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European Journal of Advances in Engineering and Technology, 2022, 9(9):16-21

Research Article ISSN: 2394 - 658X

# 3-D modeling of the influence of irradiation on the electrical power of a single-sided polycrystalline silicon photocell subjected to multi-spectral illumination

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## ABSTRACT

In this paper, we present a 3-dimensional modeling of the influence of irradiation on the electrical power of a single-sided polycrystalline silicon photocell subjected to multi-spectral illumination. Indeed, solving the continuity equation in a 3-D study model allowed us to establish the current density, photovoltage and diode current density. From these, the expression of the electrical power of the photopile is deduced and then studied as a function of the recombination rate at the junction and the irradiation.

**Key words:** Monofacial photocell, Recombination rate at the junction, Irradiation, Electrical power, Polycrystalline

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## 1. INTRODUCTION

The quality of a solar cell is closely related to its electrical and electronic properties, characterized by recombination rates, grain boundaries, grain size, and electrical power, among others. Also, some external factors such as irradiation can influence the quality of the solar cell [1], [4]. These factors are the recombination's of photo generated minority carriers in volume (Shockley-Read-Hall, Auger and radiative) [5], and in surface, photo current and photo voltage losses, shading effects, resistive losses, ... In this paper, we present a three-dimensional (3D) study of the influence of irradiation on the electrical power of a polycrystalline silicon single-facet solar cell under intense multi-spectral illumination [6].

## 2. MODELING AND THEORETICAL ANALYSIS

A bifacial solar cell is a device which generates electricity directly from visible light. When light quanta are absorbed, electron hole pairs are generated as it can be seen in **Fig. 1(a).** An $n^+$- p-$p^+$ poly crystalline solar cell, made of many small individual grains, is considered. Taking into account of the physical process simulation, the 2D representation of the solar cell is illustrated in Fig. 1(a) and in Fig. 1(b), the fibrously oriented columnar grain is considered. At the junction, $n^+$-p interface (z=0), Sfu quantifies how the excess carriers flow through the junction in actual operating conditions and then Sfu characterizes how electrons cross to the junction [7], [9] and [11]. At the back side of the solar cell, (Sbu) is used to translate the losses in this zone. It quantifies hence, the rate at which excess minority carriers are lost at the back side of the cell [5], [7] and [12].

### 2.1. Excess Minority Carriers Density

The solar cell's emitter is considered as a dead zone. So, the excess minority carriers density is determined takingaccount into only the contribution of the solar cell's base.

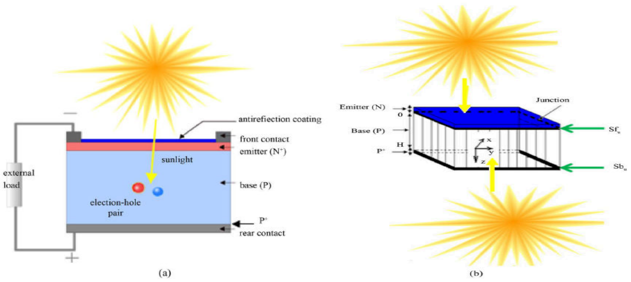

**Fig. 1: (a-left)** 2D representation of the monofacial solar cell [13]; **(b-right)** 3D representation of the solar cell $H = 130$ µm, $D = 26$ cm2·s$^{-1}$.

Considering the emitter as a dead area, the excess minority carrier distribution in the base, seen as a greater contribution to the photo-conversion, is derived from the continuity equation [12], [14]:

$$D(Kl,\phi)\times\left[\frac{\partial^2\delta(x,y,z)}{\partial x^2}+\frac{\partial^2\delta(x,y,z)}{\partial y^2}+\frac{\partial^2\delta(x,y,z)}{\partial z^2}\right]-\frac{\delta(x,y,z)}{\tau}+G(z)=0 \tag{1}$$

$D(Kl,\phi)$ is the diffusion coefficient in the presence of irradiation. It is expressed as follows:

$$D(Kl,\phi)=\frac{L(Kl,\phi)^2}{\tau} \tag{2}$$

In this expression, G(z) represents the generation rate of minority charge carriers in the base [13] whose expression is given by the following equation:

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

The values ai and bi are the values tabulated from the modeling of the absorption spectrum of the photocell for AM 1.5 [8], [20], [21].

L depend on the irradiation energy Φ and the damage coefficient Kl through the following expression [29]-[31]:

$$L(Kl,\phi)=\sqrt{\frac{1}{\frac{1}{L_0^2}+Kl\times\phi}} \tag{4}$$

$L_0$ is the diffusion length without irradiation.

The solution of the equation can be written as follows [8], [14], [15]:

$$\delta(x,y,z)=\sum_k\sum_j Z_{k,j}(z)\times\cos(C_k\times x).\cos(C_j\times y) \tag{5}$$

k, j : are the indices for the x and y directions respectively.

Ck and Cj are obtained from the conditions at the grain boundaries $\pm\frac{g_x}{2}$ et $\pm\frac{g_y}{2}$ [8] [14] [21] [22]:

$$\left[\frac{\partial\delta(x,y,z)}{\partial x}\right]_{x=\pm\frac{g_x}{2}}=\mp\frac{Sgb}{D(Kl,\phi)}\delta\left(\pm\frac{g_x}{2},y,z\right) \tag{6}$$

$$\left[\frac{\partial\delta(x,y,z)}{\partial y}\right]_{y=\pm\frac{g_y}{2}}=\mp\frac{Sgb}{D(Kl,\phi)}\delta\left(x\pm\frac{g_y}{2},z\right) \tag{7}$$

gx is the grain width, gy the grain length Sgb the recombination velocity at the grain boundaries.

From equations (6) and (7) we obtain two transcendental equations [32] which are:

$$\tan\left(C_k\times\frac{g_x}{2}\right)=\frac{Sgb}{2.C_k\times D(Kl,\phi)} \tag{8}$$

$$\tan\left(C_j\times\frac{g_y}{2}\right)=\frac{Sgb}{2.C_j\times D(Kl,\phi)} \tag{9}$$

By replacing δ(x, y, z) in the continuity equation and the fact that the cosine function is orthogonal, we obtain the following differential equation:

$$Z_{k,j}=A_{k,j}\times\cosh\left(\frac{z}{L_{k,j}}\right)+B_{k,j}\times\sinh\left(\frac{z}{L_{k,j}}\right)-\sum_{i=1}^{3}K_{i,j,k}\times\exp(-b_i\times z) \tag{10}$$

Or $K_{i,j,k}=\dfrac{L_{k,j}^2}{D_{k,j}\times\left[b_i^2\times L_{k,j}^2-1\right]}\times a_i$ (11)

With : $L_{k,j}=\left[C_k^2+C_j^2+\dfrac{1}{L(Kl,\phi)^2}\right]^{-\frac{1}{2}}$ (12)

And $$D_{k,j} = D(Kl,\phi)\times\frac{[C_k\times g_x+\sin(C_k\times g_x)][C_j\times g_y+\sin(C_j\times g_y)]}{16.\sin\left(C_k\times\frac{g_x}{2}\right).\sin\left(C_j\times\frac{g_y}{2}\right)} \tag{13}$$

The coefficients Ak,j and Bk,j are calculated from the following boundary conditions [7], [14], [23], [27]:

At the junction ( $z=0$ ):

$$\left[\frac{\partial\delta(x,y,z)}{\partial z}\right]_{z=0} = \frac{Sf}{D(Kl,\phi)}\delta(x,y,0) \tag{14}$$

Sf is the junction recombination velocity, written as [7], [14], [25], [27] Sf = $Sf_0$ + $Sf_j$ with $Sf_0$ being the intrinsic junction recombination velocity related to the shunt resistance due to losses occurring across the junction and $Sf_j$ is the imposed junction recombination velocity due external load. It defines the current flow that is the operating point of the cell. For each illumination mode, the intrinsic junction recombination velocity was calculated using the method described in [7], [14], [25], [27].

At the back side ( $z=\omega b$ ):

$$\left[\frac{\partial\delta(x,y,z)}{\partial z}\right]_{z=0} = -\frac{Sb}{D(Kl,\phi)}\delta(x,y,\omega b) \tag{15}$$

Sb is the back surface recombination velocity. It quantifies the rate at which excess minority carriers are lost at the back surface of the cell [7], [14], [25], [27]. The derivation of the photocurrent with respect to Sf, provides for each illumination mode the expression of Sb, as in [7], [14], [25], [27].

$$A_{k,j} = \sum_{i=1}^{3} K_{i,k,j}\times\frac{\frac{1}{L_{k,j}}.\left(\frac{Sf}{D(Kl,\phi)}-b_i\right)\times\exp(-b_i\times\omega b)+Y_{k,j}\left(\frac{Sf}{D(Kl,\phi)}+b_i\right)}{\frac{Sf\times Y_{k,j}}{D(Kl,\phi)}+\frac{X_{k,j}}{L_{k,j}}} \tag{16}$$

$$B_{k,j} = \sum_{i=1}^{3} K_{i,k,j}\times\frac{\frac{Sf}{D(Kl,\phi)}.\left(\frac{Sb}{D(Kl,\phi)}-b_i\right)\times\exp(-b_i\times\omega b)+X_{k,j}\left(\frac{Sf}{D(Kl,\phi)}+b_i\right)}{\frac{Sf\times Y_{k,j}}{D(Kl,\phi)}+\frac{X_{k,j}}{L_{k,j}}} \tag{17}$$

Avec: $$X_{k,j} = \frac{1}{L_{k,j}}\times\sinh\left(\frac{\omega b}{L_{k,j}}\right)+\frac{Sb}{D(Kl,\phi)}\times\cosh\left(\frac{\omega b}{L_{k,j}}\right) \tag{18}$$

$$Y_{k,j} = \frac{1}{L_{k,j}}\times\cosh\left(\frac{\omega b}{L_{k,j}}\right)+\frac{Sb}{D(Kl,\phi)}\times\sinh\left(\frac{\omega b}{L_{k,j}}\right) \tag{19}$$

### 2.2. Photocurrent density

The photocurrent density can be calculated by the following equation [8] [14] [16] [17] [24]:

$$J_{ph} = \frac{q\times D(Kl,\phi)}{g_x\times g_y}.\int_{-\frac{g_x}{2}}^{+\frac{g_x}{2}}\int_{-\frac{g_y}{2}}^{+\frac{g_y}{2}}\left[\frac{\partial\delta(x,y,z)}{\partial z}\right]_{z=0} dx.dy \tag{20}$$

After calculation we get:

$$J_{ph}(Sf,Kl,\phi) = q\times\sum_{k=1}^{5}\sum_{j=1}^{5}R_{k,j}\times Sf.\sum_{i=1}^{3}K_{i,k,j}.\frac{\frac{Sb-D(Kl,\phi)\times b_i}{D(Kl,\phi)\times Y_{k,j}}-\frac{X_{k,j}}{Y_{k,j}}+b_i\times L_{k,j}}{\frac{X_{k,j}}{Y_{k,j}}+\frac{Sf\times L_{k,j}}{D(Kl,\phi)}} \tag{21}$$

With: $$R_{k,j} = \frac{4.\sin\left(C_k\times\frac{g_x}{2}\right)\times\sin\left(C_k\times\frac{g_y}{2}\right)}{g_x\times g_y\times C_k\times C_j} \tag{22}$$

q is the charge of the electron.

### 2.3. Phtovoltage

Using the Boltzmann's relation, the photo voltage Vph can be expressed as [8], [14], [16]:

$$V_{ph} = V_T.\ln\left\{1+\frac{N_b}{n_i^2}.\int_{-\frac{g_x}{2}}^{+\frac{g_x}{2}}\int_{-\frac{g_y}{2}}^{+\frac{g_y}{2}}\delta(x,y,z).dx.dy\right\} \tag{23}$$

When the photocell is illuminated simultaneously by the front and rear sides, the photovoltage is given by the following expression:

$$V_{ph}=V_T.\ln\left\{1+\frac{N_b}{n_i^2}.\sum_{k=0}^{4}\sum_{j=0}^{4}R_{k,j}.\sum_{i=1}^{3}K_{i,k,j}.\frac{\frac{Sb-D(Kl,\phi).b_i}{D(Kl,\phi).Y_{k,j}}.\exp(-b_i\times H)-\frac{X_{k,j}}{Y_{k,j}}+b_i\times L_{k,j}}{\frac{X_{k,j}}{Y_{k,j}}+\frac{Sf\times L_{k,j}}{D(Kl,\phi)}}\right\} \tag{24}$$

Où $V_T=\frac{k\times T}{q}$ is the thermal voltage, k the Boltzmann constant, Nb the base doping rate and $n_i$ the intrinsic carrier concentration.

### 2.4. Diode current

Its expression is given by the relation [18]:

$$J_d=q\times Sf.\left[1+\frac{N_b}{n_i^2}.\int_{-\frac{g_x}{2}}^{+\frac{g_x}{2}}\int_{-\frac{g_y}{2}}^{+\frac{g_y}{2}}\left[\frac{\partial\delta(x,y,z)}{\partial z}\right]_{z=0}dx.dy\right] \tag{25}$$

### 2.5. Solar Cell's Electric Power

The power generated by the cell is given by [19]:

$$P(Sf,Sb,g,Sgb,Kl,\phi)=V_{ph}(Sf,Sb,g,Sgb,Kl,\phi)\times J(Sf,Sb,g,Sgb,Kl,\phi) \tag{26}$$

With : $J(Sf,Sb,g,Sgb,Kl,\phi)=J_{ph}(Sf,Sb,g,Sgb,Kl,\phi)-J_d(Sf,Sb,g,Sgb,Kl,\phi)$ (27)

The solar cell's generated power depends on Sfu and then is function of the solar cell's real operating point varying from the short-circuit operating point to the open one

## 3. RESULTS

In **Fig. 2** and **3** we present the profiles, in three dimensions, of the electrical power of the photocell as a function of the recombination rate at the junction, the irradiation energy Φ and the damage coefficient Kl.

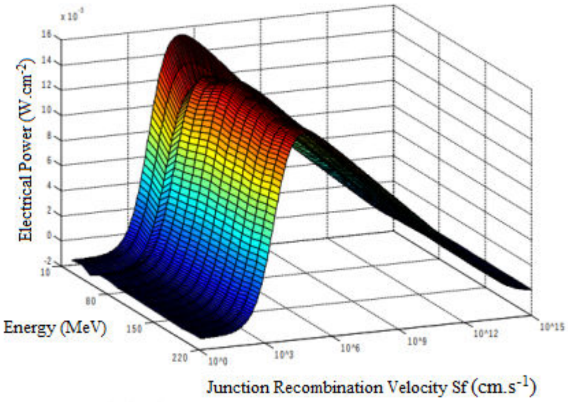

**Fig. 2**: Electrical power as a function of recombination rate at the Sfj junction and irradiation energy for grain size g=0.095 cm.
*(H=0,03 cm; Sgb=4,5*104 cm/s; Kl=10,5 cm$^{-2}$ /MeV).*

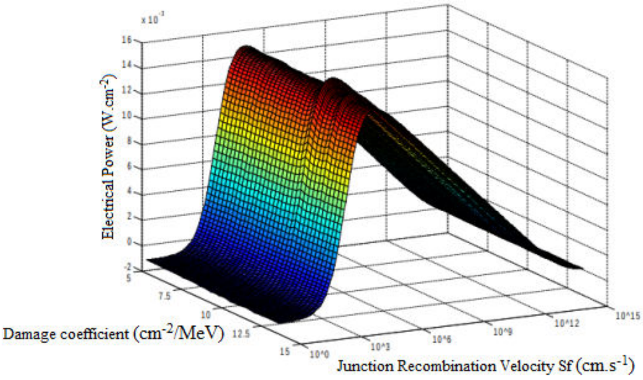

**Fig. 3:** Electrical power as a function of the recombination rate at the junction Sfj and the damage coefficient Kl for a grain size g=0 ,11 cm.
*(H=0,03 cm; Sgb=5*10$^4$ cm/s; Φ=100 MeV)*

We can see in figure 2 that the electrical power of the silicon solar cell decreases with the increase of the irradiation energy; indeed, if the irradiation energy increases, the degradations will increase to some extent leading to a decrease (small here) of the available power.

For figure 3, the increase of the damage coefficient accentuates the decrease of the electrical power of the silicon solar cell. This can be explained by the fact that the increase of the damage coefficient translates into an increase of the probability of creation of defects by irradiation, thus more important degradation of the solar cell, i.e. more important leakages. Thus, the material becomes more sensitive to the degradation caused by possible particles and thus the photovoltage will be all the more degraded as the damage coefficient will increase.

## 4. CONCLUSION

In this paper we have shown that the electrical power of the solar cell decreases with the irradiation. It was shown that the increase of the irradiation energy and of the damage coefficient degrades more or less the parameters of the photocell. For the effect of the damage coefficient, it was shown that this was noticeable especially from a certain irradiation energy.

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