Available online www.jsaer.com

Journal of Scientific and Engineering Research, 2023, 10(5):34-43

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Localization of the (p/p+) junction in the (p) base of an (n+-p-p+) silicon solar cell under front face (n+) monochromatic illumination

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Abstract This work presents the determination of the optimum base thickness (n+/p/p+) silicon solar cell, illuminated by its front face (n +). By the exploitation of the curves of back surface recombination velocity expressions (Sb (H,α)), through the point (Hopt) of zero derivative. Two expressions F(H) and G(H, α), forming a transcendental equation, are deduced and, whose graphical representation leads to (Hopt), which indicates location of the (p/p+) junction. It is then modeled according to the absorption coefficient (α) which shows the possibility of achieving the solar cell at reduced thickness, by the location of the junction (p / p +) and save material (Si).

Keywords Silicon Solar cell, Recombination velocity, Absorption coefficient, Base optimum Thickness

1. Introduction

Several techniques for characterizing (n+/p/p+) solar cell [1-3] have been developed to improve photoconversion efficiency

These techniques [4-9] keep the solar cell under darkness or under mono or polychromatic illumination, of constant amplitude, pulsed or frequency modulation and allow the determination of phenomelogical

of minority carriers [24-30], in particular (Se) on the surface of the emitter, (Sf) at the emitter-base junction, (Sb) on the rear side of the base and (Sg) at the grain boundaries in three-dimensional models

These parameters are influenced by the optical parameters [31, 32], monochromatic absorption (α(λ)) of the material, and the regime of operation of the solar cell which can be static[5-9] or frequency dynamic [10, 12], or transient[4, 20] for a given choice of the operating point [33-35]. The architecture of the solar cell [1-3, 36-38], plays an important role:

- In the capture of the maximum illumination flux by the mono or bifacial structure, and for multi vertical junctions connected in parallel or in series (JVS, JVP ....)
- Through the dimensions of the different zones [39-42] that constitute the solar cell, in particular, the transmitter, the space charge zone and the base.

This study deals with the localization of the (p/p^+)junction that characterizes the (p) base thickness of the $(n^+/p/p^+)$ silicon solar cell under constant flow monochromatic illumination, by the front face (n^+), through phenomelogical parameters [42-44]. Thus by solving the diffusion equation relating to the density of the minority charge carriers in the base, the photocurrent density Jph (Sf, Sb, D, H α) is obtained and makes it possible to deduce the expression Sb (D, H α) from the recombination rate of the minority carriers on the back side (p/p^+) [25, 26]. The exploitation of the curve of the recombination velocity of the minority charge carriers Sb(H, α)[25, 26, 45, 46], as a function of (H), through the point (Hopt) of zero derivative resulting in two expressions F(H, D) and G(H, D, α), forming a transcendental equation [47, 48]. Their graphical representation versus thickness (H), gives an intersection that leads to the optimum thickness (Hopt), location of the (p/p^+) BSF, for a given absorption coefficient (α).

2. Theory

The crystalline silicon solar cell (n^+-p-p^+) illuminated by the front (emitter), by monochromatic light, with constant flux is shown in the **figure. 1**, by its different regions.

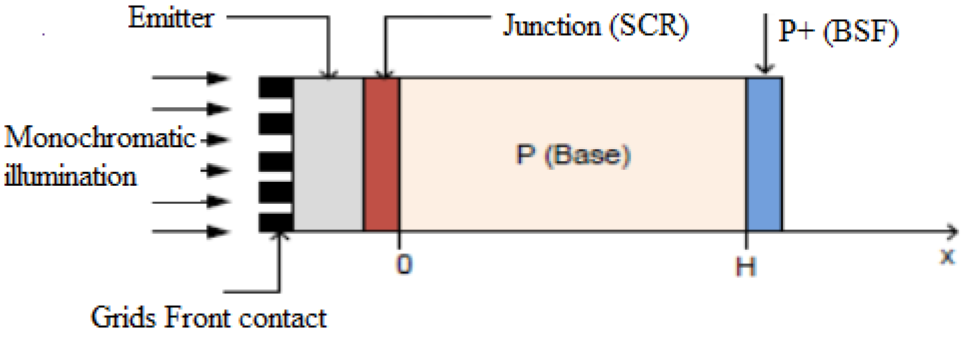

Figure 1: Schematic representation of front illuminated silicon solar cell

2.1. Continuity equation relating to the density δ(x) of minority carriers in the base:

$$D\frac{\partial^2(x)}{\partial x^2} - \frac{\delta(x)}{\tau} + G(x) = 0 \quad (1)$$

D and τ, respectively, are the diffusion coefficient and the lifetime of excess minority carriers, related by the Einstein relation: $L^2 = D\,\tau$.

The generation rate of minority carriers is expressed by: $g(x) = \alpha I_0(1-R)\,e^{-\alpha x}$ (2)

The solution of the diffusion equation is given in the following form:

$$\delta(x,\alpha(\lambda)) = A\cosh(\frac{x}{L}) + B\sinh\left(\frac{x}{L}\right) - \frac{\alpha I_0(1-R)L^2}{D(\alpha^2L^2-1)}e^{-\alpha x} \quad (3)$$

Where constants A and B are determined from the following boundary conditions:

$$\left.\frac{\partial\delta(x,\alpha(\lambda)}{\partial x}\right)_{x=0} = \frac{SF}{D}\delta(0,\alpha(\lambda)) \quad (4)$$

$$\left.\frac{\partial\delta(x,\alpha(\lambda))}{\partial x}\right)_{x=H} = -\frac{SB}{D}\delta(H,\alpha(\lambda)) \quad (5)$$

Sf and Sb denote respectively the recombination velocities of minority carriers at the junction and at the rear side of the base [25-30].

2.2. Expression Jph of photocurrent density:

It is deduced from the density δ(x) of the minority carriers in the base of the solar cell, in the form:

$$J_{ph}(Sf,Sb,H,\alpha) = q.D\frac{\partial\delta(x,Sf,Sb,H,,\alpha)}{\partial x}\Big|_{x=0} \quad (6)$$

2.3. Expression (Sb) of the recombination velocity of minority carriers on the rear side:

To obtain the expression Sb of the recombination velocity on the back side, the expression of the photocurrent density is derived with respect to Sf, (when Sf tends to large values). Indeed for large values of Sf, the photocurrent density has a zero gradient (constant short-circuit current density), this makes it possible to write [25-30, 49] :

$$\left[\frac{\partial Jph}{\partial SF}\right] = 0 \quad (7)$$

The solution of this equation gives two expressions of the recombination velocity Sb of the minority carriers on the back side of the base, one of which Sb1 depends only on the electronic parameters of the base and the other Sb2 depends in addition to the parameters of the base, the absorption coefficient (α), wavelength dependent with the incident illumination. The expressions are as follows:

$$Sb1 = -\frac{D}{L}th\left(\frac{H}{L}\right) \quad (8)$$

This solution is independent of the wavelength λ for a scattering length assumed to be wavelength invariant and reduces to Sb = -D/L for a thick solar cell (H >>L). It is thus assimilated to the diffusion velocity.
The second is given by:

$$Sb2(H,\alpha(\lambda)) = D\cdot\frac{\alpha(\lambda)\cdot\left(\cosh\left(\frac{H}{L}\right)\cdot\exp(-\alpha(\lambda)\cdot H)-1\right)+\frac{1}{L}\cdot\sinh\left(\frac{H}{L}\right)\exp(-\alpha(\lambda)\cdot H)}{1-\left(\cosh\left(\frac{H}{L}\right)+\alpha(\lambda)\cdot L\cdot\sinh\left(\frac{H}{L}\right)\right)\cdot\exp(-\alpha(\lambda)\cdot H)} \qquad (9)$$

The latter is a combination of diffusion rate and generation (because containing the term of the absorption coefficient). It can lead to Sb2 = α.D, which is a generation velocity (H >>1/α and H >>L) [25].

3. Results

1) The density δ (x) of the minority carriers is represented (Figures. 2 and 3) as a function of the depth (x) in the base of the solar cell in short circuit and under monochromatic illumination for different absorption coefficient values α(λ).

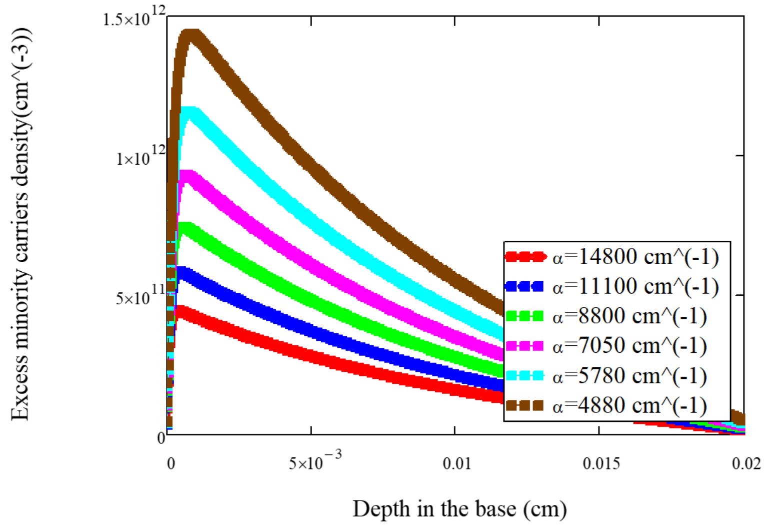

Figure 2: Density of minority carriers as a function of depth in the base for large values of the absorption coefficient: $b = 4.10^4 cm/s$ *, D=37 cm²/s L=0.011 cm,* $\tau = 3.10^{-6}s$

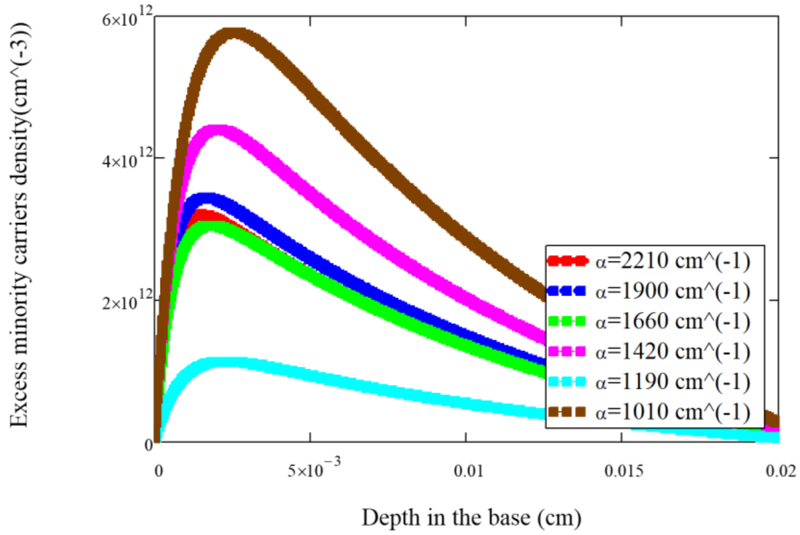

Figure 3: Density of minority carriers as a function of depth in the base for average values of the absorption coefficient: $b = 4.10^4 cm/s$, D =37 cm²/s L=0.011 cm, $\tau = 3.10^{-6} s$

3) Photocurrent density profile versus (Sf) for different values of the absorption coefficient is given on figures. 4 and 5.

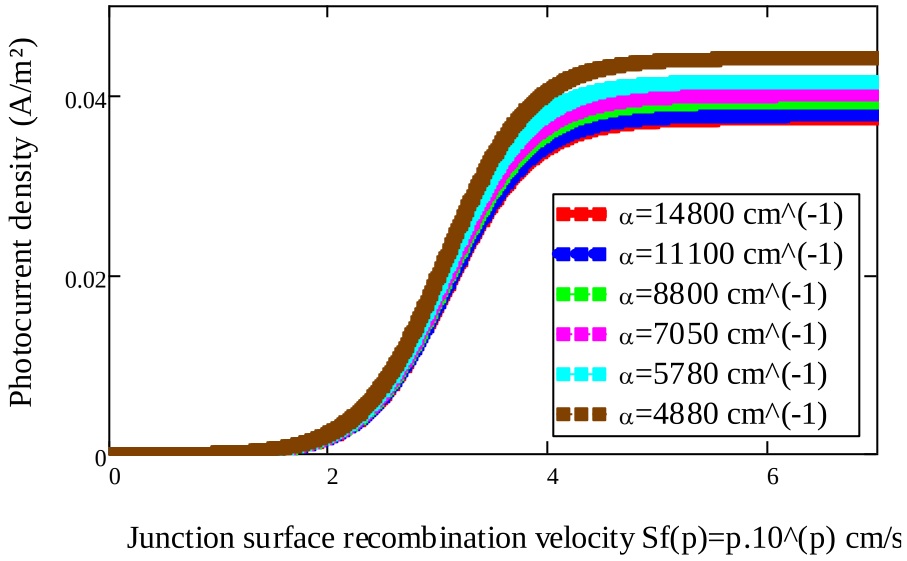

Figure 4: Density of photocurrent as a function of depth in the base for average values of the absorption coefficient: $Sb = 4.10^4 cm/s$, D=37cm²/s L=0.011 cm, $\tau = 3.10^{-6} s$

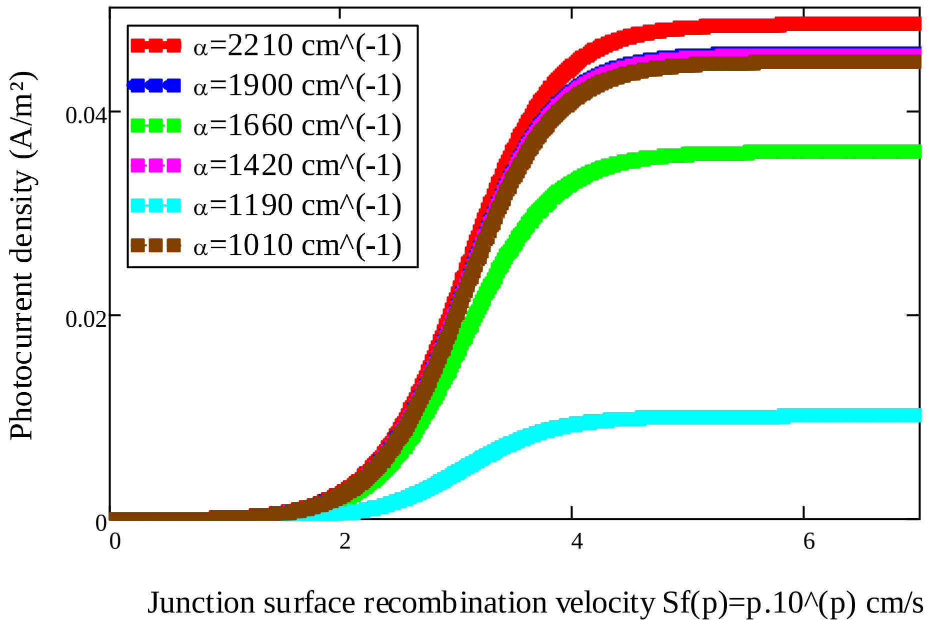

Figure 5: Photocurrent density as a function of recombination velocity (Sf) at junction for different absorption coefficient values: $Sb = 4.10^4 cm/s$, D=37cm²/s L=0.011 cm, $\tau = 3.10^{-6} s$

2) Graphic technique for determining (Hopt) of the base under monochromatic illumination α(λ)

The zero derivative of the expression (Sb) of the recombination velocity of minority carriers on the back side, with respect to (H) [46-48], is written as:

$$\frac{\partial Sb_2}{\partial H} = 0 \quad (10)$$

$$F(H) = \tanh\left(\frac{H}{L(T)}\right) \ (11) \ and \ \ G(H,\alpha) = \frac{1}{\alpha . L} . \left(1 - \frac{e^{-\alpha . H}}{\cosh\left(\frac{H}{L}\right)}\right) \quad (11)$$

Figure. 6 produces F(H) and G(H,α) representations versus base depth, for large α values at T = 300K, for medium absorption coefficient values.

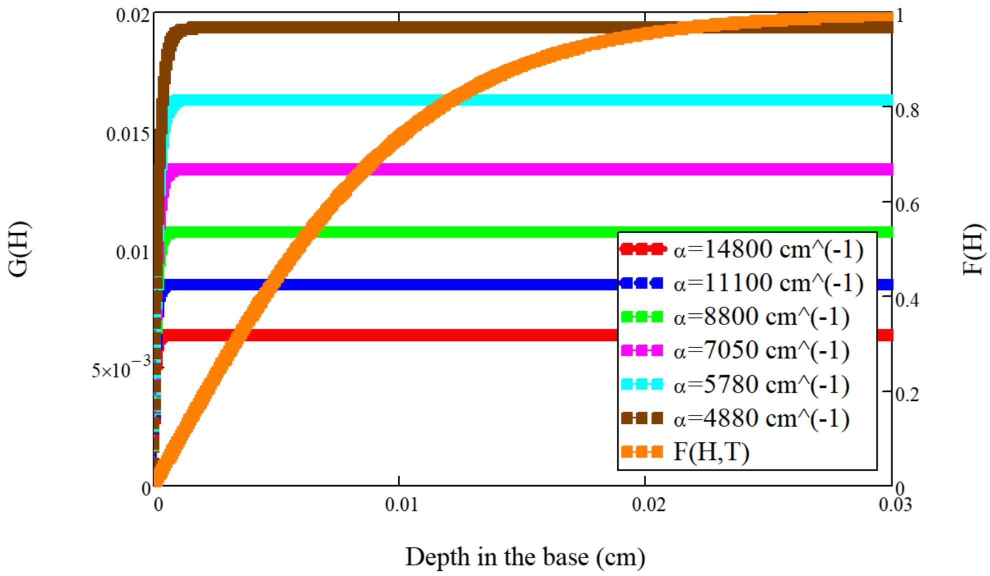

Figure 6: F(H) and G(H,α) representation versus base depth, for large α values

The obtained results of optimum base thickness is given in **table. 1**.

Table 1: Optimum base thickness for large absorption coefficient values

α	14800	11100	8800	7050	5780	4880
Hopt (cm)	0.00366	0.00488	0.00642	0.0086	0.01221	0.02209

Figure. 7, is the plot of optimum base thickness (Hopt) versus absorption coefficient (α).

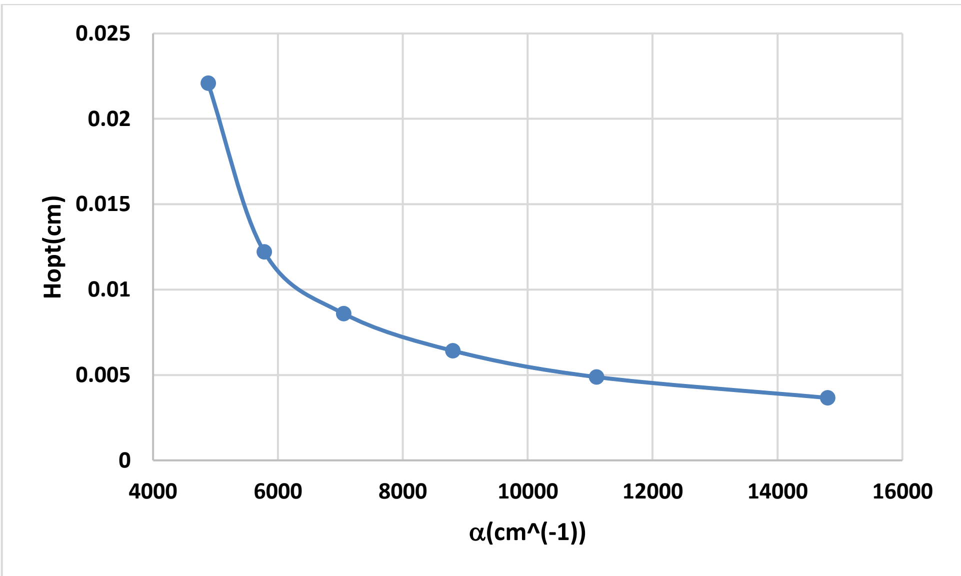

Figure 7: Plot of optimum base thickness Hopt versus large α values.

Figure. 8 produces F(H) and G(H, α) representations versus base depth, for for medium absorption coefficient (α) values at T = 300K, and the curve is modeled according to the following relationship:

$$H_{op}(cm) = 3.10^{-10}\alpha^2 - 7.10^{-6}\alpha + 0,048 \quad (12)$$

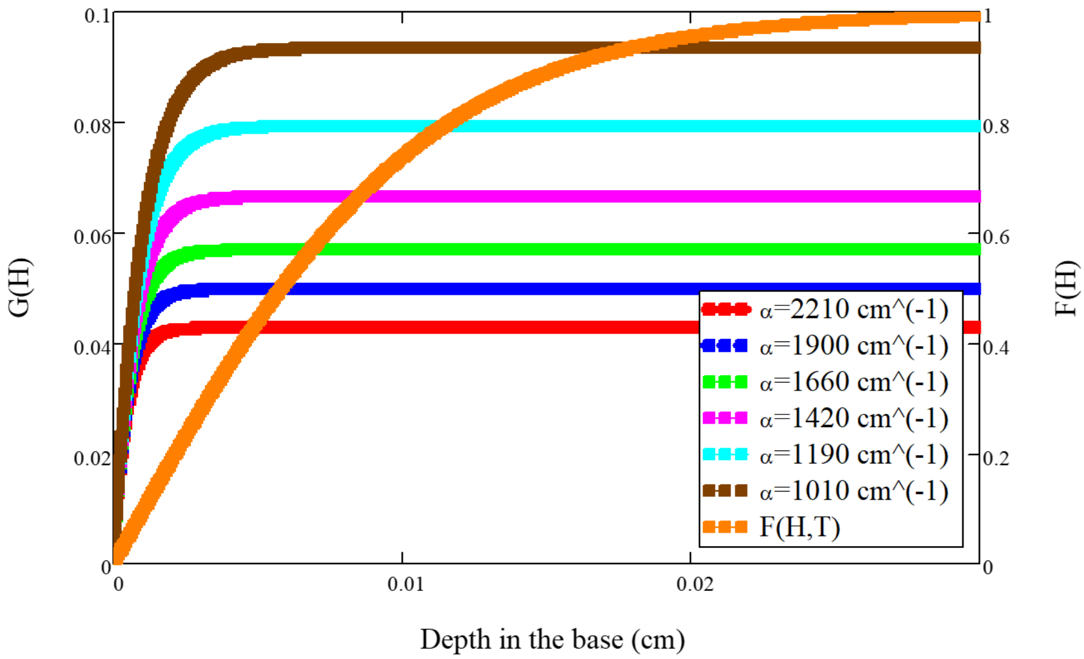

Figure 8: Plot of F(H) and G(H, α) versus base depth

Table 2: Base optimum thickness for medium absorption coefficient values

α	2210	1900	1660	1420	1190	1010
Hopt (cm)	0.0049	0.00589	0.00696	0.00865	0.0114	0.01858

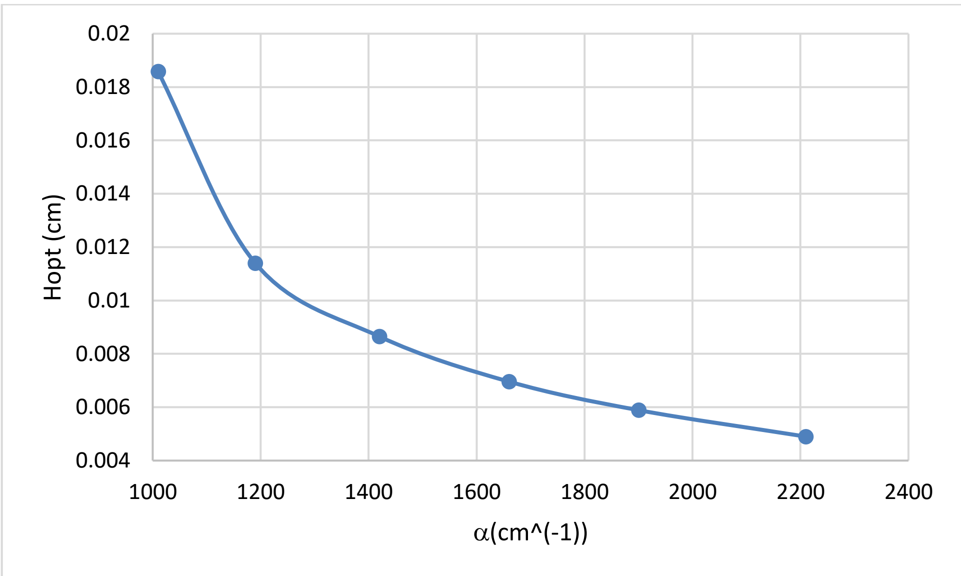

Figure 9: Plot of optimum base thickness Hopt versus α

The curve is modeled according to the following relationship:

$$H_{op}(cm) = 10^{-8}\alpha^2 - 5.10^{-5}\alpha + 0,0558 \quad (13)$$

Figures 7 and 9 show a decrease in optimum thickness with an increase in the absorption coefficient for the two areas studied. The location of the back surface field (p/p+) depends on the absorption coefficient. For high values of the absorption coefficient, it will be placed at a shallow depth in the base, thus constituting thin thickness solar cells [53- 56]. Thus, from a given absorption coefficient, the optimum thickness adequate for a solar cell could be chosen in order to save material (Si) and consequently reduce the cost of manufacturing and reselling solar cells.

Conclusion

The study of the base region of the silicon solar cell, for large and medium values of the absorption coefficient, was made on:

- the density of minority carriers as a function of the depth of the base of the short-circuited solar cell.
- the photocurrent as a function of the recombination velocity of the minority carriers at the junction.

The cancellation of the derivative of the expression of the recombination velocity in the back face, with respect to the depth of the base, gave two expressions, constituting a transcendent equation. One is dependent on the absorption coefficient and the other on intrinsic parameters. Their graphical representation led to the determination of the optimum thickness of the base of the solar cell under monochromatic illumination of absorption coefficient (α).

Thus the technique of optimizing the thickness of the base of the silicon solar cell, presented here, taking into account the depth of penetration of the incident light, would make it possible to:

- locate the position of the zone (p^+) inducing the Back Surface Field
- reduce the amount of material (Si) needed to manufacture solar cells
- reduce also the cost of manufacture and the resale price

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