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Influence of illumination grain size and grain boundary recombination velocity on the facial solar cell diffusion capacitance

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ABSTRACT
In this paper, we perform a three-dimensional modeling study of a polycrystalline silicon solar cell in the static regime and under multi-spectral illumination. From this three-dimensional model, the expression of the minority charge carriers in excess in the base of the polycrystalline silicon solar cell is obtained. From the latter we have determined and studied the expression of the diffusion capacity of minority charge carriers. This study considers parameters such as grain size and recombination rates at the grain boundaries and junction on the scattering capacity of the polycrystalline silicon solar cell.

Key words: solar cell, grain size, grain boundary recombination velocity, polycrystalline, solar cell, junction recombination velocity

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1. INTRODUCTION

Several techniques of characterization of the silicon material, determination of the phenomenological and electrical parameters have been used to improve the capacity of solar cells. Some of these techniques have been developed in static regime [1] and others in dynamic frequency regime [2]. Extensive studies on the capacity of the space charge area [3], [4], have been carried out in 3 dimensions [1], [5], [8] for these two regimes. In order to increase the efficiency of photovoltaic conversion, cells called polycrystalline silicon photovoltaic cells have been designed. This collection is influenced by recombination of carriers at the grain boundaries [20], [26], [27]. Hence the interest to study the influence of grain boundaries on the diffusion capacity of the series vertical junction solar cell. In this paper, we present a study of the diffusion capacity in a three-dimensional model by highlighting the effect of grain size and recombination velocities at grain boundaries (Sgg).

2. Modeling and Theoretical Analysis

In this study, we use n+ - p - p+ type of a bifacial polycrystalline silicon solar cell. Silicon consisting of several grain of various sizes, for our study, we use the 3D columnar model where each grain has a rectangular shape as shown in Figure 1 below [5], [9], [10]. A 3D mark is placed at the center at the space charge region.

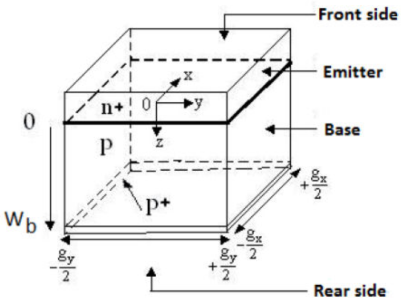

Fig. 1: Polycrystalline silicon columnar grain model

In this study, we assume that:

- the contribution of the emitter is neglected. We take into account only the base contribution [5],
- the illumination is uniform. We then have a generation rate depending only with base depth z [10];
- the existing crystalline field within the base is neglected
- in the simulation, we have equality between the grain size along x and y axes, i.e. gx = gy = g (square cross section), and that the recombination velocity at grain boundaries is perpendicular to the junction and independent to the generation rate under AM 1.5 [5] [11].

2.1. Excess Minority Carriers Density

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 [5] [12]:

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

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

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

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:

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

The values ai and bi are the values tabulated from the modeling of the absorption spectrum of the photocell for AM 1.5 [11], [14], [15].

L depend on the irradiation energy Φ and the damage coefficient Kl through the following expression [16], [18]:

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

L_0 is the diffusion length without irradiation.

The solution of the equation can be written as follows [5], [11], [19]:

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

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 $\pm\frac{g_x}{2}$ [5], [11], [20], [21]:

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

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

g_x is the grain width, g_y the grain length Sgb the recombination velocity at the grain boundaries.

From equations (6) and (7) we obtain two transcendental equations [22] which are:

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

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

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:

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

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

The coefficients Ak, j and Bk, j are calculated from the following boundary conditions [5], [20], [23], [24]:

- At the junction (z=0):

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

Sf is the junction recombination velocity, written as [5] [8] [23] [24] [25] 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 [5], [8], [23], [24], [25].

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

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

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 [5] [8] [23] [24] [25]. The derivation of the photocurrent with respect to Sf, provides for each illumination mode the expression of Sb, as in [5] [8] [23] [24] [25].

2.2. Diffusion capacity of the cell at the junction-base interface

When the silicon solar cell is illuminated, we witness a storage of opposite charges on both sides of the emitter-base junction. This leads to the establishment of a capacitor whose diffusion capacity varies according to the effects of illumination on the silicon solar cell [4] [8] [23].

The expression of the latter is defined by:

$$C(Sf,Sb,g,Sgb,Kl,\phi) = \frac{q}{V_T} \times \left[\delta(Sf,Sb,g,Sgb,Kl,\phi) + \frac{n_i^2}{N_b}\right] \qquad (16)$$

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

3. RESULTS

Are presented in **Fig. 2** and **3** the profiles of the diffusion capacity of minority charge carriers as a function of base depth, respectively for different recombination velocities at the grain boundaries, junction recombination velocity and for different grain sizes. The recombination rates at the grain boundaries and at the junction have the same effects on the scattering capacity of the photocell: increasing these two parameters leads to a decrease in the photo generated minority charge carriers at the junction-base interface.

On the other hand, the grain size g acts differently with respect to the effects of the recombination rate at the Sfj junction of the silicon solar cells. Up to short circuit (Sfj=10^6 cm/s), the increase of g leads to the increase of the photocell capacity.

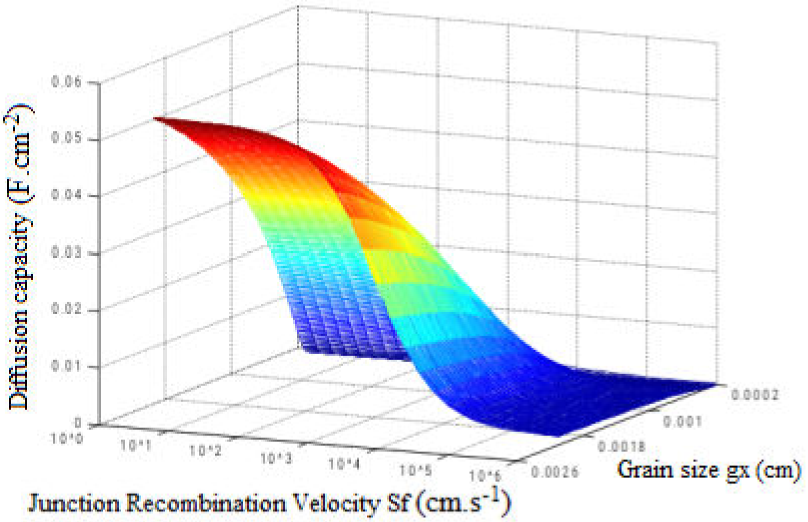

Fig. 2 Diffusion capacity as a function of recombination rate at the Sfj junction and grain size g
(H=0,03 cm; Kl=10,5 cm-2/MeV; Sgb=102 cm/s; Φ=150 MeV).

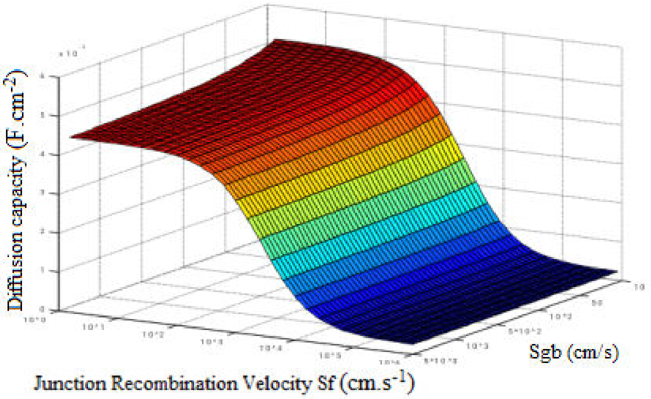

Fig. 3: Diffusion capacity as a function of the recombination rate at the Sfj junction and the recombination rate at the grain boundaries Sgb for a grain size g=0.05 cm
(H=0,03 cm; Kl=10,5 cm-2/MeV; Φ=150 MeV).

In open circuit, the maximum diffusion capacity reflects the fact that there are few minority charge carriers in excess in the base that cross the junction. In short circuit, the decrease is due to the fact that a large number of minority charge carriers in excess in the base cross the emitter-base junction to participate in the generation of the current density. This induces a depopulation of minority charge carriers in the storage region as the recombination rate at the junction increases. However, we find that the magnitude of the diffusion capacity of the photocell, for a different operating point of the short circuit, increases as the grain size on the photocell increases. This follows from the fact that increasing grain size results in fewer grain boundaries with increasing grain volume. These grain boundaries are sites where carriers are trapped thus decreasing the number of carriers stored at the junction.

4. CONCLUSION

A theoretical study was performed on the determination of the minority charge carrier diffusion capacity of a three-dimensional monofacial silicon solar cell under multi-spectral illumination. This study showed us that the diffusion capacity of the silicon solar cell increases with the grain size g. The increase of the recombination rate at the grain boundaries (Sgb) leads to a decrease of the scattering capacity. In summary, the recombination rate at the grain boundaries Sgb reduces the performance of the solar cell. Thus, we can say that an increase of the grain size g leads to an improvement of the cell quality.

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