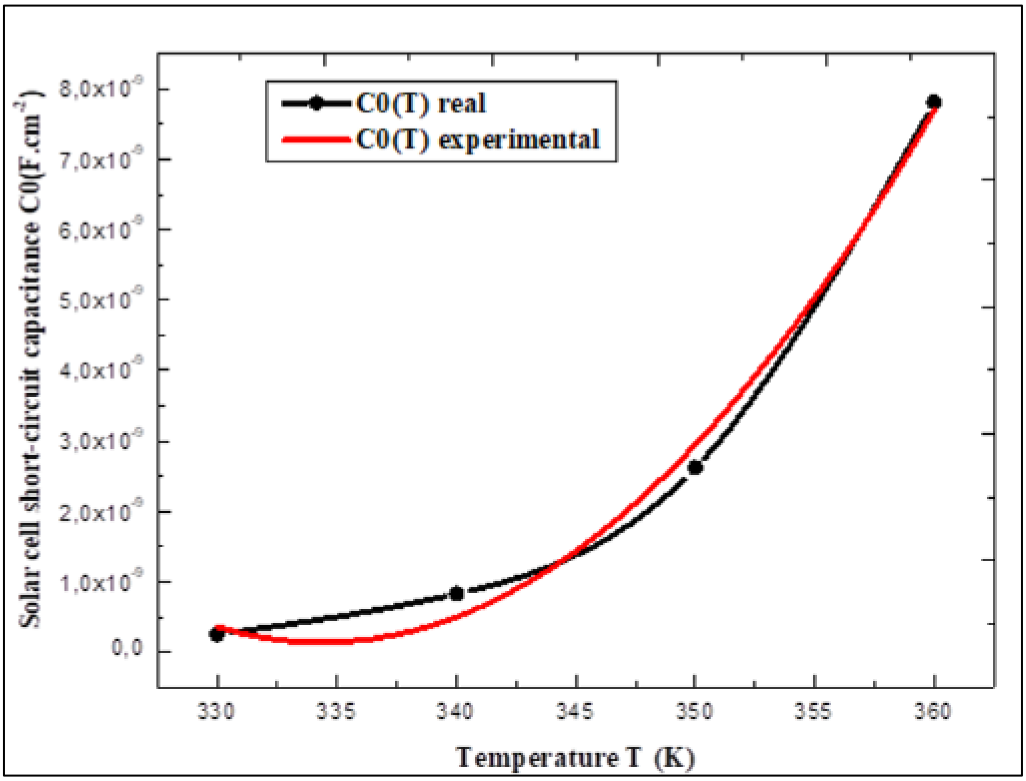

Figure 5: Solar cell short-circuit capacitance versus temperature (λ= 0.98 μm).

Figure 5 allows us to derive equations 30 and 31:

$$C0(T)_{Real} = 2.45*10^{-12}T^2 + 1.69*10^{-9}T + 2.91*10^{-7} \quad (30)$$

$$C0(T)_{Experimental} = 1.15*10^{-11}T^2 - 7.71*10^{-9}T + 1.29*10^{-6} \quad (31)$$

Then, let us plot figure 6, which represents the solar cell short-circuit capacitance natural logarithm versus temperature, based on table 1.

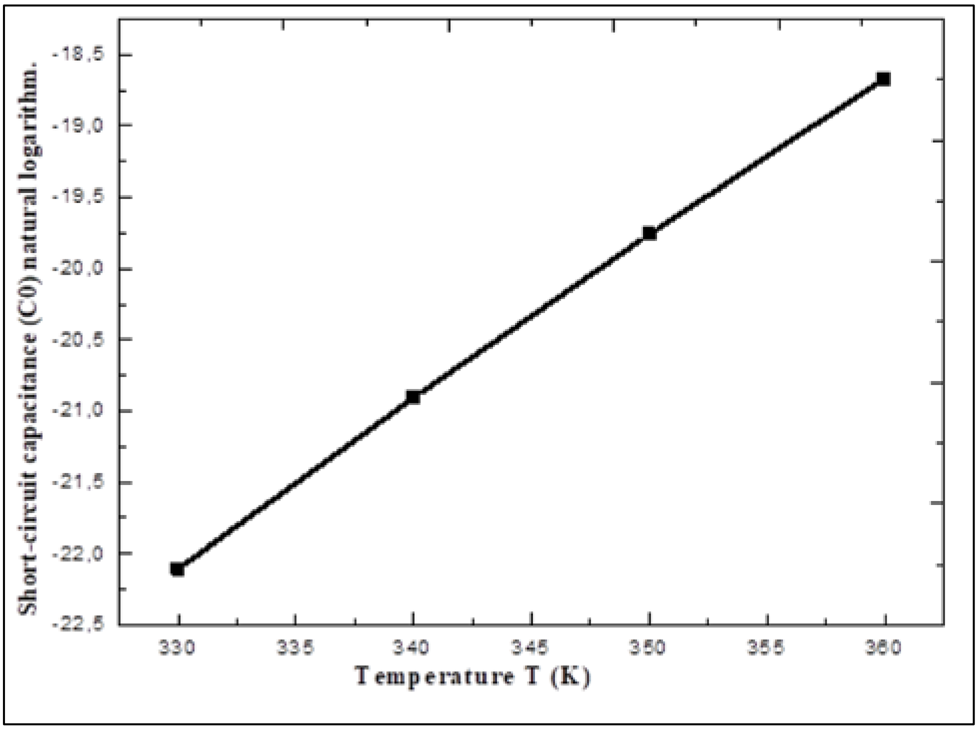

Figure 6: Short-circuit capacitance logarithm versus temperature (λ = 0.98 μm).

We note from figures 5 and 6 that, as the temperature increases, the photopile short-circuit capacitance increases. Because, as the short-circuit photocourant density is an ordered flow of minority charge carriers that all cross the junction n^+p. The increase in temperature leads to a disordered motion of minority charge carriers. This latter disordered motion causes their slowing down when crossing the junction n^+p. Thus, this slowing down promotes the storage of excess minority charge carriers in the base, at this junction. This storage consequently leads to an increase in short-circuit capacitance.

4 CONCLUSION

This work was designed to study the space charge region through capacitance and the determination of short-circuit capacitance, for longer wavelengths.

The capacitance profile versus junction recombination velocity for different and long wavelengths, with a given temperature value, has been studied. From this profile, we observed that the increase in long wavelengths leads to a decrease in the solar cell's capacitance. Therefore, we have a space charge region widening.

The solar cell capacitance natural logarithm profiles versus phototension for various long wave lengths at a fixed temperature and for various temperatures at a long wavelength, have been studied. From these profiles, a short-circuit capacitance value for various long wavelengths, on the one hand, and short-circuit capacitance values for various temperatures, on the other hand, were extracted. We observed that the short-circuit capacitance C0 depended only on the temperature. This is why we plotted C0(T) versus temperature. Thus, we observed that the increase in temprature leads to an increase in the short-circuit capacitance. Thus, we have a space charge region narrowing.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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