Energy and Power Engineering, 2017, 9, 1-10
http://www.scirp.org/journal/epe
ISSN Online: 1947-3818
ISSN Print: 1949-243X

Minority Carrier Diffusion Coefficient $D^*(B, T)$: Study in Temperature on a Silicon Solar Cell under Magnetic Field

Richard Mane[1], Ibrahima Ly[2], Mamadou Wade[2], Ibrahima Datta[1], Marcel S. Douf[1], Youssou Traore[1], Mor Ndiaye[1], Seni Tamba[2], Grégoire Sissoko[1]

[1]Laboratoire des Semi-conducteurs et d'Energie Solaire, Faculté des Sciences et Techniques, Université Cheikh Anta Diop, Dakar, Sénégal
[2]Ecole Polytechnique de Thiès, Thiès, Sénégal
Email: gsissoko@yahoo.com

How to cite this paper: Mane, R., Ly, I., Wade, M., Datta, I., Douf, M.S., Traore, Y., Ndiaye, M., Tamba, S. and Sissoko, G. (2017) Minority Carrier Diffusion Coefficient *D**(*B*, *T*): Study in Temperature on a Silicon Solar Cell under Magnetic Field. *Energy and Power Engineering*, **9**, 1-10.
http://dx.doi.org/10.4236/epe.2017.91001

Received: December 22, 2016
Accepted: January 6, 2016
Published: January 9, 2016

Abstract

This work deals with minority carrier diffusion coefficient study in silicon solar cell, under both temperature and applied magnetic field. New expressions of diffusion coefficient are pointed out, which gives attention to thermal behavior of minority carrier that is better understood with Umklapp process. This study allowed to determine an optimum temperature which led to maximum diffusion coefficient value while magnetic field remained constant.

Keywords

Solar cell, Diffusion Coefficient, Temperature, Magnetic Field

1. Introduction

The photovoltaic conversion efficiency depends on the nature and structure of the semiconductor, its manufacturing processes and the operating conditions. In order to improve solar cell performance, several characterization techniques of semiconductor material have been proposed. Among the most important parameters in the different characterization techniques, it can be noted the diffusion coefficient [1] [2] of the minority carrier (D). Thus, the diffusion coefficient was determined versus:

The applied magnetic field (B) [3] [4] [5],
The base doping rate (Nb) [6],
Modulated frequency (ω) [7] [8],
The damage coefficient (Kl) and the irradiation flux (Φp) [9],
The minority carrier recombination velocity at the grain boundaries (Sg) and

the grain size (g) [10], the temperature (T) [11] [12] and the electric field (E) [13] [14] [15].

Many of previous parameters can be combined to produce new expressions of diffusion coefficient [15], such as, D (ω, Nb) [16] [17], D (B, ω) [18] [19], D (Φp, ω) [9] [20] [21] [22], D (Sf, Sb) [23] [24].

It then affects the determination of the recombination parameters in the bulk *i.e.* lifetime (τ) and on the surfaces, specially, the back surface recombination velocity (Sb) and junction surface recombination velocity (Sf)) [24] [25]. It then affects the determination of the recombination parameters in the bulk *i.e.* lifetime (τ) and on the surfaces, specially, the back surface recombination velocity (Sb) and junction surface recombination velocity (Sf)) [24] [25] [26] according to the operating conditions [11] [12] [27] [28] (steady state, dynamic frequency and transient) and according to the space dimensional model [29] under study *i.e.* (1D) or (3D) of the solar cell, diffusion coefficient gets new expressions [30]-[35]. Taking into account the emitter, the ambipolar diffusion coefficient is then derived [20] [21].

In static regime, the photocurrent Iph is studied versus absorption coefficient wavelength dependent (λ) and leads to spectral response [36] [37] [38]. The well known current-voltage (I-V) characteristic (under dark or illumination) allows the determination of the electrical parameters such as series (Rs) and shunt resistances (Rsh), and junction transition capacitance (Cz) [39] [40].

In frequency regime, we note the studies of both Sb and Sf, excess minority carrier recombination velocity respectively at the junction and at the back side surfaces, by the help of Bode and Nyquist diagrams, leading to electrical equivalent models, with effect of both external (B, E, Φ, kl) and internal (g, Sg, (λ)) parameters [3] [41] [42] [43].

In this article, the study focuses on the minority carriers diffusion coefficient in silicon solar cell under both temperature and applied magnetic field.

2. Presentation of the Solar Cell

We consider a back surface field (B.S.F) silicon solar cell (n^+-p-p^+ type) under influence of temperature and applied magnetic field (**Figure 1**).

3. Diffusion Coefficient

When the solar cell is illuminated, the phenomena of generation, diffusion and recombination of the minority carriers in the solar cell base are considered.

The minority carrier diffusion coefficient $D\times(B)$ in the base under the influence of applied magnetic field B [3], is extended with applied temperature T and then gives the following equation:

$$D^*(B,T)=\frac{D_0(T)}{\left[1+(\mu(T)\times B)^2\right]} \tag{1}$$

where $D_0(T)$ is the diffusion coefficient versus temperature T, in the solar cell without magnetic field. It is given by the Einstein-Smoluchowski relation [44] [45]:

$$D_0(T)=\mu(T)\times\frac{k_b\times T}{q} \tag{2}$$

With $\mu(T)$ is the minority carriers mobility temperature [46] [47] dependent in the base and expresses as:

$$\mu(T) = 1.43 \times 10^{9} T^{-2.42} \text{cm}^{2} \cdot \text{V}^{-1} \cdot \text{s}^{-1} \quad (3)$$

q is the electron elementary charge and kb is Boltzmann's constant given as kb = 1.38×10^{-23} $\text{m}^2 \cdot \text{kgs}^{-2} \cdot \text{K}^{-1}$.

3.1. Magnetic Field Effect on the Diffusion Coefficient

Figure 2 shows the minority carrier diffusion coefficient versus magnetic field logarithm for different temperature values.

For a given temperature, the diffusion coefficient is maximum and almost constant when the magnetic field is weak. Indeed, for low magnetic field values, the carrier mobility is not strongly influenced by magnetic field variation and this explains the bearing observed. On the other hand, when the magnetic field is

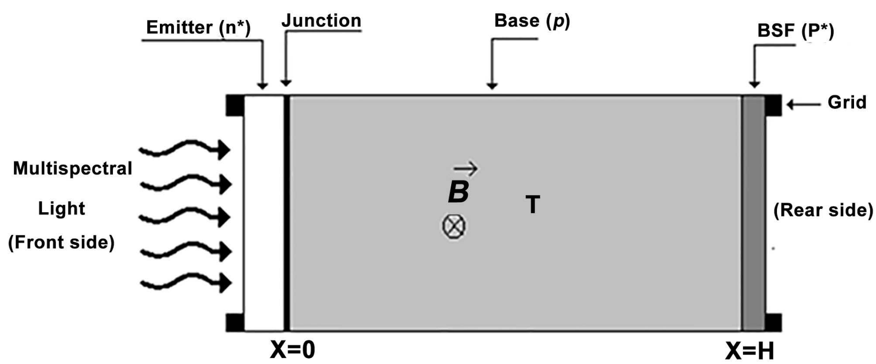

Figure 1. An n^+-p-p^+ silicon solar cell scheme.

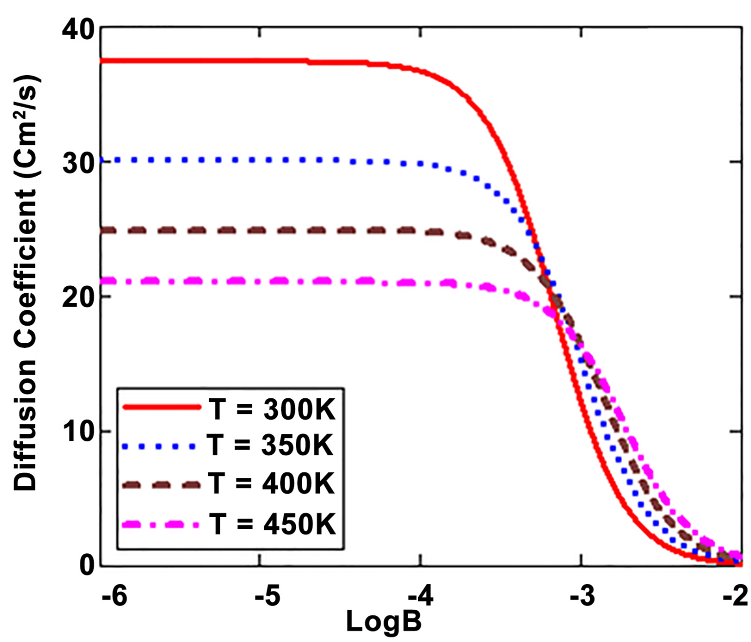

Figure 2. Diffusion coefficient versus magnetic field logarithm.

greater than 10^{-3} T, mobility and minority carrier diffusion decrease with the magnetic field [48] [49]. The diffusion coefficient is more sensitive to temperature for weak magnetic field values. However an inversion is observed when B is greater than 10^{-3} T, where the diffusion coefficient increases with temperature.

3. 2. Temperature Effect on Diffusion Coefficient

Figure 3 shows the profile of the diffusion coefficient versus temperature for different magnetic field values, obtained by plotting combined Equations (1) (2) and (3).

For lower magnetic field values ($<10^{-3}$ T), the diffusion coefficient increases with temperature and reaches a maximum value corresponding to a temperature called optimum temperature Topt (B) then decreases. Indeed, when the temperature is below Topt (B), the Umklapp process [50] does not limit the thermal conductivity which varies with T3 [51], so the thermal resistance decreases according to the temperature which leads to an increase of the diffusion coefficient [51] [52]. High thermal resistance induced by high temperatures is due to the exponential establishing of Umklapp process which provides 1/T thermal conductivity dependent [51] [52] [53]. Thermal agitation reduces minority charge carrier mobility of and causes the diffusion coefficient decreasing [48].

On the other hand, when the magnetic field is greater than 10^{-3} T, the diffusion coefficient increases with temperature.

Moreover, it may be noted that the optimum temperature increases according to the magnetic field intensity

3. 3. Magnitude of the Diffusion Coefficient as a Function of the Optimum Temperature for Different Magnetic Field Values

The optimum temperature Topt (B) for maximum diffusion is determined using two methods:

- Graphical method

From the curves in **Figure 3**, the maximum diffusion coefficient values are determined according to the optimum temperature for different magnetic field values.

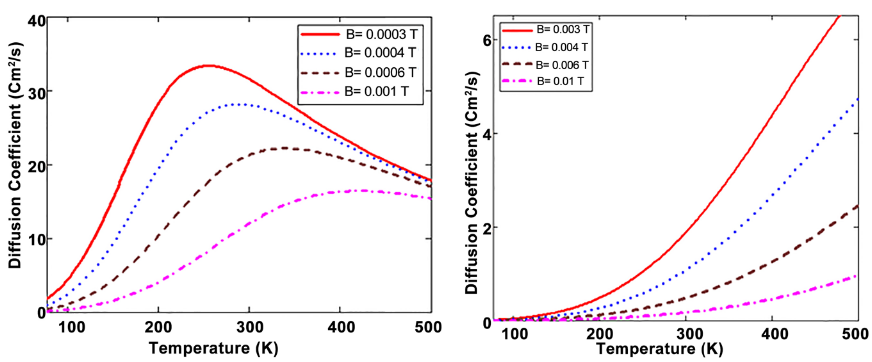

Figure 3. Diffusion coefficient versus temperature for different magnetic field values.

From **Table 1**, we represent in **Figure 4** the profile on log-log scale, diffusion coefficient versus optimum temperature.

Considering the average right, the following relationship is obtained:

$$\ln D_{\max}(B) = a \times T_{opt}(B) + b \tag{4}$$

$$\Rightarrow D_{\max}(B) = k \times \left[T_{opt}(B)\right]^{a}; \text{ with } K = eb \tag{5}$$

The constants a and b are determined from the curve, the following equations is obtained:

$$3.507 = 5.54\text{a} + \text{b} \tag{6}$$

$$3.206 = 5.73\text{a} + \text{b} \tag{7}$$

The resolution of the equations constituted by relations (6) and (7) gives:

a = −1.58 (cm^2/s·T) et b = 12.26 (cm^2/s)

Hence the relationship Topt:

$$D_{\max}(B) = 2.1 \times 10^{5} \times \left[T_{opt}(B)\right]^{-1.58} \tag{8}$$

- Analytical method

The diffusion coefficient is maximum when the temperature is equal to Topt for a given magnetic value B which remained constant. Thus, by annulling its derivative versus temperature, we can determine Topt while keeping B constant value.

Table 1. Diffusion coefficient with optimum temperature.

Magnetic field B (T)	0.0003	0.0004	0.0005	0.0006	0.0007	0.0008	0.0009	0.001
Optimum temperature T (K)	255	285	308	335	355	380	400	410
Diffusion coefficient D (cm^2/s)	33.364	28.178	24.694	22.206	20.276	18.763	17.571	16.642

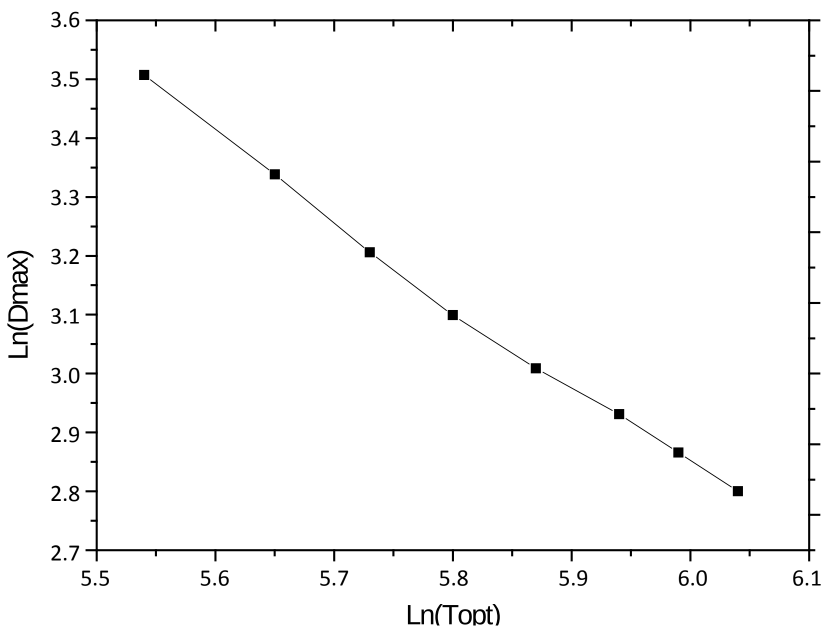

Figure 4. Log-log diffusion coefficient versus optimum temperature.

The derivative of the diffusion coefficient at T = Topt is given by the relation as:

$$D^{*\prime}(B,T) = 175 \times T^{-2.42} \times \frac{\left[-1 + 4.907 \times 10^{18} \times B^2 \times T^{-4.84}\right] \times 10^3}{\left[1 + 2.05 \times 10^{18} \times B^2 \times T^{-4.84}\right]^2} \quad (9)$$

We then deduce the relationship:

$$T_{opt}(B) = \sqrt[4.84]{2.4 \times (1.43 \times 10^9)^2 \times B^2} \quad (10)$$

Using the relation (10), the optimum temperature can be calculated for different magnetic field values. Results are presented in Table 2.

For a comparative study of the two methods, we represent in Figure 5, on log-log scale, profiles of the amplitude of diffusion coefficient versus the optimum temperature. The results for the two methods are identical to one decimal place. The two curves are almost confused. So for the rest of this work, we can justify the choice of temperatures set in the study of various parameters of the solar cell. For a given value of the magnetic field, the temperature to be used must obey the relation (8) in order to obtain an optimal response of the solar cell under magnetic field.

Table 2. Optimum temperature with magnetic field.

Magnetic field B (T)	0.0003	0.0004	0,0005	0.0006	0.0007	0.0008	0.0009	0.001
Optimum temperature (K)	254.7	286.6	313	336.5	361.4	381.9	401.0	418.8
Diffusion coefficient (cm^2/s)	33.368	28.173	24.66	22.202	20.259	18.757	17.561	16.548

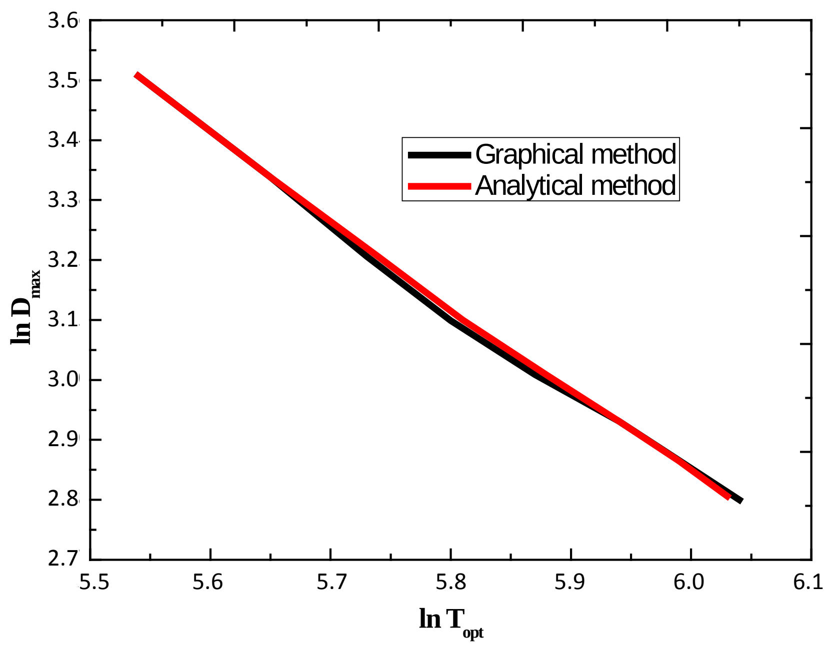

Figure 5. Log-log maximum diffusion coefficient versus optimum temperature for both methods.

4. Conclusions

The minority carrier diffusion coefficient $D^*(B,T)$ study has shown much more sensitivity to temperature for weak applied magnetic field. For low magnetic field value, the minority carrier diffusion decreases with temperature which reduces the solar cell performance.

Otherwise, the diffusion coefficient increases with temperature, reaches a maximum value corresponding to a temperature called optimum temperature. For a fixed magnetic field value, the diffusion coefficient decreases with the optimum temperature. The relation obtained between the maximum value of the diffusion coefficient and the optimum temperature allows justifying the selection of the temperature values for the study of the solar cell parameters.

References

[1] Sontag, D., Hahn, G., Geiger, P., Fath, P. and Bucher, E. (2002) Two-Dimensional Resolution of Minority Carrier Diffusion Constant in Different Silicon Materials.. *Solar Energy Materials & Solar Cells*, **72**, 533-539.

[2] 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. *Semiconductors Sciences and Technologies*, **26**, Article ID: 095023.

[3] Bester, Y., Ritter, D., Bahia, G., Cohen, S. and Sparkling, J. (1995) Method Measurement of the Minority Carrier Mobility in the Base of Heterojunction Bipolar Transistor Using a Magnetotransport Method. *Applied Physics Letters*, **67**, 1883-1884. https://doi.org/10.1063/1.114364

[4] Faye, K., Gaye, I., Gueye, S., Wade, M. and Sissoko, G. (2014) Silicon Solar Cell under Back Side Illumination: Effect of Magnetic Field. *IPASJ-International Journal of Electrical Engineering* (*IIJEE*), **2**, 1-9.

[5] Faye, K., Gaye, I., Gueye, S., Tamba, S. and Sissoko, G. (2014) Effect of Doping Level of a Silicon Solar Cell under Back Side illumination. *Current Trends in Technology & Sciences* (*CTTS*), **3**, 365-371.

[6] Liou, J.J. and Wong, W.W. (1992) Comparison and Optimization of the Performance of Si and GaAs Solar Cells. *Solar Energy Materials and Solar Cells*, **28**, 9-28. https://doi.org/10.1016/0927-0248(92)90104-W

[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.2015.311177

[8] Bousse, L., Mostarshed, S., Sartore, M., Adami, M. and Nicolini, C. (1994) Investigation of Carrier Transport through Silicon Wafers by Photocurrent measurement. *Journal of Applied Physics*, **75**, 4000-4008. https://doi.org/10.1063/1.356022

[9] Tall, I., Seibou, B., El Moujtaba, M.A.O., Diao, A., Wade, M. and Sisoko, 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* (*IJETT*), **19**, No. 2. https://doi.org/10.14445/22315381/IJETT-V19P211

[10] Deme, M.M., Mbodj, S., Ndoye, S., Thiam, A., Dieng, A. and Sissoko, G. (2010) Influence of Illumination Angle Grain Boundary Recombination Size and Grain Velocity on the Facial Solar Cell Diffusion Capacitance. *Review of Renewable Energy*,

13, 109-121.

[11] Diatta, I., Diagne, I., Sarr, C., Faye, K., Ndiaye, M. and Sissoko, G. (2015) Silicon Solar Cell Capacitance: Influence of Both Temperature and Wavelength. *International Journal of Computer Science*, **3**, 1-8.

[12] Diatta, I., Ly, I., Wade, M., Diouf, M.S., Mbodji, S. and Sissoko, G. (2016) Temperature Effect on Capacitance of a Silicon Solar Cell under Constant White Biased Light. *World Journal of Condensed Matter Physics*, **6**, 261-268.

[13] Erel, S. (2002) The Effect of Electric and Magnetic Fields on the Operation of a Photovoltaic Cell. *Solar Energy Materials & Solar Cells*, **71**, 273-280. https://doi.org/10.1016/S0927-0248(01)00088-5

[14] Moissi, A., Zoungrana, M., Diallo, A., Mbodji, S., Diallo, H.L., Hamidou, A., Ndiaye, M. and Sissoko, G. (2014) Base Transceiver Station (BTS) Antenna Electric Field Influence on the Space Charge Region in a Silicon Solar Cell. *Research Journal of Applied Sciences, Engineering and Technology*, **7**, 2554-2558.

[15] Diouf, M.S., Gaye, I., Thiam, A., Fall, M.F.M., Ly, I. and Sissoko, G. (2014) Junction Recombination Velocity Induced Open Circuit Voltage for a Silicon Solar Cell under External Electric Field. *Current Trends in Technology & Sciences*, **3**, 372-375. http://www.ctts.in/

[16] Fuyuki, T. and Matsunami, H. (1981) Determination of Lifetime and Diffusion Constant of Minority Carriers by a Phase-Shift Technique Using an Electron-Beam-Induced Current. *Journal of Applied Physics*, **52**, 3428-3432. https://doi.org/10.1063/1.329116

[17] Lemine, M., Cheikh, O., Seibou, B., Abderrahim, M., Moujtaba, O.E., Faye, K., Wade, M. and Sissoko, G. (2015) Study of Base Doping Rate Effect on Parallel Vertical Junction Silicon Solar Cell under Magnetic Field. *International Journal of Engineering Trends and Technology*, **19**, 44-55. http://www.ijettjournal.org

[18] Mbaye, M.F., Zoungrana, M., Thiam, N., Diao, A., Sahin, G., Ndiaye, M., Dieng, M. and Sissoko, G. (2013) Study of the Photo Thermal Response of a Mono Facial Solar Cell in Dynamic Regime under a Multispectral Illumination and under Magnetic Field. *International Journal of Engineering and Science Inventive*, **1**, 60-66.

[19] 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

[20] Rosling, M., Bleichner, H., Lundqvist, M. and Nordlander, E. (1989) A Novel Technique for the Simultaneous Measurement of Ambipolar Carrier Lifetime and Diffusion Coefficient in Silicon. *Solid-State Electronics*, **35**, 1223-1227.

[21] Misiakos, K. (1994) Electron and Hole Mobilities in Lightly Doped Silicon. *Applied Physics Letters*, **64**, 2007-2009.

[22] 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: Influence of Irradiation and Damage Coefficient. *Current Trends in Technology and Sciences*, **3**, 416-421.

[23] 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**, 238-247. https://doi.org/10.1063/1.331693

[24] 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.

[25] Sproul, A.B. (1994) Dimensionless Solution of the Equation Describing the Effect of

Surface Recombination on Carrier Decay in Semiconductors. *Journal of Applied Physics*, **76**, 2851-2854.

[26] Barro, F.I., Maiga, A.S., Wereme, A. and Sissoko, G. (2010) Determination of Recombination Parameters in the Base of a Bifacial Silicon Solar Cell under Constant Multispectral Light. *Physical and Chemical News*, **56**, 76-84.

[27] Jain, S.C. (1983) The Effective Lifetime in Semicrystalline Silicon. *Solar Cells*, **9**, 345-352. https://doi.org/10.1016/0379-6787(83)90028-5

[28] Sissoko, G., Museruka, C., Correa, A., Gaye, I. and Ndiaye, A.L. (1996) Spectral Light Effect on Recombination Parameters of Silicon Solar Cell. *Proceedings of World Renewable Energy Congress*, *Part* 3, Denver, 15-21 June 1996, 1487-1490.

[29] Dione, M.M., Diao, A., Ndiaye, M., Diallo, H.L., Thiam, N., Barro, F.I., Wade, M., Maiga, A.S. and Sissoko, G. (2010) 3D Study of a Mono Facial Silicon Solar Cell under Constant Mono Crhomatic Light: Influence of Grain Size, Grain Boundary Recombination Velocity, Illumination Wavelength, Back Surface and Junction Recombination Velocities. *Proceedings of* 25*th European Photovoltaic Solar Energy Conference and Exhibition*, Valencia, 6-10 September 2010, 488-491.

[30] Dugas, J. (1994) 3D Modelling of a Reverse Cell Made with Improved Multicrystalline Silicon Wafers. *Solar Energy Materials and Solar Cells*, **32**, 71-88.

[31] Dieye, M., Mbodji, S., Zoungrana, M., Zerbo, I., Dieng, B. and Sissokoa, G. (2015) 3D Modelling of Solar Cell's Electric Power under Real Operating Point. *World Journal of Condensed Matter Physics*, **5**, 275-288.

[32] Mbodji, S., Ly, I., Diallo, H.L., Dione, M.M., Diasse, O. and Sissoko, G. (2012) Modeling Study of N+/P Solar Cell Resistances from Single I-V Characteristic Curve Considering the Junction Recombination Velocity (Sf). *Research Journal of Applied Sciences*, *Engineering and Technology*, **4**, 1-7.

[33] Mbodji, S., Dieng, M., Mbow, B., Barro, F.I. and Sissoko, G. (2010) Three Dimensional Simulated Modelling of Diffusion Capacitance of Polycrystalline Bifacial Silicon Solar Cell. *Journal of Applied Sciences and Technology*, **15**, 109-114.

[34] Mbodji, S., Mbow, B., Barro, F.I. and Sissoko, G. (2010) A 3D Model for Thickness and Diffusion Capacitance of Emitter-Base Junction in a Bifacial Polycrystalline Solar Cell. *Global Journal of Pure and Applied Sciences*, **16**, 469-477.

[35] Mbodji, S., Mbow, B., Dieng, F., Barro, F.I. and Sissoko, G. (2010) 3D Modelling of Polycrystalline Silicon Bifacial Solar Cell Determination of Thickness and Diffusion Capacitance of Emitter Base Junction. *General Physics and Electrical Application*, **83**, 47-62. http://www.amse-modeling.com

[36] Saritas, M. and Mckell, H.D. (1988) Comparison of Minority-Carrier Diffusion Length Measurement in Silicon by the Photoconductive Decay and Surface Photo Voltage Methods. *Journal of Applied Physics*, **63**, 4561-4567.

[37] Agarwala, A. and Tewary, V.K. (1980) Response of a Silicon p-n Solar Cell to High Intensity Light. *Journal of Physics D*: *Applied Physics*, **13**, 1885-1898. https://doi.org/10.1088/0022-3727/13/10/018

[38] Stokes, E.D. and Chu, T.L. (1977) Diffusion Length in Solar Cells from Short-Circuit Current Measurement. *Applied Physics Letters*, **30**, 425-426. https://doi.org/10.1063/1.89433

[39] Dione, M.M., Ly Diallo, H., Wade, M., Ly, I., Thiame, M., Toure, F., Camara, A.G., Dieme, N., Bako, Z.N., Mbodji, S., Barro, F.I. and Sissoko, G. (2011) Determination of the Shunt and Series Resistance of a Vertical Multijunction Solar Cell under Constant Multispectral Light. *Proceedings of* 26*th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, 5-9 September 2011, 250-254. http://www.eupvsec-proceedings.com

[40] El Moujtaba, M.A., Ndiaye, O.M., Diao, A., Thiame, M., Barro, I.F. and Sissoko, G. (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**, 5068-5073.

[41] Ndiaye, M., Diao, A., Thiame, M., Dione, M.M., Diallo, H.L., Samb, M.L., Ly, I., Gassama, C., Mbodji, S., Barro, F.I. and Sissoko, G. (2010) 3D Approach for a Modelling Study of the Diffusion Capacitance's Efficiency of the Solar Cell. *Proceedings of* 25*th European Photovoltaic Solar Energy Conference and Exhibition*, Valencia, 6-10 September 2010, 484-487.

[42] Diallo, H.L., Wade, M., Ly, I., Diaye, M.N., Dieng, B., Lemrabott, O.H., Maïga, A.S. and Sissoko, G. (2012) 1D Modeling of a Bifacial Silicon Solar Cell under Frequency Modulation, Monochromatic Illumination: Determination of the Equivalent Electrical Circuit Related to the Surface Recombination Velocity Research. *Journal of Applied Sciences*, *Engineering and Technology*, **4**, 1672-1676.

[43] Sahin, G., Dieng, M., Moujtaba, M.A.O.E., Ngom M.I., Thiam, A. and Sissoko, G. (2015) Capacitance of Vertical Parallel Junction Silicon Solar Cell under Monochromatic Modulated Illumination. *Journal of Applied Mathematics and Physics*, **3**, 1536-1543.

[44] Sze, S.M. and Kwok, K.N. (2007) Physics of Semiconductors Devices. 3rd Edition, John Wiley and Sons, Hoboken.

[45] Levy, F. (1995) Physique et technologie des semi-conducteurs (Traité des matériaux). Vol. 18, Presses polytechniques et universitaires Romandes, Lausanne.

[46] Kunst, M. and Sanders, A. (1992) Transport of Excess Carriers in Silicon Wafers. *Semiconductor Science and Technology*, **7**, 51-59.

[47] Schroder, D.K., Whitfield, J.D. and Varker, C.J. (1984) Recombination Lifetime Using the Pulsed MOS Capacitor. *IEEE Transactions on Electron Devices*, **31**, 462-467. https://doi.org/10.1109/T-ED.1984.21551

[48] Sari-Ali, I., Benyoucef, B. and Chikh-Bled, B. (2007) Etude de la jonction d'un semi-conducteur à l'équilibre thermodynamique. *Journal of Electron Devices*, **5**, 122-126.

[49] Vardanyan, R.R., Kerst, U., Wawer, P., Nell, M.E. and Wagemann, H.G. (1998) Method for Measurement of All Recombination Parameters in the Base Region of Solar Cells. 2*nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion*, Vienna, 6-10 July 1998, 191-193.

[50] De Haas, W.J. and Biermasz, T.H. (1935) The Thermal Conductivity of Quartz at Low Temperatures. *Physica*, **2**, 673-682.

[51] Berman, R. (1951) Thermal Conductivity of Dielectric Crystals: The "Umklapp". *Nature*, **168**, 277-280.

[52] Casimir, H.B.G. (1938) Note on the Conduction of Heat in Crystals. *Physica*, **5**, 495-500.

[53] Makinson, R.E.B. (1938) The Thermal Conductivity of Metals. *Mathematical Proceedings of the Cambridge Philosophical Society*, **34**, 474-497. https://doi.org/10.1017/S0305004100020442