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Research Article

External electric field as applied to determine silicon solar cell space charge region width

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Abstract In this work, an external electric field is used on a silicon solar cell, to investigate the space charge region extension. The solar cell under monochromatic illumination is placed under electric field which acts on the excess minority carriers diffusion in the base and thus, on the diffusion capacitance. The excess minority carrier density profile as a function of base depth for different electric field values is bring out and allows the determination of the Xo position, corresponding to the maximum value of excess minority carrier density, for a given wavelength. Then, Xo is shown to increase with wavelength and extends the space charge region (ESCR) in the base, while the increase in electric field reduces Xo toward the junction. The study of the extended space charge region with electric field, yields the transitional capacitance (Co).

Keywords Silicon solar cell- Space charge region width-Capacitance-Wavelength-Electric field

1. Introduction

The operating principle of the solar cells is based on the properties of the junction and the most used are the P-N junctions. Silicon solar cell is formed with semiconductor materials of type P doped with acceptor atoms and of type N doped with donor atoms. This P-N junction causes majority charge diffusion by leaving fixed charges between P and N and creates a space charge region (SCR). In this zone, there is an intense electric field which can be assimilated by help of electric model to a capacitor of capacitance Co, also called transitional capacitance or dark capacitance [1,2]. Under illumination, the photon-matter interaction leads to charge creation in the solar cell and their diffusion yields the concept of diffusion capacitance [3,4].The solar cell operates under dark [5-7] or under different illumination modes mono or polychromatic [8-10]. The regimes are, static state [11, 12] and dynamic (transient [13-15] or frequency [6-18]). External actions can be done by placing the solar cell under: electromagnetic field [19, 20], temperature [21, 22] and irradiation energy [23, 24]. The imperfections are related to the manufacture of the solar cell through the doping rate of the base, the size of the grains and geometric parameters [25, 26]. The external conditions influence the phenomena of diffusion and recombination in the bulk and on the surfaces, then, have consequences on the capacitance. Several studies on the extension of the space charge zone [27-29] have been proposed notably with the use of: the Gauss theorem [30, 31], 3D model [32-34].

Our study deals with the extension of the space charge region (Xo) determination [35], of the solar cell, under both an external electric field and monochromatic illumination.

2. Theory

A solar cell of type n^+-p-p^+ [36] under monochromatic illumination is considered. The solar cell is subjected to an external electric field [37-39]. The structure is represented by fig.1;

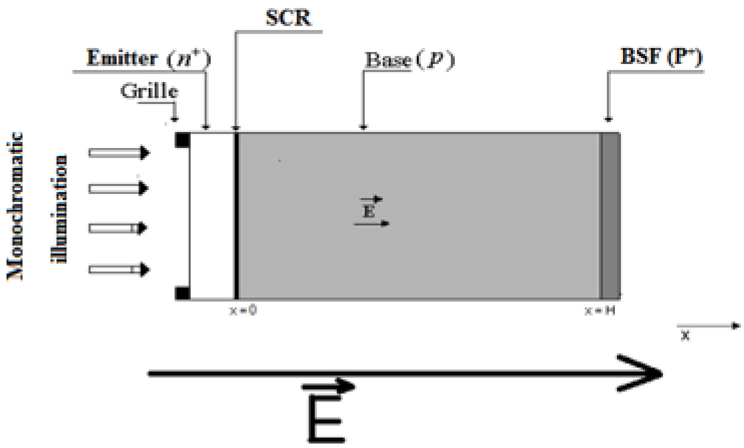

Figure 1: Structure of a n + -p-p + type silicon solar cell under an external electric field and under monochromatic illumination

The continuity equation that governs the photogenerated charge carrier density in the base under the influence of the electric field [38, 40, 41] is given by:

$$\frac{\partial^2\delta(x)}{\partial x^2}+\frac{\mu\cdot \mathrm{E}}{D}\cdot\frac{\partial\delta(x)}{\partial x}-\frac{\delta(x)}{L^2}+\frac{G(x)}{D}=0 \quad (1)$$

δ (x) represents the excess minority carrier density as a function of the depth x in the base, D and L respectively represent the diffusion coefficient and the diffusion length of the excess minority carrier, μ is the carriers mobility and E the applied electric field.

Posing, $L_E=\frac{\mu\cdot \mathrm{E}\cdot L^2}{D}$, the diffusion length in the presence of the electric field, equation 1 becomes:

$$\frac{\partial^2\delta(x)}{\partial x^2}+\frac{L_E}{L^2}\cdot\frac{\partial\delta(x)}{\partial x}-\frac{\delta(x)}{L^2}+\frac{G(x,\lambda)}{D}=0 \quad (2)$$

G (x, λ) is the minority carrier generation rate at the x position in the base. It depends on the wavelength and is given by:

$$G(x,\lambda)=\varphi(\lambda).\alpha(\lambda).(1-R(\lambda)).\exp(-\alpha(\lambda).x) \quad (3)$$

$\varphi(\lambda)$ characterizes the monochromatic incident flux of light, α(λ) is the monochromatic absorption coefficient of the material at the wavelength λ and R(λ) the monochromatic reflection coefficient of the material at the wavelength λ.

δ(x) is determined from the resolution of equation 1 and gives the following expression:

$$\delta(x,E,\lambda)=e^{\beta(E).x}(A.cosh(\varphi(E).x)+B\,sinh(\varphi(E).x))-\frac{\phi(\lambda).\alpha(\lambda).L^2.(1-R(\lambda)).e^{-(\alpha(\lambda).x)}}{D.(L^2.\alpha(\lambda)^2-1)} \quad (4)$$

With: $\varphi(E)=\frac{(L^2{}_E+4\cdot L^2)^{\frac{1}{2}}}{2\cdot L^2}$ (5)

$$\beta(E)=\frac{-L_E}{2\cdot L^2} \quad (6)$$

The coefficients A and B are determined from the boundary conditions at the junction and back of the solar cell

-at the junction *(x=0)*:

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

-at the back surface (*x=H*):

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

The parameters Sf and Sb respectively represent the recombination velocities of the excess minority carrier at the junction and at the rear surface [42, 43]. Sf characterizes the flow of excess minority carrier at the junction but also the operating point of the solar cell. Sb characterizes the losses of excess minority carrier by recombination at the rear face. The Sb expression is obtained by the derivative of equation 5 (photocurrent) with respect to Sf (for large value) [38, 44, 45]. Then it comes:

$$Sb(E,\lambda) = D.\frac{\varphi(E).\alpha(\lambda).\left[\cosh(\varphi(E).H) - e^{(\alpha(\lambda)+\beta(E)).H}\right] - \left[\varphi(E)^2 - \beta(E).(\alpha(\lambda)+\beta(E))\right].\sinh(\varphi(E).H)}{\varphi(E).\left[\cosh(\varphi(E).H) - e^{(\alpha(\lambda)+\beta(E)).H}\right] - (\alpha(\lambda)+\beta(E)).\sinh(\varphi(E).H)} \quad (9)$$

3. Results and Discussions

The solar cell, under an electric field and under monochromatic illumination, is studied in short-circuit (large Sf value) for two values of the wavelength (λ = 0.64 µm and λ = 0.88 µm). Thus, we represent at the figures 2 and 3, the profiles of the excess minority carrier density as a function of the base depth for different electric field values and for two given values of the wavelength ((λ = 0.64 µm and λ = 0.88 µm).

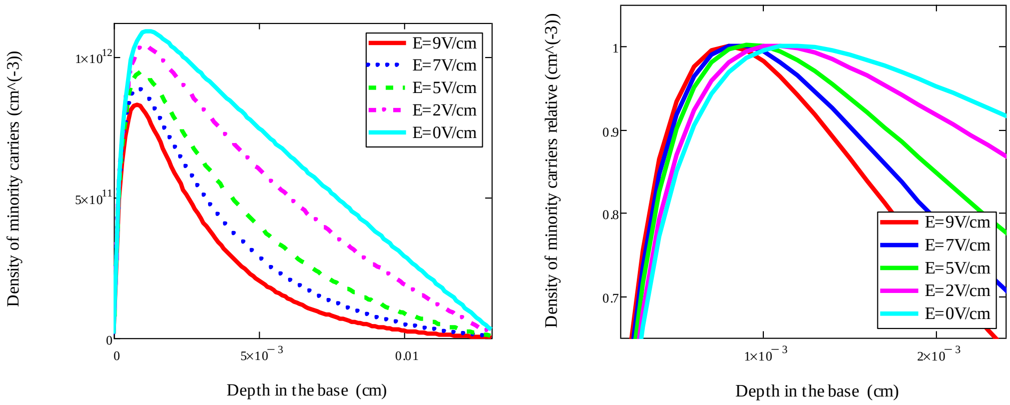

Figure 2: Density of minority carrier (a) and normalized excess minority carrier (b) as function of depth in the base for different electric field values. (D=35cm^2/s, Sf=6.10^{6}cm/s, λ=0.64 µm, H=130µm)

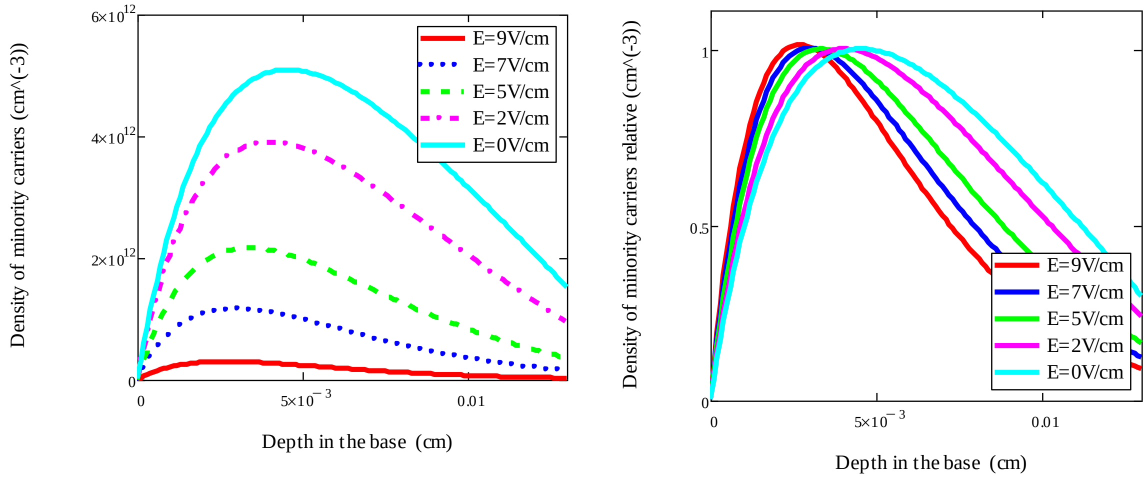

Figure 3: Excess minority carrier density (a)and normalized excess minority(b)as a function of depth in the base for different electric field values. (D=35cm^2/s, Sf=6.10^{6}cm/s, λ=0.88 µm, H=130µm)

The figures 2 and 3 show a profile with a maximum minority carrier density at Xo position. At this point (with nil gradient of excess minority carrier density), the excess minority carriers for Xo < x < H, are blocked and recombine in the bulk and the back surface. In this region, where the excess carrier density gradient is negative, bulk and back surface recombination are predominated. For a position 0 < x < X0, in the base, figs. 2 and 3 show a positive gradient [46, 47]. Excess minority carriers in this area cross the junction and participate into the photocurrent production. In the presence of the electric field, we note a decrease in minority carrier density maxima and a shifting of these minority carrier density peaks towards the junction. In fact, in the presence of an electric field, the excess minority carrier are accelerated, by conduction, towards the junction (displacement of the density peaks). Then, the X0 value corresponding to the maximum of excess minority carrier density decreases and moves toward the junction as a variation of operating point of the solar cell near the open circuit condition. The same situation is observed, for short wavelength illumination (Figure 2) the generation of excess minority carrier is closed to the junction. For the long wavelength (Figure 3), the absorption coefficient of silicon is weak and the generation of minority carriers occurs in the bulk of the base. To determine the positions of the minority carrier density peaks we represent on figs. 4 and 5 the carrier density gradient as a function of the base depth. Then the derivative of excess minority carrier density expression with respect to x, remained zero.

$$\left.\frac{d\delta(x,E,\lambda)}{dx}\right|_{x=Xo} = 0 \tag{10}$$

On the graphical representatives (fig. 4 and 5), intercept points with the horizontal axis (Ox) yield Xo values.

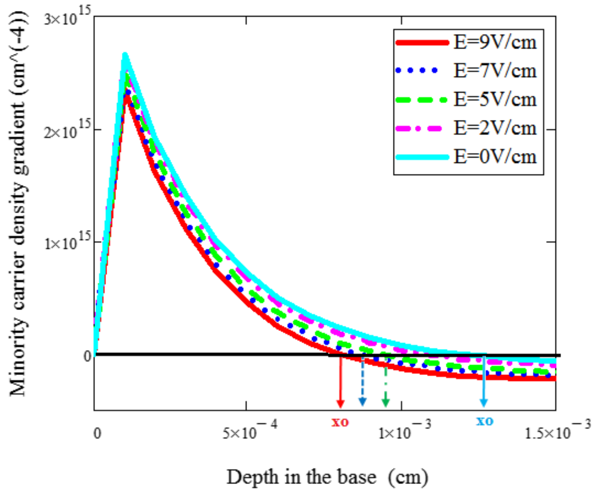

Figure 4: Minority carrier density gradient as a function of depth in the base for different electric field values (D=35cm^2/s, Sf=6.10^{6}cm/s, λ=0.64µm, H=130µm)

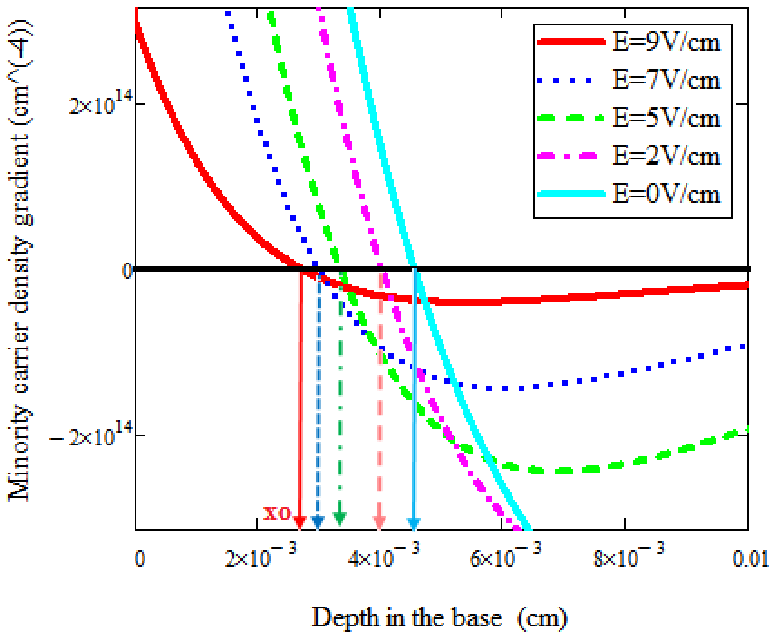

Figure 5: Minority carrier density gradient as a function of depth in the base for different electric field values. (D=35cm^2/s, Sf=6.10^{6}cm/s, λ=0.88µm, H=130µm)

We represent in Tables 1 and 2, the results obtained for different values of the electric field, and for two values of the wavelength (λ = 0.64 µm and λ = 0.88µm).

Table 1: Maximum density Xo for different values of the electric field.
($D=35cm^2/s$, $Sf=6.10^6 cm/s$, $\lambda=0.64$ µm, H= 130µm

E (V/cm)	0	2	5	7	9
Xo (µm)	11.81	10.66	9.26	8.53	7.94

Table 2: Maximum density Xo for different values of the electric field
($D=35cm^2/s$, $Sf=6.10^6 cm/s$, $\lambda=0.88$µm, H= 130µm)

E (V/cm)	0	2	5	7	9
Xo (µm)	45.61	40.30	33.53	29.92	26.93

Tables 1 and 2 show a decrease in Xo when the electric field increases which results in a reduction of the extended space charge region. The obtained Xo values yield the capacitance C for different electric field by the plane capacitor relation [11]:

$$C = \frac{\varepsilon . S}{Xo} . \qquad (11)$$

εis the silicon permitivity and S the surface of the space charge area. The relation (11) gives the capacitance Co under dark. We thus represent in Figures 6 and 7 the profiles of depth Xo as a function of the electric field for two different wavelengths ($\lambda=0.64$ µm and $\lambda=0.88$ µm)

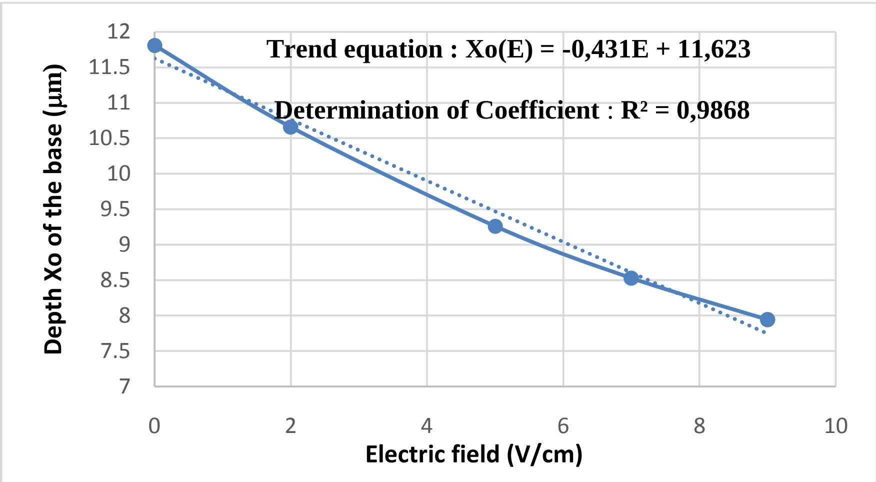

Figure 6: Depth Xo of the base as a function of the electric field.
($D=35cm^2/s$, $Sf=6.10^6 cm/s$, $\lambda=0.64$ µm, H=130µm)

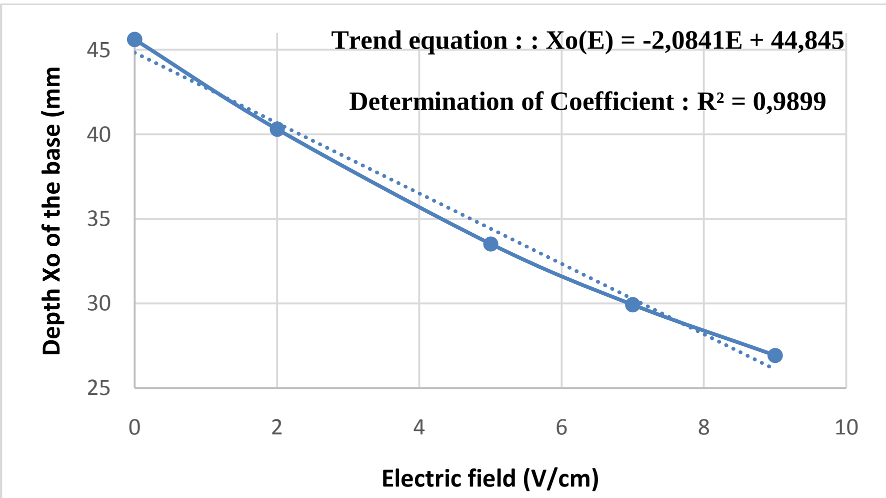

Figure 7: Depth Xo of the base as a function of the electric field.
($D=35cm^2/s$, $Sf=6.10^6 cm/s$, $\lambda=0.88$ µm, H=130µm)

4. Conclusion

The expression of the excess minority carrier density is determined from the continuity equation. The evolution of this excess minority carrier density as a function of the depth in the base for different values of the electric field is described. The study has shown a maximum carriers density at the Xo position of the base and a shifting of density peaks towards the junction as the electric field increases. In the same way, a strong generation of excess minority carrier near the junction for short wavelength, is obtained. Thus, for long wavelengths, the generation of minority carriers is done deeply in the base. The determination of the Xo positions of carrier density maxima allowed to study the reduction of the space charge region width, with the electric field and the determination of the transitional capacitance.

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