Effects of Gaussian beam radius on the conversion efficiency and the diffusion capacitance of a polycrystalline silicon solar cell

Abstract

This study presents effects of Gaussian beam radius (r_f)on the power and the conversion efficiency (η) of a polycrystalline silicon solar cell. The two-dimensional continuity equation solved using finite element method, permits to determine the excess minority carriers density, the photocurrent density and the photo voltage from which the power and the conversion efficiency of the solar cell are calculated. The capacitance (C) and the space charge region (SCR) width are also examined for various values of the radius of gaussian luminous flow. The gaussian luminous flow effects on solar cell's performances are highlighted in comparing with those of a classical monochromatic illumination.

Keywords: solar cell, gaussian flow, conversion efficiency, capacitance, space charge region, recombination velocity**.**

I. Introduction

Solar cells, generally designed to be illuminated by solar light, have an absorption spectrum of which wavelengths extend from 300 to 1100 nm [1,2]. Thus, to improve their performances, several studies have been carried out, by subjecting them to various types of illuminations such as laser beams [2-4]. These studies have permitted to determine solar cell electrical parameters, namely, the current-voltage characteristic, series resistance, and shunt resistance, as well as the diffusion length, when it is illuminated by a Gaussian luminous flow [1-4].These studies for most of the cases have not taken into account the solar cell power and its conversion efficiency.

This study aims to determine the effects of the Gaussian luminous flow radius on the power and the conversion efficiency of a polycrystalline silicon solar cell, on its diffusion capacitance and the charge space region extension, using a finite element method [2][4-8].
The power and the conversion efficiency of the solar cell will be determined for various values of gaussian beam radius, as well as the diffusion capacitance, and the space charge region (SCR) extension of the solar cell.
After solving the continuity equation using this method, we will determine the excess minority carriers density [9-10], and a comparative study will be done when the solar cell is illuminated respectively by a classical monochromatic flow, and by a Gaussian luminous beam.

Comment [G1]: Inserted: G
Comment [G2]: Deleted:g
Comment [G3]: Inserted: G
Comment [G4]: Deleted:g
Comment [G5]: Deleted:s
Comment [G6]: Inserted: ,
Comment [G7]: Deleted:,
Comment [G8]: Inserted: m
Comment [G9]: Inserted: a
Comment [G10]: Inserted: G
Comment [G11]: Deleted:e aim of th
Comment [G12]: Deleted:g
Comment [G13]: Deleted: on

II. Theoretical approach

II.1 Continuity Equation

Let us consider a polycrystalline silicon solar cell, constituted by an emitter doped n-type with a weak thickness and a base doped p-type with a depth H_1 according to x and a width H_2 according to y, as represented in figure 1.When the solar cell is not illuminated, between the emitter and the base there is a depletion region called space charge region (SCR) inside which the internal electric field $\vec{E}$, as opposed to the diffusion of the majority carriers A width W and a capacitanceC_0, characterizes this region. When the solar cell is illuminated, the excess minority carriers photogenerated diffuse towards the space charge region i.e. the electrons of the base and holes of the emitter. The charge carriers reach the space charge region are accelerated by the internal electric field, **thus creating** a diffusion photocurrent [11].

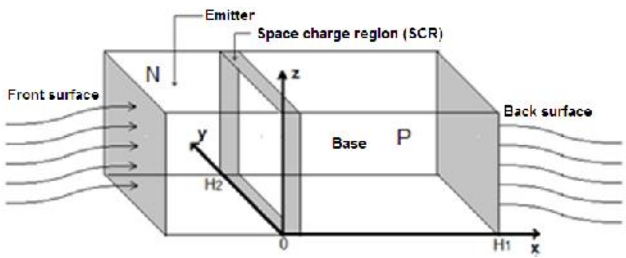

Figure 1 : Crystal of a bifacial silicon solar cell

In this study, we neglect the current contribution of the emitter into the photocurrent and the height of solar cell along the z-axis [9]. Thus the continuity equation which governs the solar cell operation is given by [4, 12, 13]:

$$\frac{\partial^2\delta(x,y)}{\partial x^2}+\frac{\partial^2\delta(x,y)}{\partial y^2}-\frac{\delta(x,y)}{L^2}=-\frac{g(x,y)}{D} \qquad (1)$$

$\delta(x,y)$ represents the excess minority carriers density, i.e., the electrons in the base P.x and y are the coordinates related to the base depth and the solar cell width respectively. L and D indicate respectively, the diffusion length and the diffusion coefficient of the electrons, and $g(x,y)$, its generation rate.

When the solar cell is illuminated on its front surface, this generation rate is given by [2, 4, 6, 14] :

$$g(x,y)=\begin{cases} I_0(1-R)exp(-\alpha x) & \text{for a classical monochromatic flow } (2\,a) \\ I_0(1-R)\frac{\alpha}{2\pi r_f}exp(-\alpha x)\cdot exp\left(-\frac{y^2}{2r_f^2}\right) & \text{for a gaussian luminous flow } (2\,b) \end{cases}$$

$I_0$is the incidental beam of photons. α and R represent respectively, the absorption coefficient and the reflection coefficient of the solar cell and r_f,the radius of gaussian luminous beam.

This continuity equation obeys to the following boundary conditions relating to the conservation of the diffusion current and the recombination current on the boundaries of the solar cell [2, 6]:

- on the junction

Comment [G14]: Inserted: a

Comment [G15]: Inserted: ,

Comment [G18]: Deleted:i

Comment [G16]: Inserted: A

Comment [G17]: Inserted: , characterizes this region

Comment [G19]: Deleted:This region is characterized by a

$$\left.\frac{\partial\delta(x,y)}{\partial x}\right|_{x=0} = \frac{Sj}{D}\cdot\delta(0,y) \quad (3)$$

- on the back surface

$$\left.\frac{\partial\delta(x,y)}{\partial x}\right|_{x=H_1} = -\frac{S_b}{D}\cdot\delta(H_1,y) \quad (4)$$

- on the y=0 boundary

$$\left.\frac{\partial\delta(x,y)}{\partial x}\right|_{y=0} = \frac{S_{bg}}{D}\cdot\delta(x,0) \quad (5)$$

- and on the y=H_2 boundary

$$\left.\frac{\partial\delta(x,y)}{\partial x}\right|_{y=H_2} = -\frac{Sbg}{D}\cdot\delta(x,H_2) \quad (6)$$

Sj indicates the junction recombination velocity, S_b the back surface recombination velocity and Sbg, the boundary recombination velocity on the boundaries y=0 and y=H_2.
Knowing the photo generated minority charge carriers density, the photocurrent density and the photo voltage are calculated from the following relations (7) and (8) :

$$J = \frac{q\cdot D}{H_2}\int_0^{H_2}\left[\frac{\partial\delta(x,y)}{\partial x}\right]_{x=0} dy \quad (7)$$

$$V = V_T\cdot Log\left(\frac{Nb}{n_i^2}\int_0^{H_2}\delta(0,y)dy + 1\right) \quad (8)$$

where V_T represents the thermal voltage, N_b, the base doping level and n_i, the silicon intrinsic carrier's density of the silicon.
Knowing the photocurrent density values and those of the photo voltage, one can easily calculate the power P provided by the solar cell:

$$P = VJA \quad (9)$$

where A is the solar cell's surface.

II.2 Solar cell conversion efficiency

An important parameter in the solar cells characterization is the conversion efficiency given by the relation (10) [15-16]:

$$\eta = \frac{P_m}{P_{inc}} = \frac{V_m I_m}{P_{inc}} \quad (10)$$

where P_m indicates the optimal solar cell power and P_{inc}. i.e, the incidental power. V_m and I_m are respectively, photo voltage and the photocurrent corresponding to the optimal power P_m.

Another interesting parameter is the fill factor which permits to evaluate the quality of a solar cell or a photovoltaic generator. The higher it is, the more exploitable power provided by the solar cell is important. It is given by the relation (16):

Comment [G20]: Inserted: ing

$$FF = \frac{V_m I_m}{V_{co} I_{cc}}$$

(11)

V_{co}, indicates the open circuit photo voltage and I_{cc} the short-circuit photocurrent.

II.3 Diffusion capacitance and space charge region width

The diffusion capacitance of the solar cell is due to the diffusion of excess minority charge carriers through the junction. It can be determined by the relation (12) [17, 18].

$$C = \frac{dQ}{dV} = \frac{q\frac{ni^2}{Nb}}{V_T} exp\left(\frac{V}{V_T}\right) \quad (12)$$

This diffusion capacitance is composed of two terms: one term related to the intrinsic capacitance and another term which depends on the solar cell operating point and thus on the junction recombination velocity Sj [19]. It is related to the space charge region width *Xp* by the relation [17, 18]:

$$C = \frac{A\varepsilon_0\varepsilon_r}{X_p} \quad (13)$$

where A indicates solar cell surafce, ε_0, vacuum's dielectric permittivity and ε_r, the relative permittivity of silicon.

III. Results and Discussions

The continuity equation (1), which is solved using the finite element method computer code that we have conceived, permits to determine the photo generated minority charge carriers density from which the others quantities can be calculated by the relations (7-13).

To highlight effects of gaussian beam radius r_f on the improvement of the conversion efficiency and on the diffusion capacitance of the solar cell, we have determined these quantities for various values of r_f, with a grain boundaries recombination velocity $Sbg = 10^2 cm/s$ and an incidental power $P_{inc} = 100\ mW/cm^2$.

In addition, when the silicon solar cell is illuminated by a gaussian luminous flow, the variation of the generation rate according to the wavelength λshows that this one is maximum around a value of$\lambda = 800\ nm$. For this wavelength of illumination, the corresponding reflexion coefficient and absorption coefficient are $R = 0{,}3448$ and $\alpha = 825{,}8\ cm^{-1}$ [2, 4].

III.1 Solar cell Power

In Figure 2, we represented the power of the solar cell versus the junction recombination velocity Sj and the grain width y, when the solar cell is illuminated on its front surface, by a gaussian luminous flow.

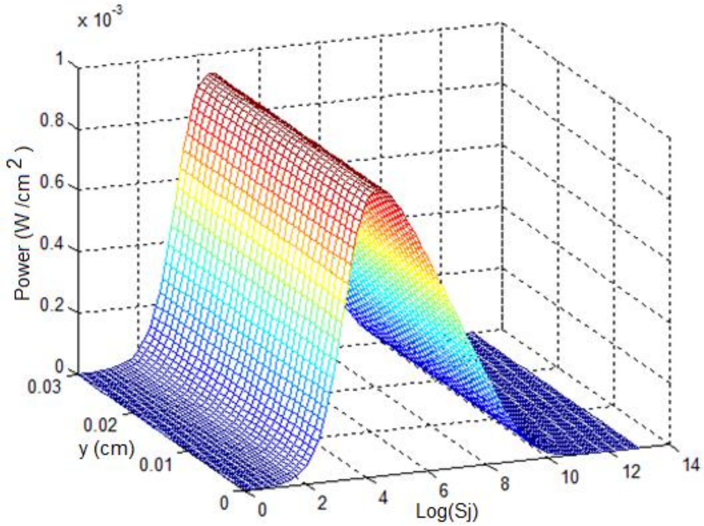

Figure 2 : Solar cell power versus Sj and y

As waited, the solar cell power increases according to Sj, reaches a maximum value corresponding to the optimal power P_m, then decreases and cancels out, when Sj becomes very great.

In Figure 3, we illustrated the solar cell power when it is illuminated by a gaussian luminous flow and a monochromatic luminous flow.

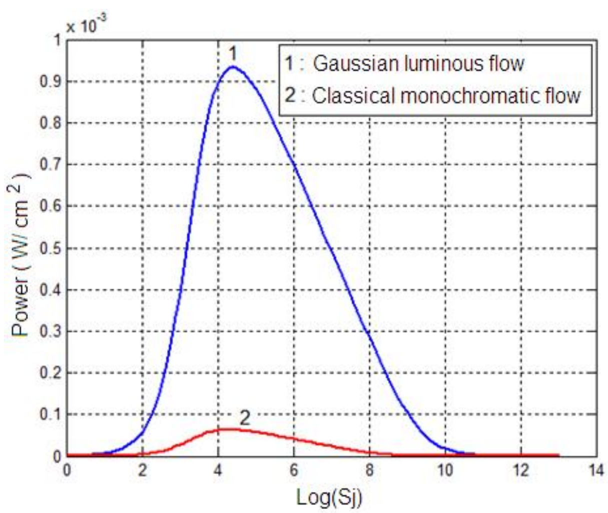

Figure 3 : Solar cell power versus Sj : gaussian andclassical monochromatic flow

As waited, this power is higher when the solar cell is illuminated by a gaussian luminous flow. In fact, for this illumination, the carriers generation phenomenon is more important. To illustrate the effects of the gaussian beam radius, we have represented the power of the solar cell in figure 4, for various values of rf, versus the junction recombination velocity Sj.

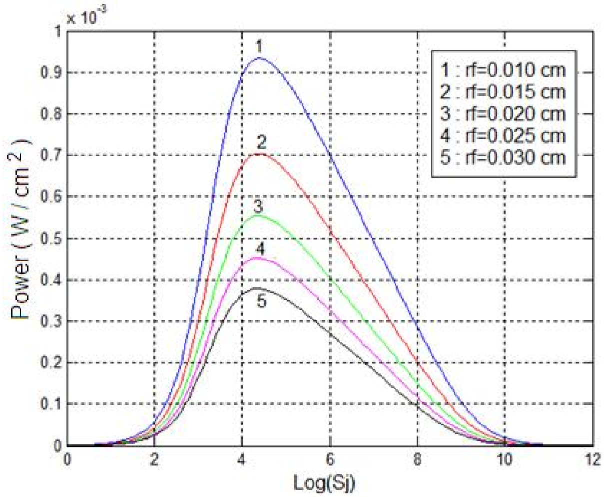

Figure 4 : Solar cell power

We can note that the gaussian beam radius has a considerable effect on the power of the solar cell. The weaker it is, the more the solar cell power is important, because the reduction of the gaussian beam radius led to the increase in the incidental power per unit of area since incidental flow I_0 is constant.

III.2 Conversion efficiency and fill factor of the solar cell

Using our matlab code for various values of rf, with $Sb = 10^2 cm/s$,$S_{bg} = 10^2 cm/s$and $Sj = 3.9311 \cdot 10^4\ cm/s$, corresponding to the optimal operating point of the solar cell. we have determined the optimal photo voltage V_m, the optimal photo courrent density J_m, the optimal power P_m, the short-circuit photocurrent density $J_{cc}$and the open circuit photo voltage V_{CO}. The conversion efficiency of the solar cell, its fill factor FF, conversion efficiency η can be easily calculated starting from the above relations (7-13). The results obtained are given in table 1

Table 1 : Conversion efficiency and fill factor of the solar cell

rf (cm)	Vm (V)	Jm (mA)	Pm (mW)	Jcc (mA)	Vco (V)	FF	[illegible](%)	PF : Sj (cm/s)
0.010	0.4596	3.2979	1.5160	3.5302	0.5374	0.7989	15.160	$3.9811 \cdot 10$[illegible]
0.015	0.4529	2.5454	1.1528	2.7198	0.5308	0.7985	11.530	$3.9811 \cdot 10$[illegible]
0.020	0.4472	2.0422	0.9536	2.1810	0.5251	0.7976	09.536	$3.9811 \cdot 10$[illegible]
0.025	0.4423	1.6926	0.7487	1.8070	0.5203	0.7966	07.487	$3.9811 \cdot 10$[illegible]
0.030	0.4382	1.4377	0.6308	1.5360	0.5161	0.7956	06.308	$3.9811 \cdot 10$[illegible]

One can note that at the optimal operating point of the solar cell, the gaussian beam radius r_f has a significant effect on the conversion efficiency as shown in figure 5. , where η is

Comment [G21]: Inserted: g

Comment [G22]: Deleted:t

represented according to r_f. On the other hand the variation of the gaussian beam radius does not seem to influence the fill factor of the solar cell.

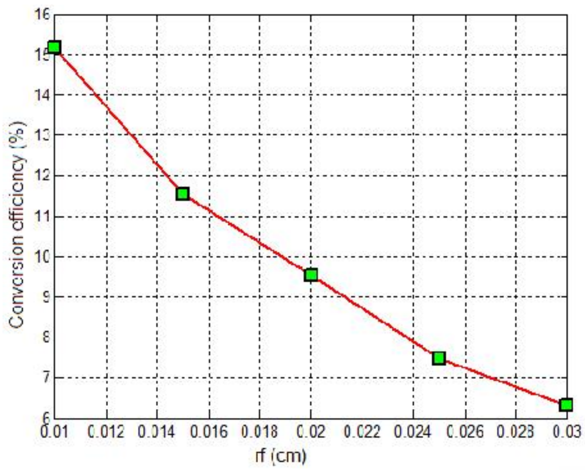

Figure 5 : Conversion efficiency versus gaussian beam radius

The conversion efficiency increases with the reduction of the gaussian beam radius, owing to the increase in the optimal power which is directly related to P_m and J_m. In the same way, J_{CC} and V_{CO} are more important when r_f is weak. This conversion efficiency which reaches the value of 15% for $rf = 0.01cm$, is definitely better than the conversion efficiency of 12% or 13% obtained for polycrystalline solar cells subjected to usual solar illuminations [20].

III.3 Diffusion Capacitance

We were also interested in the behavior of the diffusion capacitance of the solar cell when it is illuminated on its front surface by a gaussian luminous flow. It is represented in 2D in figure 6, according to the junction recombination velocity S_j and the width y of the grain of the solar cell.

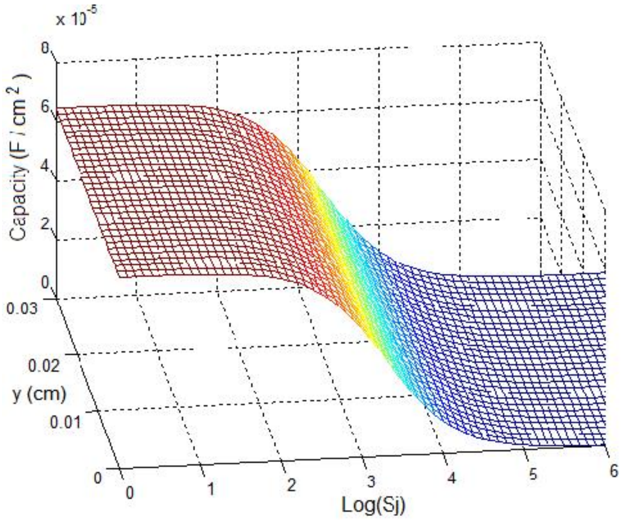

Figure 6 : Diffusion capacitance versus Sj and the grain width y of the solar cell illuminated by a gaussian luminous flow

In the same way, when we illuminate the solar cell by a classical monochromatic flow, one obtains a diffusion capacitance as represented in figure 7.

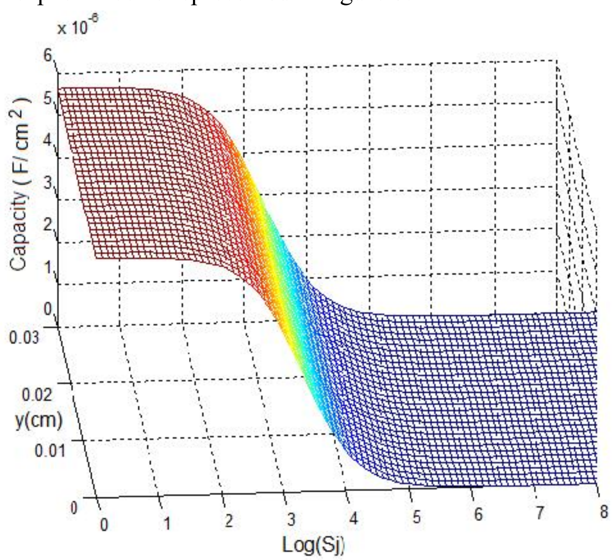

Figure 7 : Diffusion capacitance versus Sj and the grain width y of the solar cell illuminated by monochromatic luminous flow

One can note that the capacitance of the solar cell decreases according to the junction recombination velocity Sj. For the weak values of Sj, i.e. in the vicinity of the open circuit, it corresponds to the open circuit capacitanceC_{CO}. It is null for the great values of Sj, corresponding to a short-circuit operation. One also can note that the grain width of the solar cell has not effects on the capacitance, whether a gaussian luminous flow illuminates the solar cell or not.

Comment [G41]: Deleted:a
Comment [G23]: Inserted: the
Comment [G24]: Inserted: s
Comment [G25]: Inserted: flow
Comment [G26]: Inserted: nou
Comment [G27]: Inserted: um
Comment [G28]: Inserted: n
Comment [G29]: Inserted: i
Comment [G30]: Inserted: gaus
Comment [G31]: Inserted: a
Comment [G32]: Inserted: ol
Comment [G33]: Inserted: ce
Comment [G34]: Inserted: r
Comment [G35]: Deleted:the
Comment [G36]: Deleted:ol
Comment [G37]: Deleted:r
Comment [G38]: Deleted:ce
Comment [G39]: Deleted:l
Comment [G40]: Deleted:d by
Comment [G42]: Deleted:gau
Comment [G43]: Deleted:si
Comment [G44]: Deleted:n
Comment [G45]: Deleted:uminous f
Comment [G46]: Deleted:ow

To compare the diffusion capacitance of the solar cell illuminated by a gaussian luminous flow and what obtained when a classical monochromatic luminous flow illuminates it, we have represented in figure 8, both capacitances according to Sj, for $rf = 0.01\ cm$.

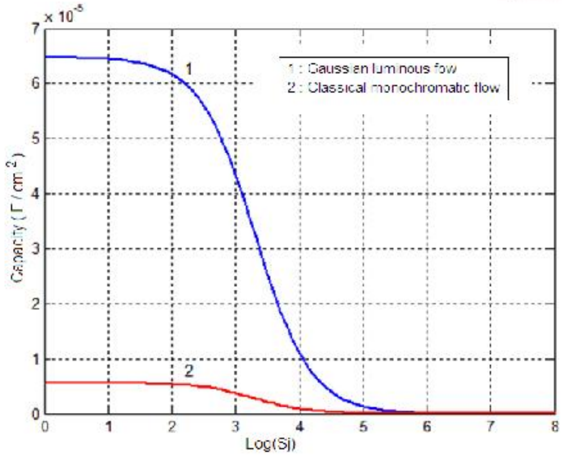

Figure 8 : Diffusion capacitance for a classical monochromatic flow and a gaussian luminous flow versus Sj

The diffusion capacitance is more important when the solar cell is illuminated by a gaussian luminous flow than when a classical monochromatic flow illuminates it. The photogenerated charge carriers density being more important when the solar cell is illuminated by a gaussian luminous flow [2], the diffusion of the charge carriers at the junction is also more important. That leads to the increase in the diffusion capacitance.

One can also note that the effects of the gaussian beam radius on the diffusion capacitance are more important on the open circuit diffusion capacitance and decreases with the increase of r_f. These effects are illustrated in figure 9.

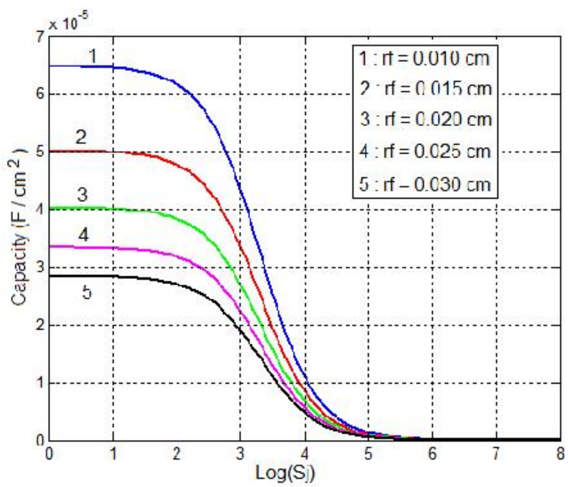

Figure 9 : Diffusion capacitance for various values of rfversus junction recombination velocity Sj

Comment [G47]: Inserted: illuminates it

Comment [G48]: Deleted:it is illuminated by

Comment [G49]: Inserted: illuminates it

Comment [G50]: Deleted:it is illuminated by

III.4 Space charge region

Just like the diffusion capacitance, we have represented in figure 10 for a value of $r_f = 0.01\ cm$, when the solar cell is illuminated by a gaussian luminous flow and by a classical monochromatic flow.

To examine the effects of gaussian beam radius on the widening of the space charge region, we represented it for various values of r_f. These curves are given in figure 10.

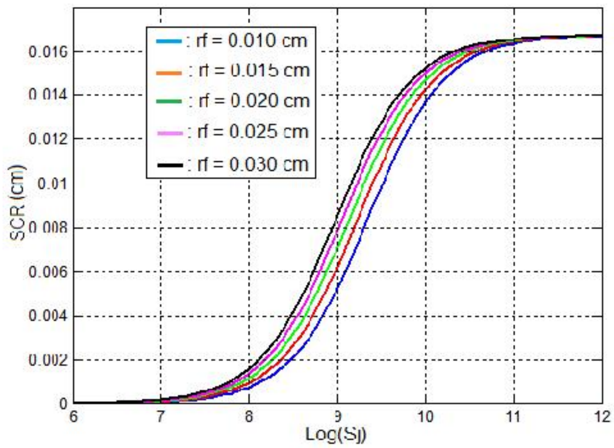

Figure 10 ***: Width of space charge region for various values of rf***

When one vary the gaussian beam flow, the profile of the width of the space charge region according to Sj is practically the same one and the saturation value is the same one for the various curves. In general, one can note that the gaussian beam radius has an effect limited on the width of the space charge region.

IV. Conclusion

After determining the charge carriers density by solving the continuity equation using finite element method from which the photocurrent density and the photo voltage of solar cell were deduced, the effects of gaussian beam radius on the power and the conversion efficiency of the cell have been highlighted. These effects are more remarkable on the capacitance of the solar cell than on the width of the space charge region. One also can note that the grain width of the solar cell does not have effects on the diffusion capacitance and the space charge region width.

Thus, from this study, we can note that compared with a classical monochromatic illumination, the gaussian luminous flow has considerable effects on the solar cell electrical parameters. These effects are characterized by the improvement of the solar cell performances, owing to the reduction of the gaussian beam radius leading to the increase in the solar cell conversion efficiency. .

Références

1. Yassine SAYAD Détermination de la longueur de diffusion des porteurs dans le silicium cristallin par interaction lumière matière, Thèse de Doctorat, 2009, Institut National des Sciences Appliquées de Lyon, France.

2. Nzonzolo, Contribution to the Caractération of a Photopile Polycristalline and Silicium on the Meteorite des Eléments Finis, Thèse de Doctorat, 2017, Université Marien NGOUABI, Congo.

3. Syad Yassine, Interaction Laser-Semi-conducteur: Contribution of the University of LBIC - Application of a photocoltaic application, Thèse de doctorat, 2009, Université Mentouri Constantine Faculty of Sciences Exertes Département de Physique, Algérie.

4. Nzonzolo, D. Lilonga-Boyenga, Beam radius effects on polycrystalline bifacial silicon solar cell electrical parameters, 2017, Journal of Scientific and Engineering Research JSAER, 4(5), 143-146.

5. Nzonzolo, Desire Lilonga-Boyenga, Camille N. Mabika and Gregoire Sissoko, Characterization of a Bifacial Silicon Solar Cell Under Multispectral Steady State Illumination Using Finite Element Method, Progress In Electromagnetics Research M, 2017,Vol. 53, 131–140,

6. Nzonzolo, Désiré Lilonga-Boyenga, Camille Nziengui Mabika, Grégoire Sissoko, Two-Dimensional Finite Element Method Analysis Effect of the Recombination Velocity at the Grain Boundaries on the Characteristics of a Polycrystalline Silicon Solar Cell, Circuits and Systems, 2016, 7, 4186-4200 (Scientific Research Publishing).

7. A. Dieng, N. Thiam, ML Samb, AS Maiga, FI Barro, G. Sissoko, Etude à 3D d'une Photopile Polycrystalline au Silicium: Influence de la taille de grain de la vitesse de recombinaison aux joints des grains sur les paramères électriques, 2009, Journal des Sciences, J. Sci.Vol. 9, N ° 1, 51 - 63.

8. M. Diaw, B. Zouma, A. Sere, S. Mbodji, A. Gueye Camara, G. Sissoko, 3D study to improve the IQE of the bifacial polycrystalline silicon solar cell from the grain's geometries and the applied magnetic field, 2012, International Journal of Engineering Science and Technology (IJEST), Vol. 4 No.08,p. 3673-3682.

9. Tao J., Cours Méthodes Numériques en Physiques Appliquées, Institut National Polytechnique de Toulouse, Université de Toulouse, France

10. Matthew N. O. Sadiku, Numerical Techniques in Electromagnetics (Second Edition) CRC Press LLC, Boca Raton London, New York , Washington, D.C, 2001

11. Henry Mathieu, Hervé Fanet, Dispositif semiconducteurs et composentes électroniques, 6e édition, Dunod Paris 2009, ISBN 978-2-10-051643-8.

12. Sze S. M., Physics and Semiconductors devices, Second Edition, Bell Laboratory Incorporated Murray Hill New Jersey, 2001.

13. Sze S. M., Semiconductor Devices Physics and Technology, 2nd Edition, ISBN 0-471-33372-7, Library of Congress Cataloging in Publication Data, United States of America, 2002.

14. Sze S. M., Kwok K. N., Physics of Semiconductor Devices,3rd edition, WILEY INTERSCIENCE, New Jersey, 2006.

15. Emmanuel Nanema, Modélisation d'une photopile bifaciale au silicium: Méthodes de détermination des paramettres des paramettres de recombinaison, The Doctorat triisième cycle, 1996, Université Cheikh Anta Diop, Dakar Sénéga.

16. Helali KAMELIA: Modélisation d'une cellule photovoltaïque Etude comparative, Mémoire de Magister en eclectrotechnique, Université MOULOUD MAMMERI de TZI-OUZOU, Faculté de Génie Electrique et Informatique, 2012, Algérie.

17. Saïdou MADOUGOU, Déterimation des paramettres electreques d'une photopile bifaciale au silicium en régime static éclairement multispectral constant et sous l'effet d'une chimetante, Thèse de Doctorat 3e cycl, 2004, Faculté des Sciences et Techniques Université Cheikh Anta Diop Dakar Sénégal

18. Biram DENG, a translation of a photopile bipassiale and silicium in a ceramics at the University of Aurelian University, in Thévez de Doctorat 3e cycle, 2002, Faculté des Sciences and Techniques Université Cheikh Anta Diop, Dakar Sénégal.

19. M.A. Ould El Moujtaba, M. Ndiaye, A. Diao, M. Thiame, I.F. Barro and G. Sissoko, 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): 2012, 5068-5073.

20. Laradji-Toumouh Nawal, Etude des Photopiles Solaris nanostructures base de Nitritures III-V: GaN, AlN, InN, Mémoire, for a Diploma of Diploma, 2012, Ecole Doctorale Nanosciences, Nanotechnologie, Nomométrologie, Université d'Oran, Algérie.