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RESEARCH ARTICLE

AC COMPOSITE BACK SURFACE RECOMBINATION VELOCITY AS APPLIED TO N⁺/P/P⁺ SILICON SOLAR CELL OPTIMUM THICKNESS BASE DETERMINATION

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Abstract

A composite light in frequency modulation is used for on an n⁺/p/p⁺ crystalline silicon solar cell. The density of the photogenerated minority carriers in the base (p) of the solar cell maintained in short circuit is obtained by resolution of the continuity equation, taking into account the condition at the back surface limit, characterized by (S_b) the recombination velocity. Expressions of this ac recombination velocity are obtained through the study of the ac photocurrent, depending on the recombination velocity at the junction (S_f). One of the expressions takes into account the spectral composition of the illumination, while the second materializes the intrinsic recombination velocity associated to diffusion. The graphic analysis of the expressions of the ac recombination velocity (S_b) according to the thickness (H) of the base, leads to the determination of the optimum thickness (H_{opt}) of the base allowing the extraction of the maximum photocurrent. This optimum thickness (H_{opt}) is modelled on the modulation frequency (□) and the effective diffusion coefficient (D (□)). A decrease in (H_{opt}) with frequency shows the possibility of reducing the thickness of the base of the solar cell during its industrial development process.

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Introduction:-

Spectroscopy [1, 2] techniques are used to extract phenomenological parameters in semiconductor materials that make up the solar cell, i.e., lifetime, diffusion length, mobility and recombination velocity of minority carriers, through the analysis of ac-current responses [3, 4, 5, 6].

The complexity of this theoretical and experimental work lies in the possibility of decoupling the effect of bulk and surface recombination [7, 8] in the response of the sample under study. Taking into account the selected incident signal parameters (frequency and monochromatic absorption coefficient imposing the depth of signal penetration) and the geometric parameters imposed by the manufacture (sample thickness and grain size) [9].

Macroscopic parameters such as impedance, through conductance and capacitance [10, 11], are studied through Bode and Nyquist diagrams of signal amplitude and shift phase of the response of the solar cell, to identify the electrical equivalent models and their representations [12, 13, 14].

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Our study deals with the determination of the optimum thickness (Hopt) [15, 16] from the base of the (n⁺/p/p⁺) silicon solar cell subjected to a composite light in frequency modulation. The expressions of ac recombination velocity are deduced from the study of the ac photocurrent [17, 18]. The optimum thickness of the base is obtained for each frequency, through the graphic technique [19, 20, 21, 22] applied to the ac recombination velocities in the rear face of the base and modeled.

Theory

The structure of the n⁺-p-p⁺ silicon solar cell [2, 23] under front polychromatic illumination, in frequency modulation, is given by figure 1.

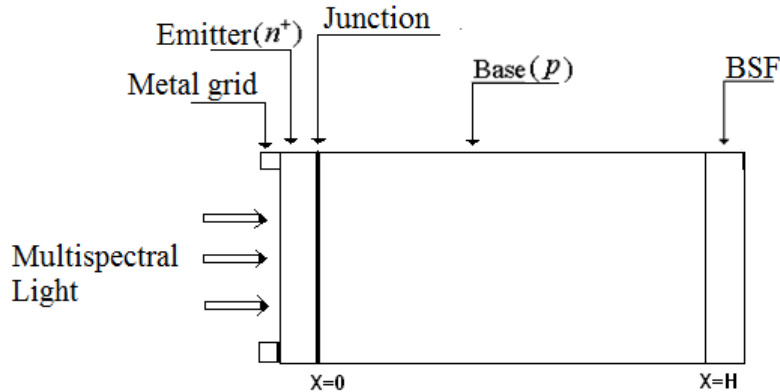


Figure 1:-Structure of an n⁺/p/p⁺ silicon solar cell.

The excess minority carriers' density $\delta(x, t)$ generated in the base of the solar cell obeying to the continuity equation at T temperature, under composite illumination in frequency modulation, is given by [4, 5, 6]:

$$D(\omega) \cdot \frac{\partial^2 \delta(x, t)}{\partial x^2} - \frac{\delta(x, t)}{\tau} = -g(x, t) + \frac{\partial \delta(x, t)}{\partial t} \tag{1}$$

The expression of the excess minority carriers' density is written, according to space coordinates (x) and time t, as: $\delta(x, t) = \delta(x) \cdot e^{i\omega t}$ (2)

- Carriers generation rate $G(x, t)$ is given by the relationship [24]:

$$G(x, t) = g(x) \cdot e^{i\omega t} \tag{3}$$

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

- x is the depth in the base.
- Coefficients a_i et b_i are obtained from tabulated values of radiation in AM 1.5 conditions
- In general the diffusion is influenced by applied external conditions, such as, temperature[25,26], magnetic field[27] electrical field[28], dopig rate [29], grain size and grain recombination velocity[30,31,32], Then in our case, D(ω) is the complex diffusion coefficient of excess minority carrier in the base. Its expression is given by the relationship [13, 33]:

$$D(\omega) = D \cdot \left(\frac{1 - j\omega^2 \tau^2}{1 + (\omega\tau)^2} \right) \tag{5}$$

By replacing equations (2) and (3) in equation (1), the continuity equation for the excess minority carriers' density in the base is reduced to the following relationship:

$$\frac{\partial^2 \delta(x)}{\partial x^2} - \left(\frac{1}{L} \right)^2 (1 + i \cdot \omega \cdot \tau) \cdot \delta(x) = - \frac{g(x)}{D(\omega)} \tag{6}$$

With:

$$(L_\omega)^{-2} = \left(\frac{1}{L} \right)^2 (1 + i \cdot \omega \cdot \tau) \tag{7}$$

L_{ω} is the complex diffusion length of excess minority carriers in frequency modulation.
 τ is the excess minority carrier's lifetime in the base.

The solution of continuity equation is:

$$\delta(x, \omega) = A(\omega) \cdot \text{ch}\left(\frac{x}{L_{\omega}}\right) + B(\omega) \cdot \text{sh}\left(\frac{x}{L_{\omega}}\right) - \sum_{i=1}^3 \frac{a_i \cdot L_{\omega}^2 \cdot e^{-b_i \cdot x}}{D \cdot (L_{\omega}^2 \cdot b_i^2 - 1)} \tag{8}$$

$$L_{\omega}^2 \cdot b_1^2 - 1 \neq 1 \tag{9}$$

Coefficients A and B are determined from the boundary conditions:

- At the junction ($x = 0$):

$$D(\omega) \cdot \left(\frac{\partial \delta(x, \omega)}{\partial x}\right)_{x=0} = S_f \cdot (\delta(x, \omega))_{x=0} \tag{10}$$

- At the rear ($x = H$):

$$D(\omega) \cdot \left(\frac{\partial \delta(x, \omega)}{\partial x}\right)_{x=H} = -S_b \cdot (\delta(x, \omega))_{x=H} \tag{11}$$

S_f and S_b are respectively the recombination velocity of the excess minority carriers at the junction and at the back surface. The recombination velocity S_f reflects the charge carrier velocity of passage at the junction, in order to participate in the photocurrent. It is then imposed by the external load which fixes the solar cell operating point [34, 35, 36;]. It has an intrinsic component which represents the carrier losses associated with the shunt resistor in the solar cell electrical equivalent model [37, 38]. The excess minority carrier's recombination velocity S_b on the back surface is associated with the presence of the p^+ layer which generates an electric field for throwing back the charge carrier toward the junction [35, 39].

Results and Discussions:-

Photocurrent

The photocurrent density is determined from the gradient of minority carriers' density at the junction. Its expression is given by Fick's law:

$$J_{ph}[S_f, S_b, \omega] = q \cdot D \cdot \left(\frac{\partial \delta(x, S_f, S_b, \omega)}{\partial x}\right)_{x=0} \tag{12}$$

Where q is the elementary electron charge.

The curves of photocurrent density variation according to recombination velocity S_f , show that for large S_f values, the photocurrent density presents a null gradient. Thus, we can determine the expression of S_b starting from the equation (12) [35]:

$$\left[\frac{\partial J}{\partial S_b}\right]_{S_b > 10^4 \text{ cm/s}} = 0 \tag{13}$$

For a multispectral illumination by the front face of the solar cell, the ac back surface recombination velocity expressions are obtained as [13, 17, 40, 41]:

$$S_b(\omega) = -\frac{D}{L_{\omega}} \cdot \text{th}\left(\frac{H}{L_{\omega}}\right) \tag{14}$$

Equation (14) is the ac intrinsic recombination velocity

$$S_b(\omega) = \sum_{i=1}^3 \frac{D \cdot b_i \cdot [\text{ch}\left(\frac{H}{L_{\omega}}\right) - e^{-b_i \cdot H}] - \frac{D}{L_{\omega}} \cdot \text{sh}\left(\frac{H}{L_{\omega}}\right)}{\text{ch}\left(\frac{H}{L_{\omega}}\right) - e^{-b_i \cdot H} - L_{\omega} \cdot b_i \cdot \text{sh}\left(\frac{H}{L_{\omega}}\right)} \tag{15}$$

While the latter is the ac composite recombination velocity, obviously dependent of composite absorption coefficient (b_i), and the sum is over the one sun spectrum [24]

Optimum thickness determination

Using the technique of comparison of the two expressions of recombination velocity [20, 21, 22, 23] inspired by the structure of the vertical multijunction[42], the figure 2, gives the representation allowing us to obtain H_{opt} from intercept curves, for each given frequency (ω).

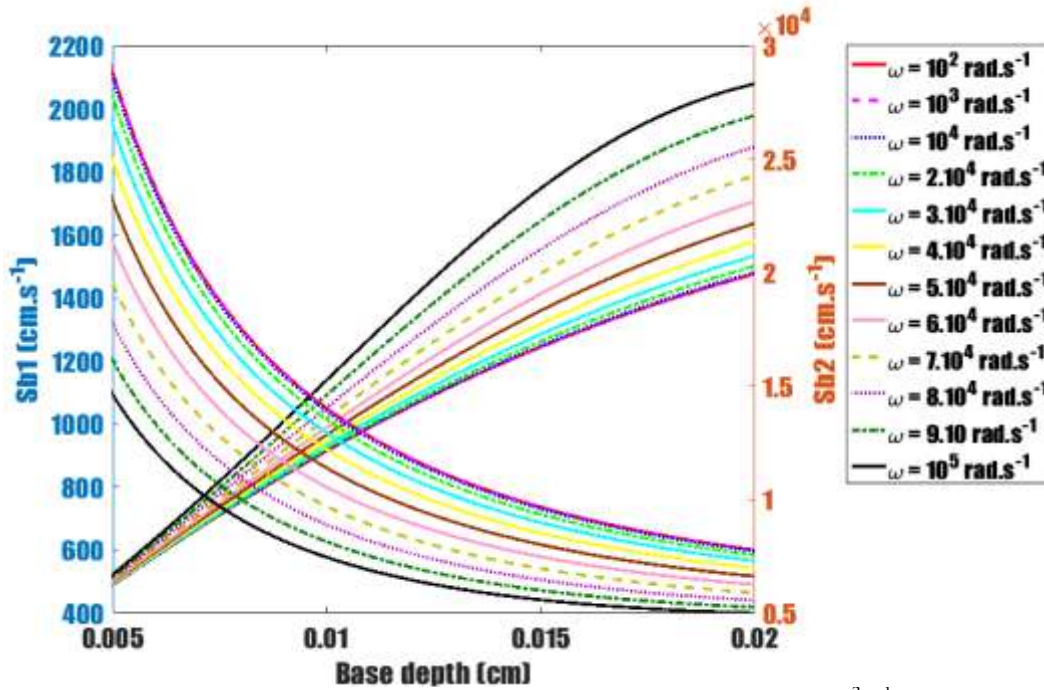


Figure 3:- Sb1 and Sb2 versus base depth for different frequency ($D_0 = 35\text{cm}^2.\text{s}^{-1}$; $T = 300\text{K}$).

Table 1, gives, for each frequency (ω), the optimum thickness, corresponding to the coefficient of effective diffusion $D(\omega)$ value.

Table 1:- Obtained optimum thickness.

$\omega(\text{rad. s}^{-1})$	10^2	10^3	10^4	2.10^4	3.10^4	4.10^4	5.10^4	6.10^4	7.10^4	8.10^4	9.10^4	10^5
$D(\square)$ (cm^2/s)	35	34.99 65	34.65 35	33.65 38	32.11 01	30.17 24	28.00 00	25.73 53	23.48 99	21.34 15	19.33 70	17.50 00
H_{op} (cm)	0.01 08	0.010 8	0.010 8	0.010 5	0.010 2	0.009 8	0.009 4	0.008 9	0.008 4	0.008 0	0.007 6	0.007 1

Figure 4 gives the optimum thickness representation according to the frequency.

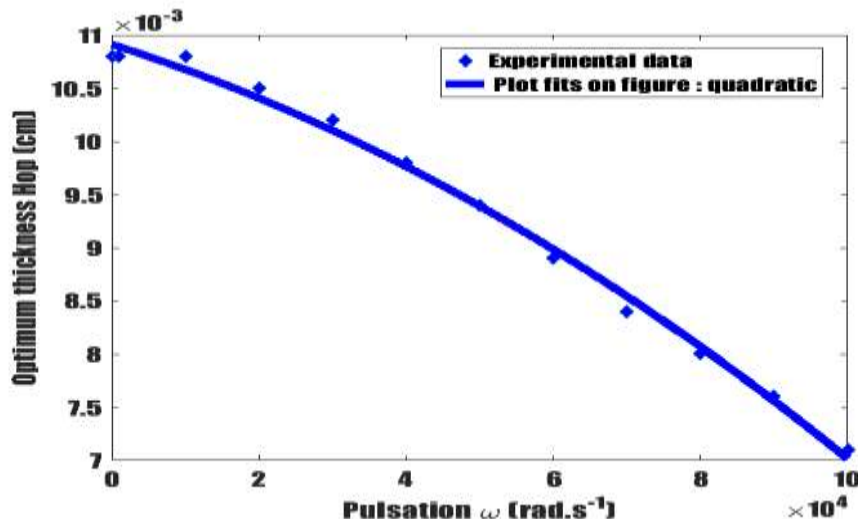


Figure 3: Optimum thickness versus pulsation.

The equation below makes possible to model the curve of figure 3, by the following expression:

$$\text{Hop(cm)} = -1.7 \cdot 10^{-13} \times \omega^2 - 2.2 \cdot 10^{-8} \times \omega(\text{rad. s}^{-1}) + 0.011 \quad (16)$$

Figure 4 gives the optimum thickness representation according to the effective diffusion coefficient $D(\omega)$.

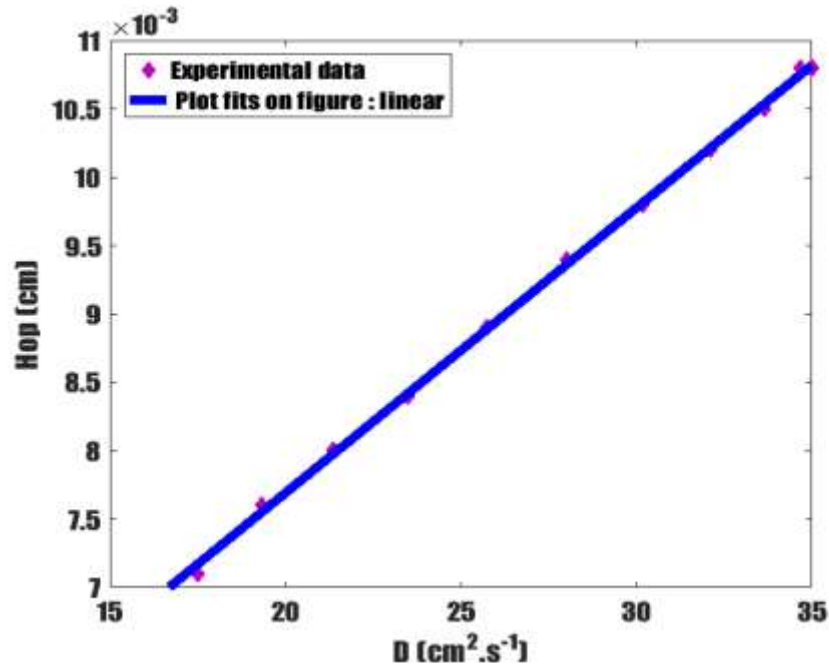


Figure 4:- Optimum thickness versus diffusion coefficient

The modeling equation of optimum thickness according to the effective diffusion coefficient $D(\omega)$ is given by:

$$\text{Hop(cm)} = 2.1 \cdot 10^{-4} \times D(\text{cm}^2 \cdot \text{s}^{-1}) + 0.0035 \quad (17)$$

Large frequencies induce a very short relaxation time for the photo carriers generated[43], therefore the density of the carriers is low and moves towards the junction [15, 17] creating a dead zone situation in the depth of the base of the photopile, whose rear side behaves like an ohmic contact due to $S_b(\omega)$ exponentially very high. Thus, large frequencies ($\omega\tau \gg 1$) accommodate thin thicknesses solar cell, for optimum operation. Low frequencies (static regime: $\omega\tau \ll 1$) allow carriers to relax to undergo new generations. Thus the density of the carriers is important in amplitude in the volume of the base of the solar cell, and leads to larger thicknesses [20]. This is why the optimum thickness required at the base of the solar cell decreases with the frequency of modulation of the incident light (Fig.3).

Similarly, a material with a high value of the diffusion coefficient of minority carriers could be used with large thicknesses of the base i.e. thick base solar cell (Fig. 4).

Conclusion:-

The effective diffusion coefficient $D(\omega)$ of minority carriers decreases with the frequency of modulation of the incident light on the base of the solar cell. Thus the actual $L(\omega)$ complex diffusion length is reduced with the increase in this frequency through Einstein's law.

The density of the excess load minority carriers in the base of the solar cell obtained by resolution of the continuity equation, decreases with the increase in frequency and its maximum amplitude moves towards the junction, leaving behind a dead zone, depopulated of charge carriers ($S_b(\omega)$) very important because the relaxation time is low compared to the frequency of arousal of multistral light.

The technique of determining the optimum thickness of the base through the graphic study of the expressions of the ac recombination velocity of minority carriers in the rear face, allowed to deduce the thickness H_{opt} for each frequency of modulation of the composite light.

The use of composite light for H_{opt} 's determination better reflects the actual operating conditions of the solar cell, and modulation allows the choice of the right thickness for its industrial development.

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