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TEMPERATURE AND MAGNETIC FIELD EFFECT ON BACK SURFACE RECOMBINATION VELOCITY IN A SILICON SOLAR CELL UNDER WHITE MODULATED ILLUMINATION

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ABSTRACT

Back surface recombination velocity of excess minority carriers in a monofacial silicon solar cell, is expressed as temperature, magnetic field, and frequency dependent. With Boode and Niquyst diagrams help, results are obtained and analyzed.

Keywords: silicon solar cell, ac back surface recombination velocity, temperature, magnetic field (Umklapp- Lorentz).

1. INTRODUCTION

Recombination velocity characterizing certain recombination phenomena of excess minority carriers at interfaces and surfaces can limit the performance of solar cells. Thus, it is important to integrate these parameters in the manufacture of solar cells, through the contacts to recover the photocréés electrical charges [1]. Different architectures to establish contact without altering but rather increasing the penetration of photons into the structure are proposed [2]. The importance of front and rear contacts has improved collection performance of excess minority carriers in a silicon solar cell (composite emitter, backfield) [2].

The characterization of the solar cells aims in theoretical research [3] and experimental [4] phenomenological parameters (doping rate, diffusion coefficient, lifetime and diffusion length, surface recombination of charge carriers) [5] and parameters of electrical equivalent model (Shunt and series resistance, capacitance, impedance, the cutoff and resonance frequencies, the factor yarn and efficiency) [6]. The solar cell can be placed under darkness or illumination and in static operation mode [7] or dynamic (transient or frequency) [8], then the answer it delivers in current and voltage, is analyzed.

The importance of diffusion coefficient of excess minority carriers in the base of silicon solar cell, has been the focus of various theoretical and experimental studies, who brought correlations with: the doping rate (SIMS method), lifetime, mobility (Einstein-mukovich relation), temperature, optical or electrical excitation frequency, the electric field (Einstein-gaussienne; Pozela et Reklaitis) or magnetic, in which is placed the solar cell, the flux and intensity of particle irradiation to which the solar cell has been subjected, the decay time constant of phototension, photocurrent or the solar cell capacitance in transient regime [9], grain size and recombination velocity at grain boundaries in the 3D model [10, 11]. The recombination velocity of minority carrier photogene rated in the rear face solar cell base type p and p^+ doped is associated with the creation an electric field that modifies the bands of energy levels of conduction and valence. This rear electric field makes it possible to return the charge carriers to transmitter-base junction, whose electric field the space charge area speeds up and improves their collection rate [12].

Thus, our study proposes a new expression of the back surface recombination velocity on the silicon solar cell, depending on the diffusion coefficient and taking into account the external conditions, temperature, applied magnetic field applied as well as the modulation frequency of the optical excitation. Spectroscopy technique [13, 14] under magnetic field and temperature, is used to propose electrical modeling.

2. THEORY

2.1 Presentation of the solar cell

The silicon solar cell shown in Figure 1 is composed mainly of four parts: emitter (n+), junction (SCR), base (p) and back side (p+) [1, 2].

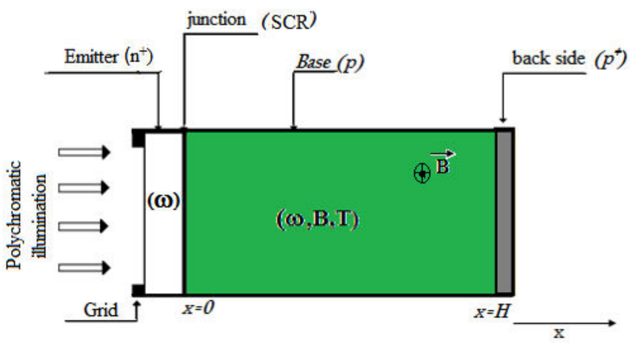

Figure-1. An n+-p-p+ type of a silicon solar cell scheme under applied magnetic field.

2.2 Continuity equation

2.2.1 Minority carrier density

When the solar cell is lit, there is creation of electron-hole pairs in the base. The minority excess carrier density in the base is governed by the continuity equation.

The continuity equation for minority carriers in the base (p) in dynamic frequency regime is [15]:

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

The expression of minority carriers density according to depth x, magnetic field B, temperature T and time t is given as follows [16]:

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

2.2.2 Generation rate

The expression generation rate of minority carriers at abscissa x in the base of solar cell under polychromatic illumination in frequency modulation is given by [17]:

$$G(x,t) = g(x)\exp(i\omega t) \quad (3)$$

The space component is given by:

$$g(x) = \sum_{i=1}^{3} a_i e^{-b_i x} \quad (4)$$

The coefficients a_i and b_i are obtained from the tabulated values of the radiation in the state AM= 1, 5 [18, 19].

2.2.3 Diffusion coefficient according to conditions imposed on solar cell

a) Variation in the temperature

$D_0(T)$ is the excess minority carrier diffusion coefficient in the solar cell in steady state, at T temperature, without magnetic field.

The Einstein-Muskovitch relation, for minority carriers in the base of silicon solar cell at temperature T, writes [20]:

$$D_0(T) = \mu(T) \times \frac{Kb \times T}{q} \quad (5)$$

The mobility of electrons function temperature is given by: [21]:

$$\mu(T) = 1.43 \times 10^9 \times T^{-2.42} cm^2.v^{-1}.s^{-1} \quad (6)$$

b) Diffusion coefficient versus magnetic field and the temperature

The study of solar cell under magnetic field B at temperature T, led to the expression of diffusion coefficient [22]:

$$D(B,T) = \frac{D_o(T)}{[1 + (\mu(T) \times B)^2]} \quad (7)$$

This relation made it possible to calculate the optimal temperature (Top) for different magnetic fields and to deduce the maximum diffusion coefficient (Dmax), through the analysis of Unklapp process [23, 24] by thermal agitation undergone by minority carriers [24], as well as the deviations of electric charges produced by the Lorentz forces:

$$D_{max}(B,T) = \alpha'.\left[T_{op}(B)\right]^{\beta'} \quad (8)$$

Or

$$D_{max}(B,T) = 1{,}4.10^5.\left[T_{op}(B)\right]^{-1{,}51} \quad (9)$$

c) Diffusion coefficient versus modulation frequency

The complex diffusion coefficient of excess minority carrier in the base of the solar cell, under modulation frequency is given by expression [25]:

$$D(\omega) = D_0\left[\frac{1+(\omega\tau)^2}{(1-\omega^2\tau^2)^2 + (2\omega\tau)^2} + \omega\tau\frac{-1-(\omega\tau)^2}{(1-\omega^2\tau^2)^2 + (2\omega\tau)^2}j\right] \quad (10)$$

d) Diffusion coefficient versus modulation frequency, temperature and magnetic field

By combining the equations (5), (6), (7) and (10), 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:

$$D^*(\omega,B,T) = D(B,T)\left[\frac{1+(\omega\tau)^2}{(1-\omega^2\tau^2)^2+(2\omega\tau)^2} + \omega\tau\frac{-1-(\omega\tau)^2}{(1-\omega^2\tau^2)^2+(2\omega\tau)^2}j\right] \quad (11)$$

$$D^*(\omega,B,T) = \frac{L(\omega,B,T)^2}{\tau} \quad (12)$$

With, $D^*(\omega,B,T)$is the diffusion coefficient as a function of both temperature and magnetic field?

2.2.4 Solving the continuity equation

By replacing (2 and 3) in (1), we get the expression:

$$\frac{\partial^2 \delta_n(x,\omega,B,T)}{\partial x^2} - \frac{1}{L_n^{*2}}(1 + i\omega\tau_n).\delta_n(x,\omega,B,T) = \frac{G(x)}{D_n^*} \quad (13)$$

$$\frac{1}{L_{\omega}^{*2}} = \frac{1}{L_n^{*2}}(1 + i\omega\tau_n) \quad (14)$$

Or L_{ω}^{*} is the diffusion length of minority carriers in the base of the solar cell, under illumination in frequency modulation ω, temperature T and magnetic field B.

L_n^{*} represents the diffusion length versus temperature and magnetic field.
The solution is in the form:

$$\delta_n(x,\omega,B,T) = A_1(\omega,B,T)\mathrm{ch}\left(\frac{x}{L_{\omega}^{*}}\right) + B_1(\omega,B,T)\mathrm{sh}\left(\frac{x}{L_{\omega}^{*}}\right) + \sum_{i=1}^{3}\beta_k(\omega,B,T).e^{-b_k x} \quad (15)$$

$$\text{With } \beta_k(\omega,B,T) = \frac{a_k.{L_{\omega}^{*}}^2}{D^*(\omega,B,T)[1-(b_k.L_{\omega}^{*})^2]} \quad (16)$$

and

$$D^*(\omega,B,T)[(b_k.L_{\omega}^{*})^2 - 1] \neq 0 \quad (17)$$

The coefficients A1(ω,B,T), B1(ω,B,T)are obtained using boundary conditions (18) et (19)

2.2.5 Boundary conditions-recombination velocities to surfaces

- At the junction[2], x = 0 :

$$D^*(\omega,B,T)\cdot\left.\frac{\partial\delta n(x,\omega,B,T)}{\partial x}\right|_{x=0} = Sf\cdot\delta(0,\omega,B,T) = \frac{Jn(\omega,B,T)}{q} \quad (18)$$

At the back side, x = H

$$D^*(\omega,B,T)\cdot\left.\frac{\partial\delta n(x,\omega,B,T)}{\partial x}\right|_{x=H} = -Sb(\omega,B,T)\cdot\delta n(H,\omega,B,T) \quad (19)$$

Sf is the excess minority carrier junction recombination velocity [26]. Sf is the sum of two terms sf0 and sfj:Sf = Sf0 + Sfj[27].

Where Sfj defines the operating point, thus, it is imposed by the external load resistor and sf0 is the intrinsic recombination velocity, whis is related to the solar cell shunt resistance.

$Sb(\omega,B,T)$ is the back surface recombination velocity of the excess minority carrier [28] BSF

3. RESULTS AND DISCUSSIONS

3.1Photocurrent density

The expression of the photocurrent density J_{Ph}(ω, B, T), the well-known diffusion current of excess minority carrier trough the junction, temperature, magnetic and frequency dependent [29] is deduced as:

$$J_{Ph}(\omega,B,T) = q.D^*(\omega,B,T).\left.\frac{\partial\delta(x,\omega,B,T)}{\partial x}\right|_{x=0} \quad (20)$$

Photocurrent density Jph, is shown in Figures 2 and 3 as a function of the recombination velocity at junction for two different frequencies chosen as function the resonant frequency.

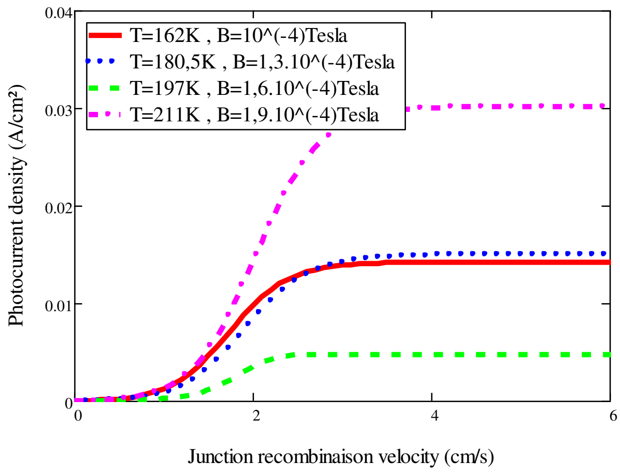

Figure-2. Photocurrent density as a function the recombination velocity for ω = 10^6rad/s less than the resonance frequency.

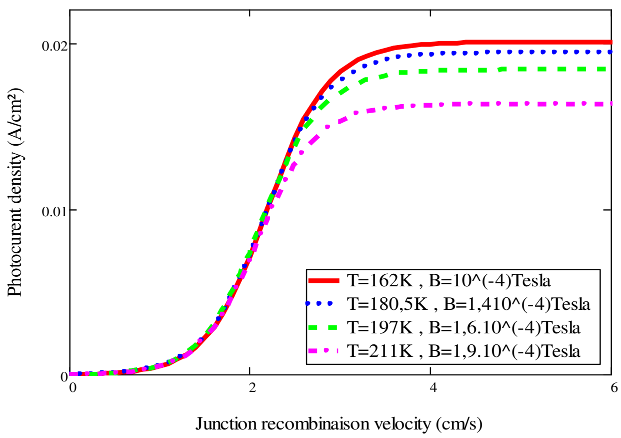

Figure-3. Photocurrent density as a function the recombination velocity for ω=10^8rad/s greater than the resonance frequency.

For the big values of Sf, Photocurrent density increases to a maximum value corresponding to a short-circuit operation. It is thus noted that the photocurrent density becomes constant as function on the recombination velocity at junction Sf.

3.2 Back surface recombination velocity determination

Calibration curve of excess minority current density as function of junction surface recombination velocity (Sf) [30], has shown, a constant value, of Jph, for large Sf value. Then deriving boundary equation relative to Sf remained zero.

$$q.D^*(\omega,B,T)\cdot\frac{\partial}{\partial Sf}\left(\left.\frac{\partial\delta n(x,\omega,B,T)}{\partial x}\right|_{x=0}\right) = \frac{\partial Jn(\omega,B,T)}{\partial Sf} = 0 \quad (21)$$

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$$\mathrm{Sb1}(\omega,B,T)=\frac{D^{*}(\omega,B,T)}{L(\omega,B,T)}.\frac{\sinh\left(\frac{H}{L(\omega,B,T)}\right)+L(\omega,B,T).\sum_{i=1}^{3}\left(b_i.e^{-b_i.H}\right)-L(\omega,B,T).\sum_{i=1}^{3}(b_i.)\cosh\left(\frac{H}{L(\omega,B,T)}\right)}{\sum_{i=1}^{3}\left(e^{-b_i.H}\right)-\cosh\left(\frac{H}{L(\omega,B,T)}\right)+L(\omega,B,T).\sum_{i=1}^{3}(b_i.).\sinh\left(\frac{H}{L(\omega,B,T)}\right)} \quad (22)$$

$$Sb2(\omega,B,T)=-\frac{D^{*}(\omega,B,T)}{L^{*}(\omega,B,T)}th\left(\frac{H}{L^{*}(\omega,B,T)}\right) \quad (23)$$

3.3 Results

Figure-4 shows the amplitude of the recombination velocity of minority carriers on the back surface of solar cell, for tabulated values of magnetic field and temperature [24] according to the frequency. This figure shows a decrease in amplitude (Pear ray, in the Niquyst diagram) and a displacement of the resonance frequency with the temperature, which is also marked in the phase diagram of the recombination velocity (Figure-5).

3.4 Back surface velocity amplitude spectrum:

We notice that in quasi-static mode the phase of Sb is negative, so capacitive effects predominate, per account in dynamic frequency, the Sb phase is positive for frequencies higher than the resonance frequency. The resonance frequency is between 10^7 and 10^8 rad/s as shown on the tableau.

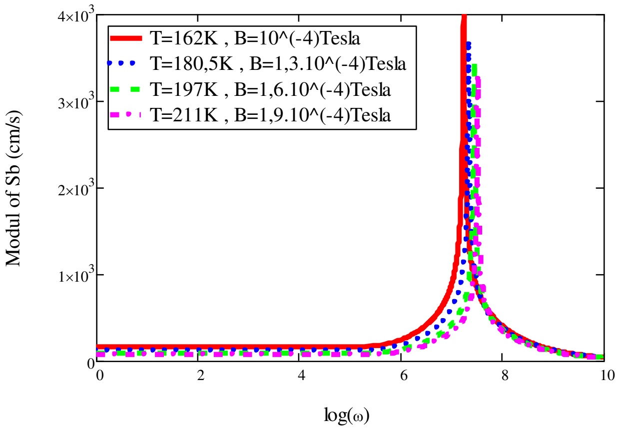

Figure-4. Amplitude of recombination velocity Sb as a function of decimal logarithm of pulsation.

3.5 Back surface recombination phase spectrum

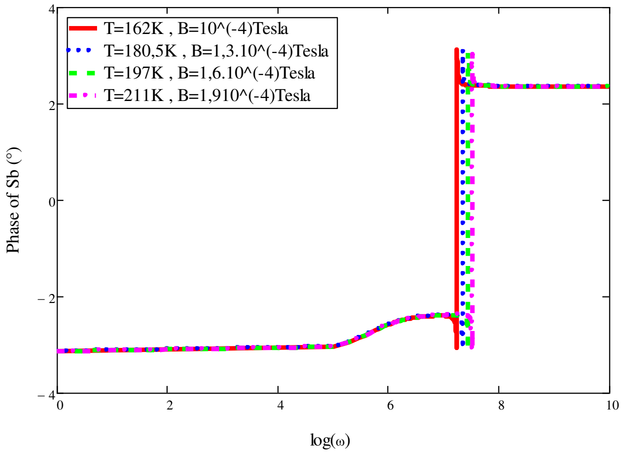

Figure-5. Phase of the recombination velocity Sb as a function of the decimal logarithm of pulsation.

3.6 Niquyst diagram

Sb is the back surface recombination velocity in complex form (real and imaginary components) by analogy of the effect Maxwell-Wagner-Sillars (MWS) [31, 32, 33]. So the representation of its imaginary part according to its real part, allows us to study relaxation due to loads present during manufacture, such as impurities under the effect of temperature and magnetic field:

$$Sb(\omega,B,T)=Sb'(\omega,B,T)+i.Sb''(\omega,B,T) \quad (24)$$

$$Sb=\left|Sb(\omega)\right|.e^{(j\omega t+\gamma(\omega))} \quad (25)$$

Thus one can write γ in the following form:

$$\tan(\gamma)=\frac{Sb''(\omega,B,T)}{Sb'(\omega,B,T)} \quad (26)$$

With $\gamma=\beta.\frac{\pi}{2}$ ou $\gamma=\alpha.\frac{\pi}{2}$

The coefficientsβ and α [32, 33, 34] are parameters depending on the shape of the semicircle obtained. The graphical determination (Figure-6) of these coefficients gives us the following values: β = 1 andα =1/2. The lower part corresponding half pear makes an angle ofΠ/2 with the horizontal (Sb')

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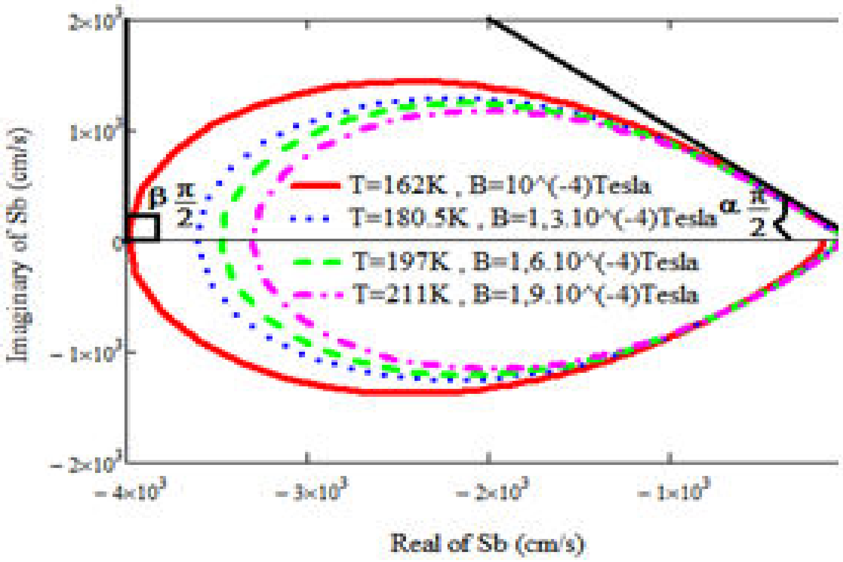

Figure-6. Imaginary of Sb recombination velocity according to real part.

It can be seen that the semicircles flatten at high frequencies. The semicircle indicates Rp//C, so only one time constant. The deviation towards flattening indicates the existence of series resistance. The non-perfect semi-circle corresponds to time constant RC= f(ω): we have a deformation of the circles.

Table-1. The values of recombination velocity corresponding to resonance frequency for the couples (Temperature, magnetic field).

Temperature (K)	Magnetic Field (Tesla)	Resonance frequency (rad/s)	Sb(cm/s)
162	10^{-4}	$10^{7,25}$	3991
180,5	$1,3.10^{-4}$	$10^{7,35}$	3558
197	$1,6.10^{-4}$	$10^{7,39}$	3469
211	$1,9.10^{-4}$	$10^{7,52}$	3301

When the temperature T and the magnetic field B increase, there is a decrease in the back surface recombination Sb: the radius of the pear decreases which leads to a modification of the electrical parameters.

4. CONCLUSIONS

This theoretical study has made it possible to determine a new complex expression of the back surface recombination velocity (Sb) minority excess carriers in a silicon solar cell (n^+ -p-p+). Using the expression of maximum diffusion coefficient D(B,T,ω), we show that Sb increases with the optimal temperature (Top) which depends on frequency and magnetic field. Boode and Nyquist diagram have extracted new electrical parameters which characterize the equivalent electric model.

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