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RESEARCH ARTICLE

BIFACIAL ($N^+/P/P^+$) SILICON SOLAR CELL BASE THICKNESS OPTIMIZATION, WHILE ILLUMINATED BY THE REAR FACE WITH MONOCHROMATIC LIGHT OF SHORTWAVELENGTHS

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Abstract

The monochromatic absorption coefficient of silicon, inducing the depth of penetration of light into the base of the solar cell, is used through back surface recombination velocity expressions, to determine the optimum thickness necessary for the production of a large photocurrent. The absorption-generation-diffusion and recombination (bulk and surface) phenomena are taken into account in determining the optimum thickness of an n^+ -p-p^+ bifacial solar cell, for it manufacture process optimization.

Introduction:-

The determination of phenomelogic parameters in the crystalline silicon solar cell (n+/p/p+) is very important, for the understanding of physical mechanisms [1, 2, 3] which, consequently, makes it possible to develop increasingly efficient architectural structures [4-19]. These phenomelogical parameters [20, 21, 22] are specific to excess minority carriers in the semiconductors constituting the solar cell (n+/p/p+) and are denoted by:

1. Lifetime (τ)[23-28]; diffusion coefficient (D) [29, 30] and diffusion length (L) [31-39], as well as mobility (μ) [40, 41], connected by the relations of Einstein Mukolovich.
2. Surface recombination velocity[5]: (Se) in the emitter[9, 12, 13, 16], (Sf) at the interface (n+/p) that constitutes the junction or space charge region(SCR) [42-45], (Sb) at the interface (p/p+) [2, 43, 46] and (Sg) at the grain joints in the 3D model [47, 48].

The use of a monochromatic light of wavelength (λ), with a constant incident flow on the solar cell, makes it possible to obtain a spectral response in current of minority charge carriers.

This response is represented as a function of the inverse (α^{-1}) of the absorption coefficient, then analyzed and interpreted through a theory that makes it possible to extract the diffusion length of the minority charge carriers in the base of the solar cell [31, 49] with thickness (H).

This technique allows the choice of the wavelength range that indicates the depth of penetration of monochromatic light into the solar cell, which would exclude the effect of surface recombination (p/p+) [50] in the solar cell response.

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Decoupling [48, 50, 51, 52, 53] volume and surface recombination mechanisms is important in the assessment of the quality of the semiconductor, taking into account its geometric dimensions [1, 54, 55].

Some theoretical works [2, 43-47, 57, 58, 59] produced expressions of the recombination surface velocity (Sb) of minority carriers at the interface (p/p+). These expressions are dependent on the absorption coefficient ($\alpha(\lambda)$) of the (Si)material, the diffusion parameters (D, L) and the thickness (H) of the base.

These theoretical results lead to the determination of the optimum thickness of the base of the solar cell [60-63], placed under different conditions.

The objective of this work is the determination of the optimum thickness of the base of a bifacial solar cell, when it receives through the back side (p+), a monochromatic illumination with constant flow, allowing to extract a maximum of photocurrent from minority charge carriers.

Theory

The illuminated bifacial silicon solar cell by the rear face with a monochromatic light (α_λ), is presented on figure 1.

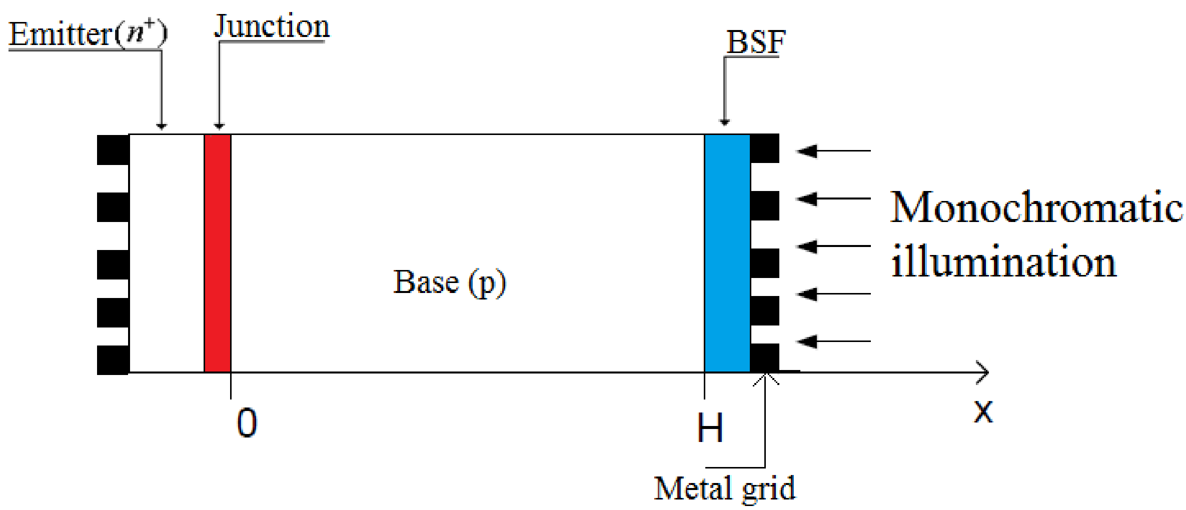

Figure 1:- Bifacial silicon solar cell illuminated by the rear.

Taking into account the phenomena of generation, recombination and diffusion, the excess minority continuity equation in the base under steady state is given by the following expression:

$$D \times \frac{\partial^2 \delta(x,\alpha_\lambda)}{\partial x^2} - \frac{\delta(x,\alpha_\lambda)}{\tau} + G(x,\alpha_\lambda) = 0 \tag{1}$$

Where:

x is absorption depth in the base of the solar cell

$\delta(x,\alpha_\lambda)$ is the excess minority carriers density generated in the base.

$G(x,\alpha_\lambda)$ is the electron-hole pairs generation rate at depth x in the base under monochromatic illumination. Its expression [6, 7, 33]is given by:

$$G(x,\alpha_\lambda) = \alpha_\lambda \times \varphi_\lambda \times (1-R_\lambda) \times \exp(-\alpha_\lambda (H-x)) \tag{2}$$

The optical parameters [64, 65, 66] are:

α_λ is monochromatic absorption coefficient of the silicon material for a wavelength λ

R_λ is monochromatic reflection coefficient

φ_λ is incident flow of monochromatic light,

The electrons diffusion coefficient (D) and diffusion Length (L) in the base are related to the lifetime(τ) by Einstein's relation as:

$$\tau = \frac{L^2}{D} \quad (3)$$

The resolution of equation (1) gives the expression of minority carrier's density in the following form:

$$\delta(x,\alpha_\lambda) = A \times ch\left(\frac{x}{L}\right) + B \times sh\left(\frac{x}{L}\right) + K(\alpha_\lambda) \times \exp\left(-\alpha_\lambda (H - x)\right) \quad (4)$$

With: $$K(\alpha_\lambda) = \frac{-\alpha_\lambda \times \varphi_\lambda \times (1 - R_\lambda) \times L^2}{D \times \left[\alpha_\lambda^2 \times L^2 - 1\right]} \quad (5)$$

The constants A and B are determined from the boundary conditions.

- **At the junction emitter-base (x = 0)**

$$\left.\frac{\partial \delta(x,\alpha_\lambda)}{\partial x}\right|_{x=0} = \frac{S_f}{D} \times \delta(0,\alpha_\lambda) \quad (6)$$

S_f represents the charge carriers recombination velocity at the junction imposed by both the external and internal(shunt resistance) charge and thus characterizes the operating point of the solar cell, varying from the open circuit to the short circuit condition[43, 44, 67].

- **At the rear face (x = H)**

$$\left.\frac{\partial \delta(x,\alpha_\lambda)}{\partial x}\right|_{x=H} = \frac{-S_b}{D} \delta(H,\alpha_\lambda) \quad (7)$$

S_b represents the minority carriers recombination velocity at the back surface. It is the consequence of the electric field created by the p/p+ junction and characterizes the high- low junction surface [43, 46, 47, 56-59].

Results And Discussions:-

Photocurrent density

The expression of the photocurrent density is defined by the following relation:

$$Jph(S_f,\alpha_\lambda) = q \times D \times \left[\frac{B(Sf,\alpha_\lambda)}{L} - K(\alpha_\lambda) \times \alpha_\lambda\right] \quad (8)$$

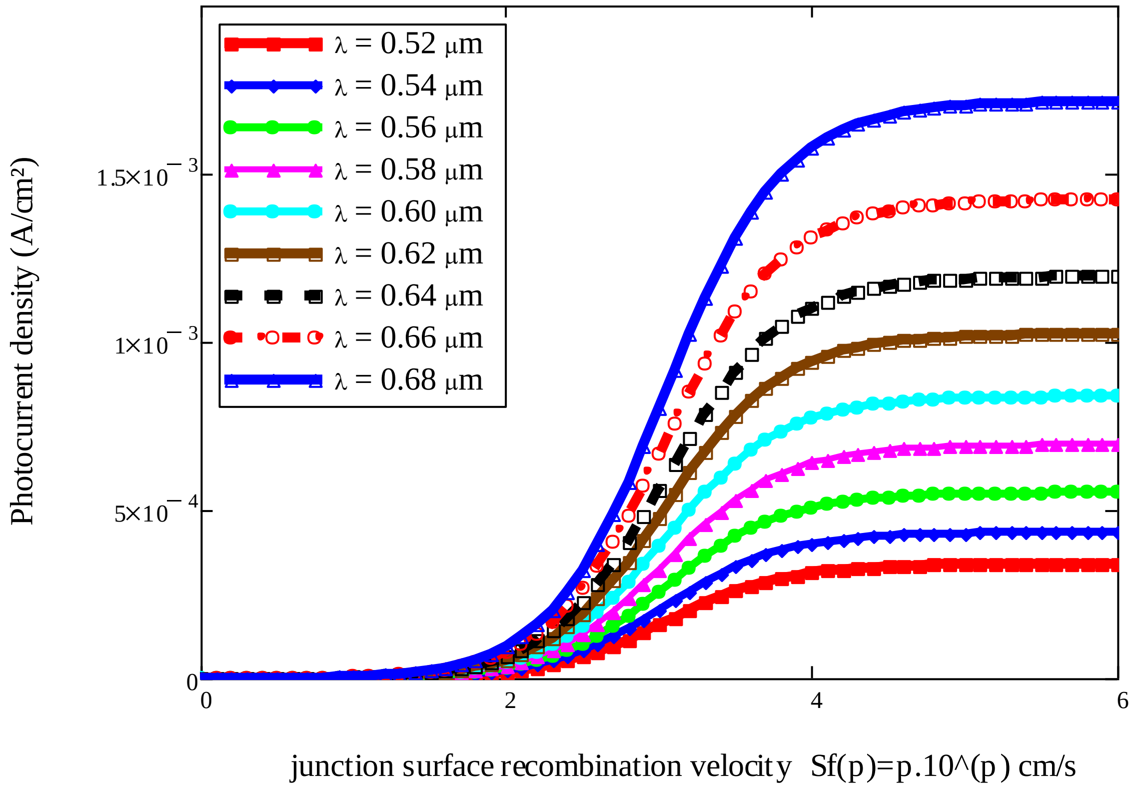

Figure 2:- shows the profile of the photocurrent density as a function of the recombination velocity at the junction for different low wavelength values (0. 5 µm <λ< 0. 7µm).

Figure 2 shows that the photocurrent density (Jph) is almost zero for recombination velocities at the junction (Sf) of less than 2.10^2 cm/s (open circuit situation). The photocurrent density is then increasing between 2.10^2 cm/s and 4.10^4 cm/s. Beyond the recombination velocity(Sf) greater than 4.10^4 cm / s the amplitude of the photocurrent density is maximum and constant (short circuit situation).

Back surface recombination velocity

The photocurrent density is constant for large recombination velocity values ofexcess minority carriers at the junction [42, 43, 44, 67].

$$\left.\frac{\partial Jph(Sf,\alpha_{\lambda})}{\partial Sf}\right|_{Sf\geq 5\times 10^{5}\,cm.s^{-1}} = 0 \qquad (9)$$

The resolution of this equation yields two solutions of the minority carrier's recombination velocity at the back surface [33, 43, 44, 46], and both depend on the thickness, and expressed as:

$$Sb0(H) = -\frac{D}{L}.\tanh\left(\frac{H}{L}\right) \qquad (10)$$

Sb0 is an intrinsic quantity depending on electronic parameters (D, L) [32, 45], whileSb1 depends onabsorption coefficient of monochromatic light for a given wavelength (λ).

$$Sb_1(H,\alpha(\lambda)) = \frac{D}{L}\cdot\left[\frac{L\cdot\alpha(\lambda) - \left(L\cdot\alpha(\lambda)\cdot ch\left(\frac{H}{L}\right) + sh\left(\frac{H}{L}\right)\right)e^{-\alpha(\lambda)\cdot H}}{\left(ch\left(\frac{H}{L}\right) + L\cdot\alpha(\lambda)\cdot sh\left(\frac{H}{L}\right)\right)e^{-\alpha(\lambda)\cdot H} - 1}\right] \qquad (11)$$

Solar cell optimum base thickness determination:
By comparing the two expressions of the recombination velocity of minority carriers on the back side in a graphic representation, with a double vertical axis [60-63], the optimum thickness (Hopt) of the base is obtained at the intercept point for each wavelength (Figure. 3).

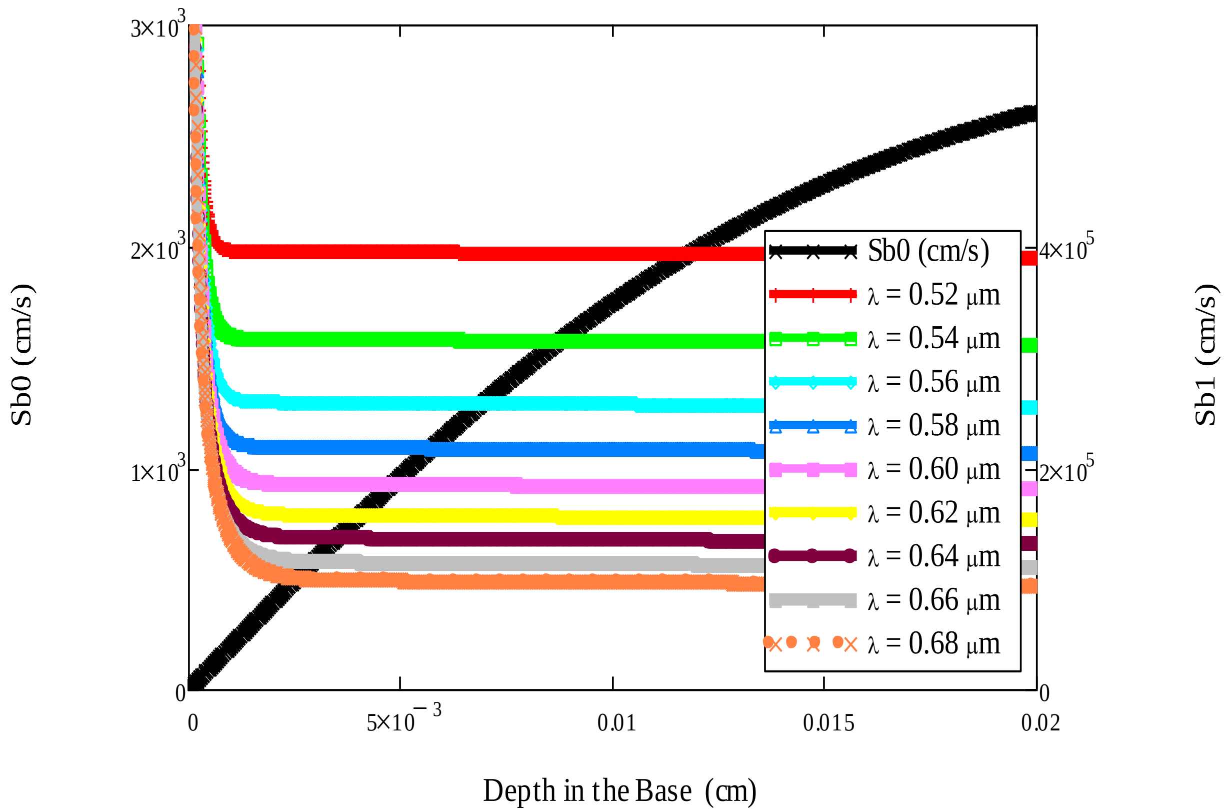

Figure 3:- The recombination velocity on the back side (Sb0(cm/s) and Sb1(cm/s) as a function of the thickness in the base for given wavelength values(0. 5 µm <λ< 0. 7µm).

Table. 1:- Optimum thickness obtained by the intercept points according to the value of the wavelength(0. 5 µm <λ< 0. 7µm).

λ (µm)	λ = 0.52	λ = 0.54	λ = 0.56	λ =0.58	λ = 0.60	λ= 0.62	λ= 0.64	λ=0.66	λ=0.68
Hopt(cm)	0.0118	0.0087	0.0069	0.0056	0.0048	0.0040	0.0035	0.0029	0.0025
Sb0(cm/s)	1966.9	1568	1290.3	1070.7	928.52	787.96	680.64	572.88	505.57
Sb1(cm/s).10^2	3933.9	3136	2580.5	2141.4	1857	1575.9	1361.3	1145.8	1011.9

The table allows the representation of the optimum thickness as a function of the wavelength, on Figure.3.

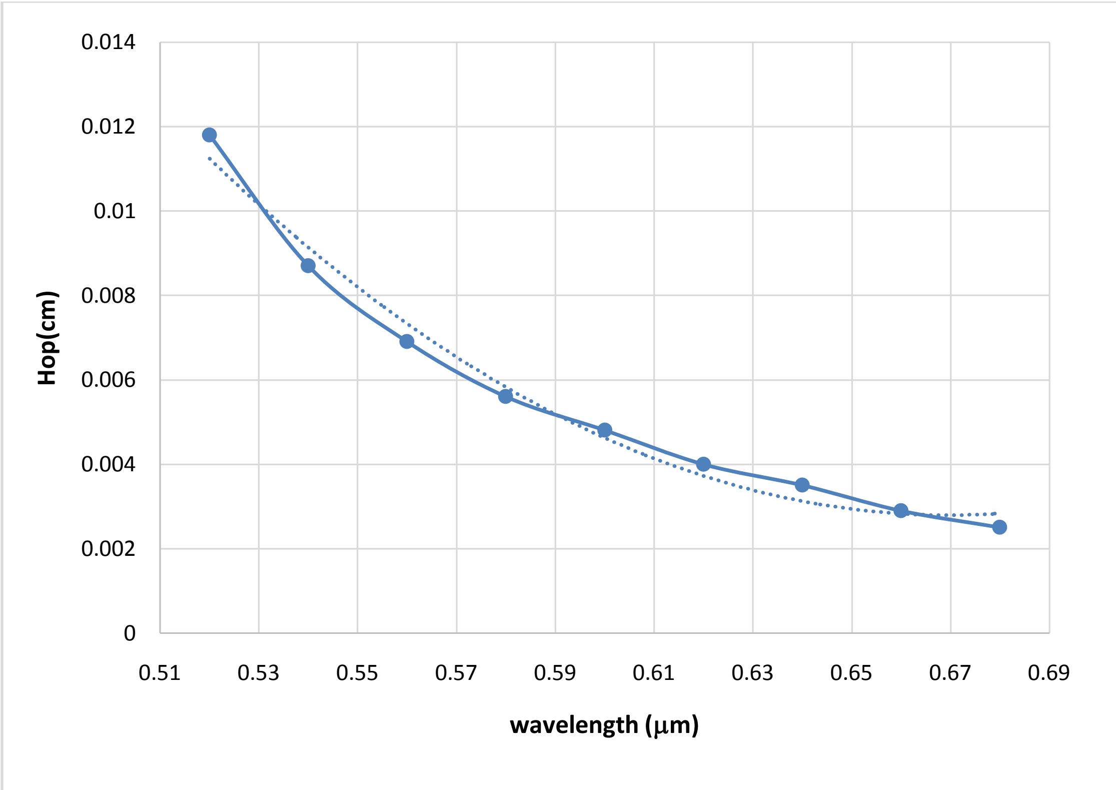

Figure. 4:- Base optimum thickness versus wavelength.

The optimum thickness is a decreasing function of the wavelength and the characteristic equation of the curve is as follows:

$$Hopt(cm) = 0{,}3766\lambda^2 - 0{,}5044\lambda + 0{,}1717 \qquad (12)$$

The results obtained from the optimum thickness of the base, for this spectrum of wavelengths(0. 5 µm <λ< 0. 7µm), illuminating the back side, shows the interest of thin film in the development of solar cells [10, 55].Thickness is a decreasing function already observed on solar cells by varying manufacturing parameters, such as the doping rate [63, 68] and those of external physical parameters such as: The irradiation flux by charged particles [69], the applied magnetic field [70], the temperature [71], the absorption coefficient of mono or polychromatic illumination with constant incident flow [60], the frequency of modulation [62] of the illumination, the combination of the magnetic field and temperature [72].

Conclusion:-

This study focused on the region of the base of the bifacial silicon solar cell (n+/p/p+) illuminated by its back face (p+), showed the influence of the wavelength on the optimum thickness of the base.The expression of the density of the minority carriers as a function of the depth of the base, made it possible to represent the photocurrent, according to the recombination velocity of the minority carriers at the junction, for different operatingpoints of the solar cell, in particular from the open circuit to the short circuit.

At the large (Sf) values, the analytical expressions of minority carriers' recombination velocity (Sb) on the back side were established.

The graphical study as a function of (H) of the expressions of the minority carriers'recombination velocity on the rear side, led to the determination of the optimum thickness of the base, which decreases with wavelength.

Thus the technique of optimizing the thickness of the base presented here taking into account the depth of penetration (wavelengths), would reduce the amount of material (If) necessary for the manufacture of crystalline solar cells in thin films, dedicated to a specific application of illumination by the back side and would also reduce the manufacturing cost and the resale price.

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