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Research Article

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Derivative of AC recombination velocity of minority carriers as applied to the determination of the optimum base thickness of an (n+/p/p+) silicon solar cell

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Abstract This work is devoted to the determination of the optimum thickness of the base of the (n+/p/p+) silicon solar cell, front illuminated by the (n+) face by a monochromatic light in frequency modulation.

The method of the derivative of the expression of AC recombination velocity of minority carriers on the back side of the base is used for the first time, and allows to obtain results of the optimum base thickness as modulation frequency dependent. The base optimum thickness decreases with the frequency and makes it possible to envisage the realization of solar cells with a reduced base, for an economy of the raw material (Si).

Keywords Silicon Solar Cell –AC Recombination Velocity - Base Optimum Thickness

Introduction

Previous works of characterization of the solar cell, have been carried out using an electrical or optical signal, in modulation frequency (ω) [1-6], applied to the solar cell.

By solving the dynamically dynamic diffusion equation, relative to the density of the minority charge carriers in the base, the photocurrent density AC Jph (Sf, Sb, D(ω), H, α) is obtained and allows to deduce the expression AC Sb(D(ω), H, α) of the minority carriers recombination velocity at the rear face (p/p+) [7-11].The graphic study of this expression as a function of the thickness (H), made it possible to deduce a technique for determining the optimum thickness of the base (Hopt) [12-22].

This work presents the determination of the optimum thickness of the base of the solar cell illuminated by its front face (n +), by the exploitation of the curve of Sb (H, D (ω), α) [23-27] versus thickness (H), through the point (Hopt) of zero derivative.

Two expressions F(H, D(ω) and G(H, D(ω), α), forming a transcendental equation [28-30], are deduced and, whose graphical representation leads to (Hopt), which is then modeled as a function of frequency and for an absorption coefficient (α) of high penetration [31, 32].

Theory

The solar cell considered is of type ($n^+/p/p^+$) [33, 34] whose structure is presented in figure.1, with (H) the base thickness.

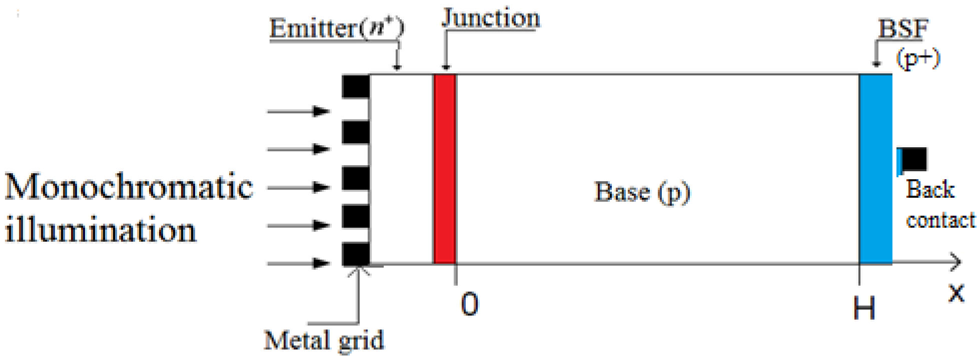

Figure 1: Structure of a front illuminated (n+-p-p+) silicon solar cell.

Dynamic continuity equation

The continuity equation of the minority carriers in the base of solar cell under dynamic state [1-4], is of the form:

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

The complex relationships under dynamic state for both diffusion length and diffusion coefficient are follow:

$$\frac{1}{L(\omega)^2}=\frac{1}{L^2}\times(i\omega\tau+1) \quad (2) \qquad \text{and} \qquad D(\omega)=D_0\times\left(\frac{1-j.\omega^2.\tau^2}{1+(\omega\tau)^2}\right) \tag{3}$$

D0 is the diffusion coefficient and (τ)is the lifetime of the minority charge carriers, in the base under steady state.

G is the AC generation rate given by the following expression:

G(x,t) = g(x)exp(i ω t) (4)

With g(x) the spatial component:

$$g_1(x)=\alpha I_0(1-R)\left[e^{-\alpha x}\right] \tag{5}$$

The monochromatic incident flux is (Io); the absorption coefficient is ($\alpha(\lambda)$) and R(λ) is the reflection coefficient of the material at wavelength λ [31, 32].

Expression of the minority carriers density

The solution of equation (1) giving the minority carriers density in the base is:

$$\delta(x,\omega,\alpha)=A\cosh\left(\frac{x}{L(\omega)}\right)+B\sinh\left(\frac{x}{L(\omega)}\right)+C.\exp(-\alpha x) \tag{6}$$

The C constant is dependent of the optical parameters.

Boundary conditions

To determine A and B the following boundary conditions are used:

At the junction, x= 0

$$\left.\frac{\partial\delta(x,\alpha,\omega)}{\partial x}\right)_{x=0}=\frac{Sf}{D}\delta(0,\omega,\alpha) \tag{7}$$

At the back surface**,** x = H:

$$\left.\frac{\partial \delta(x,\omega,\alpha)}{\partial x}\right)_{x=H} = -\frac{Sb}{D}\,\delta(H,\omega,\alpha) \tag{8}$$

Sf and Sb denote the minority carriers' recombination velocity [35-43] at the junction and rear side of the base, respectively.

Expression of photocurrent density

The photocurrent density is then deduced from minority carriers density and given by the following expression as:

$$J_{ph}(Sf,Sb,\alpha,H,\omega) = qD(\omega)\left.\frac{\partial \delta(x,Sf,Sb,\alpha,H,\omega)}{\partial x}\right|_{x=0} \tag{9}$$

q is the charge of the electron.

Expression of the recombination velocity of minority carriers on the back side of the base

The profile of the curves of variation of the density of the photocurrent as a function of recombination velocity at the junction show that at Sf large values, each curve has a horizontal step, regardless of modulation frequency. The gradient of the photocurrent with respect to (Sf) is zero [44, 45]:

$$\frac{\partial J_{ph}(Sf,Sb,\alpha,H,\omega)}{\partial Sf} = 0 \tag{10}$$

Solving this equation allows us to obtain the following expressions of minority carriers recombination velocity at the rear side of the base of the solar cell, expressed as:

$$S_{b1}(H,\omega) = -\frac{D(\omega)}{L(\omega)}\,\frac{sh\left(\frac{H}{L(\omega)}\right)}{ch\left(\frac{H}{L(\omega)}\right)} \tag{11}$$

$$S_{b2}(\alpha,H,\omega) = D(\omega)\,\frac{\alpha\left(ch\left(\frac{H}{L(\omega)}\right)-e^{-\alpha H}\right)-\frac{1}{L(\omega)}sh\left(\frac{H}{L(\omega)}\right)}{\left(ch\left(\frac{H}{L(\omega)}\right)-e^{-\alpha H}-\alpha L(\omega)sh\left(\frac{H}{L(\omega)}\right)\right)} \tag{12}$$

We propose a method for determining the optimum thickness of the base of the solar cell, trough the study of the expression of the minority carriers recombination velocity on the rear side of the base.

Thus, the curve of Sb2 versus (H) [23-27], have an optimum. Then the derivative at the point of optimum recombination velocity of Sb2 with respect to H is zero:

$$\frac{\partial \mathrm{Sb}_2\,(\alpha,H,\omega)}{\partial \mathrm{H}} = 0 \tag{13}$$

It then comes:

$$\tanh\left(\frac{\mathrm{H}}{\mathrm{L}(\omega)}\right) = \frac{1}{\mathrm{L}(\omega)\alpha}\left[\frac{1}{\mathrm{e}^{-\alpha.\mathrm{H}}\mathrm{ch}\left(\frac{\mathrm{H}}{\mathrm{L}(\omega)}\right)} - 1\right] \tag{14}$$

This transcendental equation is broken down into two functions for graphical resolution [28-30] as:

$$\mathrm{F}(\mathrm{H},\omega,\alpha) = \frac{1}{\alpha.\mathrm{L}(\omega)}\left[\frac{1}{\mathrm{e}^{-\alpha.\mathrm{H}}\mathrm{ch}\left(\frac{\mathrm{H}}{\mathrm{L}(\omega)}\right)} - 1\right] \tag{15}$$

$$\mathrm{G}(\mathrm{H},\omega) = \tanh\left(\frac{\mathrm{H}}{\mathrm{L}(\omega)}\right) \tag{16}$$

Results and Discussions

Graphic resolution

Figure 2, gives the representation of the two expressions **F(H,ω,α)** and **G(H,ω)** on a vertical bicurve scale as a function of (H), for given modulation frequency (ω) and keeping the absorption coefficient constant.

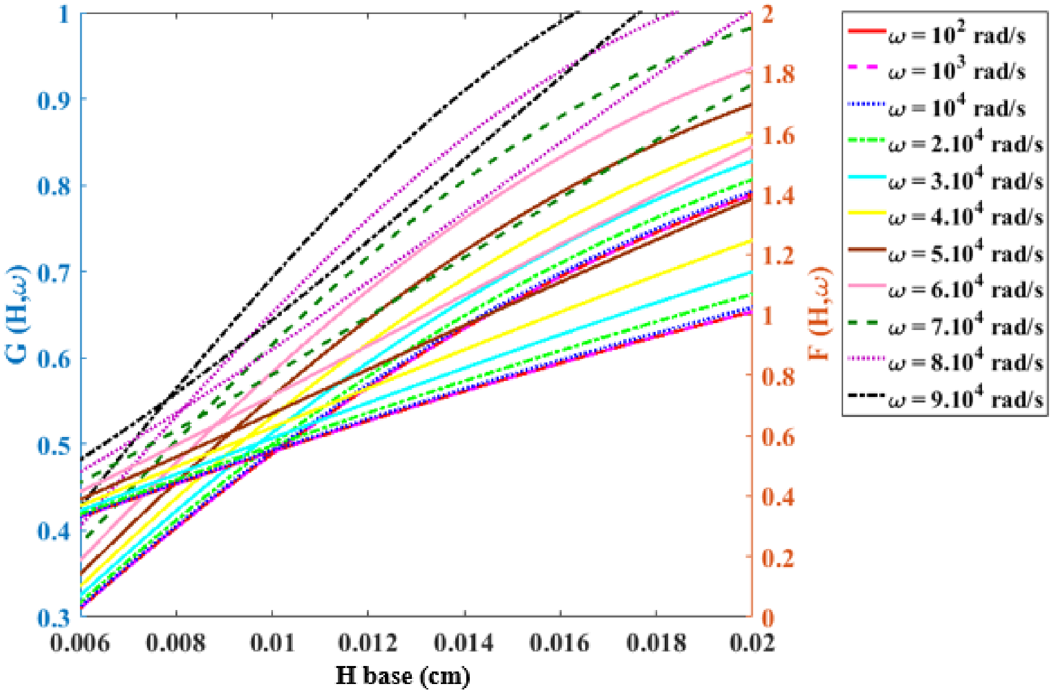

Figure 2: Profile of G and F as a function of base thickness for different frequency values and α = 6.2 cm^{-1}

The intercept point of the two curves gives the optimum thickness (Hopt) for a chosen modulation frequency (ω). Thus Table 1 shows all the Hopt values as a function of dynamic diffusion coefficient and the modulation frequency (ω).

Table 1: Values of the optimum thickness, as a function of D and ω.

ω(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
D(ω)(cm^2/s)	35	34.9965	34.6535	33.6538	32.1101	30.1724	28.0000	25.7353	23.4899	21.3415	19.3370
H_{opt} (cm)	0.0101	0.0101	0.0101	0.0099	0.0097	0.0094	0.0092	0.0089	0.0085	0.0082	0.0078

From the table above, we produce the representation (**Fig. 3**) of the optimum thickness as function of dynamic diffusion coefficient D(ω) of the minority carriers in the base.

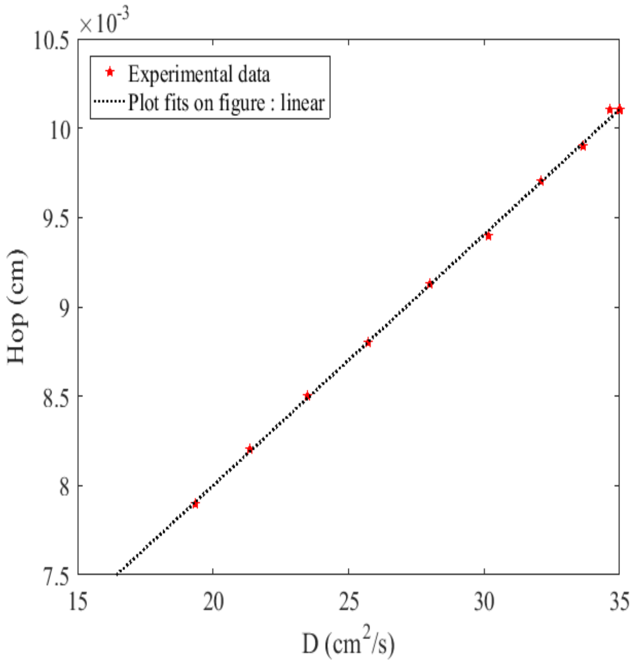

Figure 3: Optimum thickness profile versus dynamic diffusion coefficient

The expression in modeling of the optimum thickness (Hopt) as a function of minority carriers diffusion coefficient in the base, is given by the following equation:

$$Hopt(cm) = 1.4 \cdot 10^{-4} \times D(cm^2 \cdot s^{-1}) + 0.0052 \qquad (17)$$

Figure 4 and 5 produce the Hopt curve as function of (ω).

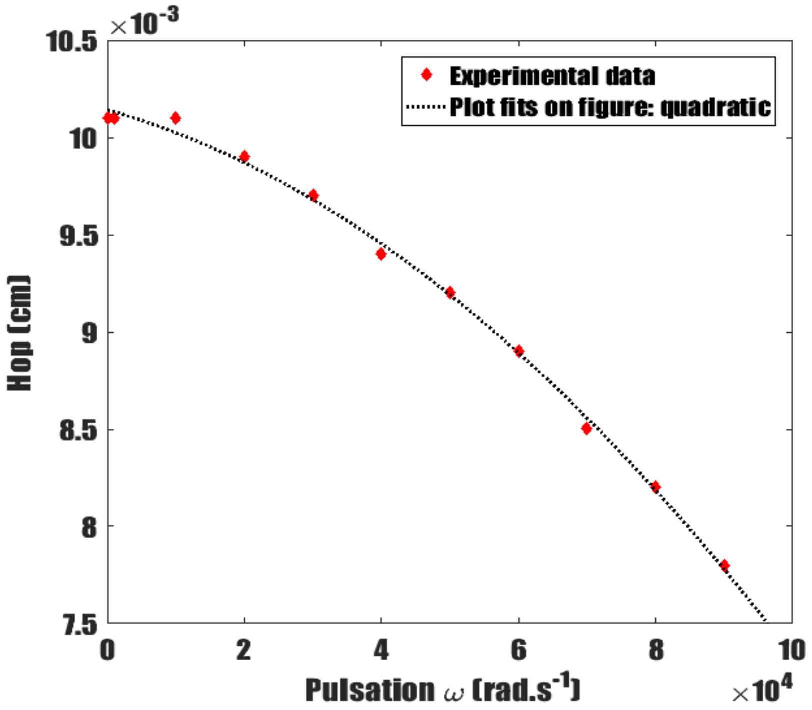

Figure 4: Optimum thickness profile as a function of modulation frequency

The following expression gives the mathematical modeling of (Hopt), which is a decreasing function of the modulation frequency (ω):

$$Hop(cm) = -1{,}8.10^{-13} \cdot \omega^2 - 10^{-8} \cdot \omega + 0{,}01 \qquad (18)$$

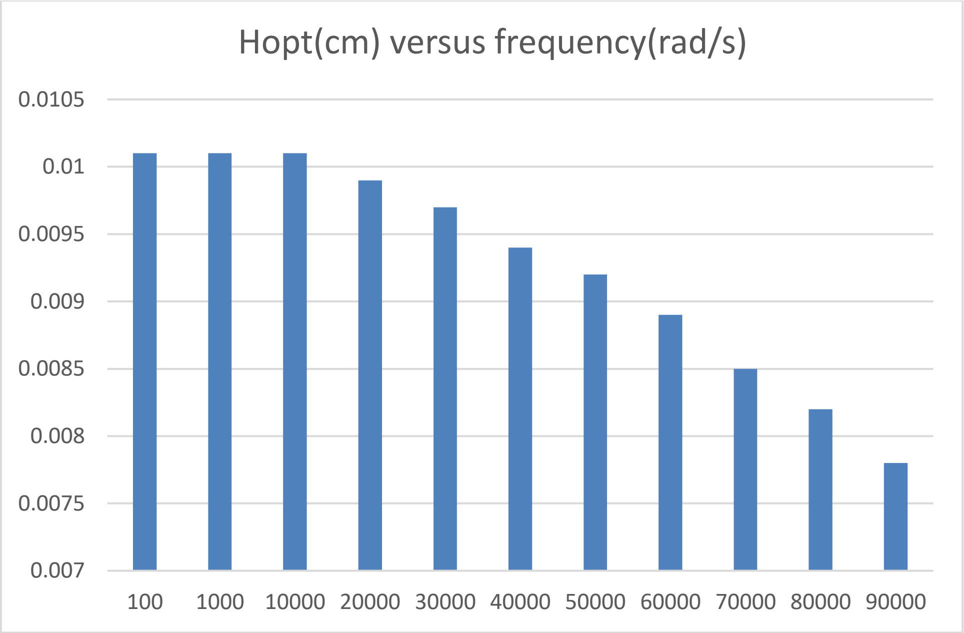

Figure 5: Histogram of optimum thickness as a function of frequency

The optimal thickness is large at low frequencies, corresponding to the static regime ($\omega\tau << 1$) of the solar cell. In this low frequency interval, the relaxation time of minority carriers is important (D large values), allowing a large distance (Einstein's relation), so a large base thickness is usable [17].

At high frequency values, the relaxation time of minority carriers is reduced ($\omega\tau >> 1$), corresponding to a short travel distance, then the optimum thickness needed to collect carriers should be low [20, 21, 46].

Other works [46-53] corroborate the above results, showing the decrease in the optimal thickness of the silicon solar cell base, when subjected to:

- Monochromatic light with constant flux absorption coefficient ($\alpha(\lambda)$) [17, 47].
- Monochromatic light $\alpha(\lambda)$ in frequency modulation (ω) [20, 21, 46].
- Constant magnetic field B [18, 19, 50].
- Irradiation with charged particles flux [52].
- Modification of base doping rate [16, 46].
- Effect of temperature [22, 48, 49, 53].

Studies wafers [54-58] of silicon for different thicknesses, do not guarantee the reproducibility of electronic parameters and however only compare the results of macroscopic parameters.

Conclusion

A new technique for determining the optimum thickness of the base of n+/p/p+, silicon solar cell under monochromatic illumination ($\alpha(\lambda)$), in frequency modulation (ω), was presented, through the analysis of the curve of (Sb2 (H, D(ω), α)) the recombination velocity of minority charge carriers on the rear side. The optimum thickness (Hopt) of the solar cell base, is deduced from the curves of the expressions (transcendental equations) obtained from the derivative of Sb (α, H, ω) with respect to (H). The Hopt thickness is modeled as a decreasing function of the frequency (ω), and increasing one with dynamic diffusion coefficient, for a given value of the absorption coefficient (α) of high penetration into the base. The importance of the thickness of the base in the manufacture of the solar cell, with a view to optimizing the amount of usable material, is economically undeniable, and also leads to an improvement in the photo conversion efficiency.

References

[1]. S. Gupta, P. Ahmed and S. Garg, (1988). A Method for the Determination of the Material parameters D, L, S and α from Measured Short-Circuit Photocurrent. Solar Cells, 25, 61-72. https://doi.org/10.1016/0379-6787(88)90058-0P.

[2]. R. R. Vardanyan, U. Kerst, B. Tierock, H. G. Wagemann (1997). Measurement of recombination parameters of solar cell in a magnetic field. Proceeding of the 14th European Photovoltaic Solar Energy Conference (Barcelona, Spain). Pp 2367-2369.

[3]. Chih Hsin Wang and Arnost Neugroschel (1991). Minority-carrier lifetime and surface recombination velocity measurement by frequency-domain photoluminescence. IEEE transactions on electron devices, vol.38, no. 9, pp2169-2180.

[4]. K. Misiakos, C. H. Wang, A. Neugroschel and F. A. Lindholm (1990). Simultaneous extraction of minority carrier parameters in crystalline semiconductors by lateral photocurrent. J.Appl. Phys. 67(1): 321-333.

[5]. N. Honma and C. Munakata (1987). Sample Thickness Dependence of Minority Carrier Lifetimes Measured Using an ac Photovoltaic Method. Japanese Journal of Applied Physics, 26, 2033-2036. https://doi.org/10.1143/JJAP.26.2033

[6]. D. Chenvidhya, K. Kirtikara, C. Jivacate (2003). A new characterization method for solar cell dynamic impedance. Solar Energy Materials & Solar Cells, Volume 80, Issue 4, Déc. 2003, Pp. 459-464. https://doi.org/10.1016/j.solmat.2003.06.011

[7]. M. Fall, I. Gaye, D. Diarisso, G. Diop, K. Loum, N. Diop, K. Sy, M. Ndiaye and G. Sissoko,. AC Back Surface Recombination Velocity in n＋-p-p＋ Silicon Solar Cell under Monochromatic Light and Temperature. Journal of Electromagnetic Analysis and Applications,2021, 13, 67-81. doi: 10.4236/jemaa.2021.135005

[8]. Diao, A., Thiam, N., Zoungrana, M., Sahin, G., Ndiaye, M. and Sissoko, G. (2014) Diffusion Coefficient in Silicon Solar Cell with Applied Magnetic Field and under Frequency: Electric Equivalent Circuits. World Journal of Condensed Matter Physics, 4, 84-92. https://doi.org/10.4236/wjcmp.2014.42013

[9]. Ly, I., Zerbo, I., Wade, M., Ndiaye, M., Dieng, A., Diao, A., Thiam, N., Thiam, A., Dione, M.M., Barro, F.I., Maiga, A.S. and Sissoko, G. (2011). Bifacial Silicon Solar Cell under Frequency Modulation and Monochromatic Illumination: Recombination Velocities and Associated Equivalent Electrical Circuits. Proceedings of 26th European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, 5-9 September 2011, 298-301.I.

[10]. Zerbo, F.I. Barro, B. Mbow, A. Diao, S. Madougou, F.Zougmore and G. Sissoko, Theoretical Study of Bifacial Silicon Solar Cell under Frequency Modulate white Light: Determination of Recombination Parameters. Proceedings of the 19th European Photovoltaic Solar Energy Conference, Paris, 7-11 June 2004, 258-261

[11]. K. Denise, L.B. Mamadou, A.B. Mamour, D., Gora, S. El Hadj, M. Oulimata and S. Gregoire (2020). AC Back Surface Recombination in n＋-p-p＋ Silicon Solar Cell: Effect of Temperature. International Journal of advanced Research (IJAR), 8, 140-151. https://doi.org/ 10.21474/ IJAR01 /11273

[12]. Yasar S., Kahraman S., Cetinkaya S., Apaydin S., Bilican I., Uluer I. (2016). Numerical thickness optimization study of CIGS based solar cells with wxAMPS, Optik, 127 (20), pp. 8827-8835.

[13]. A. A. Sayem, Y. Arafat and M. M. Rahman (2014). Thickness optimization and composition grading effect in heterojunction CIGS Solar Cell. 8th International Conference on Electrical and Computer Engineering (20-20 Dec, Dhaka, Bangladesh), 2014, pp. 524-527, doi: 10.1109/ICECE.2014.7026952.

[14]. Demesmaeker, E., Symons, J., Nijs, J. and Mertens, R. (1991) The Influence of Surface Recombination on the Limiting Efficiency and Optimum Thickness of Silicon Solar Cells. 10th European Photovoltaic Solar Energy Conference, Lisbon, 8-12 April 1991, 66-67. https://doi.org/10.1007/978-94-011-3622-8_17

[15]. X. Sun, M. R. Khan, C. Deline and M. A. Alam (2018). Optimization and performance of bifacial solar modules: A global perspective. Appl. Energy, vol. 212, pp. 1601-1610, https://doi.org/10.1016/j.apenergy.2017.12.041.

[16]. Diop, M., Ba, H., Thiam, N., Diatta, I., Traore, Y., Ba, M., Sow, E., Mballo, O. and Sissoko, G. (2019) Surface Recombination Concept as Applied to Determinate Silicon Solar Cell Base Optimum

Thickness with Doping Level Effect. World Journal of Condensed Matter Physics, 9, 102-111. doi: 10.4236/wjcmp.2019.94008.

[17]. Sidi Dede, M., Lamine Ba, M., Amadou Ba, M., Ndiaye, M., Gueye, S., Sow, E., Diatta, I., Diop, M., Wade, M. and Sissoko, G. (2020) Back Surface Recombination Velocity Dependent of Absorption Coefficient as Applied to Determine Base Optimum Thickness of an n+/p/p+ Silicon Solar Cell. Energy and Power Engineering, 12, 445-458. doi: 10.4236/epe.2020.127027.

[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, 1596-1605 https://www.scirp.org/journal/jmp

[19]. Diop, G., Ba, H.Y., Thiam, N., Traore, Y., Dione, B., Ba, M.A., Diop, P., Diop, M.S., Mballo, O. and Sissoko, G. (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, 14, 4078-4085.

[20]. Sall. M, Diarisso. D,Faty Mbaye Fall. M, Diop. G, Ndiaye. M, Loum/ K and Sissoko, G. (2021). Back Illuminated N/P/P+ Bifacial Silicon Solar Cell under Modulated Short-Wavelength: Determination of Base Optimum Thickness. Energy and Power Engineering, 13, 207-220. doi: 10.4236/epe.2021.135014

[21]. Ndiaye, A., Gueye, S., Sow, O., Diop, G., Ba, A., Ba, M., Diatta, I., Habiboullah, L. and Sissoko, G. (2020) A.C. Recombination Velocity as Applied to Determine n+/p/p+ Silicon Solar Cell Base Optimum Thickness. Energy and Power Engineering, 12, 543-554. doi: 10.4236/epe.2020.1210033.

[22]. Sega Diagne, Ousmane Sow, Gora Diop, Richard Mane, Ibrahima Diatta, Djiby Ndiongue, Youssou Traore, Lemrabott Habiboullah Mamadou Wade and Gregoire Sissoko. (2022) Optimization of silicon solar cell base thickness, while illuminated by a long wavelength monochromatic light: influence of both Lorentz law and Umclapp process. International Journal of Advanced Research, 10(08), 133-143. http://dx.doi.org/10.21474/IJAR01/151508

[23]. Sissoko, G., Museruka, C., Corréa, A., Gaye, I. and Ndiaye, A.L. (1996). Light Spectral Effect on Recombination Parameters of Silicon Solar Cell. World Renewable Energy Congress, Pergamon, Part III, pp. 1487-1490.

[24]. Traore, Y., Thiam, N., Thiame, M., Thiam, A., Ba, M., Diouf, M., Diatta, I., Mballo, O., Sow, E., Wade, M. and Sissoko, G. (2019). AC Recombination Velocity in the Back Surface of a Lamella Silicon Solar Cell under Temperature. Journal of Modern Physics, 10, 1235-1246. doi: 10.4236/jmp.2019.1010082

[25]. Gueye, M., Diallo, H., Moustapha, A., Traore, Y., Diatta, I. and Sissoko, G. (2018) Ac Recombination Velocity in a Lamella Silicon Solar Cell. World Journal of Condensed Matter Physics, 8, 185-196. doi: 10.4236/wjcmp.2018.84013.

[26]. Dede, M.M.S., Ba, M.L., Ba, M.A., Ndiaye, M., Gueye, S., Sow, E. H., Diatta, I., Diop, M.S., Wade, M. and Sissoko, G. (2020). Back Surface Recombination Velocity Dependent of Absorption Coefficient as Applied to Determine Base Optimum Thickness of an n+/p/p+ Silicon Solar Cell. Energy and Power Engineering, 12, 445-458. https://doi.org/10.4236/epe.2020.127027

[27]. O. Diasse, A. Diao, I. Ly, M.S. Diouf, I. Diatta, R. Mane, Y. Traore and G. Sissoko (2018). Back Surface Recombination Velocity Modeling in White Biased Silicon Solar Cell under Steady State. Journal of Modern Physics, 9, 189-201. https://doi.org/10.4236/jmp.2018.92012

[28]. G. Sissoko, B. Dieng, A. Corréa, M. Adj, D. Azilinon (1998). Silicon Solar cell space charge region width determination by a study in modelling. Renewable Energy, vol-3, pp.1852-55-Elsevier Science Ltd, 0960-1481/98/#

[29]. Sylla, B., Ly, I., Sow, O., Dione, B., Traore, Y. and Sissoko, G. (2018) Junction Surface Recombination Concept as Applied to Silicon Solar Cell Maximum Power Point Determination Using Matlab/Simulink: Effect of Temperature. Journal of Modern Physics, 9, 172-188. doi: 10.4236/jmp.2018.92011

[30]. 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), p.433-445 www.jsaer.com

[31]. K. Rajkanan, R. Singh and J. Schewchun (1972). Absorption coefficient of silicon for solar cell calculations. Solid-State Electronics, 22, 793-795.https://doi.org/10.1016/0038-1101(79)90128-X

[32]. M.A. Green and M. Keevers, Optical Properties of Intrinsic Silicon at 300K. Progress in Photovoltaics, 1995, 3, 189-192. http://dx.doi.org/10.1002/pip.4670030303

[33]. Le Quang Nam, M. Rodot, M. Ghannam, J. Cppye, P. de Schepper, J. Nijs, (1992) Solar Cells with 15.6% efficiency on multicristalline silicone, using impurity gettering, back surface field and emitter passivation. Int. J. Solar Energy. Vol. 11, pp.273-279.

[34]. Fossum, J.G. (1977) Physical Operation of Back-Surface-Field Silicon Solar Cells. IEEE Transactions on Electron Devices, 2, 322-325. https://doi.org/10.1109/T-ED.1977.18735

[35]. G. Sissoko, S. Sivoththanam, M. Rodot and P. Mialhe (1992). Constant Illumination-Induced Open Circuit Voltage Decay (CIOCVD) Method, as Applied to High Efficiency Si Solar Cells for Bulk and Back Surface Characterization. 11th European Photovoltaic Solar Energy Conference and Exhibition, Montreux, 12-16 October 1992, 352-354.

[36]. Grégoire Sissoko and Senghane Mbodji (2015). A method to determine the solar cell resistances from single I-V characteristic curve considering the junction recombination velocity (sf). Int. J. Pure Appl. Sci. Technol., 6(2) (2011), pp.103-114-ISSN 2229 – 6107, www.ijopaasat.in

[37]. G. Sissoko, E. Nanema, A. Correa, M. Adj, A.L. Ndiaye, M.N. Diarra (1998). Recombination parameters measurement in double sided surface field solar cell. Proceedings of World Renewable Energy Conference, Florence–Italy, pp. 1856–1859

[38]. Y. L. B. Bocande, A. Correa, I. Gaye, M. L. Sow and G. Sissoko (1994). Bulk and surfaces parameters determination in high efficiency Si solar cells. Renewable Energy, vol 5, part III, pp. 1698-1700, Pergamon, 0960-1481 / 94$ 700 +0.00.

[39]. Joardar, K., Dondero, R.C. and Schroder, 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, 479-483. https://doi.org/10.1016/0038-1101(89)90030-0

[40]. Zondervan, A., Verhoef, L.A. and Lindholm, F.A. (1988). Measurement Circuits for Silicon-Diode and Solar Cells Lifetime and Surface Recombination Velocity by Electrical Short-Circuit Current Delay. IEEE Transactions on Electron Devices, 35, 85-88. https://doi.org/10.1109/16.2419

[41]. H.L. Diallo, A.S. Maiga, A. Wereme and G. Sissoko, (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, 193-211. http://dx.doi.org/10.1051/epjap:2008085

[42]. Dieng, A., Zerbo, I., Wade, M., Maiga, A.S. and Sissoko, G. (2011). Three-Dimensional Study of a Polycrystalline Silicon Solar Cell: The Influence of the Applied Magnetic Field on the Electrical Parameters. Semiconductor Science and Technology, 26, Article ID: 095023. http://dx.doi.org/10.1088/0268-1242/26/9/095023

[43]. E. Gaubas and J. Vanhellemont (1996). A simple Technique for the Separation of Bulk and Surface Recombination Parameters in Silicon. Journal of Applied Physics, 80, 6293-6297. https://doi.org/10.1063/1.363705M

[44]. Ly, I., Ndiaye, M., Wade, M., Thiam, N., Sega, Gueye. and Siaaoko, G. (2013) Sissoko Concept of Recombination Velocity Sfcc at the Junction of a Bifacial Silicon Solar Cell, in Steady State, Initiating the Short-Circuit Condition. Research Journal of Applied Sciences, Engineering and Technology, 5, 203-208. https://doi.org/10.19026/rjaset.5.5105

[45]. Ndiaye, E.H., Sahin, G, Dieng, M., Thiam, A, Diallo, H.L., Ndiaye, M. and Sissoko, G. (2015) Study of the Intrinsic Recombination Velocity at the Junction of Silicon Solar under Frequency Modulation and Irradiation. Journal of Applied Mathematics and Physics, 3, 1522-1535.

https://doi.org/10.4236/jamp.2015.311177

[46]. Malick Ndiaye, Ousmane Sow, Ibrahima Diatta, Gora Diop, Dibor Faye, Khady Loum, Youssou Traore, Moustapha Thiame, Mamadou Wade and Gregoire Sissoko (2022). Optimization of the thickness of the doping rate base (Nb) of the (n+/p/p+) silicon solar cell with vertical multi-junction connected in series and placed under monochromatic illumination in frequency modulation. Journal of Chemical, Biological and Physical Sciences, Vol. 12, N0 4, 266-280. https://doi.org/10.24214/jcbps.C.12.4.26680

[47]. Gilbert Ndiasse Dione, Hamet Yoro BA, Gora Diop, Malick Ndiaye, Ibrahima Diatta, Khady Loum, Youssou Traore, Moustapha Thiame, Ousmane Sow, Mamadou Wade and S. Gregoire. Bifacial (n＋-p-p＋) Silicon Solar Cell base thickness optimization, while illuminated by the rear face with monochromatic light of short wavelenths. International Journal of advanced Research (IJAR), 2022, 10(09), 409-418. https://doi.org/ 10.21474/ IJAR01 /15372

[48]. Diop, G., Sow, O., Thiame, M., Mane, R., Diatta, I., Loum, K., Gueye, S., Wade, M. and Sissoko, G. (2022). Diffusion Coefficient at Double Resonances in Frequency and Temperature, Applied to (n+/p/p+) Silicon Solar Cell Base Thickness Optimization under Long Wavelength Illumination. Journal of Electromagnetic Analysis and Applications, 14, 89-103. doi: 10.4236/jemaa.2022.148008.

[49]. Francois Michel Ndiaye, Mamadou Lamine Ba, Mamour Amadou Ba, Gora Diop, Ibrahima Diatta, El Hadj Sow, Oulimata Mballo and Gregoire Sissoko, (2020). Lamella Silicon Optimum Width Determination Under Temperature. Int. J. Adv. Res. 8(06), 1409-1419.

[50]. Thiaw, C., Ba, M., Amadou Ba, M., Diop, G., Diatta, I., Ndiaye, M. and Sissoko, G. (2020) n+-p-p+ Silicon Solar Cell Base Optimum Thickness Determination under Magnetic Field. Journal of Electromagnetic Analysis and Applications, 12, 103-113. doi: 10.4236/jemaa.2020.127009.

[51]. Ndiaye, A., Gueye, S., Mbaye Fall, M., Diop, G., Ba, A., Ba, M., Diatta, I., Habiboullah, L. and Sissoko, G. (2020) Diffusion Coefficient at Resonance Frequency as Applied to n+/p/p+ Silicon Solar Cell Optimum Base Thickness Determination. Journal of Electromagnetic Analysis and Applications, 12, 145-158. doi: 10.4236/jemaa.2020.1210012.

[52]. 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, 173-185. https://doi.org/10.4236/jemaa.2019.1110012

[53]. Loum, K., Sow, O., Diop, G., Mane, R., Diatta, I., Ndiaye, M., Gueye, S., Thiame, M., Wade, M. and Sissoko, G. (2023) AC Back Surface Recombination Velocity as Applied to Optimize the Base Thickness under Temperature of an (n+-p-p+) Bifacial Silicon Solar Cell, Back Illuminated by a Light with Long Wavelength. World Journal of Condensed Matter Physics, 13, 40-56. doi: 10.4236/wjcmp.2023.131003.

[54]. J.A. Giesecke, M.C. Schubert, B. Michl, F. Schindler, W. Warta (2011). Minority carrier lifetime imaging of silicon wafers calibrated by quasi-steady-statephotoluminescence. Solar Energy Materials and Solar Cells Vol. 95 issue 3, Pp. 1011-1018 http://dx.doi.org/10.1016/j.solmat.2010.12.016

[55]. R. Van Steenwinkel, M.C. Carotta, G. Martinelli, M. Mercli, L. Passari and D. Palmeri (1990). Lifetime Measurement in Solar Cell of Various Thickness and Related Silicon Wafer. Solar Cells, 28, 287-292. https://doi.org/10.1016/0379-6787(90)90063-BG.

[56]. D. J. Paez, E. Huante-Ceron, A. P. Knights (2013). A Vertical PN Junction Utilizing the Impurity Photovoltaic Effect for the Enhancement of Ultra-thin Film Silicon Solar Cells MRS Proceedings Vol. 1536, Pp.39 to 44 http://dx.doi.org/10.1557/opl.2013.750

[57]. J. Dugas, (1994). 3D modelling of a reverse cell Made with improved multicrystalline silicon wafers. Solar Energy Materials and Solar Cells 32, pp71-88.

[58]. Nobuyuki Andoh, Kenichi Hayashi, Takatoshi Shirasawa, Toshiyuki Sameshima, Koichi Kamisako (2001). Effect of film thickness on electrical property of microcrystalline silicon. Solar Energy Materials and Solar Cells, Vol. 66 issue 1-4 Pp. 437-441 http://dx.doi.org/10.1016/s0927-0248(00)00205-1