Base Thickness Optimization of a (n+-p-p+) Silicon Solar Cell in Static Mode under Irradiation of Charged Particles

Mamadou Lamine Ba¹, Ndeye Thiam¹, Moustapha Thiame², Youssou Traore², Masse Samba Diop², Mamour Ba², Cheikh Tidiane Sarr², Mamadou Wade¹, Gregoire Sissoko²

¹Laboratory of Sciences and Techniques of Water and Environment, Polytechnic School of Thiès, Thiès, Senegal
²Laboratory of Semiconductors and Solar Energy, Physics Department, Faculty of Science and Technology, University Cheikh Anta Diop, Dakar, Senegal

Email: gsissoko@yahoo.com

How to cite this paper: Ba, M.L., Thiam, N., Thiam, 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

Received: August 26, 2019
Accepted: October 8, 2019
Published: October 11, 2019

Copyright © 2019 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution-NonCommercial International License (CC BY-NC 4.0). http://creativecommons.org/licenses/by-nc/4.0/

1. Introduction

Studies of the effect irradiation of charged particles on photovoltaic solar cells have always preoccupied scientific minds around different aspects and parameters. The study of the displacement of atoms during irradiation was first presented in 1956 [1]. It follows that of the radiation effects in solids in 1957 [2] then the solar cell radiation handbook in 1982 [3]. The fundamental processes occurring in GaAs solar cells exposed to ionizing radiation, such as energetic electrons and protons were presented in 1996. The interaction of radiation with matter and the resulting deposition of energy are covered, along with the corollary subjects of radiation exposure and dose [4].
On the other side, authors have studied the effect of irradiation of these particles on the solar cells (mono or bifacial [5], vertical multi-junctions [6]) for the determination of electrical parameters [7] such as photocurrent density, open circuit voltage, fill factor, maximum power, conversion efficiency [8], shunt and series resistances and diffusion capacitance [9].

Also, on determining phenomenological parameters i.e. excess minority carrier recombination velocity [10] at the junction and back surfaces, mobility, lifetime [11] and diffusion length [12] [13], charged particles irradiation effects were pointed out.

The incident illumination wavelength under steady [14] [15] [16] or dynamic frequency mode [17]-[21] was investigated.

This work deals with a method, to determinate the optimum thickness of a silicon solar cell under the effect of irradiation charged particles. Then, from the excess minority carrier density continuity equation in the base, expressions of photocurrent density [20] and recombination velocity of the rear surface, all depending on the irradiation of the charged particles are deducted. The optimum thickness \(H\) of the silicon solar cell base dependent of both irradiation energy flows \((\phi_p)\) and damage coefficient \((kl)\), is determined through the intercept point of the curves of the excess minority carrier recombination velocity \((S_{b0}\) and \(S_{b1}\)) at the back surface. As a result, the manufacture of the solar cell would be calibrated according to the irradiation conditions, thus allowing to reduce the amount of material to be used in the base.

2. Theory

**Figure 1** shows the structure of a front-illuminated silicon solar cell \((n^+ - p - p^+)\) [22] under irradiation.

### 2.1. Minority Carrier’s Density

When the solar cell is properly illuminated by a static polychromatic light, all the processes for generation, recombination in the bulk and surfaces and diffusion of excess minority carrier in the base are governed by the following continuity equation:

\[
D(kl,\phi_p)\frac{\partial^2 \delta(x, kl, \phi_p)}{\partial x^2} - \frac{\delta(x, kl, \phi_p)}{\tau} + G(x) = 0.
\]  

**Figure 1.** Structure of the silicon solar cell \((n^+ - p - p^+)\).
\( \delta(x, kl, \phi_p) \) represents the excess minority carrier density in the base of the solar cell at the x-position, dependent of the irradiation energy. 

\( D(kl, \phi_p) \) and \( \tau \) are respectively the diffusion coefficient of the electrons in the base under irradiation and the lifetime of the excess minority carrier in the base of the solar cell linked by the following Einstein relationship:

\[
\left[ L(kl, \phi_p) \right]^2 = \tau \times D(kl, \phi_p),
\]

with \( L(kl, \phi_p) \) the diffusion length of the excess minority carrier in the base as a function of the irradiation energy flux \( (\phi_p) \) and the damage coefficient intensity \( (kl) \). It also represents the average distance traveled by the minority carrier before their recombination in the base under irradiation. It is related to the diffusion length before irradiation by the following empirical relation [10]:

\[
L(kl, \phi_p) = \frac{1}{\left( \frac{1}{L_0} + kl \phi_p \right)^{1/2}},
\]

where:

- \( L_0 \) is the diffusion length of the excess minority carriers in the base before irradiation.
- \( \phi_p \) is the irradiation energy flux.
- \( kl \) is the damage coefficient intensity.

\( G(x) \) is the excess minority carrier generation rate [23] [24], given by:

\[
KlG(x) = n \sum_{i=1}^{3} a_i e^{-b_i x}.
\]

- \( n \) is the number of sun or illumination concentration [25].
- The coefficients \( a_i \) and \( b_i \) take into account the tabulated values of solar radiation and the dependence of the absorption coefficient of silicon with the wavelength [24].

The carrier density is subjected to the following boundary conditions:

1) At the junction: emitter-base \( (x = 0) \)

\[
D(kl, \phi_p) \left| \frac{\partial \delta(x, kl, \phi_p)}{\partial x} \right|_{x=0} = S_f \cdot \delta(0, kl, \phi_p).
\]

2) At the back side \( (x = H) \)

\[
D(kl, \phi_p) \left| \frac{\partial \delta(x, kl, \phi_p)}{\partial x} \right|_{x=H} = -S_b \cdot \delta(H, kl, \phi_p).
\]

\( S_f \) is the excess minority carrier recombination velocity at the junction and also indicates the solar cell operating point [26] [27].

\( S_b \) is the excess minority carrier recombination velocity on the back side surface [28] [29] [30].

It is the consequence of the electric field produced by the p-p⁺ junction and characterizes the behavior of the density of the excess carrier at this interface.
yields to send back to the emitter-base interface the minority carriers generated near the rear face.

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

\[
\delta(x, kl, \phi_p) = A \cdot \cosh \left[ \frac{x}{L(kl, \phi_p)} \right] + B \cdot \sinh \left[ \frac{x}{L(kl, \phi_p)} \right] - \sum K_i \cdot e^{-h_x},
\]

where:

\[
K_i = -\frac{n \times [L(kl, \phi_p)]^2 \times a_i}{D(kl, \phi_p) \left( b_i^2 \times [L(kl, \phi_p)]^2 - 1 \right)}.
\]

The expressions of, \( A \) and \( B \) are determined from the following boundary conditions and are given by:

\[
A = L(kl, \phi_p) \times K_i \left[ D(kl, \phi_p) \times Sb(kl, \phi_p) - D \left( k \cdot x, \phi_p \right) \times b_i \right] e^{-h_x} + \chi(kl, \phi_p),
\]

\[
\chi(kl, \phi_p) = \left[ D(kl, \phi_p) \times \cosh \left( \frac{H}{L(kl, \phi_p)} \right) + L(kl, \phi_p) \times Sb(kl, \phi_p) \right] \times \sinh \left( \frac{H}{L(kl, \phi_p)} \right) \times Sf + D(kl, \phi_p) \times b_i.
\]

\[
Y = \left[ L^2 \left( k \cdot x, \phi_p \right) \times Sb(kl, \phi_p) \times Sf + D \left( k \cdot x, \phi_p \right) \right],
\]

\[
X = D(kl, \phi_p) \times L(kl, \phi_p) \times Sf + Sb(kl, \phi_p).
\]

\[
B = L(kl, \phi_p) \times K_i \left[ L(kl, \phi_p) \times Sf \times Sb(kl, \phi_p) - D \left( k \cdot x, \phi_p \right) \times b_i \right] e^{-h_x} + \zeta(kl, \phi_p),
\]

\[
\zeta(kl, \phi_p) = \left[ D(kl, \phi_p) \times \sinh \left( \frac{H}{L(kl, \phi_p)} \right) + L(kl, \phi_p) \times Sb(kl, \phi_p) \right] \times \cosh \left( \frac{H}{L(kl, \phi_p)} \right) \times Sf + D(kl, \phi_p) \times b_i.
\]

### 2.2. Photocurrent Density

The expression of the photocurrent density is given by the relation:

\[
J_{ph} (Sf, H, kl, \phi_p) = q \cdot D(kl, \phi_p) \left[ \frac{\partial \delta(Sf, x, H, kl, \phi_p)}{\partial x} \right]_{x=0}.
\]

For polychromatic illumination we obtain:
\[ J_{ph}(S_f, H, k_l, \phi_p) = q \cdot D(k_l, \phi_p) \left[ \frac{B(S_f, H, k_l, \phi_p)}{L(k_l, \phi_p)} + \sum_{i=1}^{3} K_i \cdot b_i \right]. \] (16)

This photocurrent density is constant for the large values of the carrier recombination rate at the junction between \(3 \times 10^3 \leq S_f \leq 6 \times 10^6 \text{ cm/s} \) [27] [31] [32] [33].

The \( S_b \) expression is obtained from the derivative of the photocurrent density for large \( S_f \) values [28] [33].

\[ \frac{\partial J_{ph}(S_f, k_l, \phi_p)}{\partial S_f} = 0. \] (17)

The resolution of this equation yields to establish the following expressions of the excess minority carrier recombination velocity at the rear face, \( S_{b0}(H, k_l, \phi_p) \) and \( S_{b1}(H, k_l, \phi_p, b_i) \):

\[ S_{b0}(H, k_l, \phi_p) = -\frac{D(k_l, \phi_p)}{L(k_l, \phi_p)} \tan \left( \frac{H}{L(k_l, \phi_p)} \right). \] (18)

It represents the intrinsic recombination velocity at the \( p-p^+ \) junction of the minority carrier.

\[ S_{b1}(H, k_l, \phi_p) = \frac{D(k_l, \phi_p)}{L(k_l, \phi_p)} \sum_{i=1}^{3} b_i \left( e^{\phi_{H}} - \cosh \left( \frac{H}{L(k_l, \phi_p)} \right) \right) - \sinh \left( \frac{H}{L(k_l, \phi_p)} \right). \] (19)

It represents the recombination rate at the rear face influenced by the effect of the absorption of light in the material through the coefficients \( (b_i) \) and leads to a generation rate.

3. Results and Discussion
3.1. Photocurrent Density

From the expression (16), we represent in Figures 2-4 the profiles of the photocurrent density as a function of excess minority carrier recombination velocity at the junction for different values of the irradiation energy, the damage coefficient and the base thickness.

Figure 2 and Figure 3 show the profile of the photocurrent density as a function of the excess minority carrier recombination velocity at the junction for different values of both the irradiation energy and the damage coefficient.

On this figure, we note three different parts on the profile of the photocurrent density:
The photocurrent density is almost zero for low values of the recombination velocity ($S_f < 200$ cm/s), the solar cell operates then in open circuit.

Then for $200$ cm/s < $S_f < 4 \times 10^4$ cm/s, the photocurrent density increases with the recombination velocity to reach a maximum of amplitude. This shows that the excess minority carrier has acquired sufficient energy to cross the junction.

- The photocurrent density is almost zero for low values of the recombination velocity ($S_f < 200$ cm/s), the solar cell operates then in open circuit.
- Then for $200$ cm/s < $S_f < 4 \times 10^4$ cm/s, the photocurrent density increases with the recombination velocity to reach a maximum of amplitude. This shows that the excess minority carrier has acquired sufficient energy to cross the junction.
Figure 4. Photocurrent density versus junction recombination velocity for different values of base thickness with $k_l = 11$ cm$^{-2}$/MeV, $\phi_p = 220$ MeV and $D(k_l, \phi_p) = 27$ cm$^2$/s.

- For $S_f > 4 \times 10^4$ cm/s, the photocurrent density is maximum and constant, corresponding to the short-circuit photocurrent. The figure also shows that as the irradiation energy and damage coefficient increases, the maximum amplitude of the photocurrent density decreases. This phenomenon can be explained by the interaction of the irradiating particles with the silicon material which increases and reduces the excess minority carrier density.

Figure 4 shows that the photocurrent density increases with the junction recombination velocity for different values of the thickness.

3.2. Back Surface Recombination Velocity

3.2.1. Influence of the Irradiation Energy on the Back Surface Recombination Velocity

Figure 5 below shows the plots of excess minority carrier recombination rates at the back as a function of the base thickness for different values of the irradiation energy.

In Figure 5, the optimum thickness of the base of the solar cell subjected to variations in the irradiation energy flux is obtained with the intercept point from the curves of $S_{b0} (H)$ and $S_{b1} (H)$, representing the excess minority carrier recombination velocity at the rear face.

Table 1 below shows the variations of the optimum thickness in the base of the solar cell under irradiation energy leading to the different precise values of the diffusion coefficient, short-circuit currents $J_{sc0}$ and $J_{sc1}$ corresponding to $S_{b0}$ and $S_{b1}$.

Figure 6 below shows the profile of the thickness in the base as a function of both, irradiation energy and constant damage coefficient.
Figure 5. Recombination velocity at the back face as a function of the thickness for different irradiation energy values with $kd = 11$ cm$^2$/MeV.

Figure 6. Optimum depth in the base versus irradiation energy.

Table 1. Thickness values in the base $H$, diffusion coefficient $D$, short-circuit currents $J_{sc0}$ and $J_{sc1}$ corresponding to $Sb0$ and $Sb1$ for different irradiation energy flows.

| $\phi$ (MeV) | 100  | 130  | 160  | 190  | 220  |
|--------------|------|------|------|------|------|
| $D$ (cm$^2$/s) | 30.063 | 29.204 | 28.375 | 27.546 | 26.688 |
| $H$ (cm) | 0.0127 | 0.0123 | 0.0119 | 0.0116 | 0.0113 |
| $Sb0$ (cm/s) | 5377.5 | 5287.5 | 5202.5 | 5127.5 | 5042.5 |
| $Sb1$ ($10^5$ cm/s) | 2.222 | 2.150 | 2.082 | 2.022 | 1.954 |
| $J_{sc0}$ (A/cm$^2$) | 0.0353 | 0.0353 | 0.0353 | 0.0354 | 0.0354 |
| $J_{sc1}$ (A/cm$^2$) | 0.0266 | 0.0266 | 0.0265 | 0.0265 | 0.0264 |

The correlation between the irradiation energy and optimum thickness of the base is established:

$$H (\text{cm}) = a \times \phi^b - b \times \phi + c.$$  \hspace{1cm} (20)

With: $a = 2 \times 10^{-8}$ cm/MeV, $b = 2 \times 10^{-5}$ cm/MeV, $c = 0.014$ cm.
3.2.2. Influence of the Damage Coefficient on the Back Surface Recombination Velocity

Figure 7 below shows the plots of excess minority carrier recombination velocity at the back as a function of the thickness in the base for different values of the damage coefficient.

In Figure 7, the optimum thickness of the base of the solar cell subjected to variations in the level of degradation of the solar cell during the interactions of the particles is obtained by the intercept point deduced of the plotted curves of excess minority carrier recombination velocity at the rear face $Sb_0$ ($H$) and $Sb_1$ ($H$).

Table 2 below shows the variations of the thickness in the base as a function of the damage coefficient leading to the different precise values of the diffusion coefficient, short-circuit currents $J_{sc0}$ and $J_{sc1}$ corresponding to $Sb0$ and $Sb1$.

Figure 8 below shows the profile of the thickness in the base as a function of the damage coefficient and constant irradiation energy.

![Figure 7. Recombination velocity at the back face as a function of the thickness for different damage coefficients values with $\phi_p = 220$ MeV.](image1)

![Figure 8. Optimum depth in the base versus damage coefficient.](image2)
Table 2. Thickness values in the base $H$, diffusion coefficient $D$, short-circuit currents $J_{sc0}$ and $J_{sc1}$ corresponding to $Sb0$ and $Sb1$ for different damage coefficients.

| $k/({cm^2}/{MeV})$ | 5    | 7    | 9    | 10   | 11   |
|---------------------|------|------|------|------|------|
| $D$ (${cm^2/s}$)    | 30.079 | 28.895 | 27.895 | 27.368 | 26.789 |
| $H$ ($cm$)          | 0.0126 | 0.0121 | 0.0117 | 0.0115 | 0.0113 |
| $Sb0$ ($cm/s$)      | 5377.5 | 5267.5 | 5165  | 5107.5| 5052.5 |
| $Sb1$ ($10^5 cm/s$)| 2.222 | 2.134 | 2.052 | 2.006 | 1.962 |
| $J_{sc0}$ ($A/cm^2$)| 0.0353 | 0.0353 | 0.0353 | 0.0354 | 0.0354 |
| $J_{sc1}$ ($A/cm^2$)| 0.0266 | 0.0265 | 0.0265 | 0.0264 | 0.0264 |

The correlation between the damage coefficient and optimum thickness of the base is established:

$$H (cm) = a \times \phi_p^2 - b \times \phi_p + c.$$  \hspace{1cm} (21)

With: $a = 6 \times 10^{-6} \text{MeV} \cdot \text{cm}^2/\text{cm}^{-2}$, $b = 3 \times 10^{-4} \text{MeV} \cdot \text{cm}^2/\text{cm}^{-2}$, $c = 0.014 \text{cm}$.

4. Conclusions

In this work, we have proposed a method for determining the optimal thickness of a monofacial solar cell subjected to the effect of the irradiation of charged particles. The expressions of the excess minority carrier in the base and the photocurrent density have been proposed. Calibration curves of the photocurrent density were plotted versus the junction recombination rate for different values of the irradiation energy and the damage coefficient.

The expressions of the excess minority carrier recombination rates at the back face have been deduced from the derivative of the photocurrent density with respect to the excess minority carrier recombination velocity at the junction, when this tends to large values corresponding to the short-circuit situation of the solar cell.

The graphical resolution of the equations of recombination rates at the rear face yields to obtain at the points of intersection of the curves the value of the optimum thickness for a given irradiation energy and a given damage coefficient in the vicinity of the short-circuit current.

Finally, a correlation between the irradiation energy, the damage coefficient and the optimal thickness of the solar cell has been established.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Seitz, F. and Koehler, J.S. (1956) Displacement of Atoms during Irradiation. In: Seitz, E. and Turnbull, D., Eds., Solid State Physics, Vol. 2, Academic Press, Lon-
[2] Dienes, G.J. and Vineyard, G.H. (1957) Radiation Effects in Solids. Interscience Publishers, Inc., New York.

[3] Tada, H.Y., Carter, J.R., Anspaugh, B.E. and Downing, R.G. (1982) Solar Cell Radiation Handbook. JPL Publication 82-69, Jet Propulsion Laboratory, California Institute of Technology, Pasadena.

[4] Martin, J.E. (2013) Physics for Radiation Protection: A Handbook. 3rd Edition, Wiley-VCH, Hoboken.

[5] Ould El Moujtaba, M.A., Ndiaye, M., Diao, A., Thiam, M., Barro, I.F. and Sissoko, G. (2012) Theoretical Study of Influence of Irradiation on a Silicon Solar Cell under Multispectral Illumination. Research Journal of Applied Sciences Engineering and Technology, 23, 5068-5073.

[6] Gueye, M., Diallo, H.L., Moustapha, A.K.M., 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. https://doi.org/10.4236/wjcmp.2018.84013

[7] 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.2015.31177

[8] Dieng, A.B., Seibou, B., Ndiaye, S.A., Wade, M., Diouf, M.S., Ly, I. and Sissoko, G. (2016) Illumination Wavelength Effect on Electrical Parameters of a Parallel Vertical Junction Silicon Solar Cell under Steady State and under Irradiation. International Journal of Research in Engineering and Technology, 5, 128-135.

[9] Ndoeye, M.S., Seibou, B., Ly, I., Diouf, M.S., Wade, M., Mbojdi, S. and Sissoko, G. (2016) Irradiation Effect on Silicon Solar Cell Capacitance in Frequency Modulation. International Journal of Innovative Technology and Exploring Engineering, 6, 21-25. https://www.ijitee.org/

[10] Ohshima, T., Sumita, T., Imaizumi, M., Kawakita, S., Shimazaki, K., Kuwajima, S., Ohi, A. and Itoh, H. (2005) Evaluation of the Electrical Characteristics of III-V Compounds Solar Cells Irradiated with Protons at Low Temperatures. Proceedings of the 31st IEEE Photovoltaic Specialists Conference, Lake Buena Vista, 3-7 January 2005, 806-809. https://doi.org/10.1109/PVSC.2005.1488255

[11] Cristina Constanta Stanescu (2002) SiO₂ sur silicium: Comportement sous irradiation avec des ions lourds. Thèse Doctorat de l’Université de Caen/Basse Normandie.

[12] Kraner, H.W. (1983) Radiation Damage in Silicon Detectors. 2nd Pisa Meeting on Advanced Detectors, Grosetto, Italy, 3-7 June, 10.

[13] Shin, G.H., et al. (2008) Radiation Effect Test for Single-Crystalline and Polycrystalline Silicon Solar Cells. Journal of the Korean Physical Society, 52, 843-847. http://hdl.handle.net/10203/89159 https://doi.org/10.4236/jkps.2018.52.843

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

[15] Gaye, I., Sam, R., Seré, A.D., Barro, I.F., Ould El Moujtaba, M.A., Mané, R. and Sissoko, G. (2012) Effect of Irradiation on the Transient Response of a Silicon Solar Cell. International Journal of Emerging Trends and Technologies in Computer Science, 1, 210-214.

[16] Tall, I., Seibou, B., Ould El Moujtaba, M.A., Diao, A., Wade, M. and Sissoko, G.
(2015) Diffusion Coefficient Modeling of a Silicon Solar Cell under Irradiation Effect in Frequency: Electric Equivalent Circuit. *International Journal of Engineering Trends and Technology, 19*, 56-61. [http://www.ijettjournal.org/](http://www.ijettjournal.org/) [https://doi.org/10.14445/22315381/IJETT-V19P211](https://doi.org/10.14445/22315381/IJETT-V19P211)

[17] Ly, I., Wade, M., Ly Diallo, H., El Moujtaba, M.A.O., Lemrabott, O.H., Mbojji, S., Diasse, O., Ndiaye, A., Gaye, I., Barro, F.I., Wereme, A. and Sissoko, G. (2011) Irradiation Effect on the Electrical Parameters of a Bifacial Silicon Solar Cell under Multispectral Illumination. *Proceedings of 26th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, 5-6 September 2011, 785-788. [https://www.eupvsec-proceedings.com/](https://www.eupvsec-proceedings.com/)

[18] Diop, N.M., Seibou, B., Wade, M., Diouf, M.S., Ly, I., Diallo, H.L. and Sissoko, G. (2016) Theoretical Study of Vertical Parallel Junction Silicon Solar Cell Capacitance under Modulated Polychromatic Illumination: Influence of Irradiation. *International Journal of Innovative Technology and Exploring Engineering, 6*, 1-7.

[19] Diallo, M.M., Tamb, S., Seibou, B., Cheikh, M.L.O., Diatta, I., Ndiaye, E.H., Traore, Y., Sarr, C.T. and Sissoko, G. (2017) Impact of Irradiation on the Surface Recombination Velocity of a Back Side Monochromatic Illuminated Bifacial Silicon Solar Cell under Frequency Modulation. *Journal of Scientific and Engineering Research, 4*, 29-40.

[20] Zerbo, I., Koalaga, Z., Barro, F.I., Zougmore, F., Ndiaye, A.L., Diaa, A. and Sissoko, G. (2004) Silicon Solar Cell Recombination Parameters Determination under Frequency Modulated White Light Using the Short Circuit Current Phase. *Journal des Sciences, 4*, 42-46.

[21] Gaye, I., Ould El Moujtaba, M.A., Thiam, N., Tall, I. and Sissoko, G. (2014) Influence of Irradiation and Damage Coefficient on the Minority Carrier Density in Transient Response for a Bifacial Silicon Solar Cell. *Current Trends in Technology and Science, 3*, 98-104.

[22] Nam, L., Rodot, M., Nijs, J., Ghannam, M. and Coppye, J. (1992) Réponse spectrale de photopiles de haut rendement au silicium multicristalline. *Journal de Physique III, EDP Sciences, 2*, 1305-1316. [https://doi.org/10.1051/jp3:1992108](https://doi.org/10.1051/jp3:1992108)

[23] Furlan, J. and Amon, S. (1985) Approximation of the Carrier Generation Rate in Illuminated Silicon. *Solid State Electronics, 28*, 1241-1243. [https://doi.org/10.1016/0038-1101(85)90048-6](https://doi.org/10.1016/0038-1101(85)90048-6)

[24] Mohammad, S.N. (1987) An Alternative Method for the Performance Analysis of Silicon Solar Cells. *Journal of Applied Physics, 28*, 767-772. [https://doi.org/10.1063/1.338230](https://doi.org/10.1063/1.338230)

[25] Jain, G.C., Singh, S.N. and Kotnala, R.K. (1983) Diffusion Length Determination in n"-p"-p" Based Silicon Solar Cells from the Intensity Dependence of the Short Circuit for Illumination from the p" Side. *Solar Cells, 82*, 39-48. [https://doi.org/10.1016/0379-6787(83)90063-7](https://doi.org/10.1016/0379-6787(83)90063-7)

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

[27] Diallo, H.L., Seidou, A., Maiga, Wereme, A. 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*, 203-211. [https://doi.org/10.1051/epjap:2008085](https://doi.org/10.1051/epjap:2008085)

[28] Rose, B.H. and Weaver, H.T. (1983) Determination of Effective Surface Recombination Velocity and Minority-Carrier Lifetime in High-Efficiency Si Solar Cells. *Jour-
nal of Applied Physics, 54, 238-247. https://doi.org/10.1063/1.331693

[29] Joardar, K., Dondero, R.C. and Schroda, D.K. (1989) 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

[30] 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, 1487-1490.

[31] 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, 1698-1700.

[32] Sissoko, G., Nanema, E., Correa, A., Biteye, P.M., Adj, M. and Ndiaye, A.L. (1998) Silicon Solar Cell Recombination Parameters Determination Using the Illuminated I-V Characteristic. Renewable Energy, 3, 1848-1851.

[33] Diallo, M.M., Seibou, B., Ba, H.Y., Zerbo, I. and Sissoko, G. (2014) One Dimensional Study of a Bifacial Silicon Solar Cell Illuminated from the Front Surface by a Monochromatic Light under Frequency Modulation. Current Trends in Technology and Sciences, 3, 416-421.