Available online www.jsaer.com

Journal of Scientific and Engineering Research, 2018, 5(7):317-324

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Diffusion capacitance in a silicon solar cell under frequency modulated illumination: Magnetic field and temperature effects

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Abstract We propose a study about a silicon solar cell under polychromatic illumination in frequency modulation by the emitter face. From the minority carrier density in excess, the photovoltage and the capacitance are determined, according to, the resonant frequency, the magnetic field and the temperature.

Keywords Silicon Solar cell- Frequency – magnetic field-Temperature- Capacitance

1. Introduction

The manufacture of silicon solar cell leads to the development of a junction (n / p) between the semiconductor silicon type (n) and type (p). This junction is established by the migration of electrical charge between two semiconductors, which are established as fixed charges with opposed sign [1-2]. Thus, the electrical analogy of this junction to a planar capacitor is established and called transition capacitance, depending on the doping rate of two semiconductors as donor and acceptor impurities [3]. Dimensions of semiconductors are located in the emitter and the base of solar cell. Several researches were investigated about this capacitance, which is the solar cell capacitance under darkness [4]. When the solar cell is under illumination, there is light absorption, generation of electron-hole pairs, diffusion and recombination in volume and in surface. This minority carrier contributes to create a new capacitance by their move and this capacitance is called capacitance of diffusion [5-8] depending on:

a) The recombination velocity at the junction (Sf), which sets the operating point of the solar cell (open circuit to short circuit),
b) The light wavelength [9], frequency [10-11], sun concentration, incident flux and angle [12] and diffusion parameters as, doping rate [13], junction and back rear surfaces recombination velocity [14], or at grain boundaries in a 3D model [15-16] and experimental conditions like, Temperature [17-18], applied magnetic field [19], electric excitation [20].

Thus, solar cell can be studied in, static [21], transient [22]or frequency modulation [23-25] regime, to access to, the transition or diffusion capacitance [26].

The contribution to this work is, to determine, under modulated illumination, the effect of the temperature and the applied magnetic field, on the base of the silicon solar cell capacitance, for an operating point closed to the open circuit. This study will allow to establish, more elaborated equivalent electrical models associating, resistances, self-inductance, from the phenomenological parameters [27]. The emitter contribution has been already taken into account [28].

2. Theory

In this one-dimensional space study, we consider in figure (1), the illuminated silicon solar cellbase (thickness H) of n^+-p-p^+, by the n+ surface, with white light, in frequency modulation (ω), under magnetic field (B) and at the temperature (T).

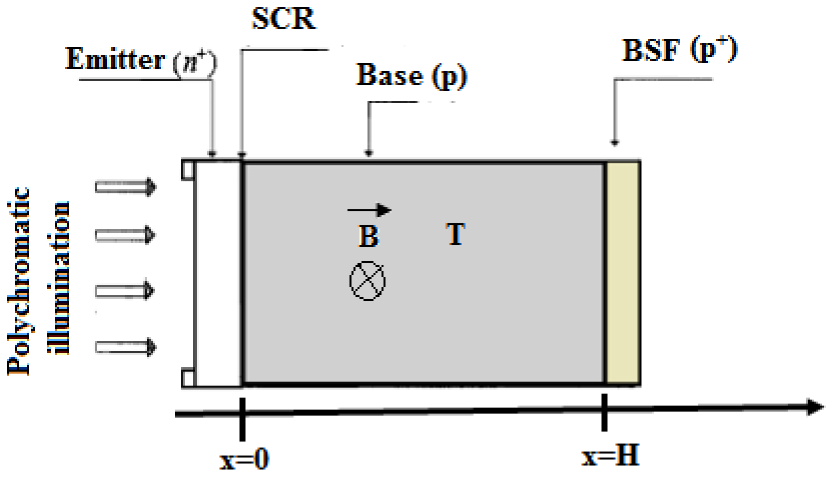

Figure 1: n^+-p-p^+ solar cell structure under polychromatic illumination, magnetic field and temperature T

The excess minority carrier density δn(x, t) generated in the base of the solar cell, obeys to the continuity equation, when the solar cell is under modulated frequency illumination [29-30]:

$$\frac{\partial^2 \delta n(x,B,T,t)}{\partial x^2} - \frac{1}{D(\omega,B,T)}\frac{\partial \delta n(x,B,T,t)}{\partial t} - \frac{\partial \delta n(x,B,T,t)}{D(\omega,B,T)\tau_n} = -\frac{G(x,t)}{D(\omega,B,T)} \quad (1)$$

The expression of the excess minority carrier density in the base depth x of a silicon solar cell at T temperature, under magnetic field B, time t dependent, is given by:

$$\delta n(x,B,T,t) = \delta n(x,B,T)e^{i\omega t} \quad (2)$$

2.1. Excess minority carrier diffusion coefficient in the base

The complex diffusion coefficient of excess minority carrier in the base of the solar cell, under modulation frequency (ω) [31-33], is giving by the following expression:

$$D(\omega) = D_0\left[\frac{1+(\omega\tau)^2}{(1-\omega^2\tau^2)^2+(2\omega\tau)^2} + \omega\tau\frac{-1-(\omega\tau)^2}{(1-\omega^2\tau^2)^2+(2\omega\tau)^2}j\right] \quad (3)$$

D_0(T) is the excess minority carrier diffusion coefficient in the solar cell in steady state, at T temperature, without magnetic field. And **τ** is the excess minority carrier lifetime in the base.

The well-known Einstein-Smoluchowski equation yields:

$$D_0(T) = \mu(T)\times\frac{Kb\times T}{q} \quad (4)$$

And $\mu(T)$ characterizes the mobility of electrons and is a function of temperature [18], its expression is given by:

$$\mu(T) = 1.43\times10^9\times T^{-2.42}cm^2.v^{-1}.s^{-1} \quad (5)$$

The complex diffusion coefficient of the minority carrier in the base of the solar cell in frequency regime (ω), temperature (T), and magnetic field (B) is derived as:

$$D(\omega,B,T) = D(B,T)\left[\frac{1+\tau^2\omega^2}{(1-\tau^2\omega^2)^2+4\tau^2\omega^2} + \omega\times\tau\frac{-\tau^2\omega^2-1}{(1-\tau^2\omega^2)^2+4\tau^2\omega^2}j\right] \quad (6)$$

$D(B,T)$ is the diffusion coefficient as a function of temperature, and of the magnetic field :

With $D(B,T) = \dfrac{L(B,T)^2}{\tau}$ (7)

Or $D(B,T) = \dfrac{D_0(T)}{[1+(\mu(T)\times B)^2]}$ (8)

$L(B,T)$ represents the diffusion length, temperature and magnetic field dependent.

2.3. Minority carrier generation rate induced by a polychromatic illumination

The minority carrier generation rate in the base of a solar cell under polychromatic illumination is given by the expression:

$$G(x,t) = g(x)\exp(j\omega t) \quad (9)$$

With $g(x) = \sum_{i=1}^{3} a_i . e^{-b_i x}$ (10)

The coefficient ai and bi are obtained from the tabulated values of the radiation under A.M=1.5 [33].

2.4. Boundary conditions

Equation (1) is resolved using boundary conditions:

At the junction (x=0)

$$D(\omega,B,T).\left.\frac{\partial\delta_n(x,B,T)}{\partial x}\right|_{x=0} = Sf.\delta_n(x=0,B,T) \quad (11)$$

At the back surface(x= H)

$$D(\omega,B,T).\left.\frac{\partial\delta_n(x,B,T)}{\partial x}\right|_{x=H} = -Sb.\delta_n(x=H,B,T \quad (12)$$

Sf and Sb are respectively the excess minority carrier's surface recombination velocity at the junction and the rear. Sf indicates also the solar cell operating point, while Sb the back surface field at the p/p+ interface [34, 27].

2.5. Photovoltage

It is obtained using the Boltzmann expression:

$$V_{ph}(\omega,B,T) = VT\times\ln\left(\frac{Nb}{ni^2(T)}\times\delta(0,\omega,B,T)+1\right) \quad (13)$$

With

$$VT = \frac{K_b}{q}\times T \quad (14)$$

VT represents the thermal voltage; q is electron charge, K_b is Boltzmann constant

Nb the base doping density and ni the intrinsic carrier's density, given by [35]:

$$n_i^2(T) = A\times T^3\exp\left(-\frac{Eg}{K_b\times T}\right) \quad (15)$$

$Eg = 1{,}12.1{,}6.10^{-19}J$, is the gap energy. This energy is the difference between the energy of the conduction band E_c and that of the valence band E_v. A is a constant, $A = 3{,}87.10^{16}cm^{-3}.K^{-3/2}$

2.6. Capacitance of the solar cell

The expression of the diffusion capacitance of the solar cell is obtained according to the following relation:

$$C(Sf,B,\omega,T)=\frac{dQ(Sf,B,\omega,T)}{dV(Sf,B,\omega,T)} \tag{16}$$

$$Q(Sf,B,\omega,T)=q\delta(x=0,Sf,B,\omega,T) \tag{17}$$

Considering the excess minority carrier density in the base and the photovoltage at the junction of the solar cell, the capacitance expression is obtained:

$$C(Sf,B,\omega,T)=q*\frac{d\delta(x=0,Sf,B,\omega,T)}{dV(Sf,B,\omega,T)} \tag{18}$$

$$C(Sf,B,\omega,T)=q*\frac{d\delta(x=0,Sf,B,\omega,T)}{dSf}*\frac{1}{\frac{dV(Sf,B,\omega,T)}{dSf}} \tag{19}$$

$$C(Sf,B,\omega,T)=\frac{q.(n_i(T))^2}{N_b.V_T}+\frac{q.\delta(x=0,Sf,B,\omega,T)}{V_T} \tag{20}$$

$$C(Sf,B,\omega,T)=C_o(T)+C_d(Sf,B,\omega,T) \tag{21}$$

$$C_o(T)=\frac{q.(n_i(T))^2}{N_b.V_T} \tag{22}$$

$C_0(T)$ is the capacitance of the solar cellan short-circuit.

$$C_d(Sf,B,\omega,T)=\frac{q.\delta(x=0,Sf,B,\omega,T)}{V_T} \tag{23}$$

$C_0(T)$ and $C_d(Sf,B,\omega,T)$ are respectively the solar cell capacitance in the dark (or transitional) and the diffusion capacitance under illumination.

3. Results and Discussions

We present in this section the capacitance amplitude spectrum for the solar cell under a short-circuit conditions, as well as the Niquyst diagram for different magnetic field and temperature. There profiles are shown in figures (2-a, b, c)

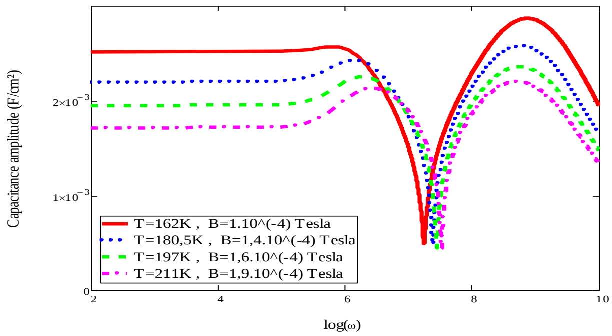

Figure 2.a: Capacitance amplitude versus logarithmic of frequency for different Temperature and magnetic field ($Sf=2.10^2 cm/s$).

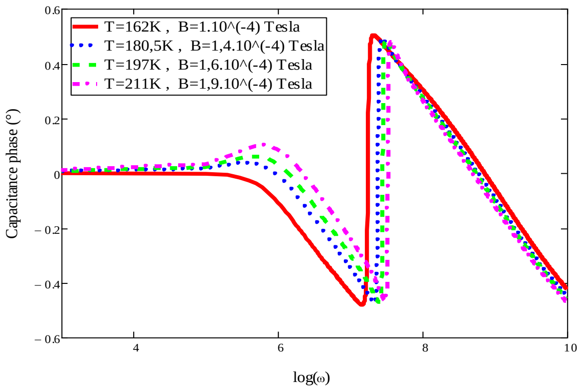

Figure 2.b: Capacitance phase versus logarithmic of frequency for different temperature and magnetic field. $Sf=2.10^2 cm/s$

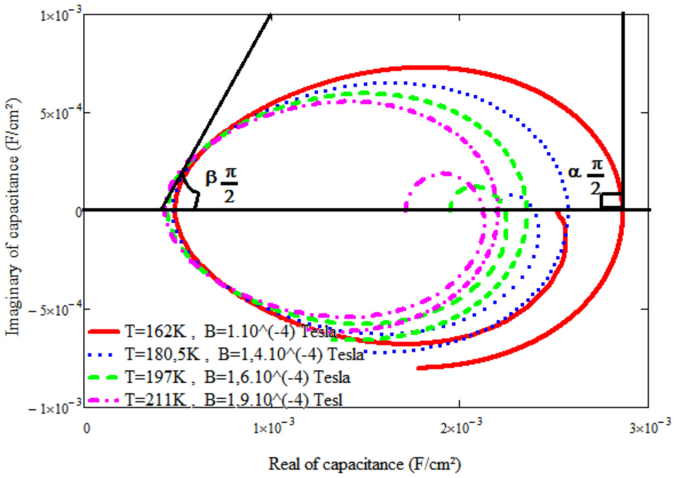

Figure 2-c: Imaginary capacitance component versus real of component, for different temperature and magnetic field. (Sf=2.10^{2}cm/s).

Figure 2.a shows the modulus of solar cell capacitance for tabulated values of magnetic field and temperature [19] as a function of frequency. This figure shows a decrease in amplitude of the pear radius, in the Niquyst diagram (Fig. 2.c) and a displacement of the resonance frequency with the tabulated values of the couple (Magnetic field, Temperature), that is also marked in the phase diagram of the capacitance (Fig. 2.b). Resonance frequency is confirmed between 10^7 and 10^8 rad/s. Constant phase is observed, for ω less than 10^6, and greater than 10^8 rad/s.

Table 1: resonance frequency for different magnetic field and temperature values

(T_{op} ; B_{op})	**Resonance frequency(rad/s)**		
(162K ;10^{-4}Tesla)		$10^{7,24}$	$10^{8,85}$
(180K ;1,4/10^{-4}Tesla)	$10^{5,91}$	$10^{7,39}$	$10^{8,72}$
(197K ;1,5.10^{-4}Tesla)	$10^{6,11}$	$10^{7,41}$	$10^{8,70}$
(211K ;1,9.10^{-4}Tesla)	$10^{6,34}$	$10^{7,52}$	$10^{8,69}$

In this study, we summarize that, there is an open-circuit capacitance which decreases with increasing temperature atthe corresponding magnetic field. The excess minority carriers are blocked and stored in the vicinity of the junction.

Capacitance in complex form(real and imaginary components) is presented by analogy of the effect ofMaxwell-Wagner-Sillars (MWS) model [36, 37, 38] is written as:

$$C(\omega,B,T) = C^{'}(\omega,B,T) + J.C^{''}(\omega,B,T) \tag{24}$$

So by analogy with the tangent of the dielectric loss angle, we have the following equation:

$$\tan(\gamma) = \frac{C^{''}(\omega,B,T)}{C^{'}(\omega,B,T)} \tag{25}$$

with $\gamma = \beta.\frac{\pi}{2}or\gamma = \alpha.\frac{\pi}{2}$

The coefficient β and α [39, 40, 41] are parameters depending on the shape of the relaxation peak. The graphical determination (figure 2. c) of these coefficients gives us the following values: β=1/2 and α=1.

The lower part of the half pear corresponds to an angle of $\frac{\pi}{2}$ with the horizontal axis (C ')

Half regular circle induced a single time constant (Rp.C), consisting of a resistance Rp in parallel with a capacitance(C). Half circle that flattens at high frequencies, indicates an association of series resistance (r) with a capacitor and resistance in parallel (Rp.C). Deflection towards flattening, indicates existence of a series resistance- Half unperfected circles, cause a deformation of circles that induced a time constant (RC) frequency dependent.

The transition capacitance is not a function of frequency, so it is the diffusion capacitance due to the reflected excess minority carrier at the solar cell rear side (Back surface field).

These excess carrier, that induced change in the time constant value, are function of the parameters of absorption, generation and recombination, and the depth H.

Conclusion

Theoretical study has carried out electric parameters, using capacitance spectroscopy at different magnetic field and temperature in a silicon solar cell under white modulated illumination. Phenomelogical parameters were used, through excess minority continuity equation in the base of the solar cell to build this new approach, taking into account Umklapp and Lorentz processes.

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