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### RESEARCH ARTICLE

#### OPTIMUM THICKNESS DETERMINATION TECHNIQUE AS APPLIED TO A SERIES VERTICAL JUNCTION SILICON SOLAR CELL UNDER POLYCHROMATIC ILLUMINATION: EFFECT OF IRRADIATION

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#### Abstract

The study of an  $n^+p-p^+$  type silicon solar cell with vertical junction series illuminated by polychromatic light and under irradiation was realized under steady state. The aim of the work is to determine the optimum thickness of this type of solar cell from the expressions of the back surface recombination velocity ( $S_b$ ) obtained by calculating the derivative of the photocurrent density ( $J_{ph}$ ) with respect to the recombination velocity at the junction ( $S_f$ ) which tends to large values, translating the short circuit situation. Correlations between the optimum thickness, the irradiation energy flow ( $\phi_p$ ) and the intensity of the damage coefficient ( $kl$ ) have been established by a mathematical relationship.

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#### Introduction:-

Various studies have focused on determining the optimum thickness of the base of the solar cell as limiting efficiency. It depends on several factors, including:

The type of solar cell such as: horizontal junction [1], multiple vertical junction [2] of parallel type [3] [4] or series [5].

The operating mode and the illumination (monochromatic or polychromatic) of the solar cell that can be maintained in regimes as:

1. steady [6] [7] [8],
2. transient dynamic [9] [10] [11] [12],
3. frequency dynamic [13] [14].

#### Influences from the external environment :

electric field [15] [16],

#### The applied external conditions, such as:

1. magnetic field [15], [16], [17], [18],
2. temperature [18], [19],
3. irradiation of charged particles [20], with ( $\phi_p$ ) flux and ( $kl$ ) intensity.

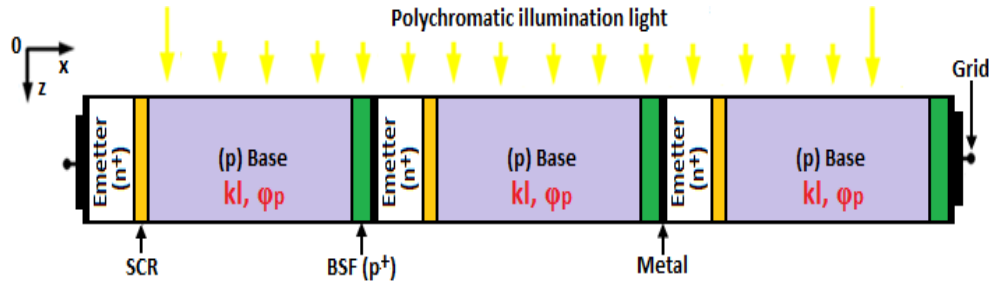
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Among the previous techniques [ 8], [14], this work will apply the technique for optimizing the thickness of the base [17],[18], [20],[21] on a silicon solar cell with vertical junction series under polychromatic illumination and under irradiation. In this one, the optimum thickness ( $H_{opt}(kl, \phi_p)$ ) is obtained through the expressions (Sb) of back surface recombination velocity of excess minority carriers [22].

**Theory:**

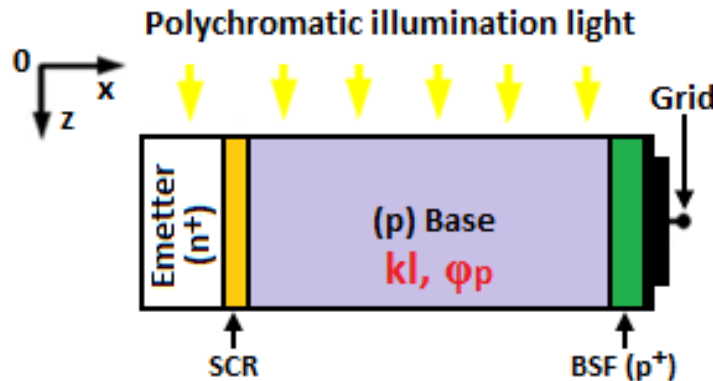
The structure of the series vertical junction solar cell, illuminated by polychromatic light and under irradiation is represented by figure 1 below [2], [4],[5], [23].



**Figure 1:-** Vertical series junction silicon solar cell to the  $n^+ - p - p^+$  type under irradiation and polychromatic illumination.

The incidental polychromatic illumination is parallel to the surface of the space charge region (SCR), which separates the emitter ( $n^+$ ) from the base ( $p$ ). The zone ( $p^+$ ) allows the creation of a rear electric field area that allows the minority carriers to be returned towards the space charge region, and then to be collected. This solar cell unit is connected to several others in series, in order to increase the phototension.

Figure 2 shows the structure of a unit cell of the vertical series junction solar cell under polychromatic illumination and under irradiation.



**Figure 2:-** Unit vertical series junction solar cell under monochromatic illumination and irradiation.

The continuity equation governing the phenomena of generation, diffusion and recombination of excess minority carriers in the base of the solar cell under both irradiation and polychromatic illumination, is defined by the expression below:

$$D(kl, \phi_p) \frac{\partial^2 \delta(x, z, kl, \phi_p)}{\partial x^2} - \frac{\delta(x, z, kl, \phi_p)}{\tau} + G(z) = 0 \tag{1}$$

$\delta(x, z, kl, \phi_p)$  represents the excess minority carrier density in the base of the solar cell at the position, dependent of  $\phi_p$  the irradiation energy flux, and  $kl$  the damage coefficient intensity.

$D(kl, \phi_p)$  is the diffusion coefficient of excess minority carriers in the base of the solar cell.

and  $\tau$  is the lifetime of excess minority carriers in the base defined by the following Einstein relationship:

$$\tau = \frac{L^2(kl, \phi_p)}{D(kl, \phi_p)} \quad (2)$$

with  $L(kl, \phi_p)$  the excess minority carriers diffusion length in the base and also both, irradiation energy flux ( $\phi_p$ ) and damage coefficient intensity ( $kl$ ) dependent. It is related to the diffusion length ( $L_0$ ) without irradiation by the following empirical relation [24] [25] [26]:

$$L(kl, \phi_p) = \frac{1}{\sqrt{\left(\frac{1}{L_0^2} + kl \times \phi_p\right)}} \quad (3)$$

Where:

$L_0$  is the diffusion length of the excess minority carriers in the base before irradiation,

$\phi_p$  is the irradiation energy flux, and  $kl$  the damage coefficient intensity.

$G(z)$  is the carrier's generation rate for a polychromatic illumination in the base. Its expression, for a series vertical junction solar cell is given by:

$$G(z) = n \times \sum_{i=1}^3 (a_i \times \exp(-b_i \times z)) \quad (4)$$

The resolution of continuity equation (1) gives the expression of the excess minority carrier density in the base as:

$$\delta(x, z, kl, \phi_p) = A \times \operatorname{ch}\left(\frac{x}{L(kl, \phi_p)}\right) + B \times \operatorname{sh}\left(\frac{x}{L(kl, \phi_p)}\right) - \sum_{i=1}^3 (K(kl, \phi_p) \times \exp(-b_i \times z)) \quad (5)$$

With :

$$K(kl, \phi_p) = \frac{a_i \times n \times L^2(kl, \phi_p)}{[L^2(kl, \phi_p) \times b_i^2 - 1] \times D(kl, \phi_p)} \quad (6)$$

The coefficients A and B are determined from the boundary conditions:

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

$$\left. \frac{\partial \delta(x, z, kl, \phi_p)}{\partial x} \right|_{x=0} = \frac{S_f}{D(kl, \phi_p)} \times \delta(0, z, kl, \phi_p) \quad (7)$$

$S_f$  is the recombination velocity of the minority carriers at the junction imposed by the external charge and thus characterizes the operating point of the solar cell varying from the open circuit to the short-circuit [27] [28] [29].

**At the rear face ( $x = H$ ):**

$$\left. \frac{\partial \delta(x, z, kl, \phi_p)}{\partial x} \right|_{x=H} = \frac{-S_b}{D(kl, \phi_p)} \times \delta(H, z, kl, \phi_p) \quad (8)$$

$S_b$  is the recombination velocity of the excess minority carriers on the back surface [22], [30], [31], [32]. It is the consequence of the electric field created by the p/p+ (low-high) junction and characterizes the behavior of excess minority carriers at the base-rear junction [33].

The photocurrent density is defined by the following relation:

$$J_{ph}(S_f, kl, \phi_p) = q \times D(kl, \phi_p) \times \left. \frac{\partial \delta(x, z, kl, \phi_p)}{\partial x} \right|_{x=0} \quad (9)$$

Where  $q$  is the electrical charge of the electron.

At high recombination velocity of excess minority carriers at the junction ( $S_f$ ), the photocurrent density is constant and corresponds to ( $J_{sc}$ ) the short-circuit current density. This yields to establish the following equation :

$$\left. \frac{\partial J_{ph}(S_f, kl, \phi_p)}{\partial S_f} \right|_{S_f \geq 4 \times 10^4 \text{ cm.s}^{-1}} = 0 \tag{10}$$

The resolution of the equation (10) gives two expressions of excess minority carriers recombination velocity at the back surface [17] [27], respectively  $Sb1(H, kl, \phi_p)$  and  $Sb2(H, kl, \phi_p)$ , written below.

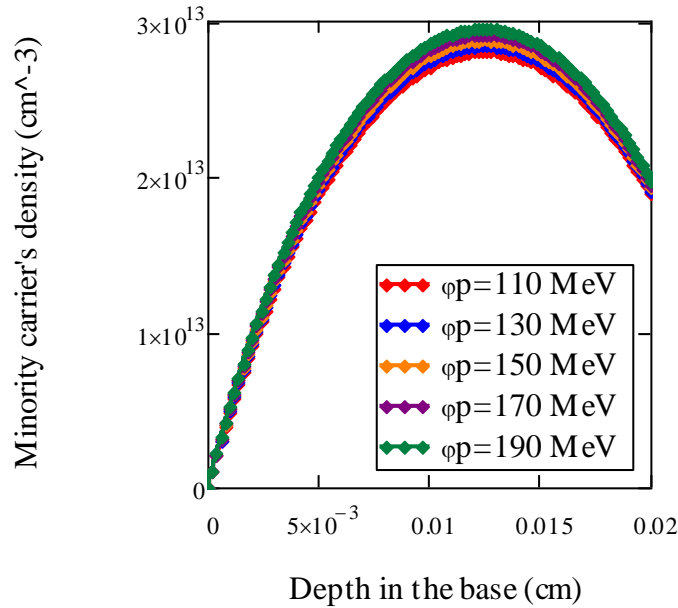
$$Sb1(H, kl, \phi_p) = -\frac{D(kl, \phi_p)}{L(kl, \phi_p)} \times \tanh\left(\frac{H}{L(kl, \phi_p)}\right) \tag{11}$$

$$Sb2(H, kl, \phi_p) = \frac{D(kl, \phi_p)}{L(kl, \phi_p)} \times \left[ \frac{\sinh\left(\frac{H}{L(kl, \phi_p)}\right)}{1 - \cosh\left(\frac{H}{L(kl, \phi_p)}\right)} \right] \tag{12}$$

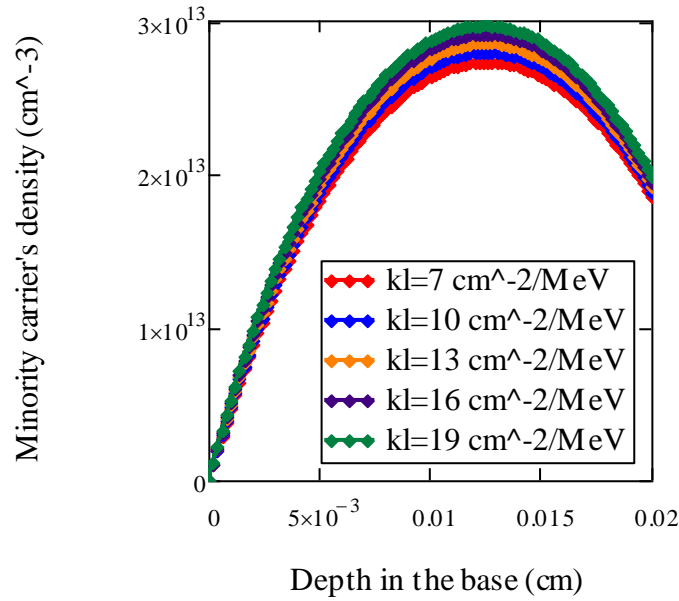
**Results and Discussions:-**

**Minority Carrier’s Density:**

Figures 3 and 4 show the behavior of the minority carriers density in the base of the solar cell, operating in short-circuit conditions, for both, irradiation energy flow ( $\phi_p$ ) and damage coefficient intensity ( $kl$ ) respectively.



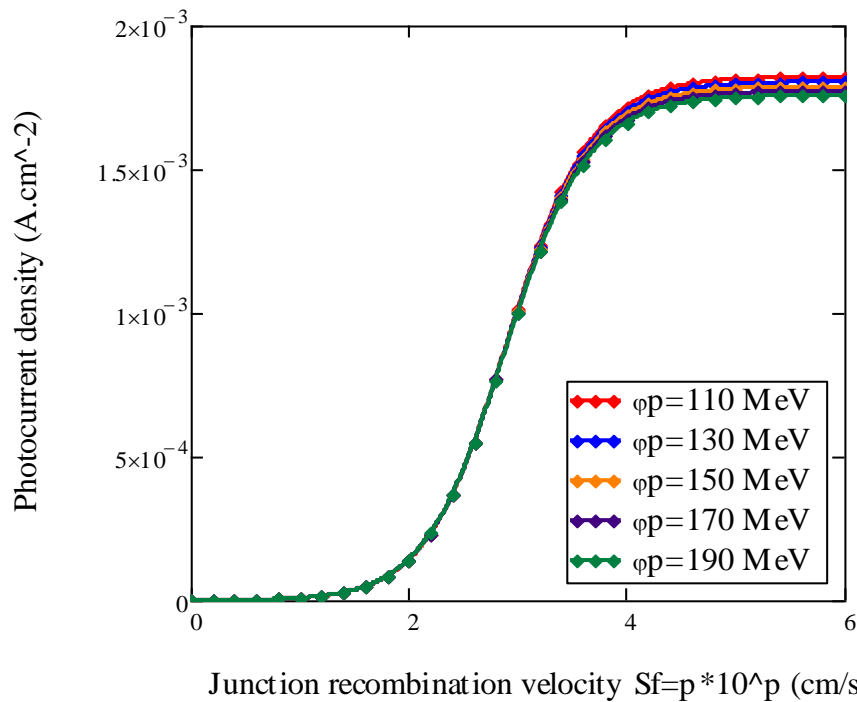
**Figure 3:-** Minority carrier’s density versus depth in the base for different irradiation energy flow values with  $S_f=6 \times 10^6 \text{ cm/s}$ ,  $Sb2=f(kl, \phi_p) \text{ cm/s}$ ,  $kl=16 \text{ cm}^{-2}/\text{MeV}$ ,  $z=0.015 \text{ cm}$ ,  $D(kl, \phi_p)=26 \text{ cm}^2/\text{s}$ .



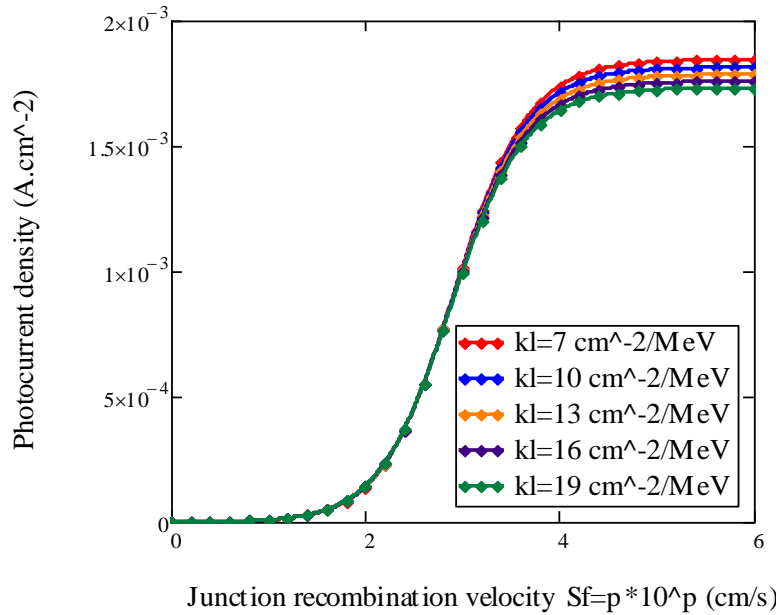
**Figure 4:-** Minority carrier's density versus depth in the base for different intensity damage coefficient values with  $S_f=6 \times 10^6$  cm/s,  $S_{b2}=f(k_l, \phi_p)$  cm/s,  $\phi_p=170$  MeV,  $z=0.015$  cm,  $D(k_l, \phi_p)=26$  cm<sup>2</sup>/s.

**Photocurrent density:**

Figures 5 and 6 show the shape of photocurrent density as a function of excess minority carriers recombination velocity at the junction for different values of the irradiation energy flow ( $\phi_p$ ) and the intensity of the damage coefficient ( $k_l$ ). The photocurrent density is more sensitive to irradiation for large junction recombination value. At low junction recombination velocity, the solar cell is under open circuit, while at large value it is in short circuit condition. Thus the junction recombination velocity indicates the solar cell operating point, as gradient of excess minority carriers at the junction.

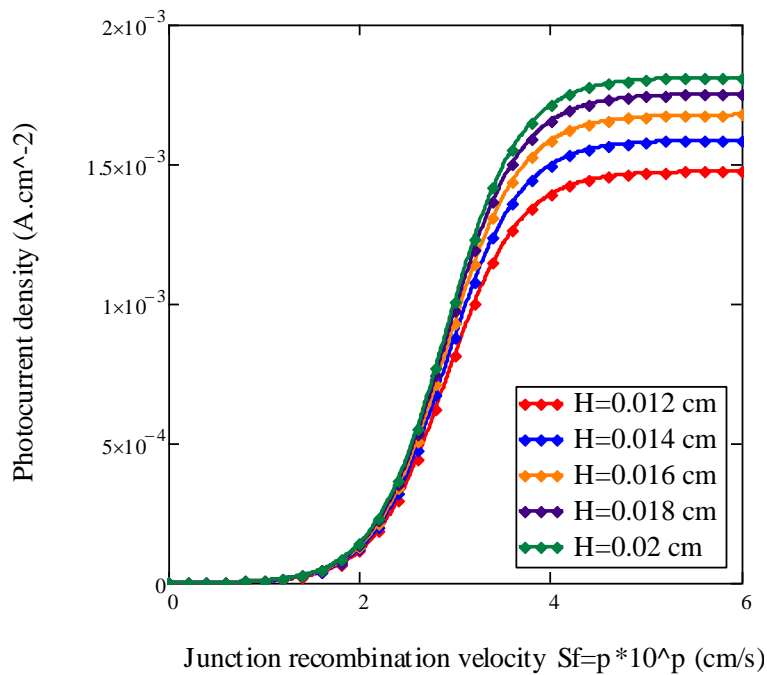


**Figure 5:-** Photocurrent density versus  $S_f$  for different irradiation energy flow values with  $k_l=16$  cm<sup>-2</sup>/MeV,  $z=0.015$  cm,  $D(k_l, \phi_p)=26$  cm<sup>2</sup>/s,  $S_{b2}=f(k_l, \phi_p)$  cm/s.



**Figure 6:-** Photocurrent density versus Sf for different damage coefficient intensity values with  $\phi_p=170$  MeV,  $z=0.015$  cm,  $D(kl,\phi_p)=26$  cm<sup>2</sup>/s,  $Sb_2=f(kl,\phi_p)$  cm/s.

Figure 7 below shows the influence of the thickness of the base on the profiles of the photocurrent density versus junction recombination velocity, for given both, the irradiation energy flow ( $\phi_p$ ) and the intensity of the damage coefficient (kl).



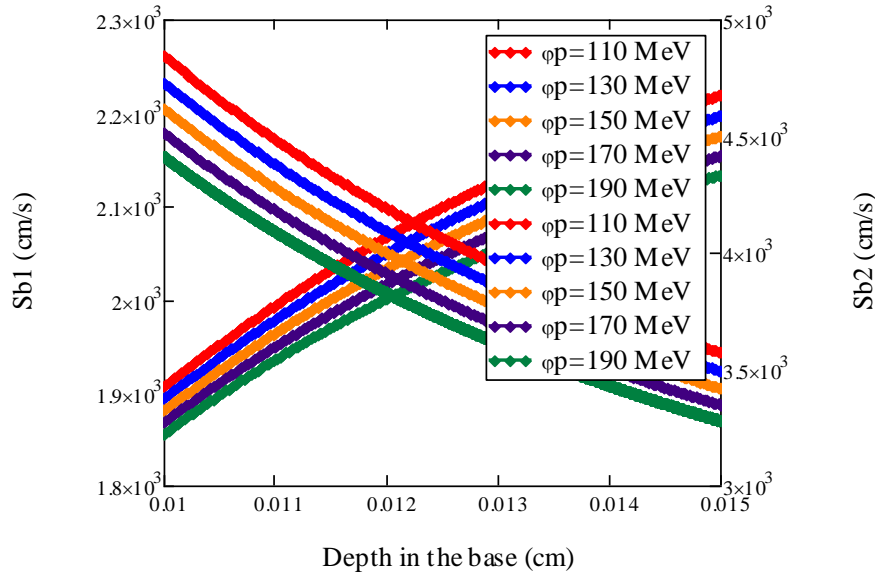
**Figure 7:** Photocurrent density versus Sf for different depth values with  $\phi_p=150 \text{ MeV}$ ,  $kl=13 \text{ cm}^2/\text{MeV}$ ,  $z=0.015 \text{ cm}$ ,  $D(kl,\phi_p)=26 \text{ cm}^2/\text{s}$ ,  $Sb_2=f(kl,\phi_p) \text{ cm/s}$

Photocurrent at large junction recombination, is shown to be sensitive to base thickness whatever the irradiation.

**Optimum thickness determination:**

**Influence the d'irradiation flow ( $\phi_p$ ):**

Figure 8 materializes the technique for determining the optimum thickness of the base through the expressions of the recombination velocity at the rear face for different values of the irradiation energy flow. Optimum thickness of the base represents the abscissa of the intercept point of the two curves.



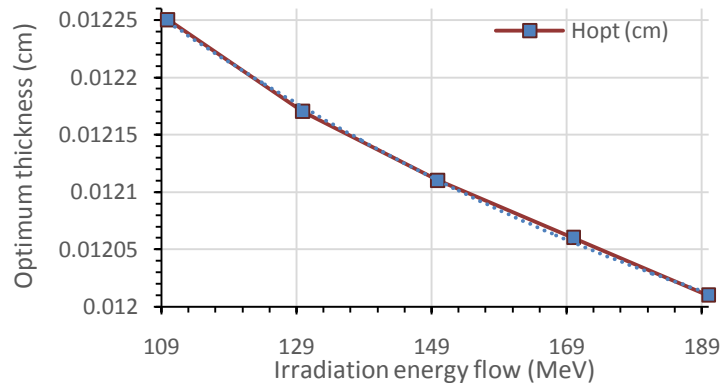
**Figure 8:-** Graphical determination of optimum thickness in the base for different irradiation energy flow values with  $kl=16 \text{ cm}^2/\text{MeV}$ .

Table 1 shows the numerical values of the optimum thickness extracted from the figure 8, for different irradiation energy flows.

**Tableau 1:-** Optimum thickness values for different  $\phi_p$  with  $kl=16 \text{ cm}^2/\text{MeV}$ .

$\phi_p$ (MeV)	110	130	150	170	190
Hopt (cm)	0.01225	0.01217	0.01211	0.01206	0.01201

Figure 9 represents the profile of the optimum thickness according to the variations of the irradiation energy flow.



**Figure 9:-** Optimum thickness in the base versus irradiation energy flow.

A correlation equation between the optimum thickness and the irradiation energy flow is defined by the following expression:

$$Hopt(cm) = \beta * \phi p^2 - \chi * \phi p + \gamma \tag{13}$$

$$\beta = 10^{-8} \text{ MeV}^{-2} \cdot \text{cm} \quad \chi = 7 * 10^{-6} \text{ MeV}^{-1} \cdot \text{cm} \quad \gamma = 128 * 10^{-4} \text{ cm}$$

**Influence the intensity of damage coefficient (kl):**

Figure 10 materializes the technique for determining the optimum thickness of the base through the intercept point of the plots of back surface recombination expressions, for different intensity damage coefficient values.

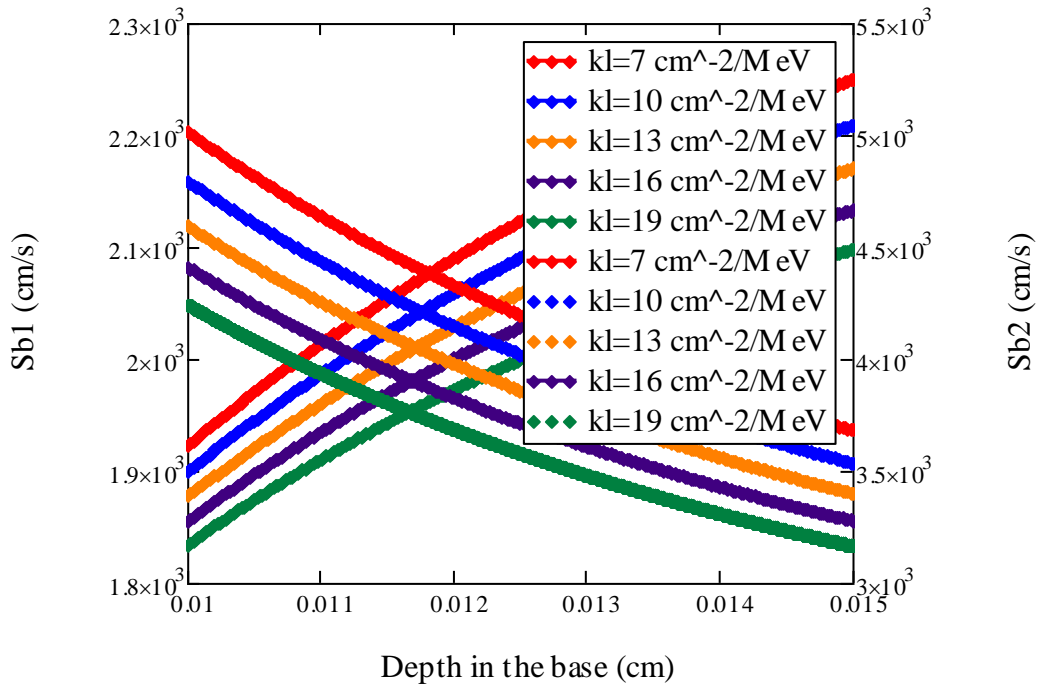


Figure 10:- Graphical determination of optimum thickness in the base for different damage coefficient intensity values with  $\phi p = 190 \text{ MeV}$ .

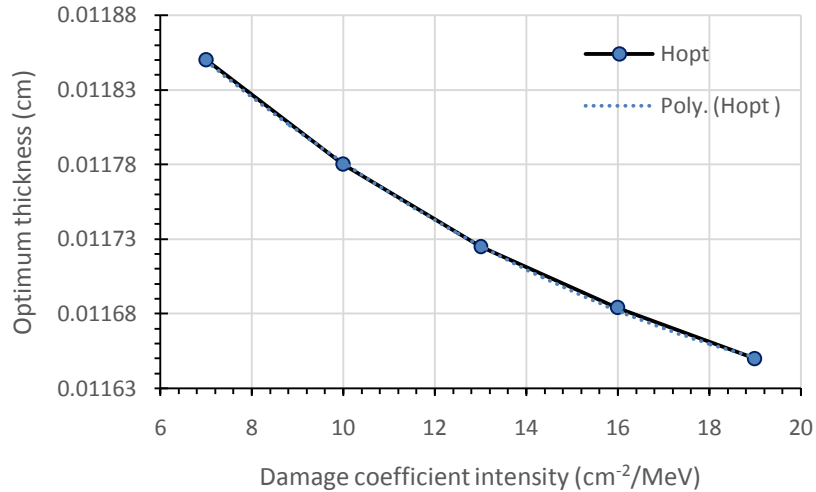
Table 2 represents the numerical values of the optimum thickness extracted for different intensity damage coefficient.

Table 2:- Optimum thickness values for different kl with  $\phi p = 190 \text{ MeV}$ .

kl (cm <sup>2</sup> /MeV)	7	10	13	16	19
Hopt (cm)	0.01185	0.01178	0.01172	0.01168	0.01165

Figure 11 represents the profile of the optimal thickness according to the variations in the intensity damage coefficient.





**Figure 11:-** Optimum thickness in the base versus damage coefficient intensity.

A correlation equation between the optimum thickness and the intensity of the damage coefficient is defined by the following expression:

$$Hopt(cm) = m * kl^2 - n * kl + c \quad (14)$$

$$m = 7 * 10^{-7} \text{ MeV}^2 \cdot \text{cm}^{-3} \quad n = 3 * 10^{-5} \text{ MeV} \cdot \text{cm}^3 \quad c = 121 * 10^{-4} \text{ cm}$$

We observe through these results modulated by mathematical relationships, a slight decrease in the optimum thickness of the base of the solar when the flow and intensity of irradiation vary.

### Conclusion:-

The influence of irradiation (flow  $\phi_p$  and intensity  $kl$ ) has been studied on the density of minority carriers of excess charge in the base, on the photocurrent density and on the determination of the optimum thickness of the solar cell. The optimum thickness of the base is deduced from the intersection of the back surface recombination velocity curves for different values of the radiation energy flow and the intensity of the damage coefficient. The variation of these two elements induces a slight decrease in the optimum thickness of the base of the solar cell. This technique for optimizing the thickness of the base contributes to reducing the quantity of material (Si) to be used for the manufacture of solar cells which could operate in a radiative medium while retaining a good conversion efficiency, to minimize the manufacturing costs and reduce the resale price.

### References:-

1. Le Quang Nam M. Rodot, (1992). Solar cells with 15.6% efficiency on multicrystalline silicon, using impurity gettering back surface field and emitter passivation. Int. J. Solar Energy, vol. 11, pp. 273-279.
2. J. F. Wise (1970). Vertical junction hardened solar cell. U. S Patent 3, p 690-953
3. B. MAZHARI and H. Morkoç (1993) Theoretical study of a parallel vertical multi-junction silicon, J. App. Phys. 73(11), pp.7509-7514.
4. A Gover, and P. Stella (1974). Vertical Multijunction Solar-Cell One-Dimensional Analysis" IEEE Transactions on Electron Devices, Vol. ED-21:6pp.351-356.
5. Terheiden, B., Hahn, G., Fath, P. and Bucher, E. (2000) The Lamella Silicon Solar Cell. 16th European Photovoltaic Solar Energy Conference, Glasgow, pp.1377-1380.
6. E. D. Stokes and T. L. Chu, (1977) Diffusion Lengths in Solar Cells From Short-Circuit Current Measurements » Applied Physics Letters, Vol. 30, N°8, pp.425-426.
7. G. Sissoko, E. Nanéma, A. Corréa, P. M. Biteye, M. Adj, A. L. Ndiaye, (1998) Silicon Solar cell recombination parameters determination using the illuminated I-V characteristic. Renewable Energy, vol-3, pp.1848-51. Elsevier Science Ltd, 0960-1481/98/#
8. E. Demesmaeker, J. Symons, J. Nijs, R. Mertens (1991). The Influence Of Surface Recombination On The Limiting Efficiency And Optimum Thickness Of Silicon Solar Cells. 10th European Photovoltaic Solar Energy Conference Lisbon, Portugal-Pp.66-67

9. Sissoko, G., Sivoththanam, S., Rodot, M. and Mialhe, P. (1992) Constant Illumination-Induced Open Circuit Voltage Decay (CIOVD) Method, as Applied to High Efficiency Si Solar Cells for Bulk and Back Surface Characterization. 11 th European Photovoltaic Solar Energy Conference and Exhibition, Montreux, pp.352-354.
10. Barro, F. I., A S Maiga, Wereme A, Sissoko G (2010). Determination of recombination parameters in the base of a bifacial silicon solar cell under constant multispectral light; Phys. Chem. News 56, pp.76-84.
11. Carsten Schinke, David Hinken, Karsten Bothe, Christian Ulzhöfer, Ashley Milsted, JanSchmidt, Rolf Brendel (2011) Determination of the Collection Diffusion Length by Electroluminescence Imaging Energy Procedia, 8, pp.147-152.
12. Kalidou Mamadou Sy, Alassane Diene, Séni Tamba, Marcel Sitor Diouf, Ibrahima Diatta, Mayoro Dieye, Youssou Traore, Grégoire Sissoko (2016).Effect of temperature on transient decay induced by charge removal of a silicon solar cell under constant illumination. Journal of Scientific and Engineering Research, 3(6), pp.433-445 www.jsaer.com
13. Konstantinos Misiakos and Dimitris Tsamakis (1994). Electron and Hole Mobilities in Lightly Doped Silicon. Appl. Phys. Lett. 64(15), pp.2007-2009.
14. Noriaki Honna and Chusuke Munakata(1987). Samplethickness dependence of minority carrier lifetimes measured using an ac photovoltaic method. Japanese journal of applied physics, Vol. 26, pp2033-2036
15. M. Zoungrana, B. Dieng, O.H. Lemrabott, F. Toure, M.A. Ould El Moujtaba, M.L. Sowand G. Sissoko, (2012) External Electric Field Influence on Charge Carriers and Electrical Parameters of Polycrystalline Silicon Solar Cell. Research Journal of Applied Sciences, Engineering and Technology 4(17), pp.2967-2972.
16. Faye, D. , Gueye, S. , Ndiaye, M. , Ba, M. , Diatta, I. , Traore, Y. , Diop, M. , Diop, G. , Diao, A. and Sissoko, G. (2020) Lamella Silicon Solar Cell under Both Temperature and Magnetic Field: Width Optimum Determination. Journal of Electromagnetic Analysis and Applications, 12, 43-55. doi: 10.4236/jemaa.2020.124005.
17. Gora Diop, Hamet Yoro Ba, Ndeye Thiam, Youssou Traore, Babou Dione, Mamour Amadou Ba, Pape Diop, Masse Samba Diop, Oulimata Mballo and Gregoire Sissoko, (2019) Base thickness optimization of a vertical series junction silicon solar cell under magnetic field by the concept of back surface recombination velocity of minority carrier. ARPN Journal of Engineering and Applied Sciences Vol. 14, No. 23, pp.4078-4085.
18. Nouh Mohamed Moctar Ould Mohamed, Ousmane Sow, Sega Gueye, Youssou Traore, Ibrahima Diatta, Amary Thiam, Mamour Amadou Ba, Richard Mane, Ibrahima Ly, Gregoire Sissoko, (2019) Influence of Both Magnetic Field and Temperature on Silicon Solar Cell Base Optimum Thickness Determination. Journal of Modern Physics, 10, pp.1596-1605 <https://www.scirp.org/journal/jmp>
19. Youssou Traore, Ndeye Thiam, Moustapha Thiame, Amary Thiam, Mamadou Lamine Ba, Marcel Sitor Diouf, Ibrahima Diatta, Oulymata Mballo, El Hadji Sow, Mamadou Wade, Grégoire Sissoko, (2019) AC Recombination Velocity in the Back Surface of a Lamella Silicon Solar Cell under Temperature. Journal of Modern Physics, 10, pp.1235-1246 <https://www.scirp.org/journal/jmp>
20. Ba. M.L, Thiam. N, Thiame. M, Traore. Y, Diop. M.S, Ba. M., Sarr. C.T, Wade. M. and Sissoko, G. (2019) Base Thickness Optimization of a (n+-p-p+) Silicon Solar Cell in Static Mode under Irradiation of Charged Particles. Journal of Electromagnetic Analysis and Applications, 11, pp.173-185. <https://doi.org/10.4236/jemaa.2019.1110012>
21. Masse Samba Diop, Hamet Yoro Ba, Ibrahima Diatta, Youssou Traore, Marcel Sitor Diouf, El Hadji Sow, Oulymata Mballo, and Gregoire Sissoko, (2019) Concept de la vitesse de recombinaison surfacique appliqué à la détermination de l'épaisseur optimum de la base de la photopile au silicium avec effet du taux de dopage. International Journal of Innovation and Applied Studies ISSN 2028-9324 Vol. 27 No. 3, pp.809-817.
22. G. Sissoko, C. Muserika, A. Correa, I. Gaye, (1996) Light Spectral Effect on Recombination Parameters of Silicon Solar Cell. Proc. World Renewable Energy Congress, Part II, pp.1668-1670, Denver (Colorado, U.S.A).
23. Matar Gueye, Hawa Ly Diallo, Attoumane Kosso Mamadou Moustapha, Youssou Traore, Ibrahima Diatta, Gregoire Sissoko. (2018) Ac Recombination Velocity in a Lamella Silicon Solar Cell. World Journal of Condensed Matter Physics, 8, pp.185-196, <http://www.scirp.org/journal/wjcmp>
24. I. Gaye, R. Sam, A. D. Seré, I. F. Barro, M. A. Ould El Moujtaba, R. Mané, G. Sissoko. (2012) Effect of irradiation on the transient response of a silicon solar cell. International journal of emerging trends and technologies in computer science (IJETTCS) Volume 1, Issue 3, ISSN 2278-6856, pp.210-214.
25. M.A. Ould El Moujtaba, M. Ndiaye, A. Diao, M. Thiame, I.F. Barro and G. Sissoko, (2012) Theoretical Study of the Influence of Irradiation on a Silicon Solar Cell Under Multispectral Illumination. Research Journal of Applied Sciences, Engineering and Technology 4(23), pp.5068-5073.
26. I. Ly, M. Wade, H. Ly Diallo, M. A. O. El Moujtaba, O. H. Lemrabott, S. Mbodji, O. Diassé, A. Ndiaye, I. Gaye, F. I. Barro, A. Wereme, G. Sissoko, (2011) Irradiation effect on the electrical parameters of a bifacial

- silicon solar cell under multispectral illumination. 26th European Photovoltaic Solar Energy Conference and Exhibition, pp.785-788.
27. Rose, B.H. and Weaver, H.T. (1983) Determination of Effective Surface Recombination Velocity and Minority-Carrier Lifetime in High-Efficiency Si Solar Cells. *Journal of Applied Physics*, 54, pp.238-247. <https://doi.org/10.1063/1.331693>.
  28. Mandelis, A. (1989) Coupled ac Photocurrent and Photothermal Reflectance Response Theory of Semiconducting p-n Junctions. I. *Journal of Applied Physics*, 66, pp.5572-5583. <https://doi.org/10.1063/1.343662>
  29. Diallo, H.L., Wereme, A., Maiga, A.S. and Sissoko, G. (2008) New Approach of Both Junction and Back Surface Recombination Velocities in a 3D Modelling Study of a Polycrystalline Silicon Solar Cell. *The European Physical Journal Applied Physics*, 42, pp.203-211. <https://doi.org/10.1051/epjap:2008085>
  30. Fossum, J.G. (1977) Physical Operation of Back-Surface-Field Silicon Solar Cells. *IEEE Transactions on Electron Devices*, 2, pp.322-325. <https://doi.org/10.1109/T-ED.1977.18735>
  31. Joardar, K., Dondero, R.C. and Schroda, D.K. (1989) A Critical Analysis of the Small-Signal Voltage-Decay Technique for Minority-Carrier Lifetime Measurement in Solar Cells. *Solid-State Electronics*, 32, pp.479-483. [https://doi.org/10.1016/0038-1101\(89\)90030-0](https://doi.org/10.1016/0038-1101(89)90030-0)
  32. Diasse, O., Diao, A., Ly, I., Diouf, M.S., Diatta, I., Mane, R., Traore, Y. and Sissoko, G. (2018) Back Surface Recombination Velocity Modeling in White Biased Silicon Solar Cell under Steady State. *Journal of Modern Physics*, 9, pp.189-201. <https://doi.org/10.4236/jmp.2018.92012>
  33. Bocande, Y. L., Correa, A., Gaye, I., Sow, M. L. and Sissoko, G. (1994) Bulk and surfaces parameters determination in high efficiency Si solar cells. *Proceedings of the World Renewable Energy Congress*, vol.3, pp.1698-1700.