Irradiation Effect on Silicon Solar Cell Capacitance in Frequency Modulation

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***Abstract:** This paper shows the irradiation effect on a solar cell capacitance under monochromatic illumination in dynamic frequency mode. From the continuity equation, we determine the expression of excess minority carrier density from which the capacitance and the capacitance efficiency are deduced thereafter studied according to the modulation frequency and the irradiation energy. This paper shows that the capacitance efficiencyand the thickness of the space charge region (SCR)in short-circuit decrease accordingto the irradiation energy increasing.*

***Keywords:** Solar cell, Irradiation, frequency, capacitance efficiency.*

I. INTRODUCTION

Photovoltaic conversion is provided by a solar cell whose conversion efficiency depends on the nature of the semiconductor structure and its manufacturing technics. Considering the low efficiency of these solar cells, researchers have been involved in various research works by offering several characterization technics as the static mode [1], [2], the transient state [3], [4] and the dynamic frequency mode [5], [6]. When the solar cell is illuminated, we have opposite storage charges on both sides of the emitter-base junction. What involves the establishment of a plane condenser whose capacitance varies according to the junction recombination velocity, the frequency and the irradiation energy. Diffusion capacitance was the object of several studies under static regime in order to determine the doping rate [7, 8]. Space charge region extension is obtained in transient regime [9], [10]. In dynamic frequency regime, recombination parameters in the bulk and surfaces are sought [11, 12]. Indeed, when there's a high absorption of radiation, the concentration of electrons and holes are modified, and the solar cell parameters are heavily modified [13]. The aim of this study is to show the influence of the irradiation and the pulsation on a solar cell capacitance under monochromatic illumination.

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II. THEORY

We consider in the figure1 a crystalline silicon solar cell (n + -p- p +) [14], [15] illuminated by the front side:

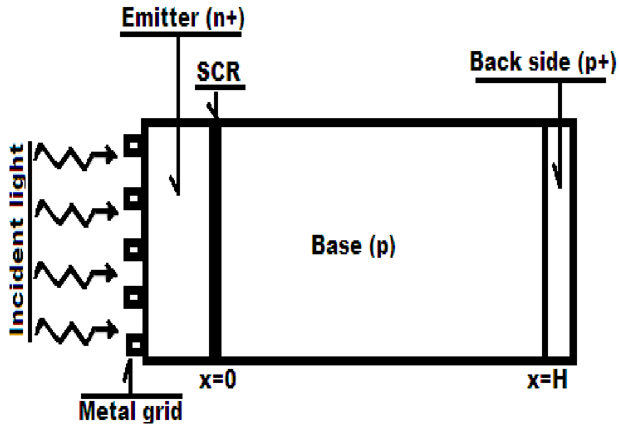

Figure 1: An n+-p-p+ structure of a silicon solar cell.

The emitter contribution and the crystalline field that exists in the base are neglected. When the solar cell is illuminated, different phenomena occur within it, such as the generation, the recombination and the diffusion. The distribution of the excess minority charge carrier density which is the electrons, photo-generated in the base is governed by the following continuity equation (1) [16]:

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

$\delta(x,t)$ and $G(x,t)$ [17]are respectively the excess minority carrierdensity and the generation rate.

They are expressed by following forms :

$$\delta(x,t)=\delta(x)\cdot\exp(j\cdot\omega\cdot t) \qquad (2)$$

$$G(x,t)=g(x)\cdot\exp(j\cdot\omega\cdot t) \qquad (3)$$

where:

$$g(x)=\alpha_\lambda\cdot\phi_\lambda\cdot(1-R_\lambda)\cdot\exp(-\alpha_\lambda\cdot x) \qquad (4)$$

ϕ_λ isthe monochromatic incident flux,

α_λ is the monochromatic absorption coefficient of material to the wavelength λ,

R_λ is the monochromatic reflexion coefficient of material to the wavelength λ.

D is the electron diffusion coefficient in the base[18], given by the relation

$$D=D(\omega,kl,\phi_p,T)=D(kl,\phi_p,T)\cdot\left(\frac{1+\omega^2\cdot\tau^2}{\left(1-\omega^2\cdot\tau^2\right)^2+4\omega^2\cdot\tau^2}\right)\left(1-j\cdot\omega\cdot\tau\right) \qquad (5)$$

$$D(kl,\phi_p,T)=\frac{1}{\tau\cdot\left(\frac{1}{L(T)^2}+kl\cdot\phi_p\right)} \quad (6)$$

L(T) is the electron diffusion length in the base temperature-dependent:

$$L(T)=\sqrt{D(T)\cdot\tau} \quad (7)$$

τ is the carriers lifetime depending on the irradiation energy (φp) and damages coefficient (kl) according to equation [19], [20] :

$$\frac{1}{\tau}=\frac{1}{\tau_0}+kl\cdot\phi_p \quad (8)$$

And well known Einstein relation gives

$$D(T)=\frac{\mu(T)\cdot K_b\cdot T}{q} \quad (9)$$

$$\mu(\mathrm{T})=1.43\cdot10^{9}\cdot T^{-2.42}cm^2/\mathrm{V\cdot s} \quad (10)$$

is the electron mobility coefficient temperature dependent**[21]**. $K_b$is the Boltzmann constant, q is the elementary electron charge and T is the absolute temperature.

In dynamic mode frequency equation (1) becomes:

$$\frac{\partial^2\delta(x)}{\partial x^2}-\frac{\delta(x)}{L_\omega^2}=-\frac{g(x)}{D} \quad (11)$$

With: $$\frac{1}{L_\omega^2}=\frac{1+j\cdot\omega\cdot\tau}{L^2} \quad (12)$$

The general solution of equation (11) is given by:

$$\delta(x)=\left[A\cdot\cosh(\frac{H}{L_\omega})+B\cdot\sinh(\frac{H}{L_\omega})-\frac{\alpha_\lambda\cdot\phi_\lambda\cdot(1-\mathrm{R}_\lambda)\cdot L_\omega^2}{D\cdot(\alpha_\lambda^2\cdot L_\omega^2-1)}\right] \quad (13)$$

Wherethe coefficients A and B are determined by boundary conditions respectively at the junction and on the backsurface of the solar cell [22, 23].

At the junction $x=0$: $\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=0}=\frac{Sf}{D}\cdot\delta(0)$ (14)

At the back surface $x=H$ $\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=H}=-\frac{Sb}{D}\cdot\delta(\mathrm{H})$ (15)

Sf and Sb are respectively recombination velocity at the junction base-emitter and at the back surface [22], [23].

The solar cell photovoltage is determined from the expression of the excess minority charge carrier density according to the Boltzmann relation:

$$V_{ph}(\omega,\lambda,kl,\phi_p,Sf,T)=V_T\cdot\ln(1+\frac{Nb}{n(T)^2}\cdot\delta(x,\omega,\lambda,kl,\phi_p,Sf,T)\Big|_{x=0}) \quad (16)$$

Where Nb is the base doping level and n(T) is the temperature dependent intrinsic minority carrier density [24]expressed as:

$$n(T)=A\cdot T^{\frac{3}{2}}\cdot\exp(-\frac{Eg}{2\cdot K_b\cdot T}) \quad (17)$$

$E_g$is the gap energy ($Eg=1.12\cdot1.6\cdot10^{-19}\,J$).

A is a constant: $A=3.87\cdot10^{16}cm^{-3}\cdot K^{-\frac{3}{2}}$

And V_T the thermal voltage defined by the equation:

$$V(T)=\frac{K_b\cdot T}{q} \quad (18)$$

The solar cell diffusion capacitance is obtained according to the following relation [25], [26]:

$$C(\omega,Sf,kl,\phi_p,\lambda,T)=\frac{dQ}{dV_{ph}} \quad (19)$$

With $Q=q\cdot\delta(0,\omega,\lambda,kl,\phi_p,Sf,T)$ (20)

Taking into account the photo voltage expression and the minority carrier density, we get
the following relation:

$$C(\omega,Sf,kl,\phi_p,\lambda,T)=\frac{q\cdot n(T)^2}{Nb\cdot V_T}+\frac{q\cdot\delta(0,\omega,Sf,kl,\phi_p,\lambda,T)}{V_T} \quad (21)$$

$$C_0(T)=\frac{q\cdot n(T)^2}{Nb\cdot V_T} \quad (22)$$

and: $$C_1(\omega,Sf,kl,\phi_p,\lambda,T)=\frac{q\cdot\delta(0,\omega,Sf,kl,\phi_p,\lambda,T)}{V_T} \quad (23)$$

$$C(\omega,Sf,kl,\phi_p,\lambda,T)=C_0(T)+C_1(\omega,Sf,kl,\phi_p,\lambda,T) \quad (24)$$

$C_0(T)$ and $C_1(\omega,Sf,kl,\phi_p,\lambda,T)$ are respectively the solar cell capacitance under dark(or transitional) and the diffusion capacitance due to illumination.

III. RESULTS AND DISCUSSIONS

Figure 2 shows the excess minority charge carrier density under open circuit versus the base depth x for different irradiation energy values.

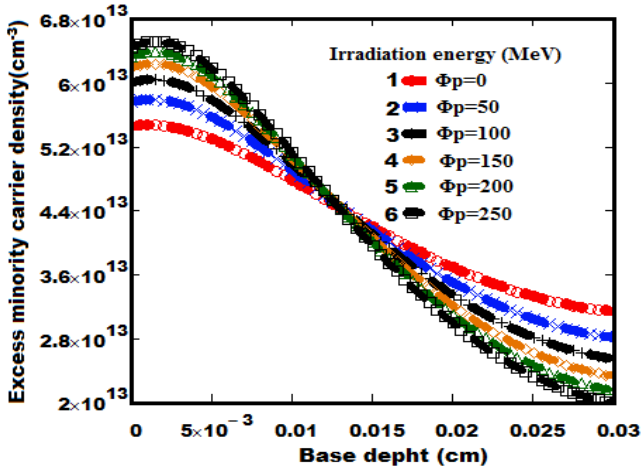

Figure 2: Minority charge carrier density versus base depth x in open circuit.

$\omega=10^5$rad/s, H=0.03cm,λ=0.98µm,$Sf_j=2.10^2$cm/s, kl=25cm^{-2}/MeV, T=330K.

1-Sb_0=2320cm/s; 2-Sb_0=1890cm/s; 3-Sb_0=1650cm/s; 4-Sb_0=1490cm/s; 5-Sb_0=1375cm/s; 6-Sb_0=1290cm/s.

$Sb_0=Sb(\omega,Sf,kl,\phi_p,\lambda,T)$ is the intrinsic recombination velocity at the back face. In open circuit, the curve presents two gradients:

The first gradient (gradient null) is located at the junction and corresponds to the maximum density point. It is related to an accumulation of minority charge carriers and defined a storage barrier charge carriers in this point. Then the junction surface recombination gives rise to the solar cell operating point.

The second are negative gradient who prevents minority charge carriers to cross the barrier. This is due to an attenuation of the incident light flux in the base depth, resulting in a reduction of the generation of minority charge carriers that contribute to the photocurrent.

At the junction, we notice that irradiation effect causes an increase of the excess minority charge carrier density because the concentration of carriers is maximal close to the junction. In the rear sides, we note a reversal of the excess minority charge carrier density due to the blockade of carriers at the junction and the increasing recombination rate of the carriers.

Figure 3 shows the normalized excess minority charge carrier density versus the base depth x when the solar cell operates either in short circuit or in open circuit.

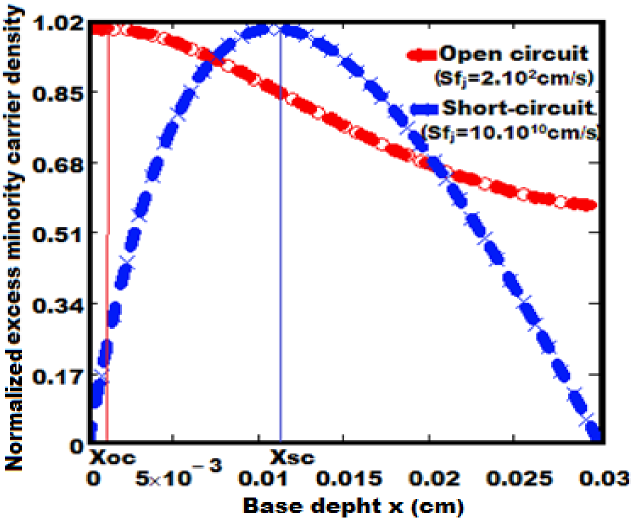

Figure 3: Normalized excess minority charge carrier density versus the base depth x

ω=10^5rad/s,λ=*0.98µm*,*Sf_j=2.10^2cm/s*, *Sf_j=10.10^{10}cm/s*, *Sb_0=2320cm/s*, kl=25cm^{-2}/MeV,*T=330K*.

On figure 3, we notice that the normalized excess minority charge carrier densityincreases until reaching maxima which is a storage barrier charge carriers (null gradient).The corresponding abscissas are respectively Xoc and Xsc.

$X_{oc}(\omega,kl,\phi_p,\lambda,T)$ is the abscissa of the maximum's normalized excess minority charge carrier densityin open circuit and $X_{sc}(\omega,kl,\phi_p,\lambda,T)$ is the abscissa of the maximum's normalized excess minority charge carrier densityin short-circuit.

Beyond these values, we have a negative gradient. This maximum displacement in the depth, when the junction recombination velocity increases, causes a widening of the space charge zone.

The X-coordinates $X_{oc}(\omega,kl,\phi_p,\lambda,T)$ and $X_{sc}(\omega,kl,\phi_p,\lambda,T)$ enable us to determine the solar cell capacitance efficiency $\eta(\omega,kl,\phi_p,\lambda,T)$ **[9]** according to the relation:

$$\eta(\omega,kl,\phi_p,\lambda,T)=1-\frac{X_{oc}(\omega,kl,\phi_p,\lambda,T)}{X_{sc}(\omega,kl,\phi_p,\lambda,T)} \quad (25)$$

$X_{oc}(\omega,kl,\phi_p,\lambda,T)$ and $X_{sc}(\omega,kl,\phi_p,\lambda,T)$ are related to the diffusion capacitance by:

$$C_{oc}(\omega,kl,\phi_p,\lambda,T)=\frac{\varepsilon_0\cdot\varepsilon_r\cdot S}{X_{oc}(\omega,kl,\phi_p,\lambda,T)} \quad (26)$$

And

$$C_{sc}(\omega,kl,\phi_p,\lambda,T)=\frac{\varepsilon_0\cdot\varepsilon_r\cdot S}{X_{sc}(\omega,kl,\phi_p,\lambda,T)} \quad (27)$$

$C_{oc}(\omega,kl,\phi_p,\lambda,T)$ and $C_{sc}(\omega,kl,\phi_p,\lambda,T)$ are respectively the open circuit and short-circuit diffusion capacitances of the solar cell.

ε_0 is the vacuum permittivity, $\varepsilon_r$is the relative permittivity of silicium and S is the area of the solar cell.

Some values of the solar cell capacitance efficiency are given on table 1 and table 2 for various pulsation and irradiation energy.

Table 1: Solar cell capacitance efficiency valuewhen irradiation energy and pulsation vary. λ=0.68µm, kl=25cm^{-2}/MeV,T=330K.

Pulsation ω	Irradiation energy (MeV)	Recombination velocity at the back side	Xoc (µm) *Sf_j=2.10^2cm/s*	Xsc (µm) *Sf_j=9.10^9cm/s*	η
ω=10^5rad/s	0	Sb_0=2160cm/s	0.45	16.7	0.973
	50	Sb_0=1820cm/s	0.55	16.0	0.966
	100	Sb_0=1615cm/s	0.58	15.5	0.963
	150	Sb_0=1475cm/s	0.67	15.1	0.956
	200	Sb_0=1370cm/s	0.69	14.8	0.953
	250	Sb_0=1287cm/s	0.71	14.6	0.951
ω=10^6rad/s	0	Sb_0=5740cm/s	0.68	13.6	0.950
	50	Sb_0=4860cm/s	0.74	13.0	0.943
	100	Sb_0=4306cm/s	0.79	12.5	0.937
	150	Sb_0=3915cm/s	0.86	12.1	0.929
	200	Sb_0=3620cm/s	0.93	11.8	0.921
	250	Sb_0=3390cm/s	1.0	11.5	0.913

Table 2: Solar cell capacitance efficiency value when irradiation energy and pulsation vary.λ=0.98µm, kl=25cm⁻²/MeV,T=330K.

Pulsation ω (rad/s)	Irradiation energy (MeV)	Recombination velocity at the back side	Xoc (µm) $Sf_j=2.10^2 cm/s$	Xsc (µm) $Sf_j=9.10^9 cm/s$	η
$\omega=10^5$rad/s	0	Sb_0=2320cm/s	9.7	125.8	0.923
	50	Sb_0=1890cm/s	11.2	117.0	0.904
	100	Sb_0=1650cm/s	12.3	110.8	0.889
	150	Sb_0=1490cm/s	13.2	105.7	0.875
	200	Sb_0=1375cm/s	14.0	101.6	0.862
	250	Sb_0=1290cm/s	14.7	98.1	0.850
$\omega=10^6$rad/s	0	Sb_0=5725cm/s	12.1	82.5	0.853
	50	Sb_0=4865cm/s	13.3	74.4	0.821
	100	Sb_0=4310cm/s	14.4	70.6	0.796
	150	Sb_0=3920cm/s	15.1	64.9	0.767
	200	Sb_0=3620cm/s	15.7	61.7	0.745
	250	Sb_0=3390cm/s	16.2	59.0	0.725

The thickness of the space charge region under open circuit increases with irradiation energy. However, under short-circuit $X_{sc}(\omega, kl, \phi_p, \lambda, T)$ decreases with irradiation energy and pulsation. Thus, irradiation energy and high frequency entail the slowing of electrons that move across the junction and increase their probability of recombination in the base. Figure 4 and figure 5 show solar cell capacitance efficiency versus irradiation energy for various pulsation values.

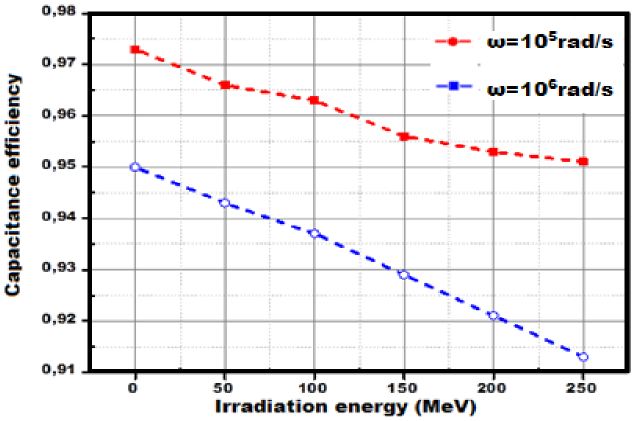

Figure 4: Capacitance efficiency versus irradiation energy. H=0.03cm,λ=0.68µm, kl=25cm⁻²/MeV,T=330K.

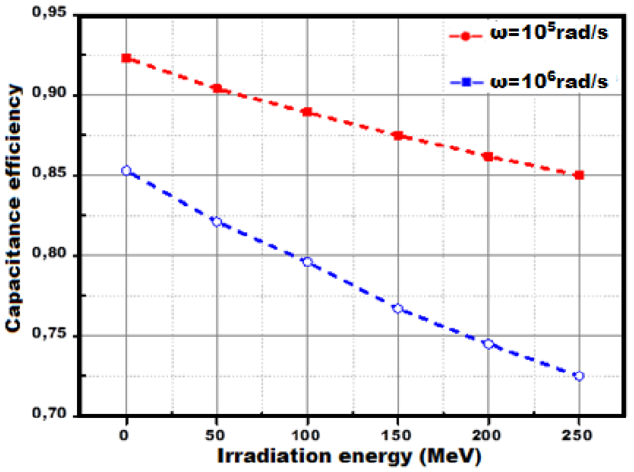

Figure 5: Capacitance efficiency versus irradiation energy. H=0.03cm,λ=0.98µm, kl=25cm⁻²/MeV,T=330K.

Analyzing the above graphs, we notice that the capacitance efficiency decreases with irradiation energybecause irradiation accelerates the recombination rate of the minority charge carrier density. We also note that the performance of the capacitance is less important with large pulsations (fig 4 and fig 5).

Figure 6 represents the solar cell diffusion capacitance versus junction recombination velocity for various irradiation energy values.

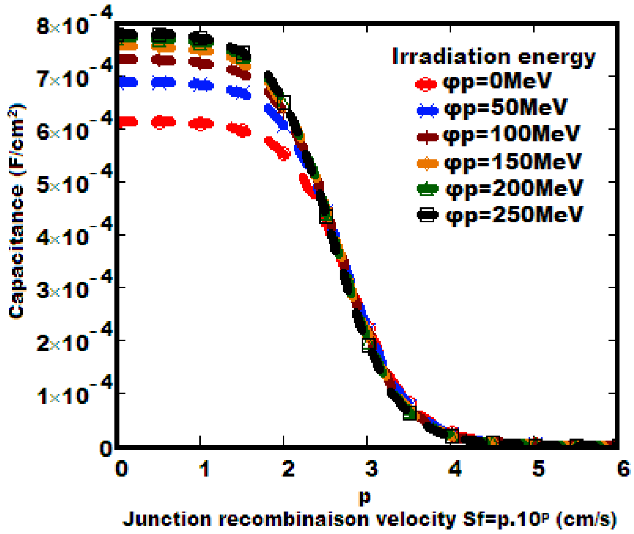

Figure 6: Capacitance versus junction recombination velocity for various irradiation energy values. $\omega=10^5$rad/s, H=0.03cm, λ=0.98µm,kl=25cm⁻²/MeV,Sb=2320cm/s, T=330K.

This figure6 shows three parts including two bearings:

The first corresponding to the open circuit situation where the diffusion capacitance, with a maximum value is equal to the open circuit capacitance (Coc). The minority carriers are blocked and stored close to the junction;

The second bearing corresponding to the short-circuit situation where the solar cell diffusion capacitance with a minimal value is equal to the capacitance of short circuit (Csc). Between the two levels, the diffusion capacitance decreases quickly.

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Moreover the solar cell diffusion capacitance under open circuit increases with irradiation energy because the excess minority charge carrier density stored in the vicinity of the junction are important.

IV. CONCLUSION

In this paper, we made the study of silicon solar cell under monochromatic illumination from the front side in modulation frequencies. Taking account of the normalized excess minority carrier density, the thickness of the space charge region under open circuit and short-circuit value was done from which the capacitance efficiency is deducted. This study shows that the capacitance efficiency decreases with the increasing irradiation energy and pulsation, meaning that best solar cells capacitance are characterized by low irradiation energy andlow frequency values.

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