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A Three-Dimensional Transient Study of a Polycrystalline Silicon Solar Cell under Constant Magnetic Field

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Abstract: In this paper, a theoretical and experimental transient study of polycrystalline silicon solar cell under constant magnetic field is conducted. A theoretical approach is based on the columnar model of the grains and the boundaries conditions are defined in order to use Green's functions to solve the three dimensional diffusion equation. After extraction of the effective minority carrier lifetime and the reduced magnitude of the transient voltage from the experimental curve of transient voltage, the values of constraint coefficients at interfaces of the grain are computed thanks to a reverse approach method.The effects of magnetic field on the bulk component of minority carrier lifetime are then analyzed. This study showed that, the effect of the magnetic field is only significant when the values of the field are greater than or equal to 5.10^{-3}T.

Keywords— magnetic field, bulk lifetime, transient study

I. Introduction

The earliest conventional photovoltaic cells produced in the decade 1950-1960 of the last century were mainly used to provide electrical power for milatary needs or for artificial satellites orbiting. Two important events , the increasingly scarcity of traditional electricity sources such as coal and fuel oil (nuclear, not included [1] and the global climate change, combined with the population growth on the Earth , had crucial impact on our point of view and our behavior about solar energy : the sunlight is free of cost and is available for many hours/ day in different parts of the Globe [2, 3] and this energy is environmental friendly and generates electrical energy without emission of greenhouse gases like CO_2. So, solar energy belongs to favored renewable energy resources and has become an important part of power generation in the new millennium: grid connected PV system, stand-alone PV system and hybrid system. Around the world 31.1 GW of PV systems were installed in 2012, up from 30.4 GW in 2011 [3]. Silicon solar cells, both amorphous and crystalline, take up the important part, 99% of the market [3, 4]. Despite this progress the efficiency remains low : η equals to 24¨% in laboratory experiment and 12 to 16% for commercial solar cells [4,5]. So many research activities are developed in order to enhance the conversion efficiency. Various methods, both experimental and theoretical, and many models are used to provide useful information about semiconductor material characteristics. The 1D model is often used for polycrystalline study but it seems that this model is not suitable to interpret the results [6]. This is probably due to the fact that the one-dimensional model does not allow one to describe the diffusion of carriers because it does not take account of the effect of grain boundaries. In the case of polycrystalline cell, the action of grain boundaries recombination generates a high diffusion of carriers from grain center to its boundaries [7, 8, and 9].

In the other hand it is of great interest to understand how the solar cell performance is affected by an external magnetic field. This is the purpose of this study.

II. Material and Methods

Polycrystalline materials are characterized by the non uniformity of their structure. Opposite to monocrystalline ones they are constituted by a lot of grains randomly oriented or relatively ordered and with various sizes. So, to understand this structural complexity we used, in this study, a theoretical description of generation, diffusion and recombination of carriers which is based on some assumptions [10, 11]. Thus, we assume, for geometrical simplification, the polycrystalline solar cell is structured as a rectangular array of many unit cells connected in parallel as shown on figure 1 bellow; dimensions of each of them are taken to be: 2a in x-direction, 2b in y-direction and H in z-direction. The grain boundary planes are located at x = ± a and y = ± b. For simplicity it is considered a square section for the grain (i.e. grain size Xg = 2a =2b)

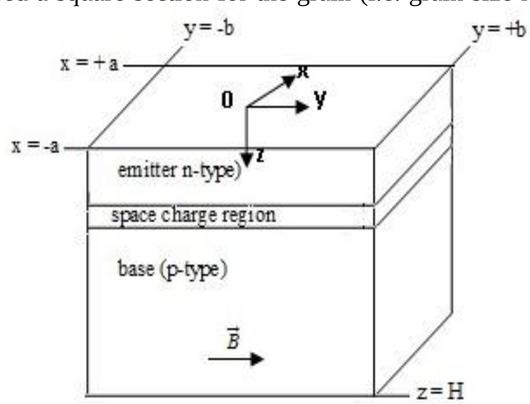

Fig 1: a model of grain in the polycrystalline sample

The transient response is obtained by disturbance of steady state. While exciting the photovoltaic cell, we carry it towards a state characterized by a balance between the phenomena of recombination and generation of the pairs electron-hole [12]. This stationary state defines an operating point named Pi. After a duration Te (pulse duration of the stroboscope), the excitation is abruptly switched off; the balance between the generation and the recombination is

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broken. A transient response appears and the photovoltaic cell relaxes towards a new stationary state: its fundamental state. This other state later defines a new operating point that we call Pf. The transient response corresponds to the relaxation state of the sample between these two operating points Pi and P_f

Considering the optoelectronic properties identical for all the lot of grains, then the study of the phenomena of generation, diffusion and recombination of the charge carriers in the photovoltaic cell during the transient state can be described by the study of these various phenomena on a only one grain.

In the base of the cell, the minority carriers are electrons, and their density δn satisfies to the equation below:

$$\frac{\partial \delta n}{\partial t} = \frac{1}{e}\vec{\nabla}.\vec{j_n} + g_n - r_n \quad (1)$$

g_n and r_n are respectively the rate of generation and recombination of carriers

The current density $\vec{j_n}$ is given by:

$$\vec{j_n} = eD_n\vec{\nabla}\delta_n + e\mu_n\vec{E} - \mu_n\vec{j_n}\Lambda\vec{B} \quad (2)$$

E is the electric field of the crystal lattice and μ_n is the mobility of the electrons.

Substituting equation (2) into (1) and and taking account the assumption of quasi-neutrality of the base, the diffusion equation off the electrons in the base is becomes:

$$\frac{\partial\delta(x,y,z,t)}{\partial t} - D^*\left(\vec{\nabla}^2\delta(x,y,z,t) - \frac{\delta(x,y,z,t)}{L^*}\right) = g(x,y,z,t) \quad (3)$$

where:

- $$\theta = 1 + (\mu B)^2 \quad (4)$$
- $$D^* = \frac{D}{1+(\mu B)^2} \quad (5)$$

D, μ, B are respectively the coefficient of electrons diffusion, the mobility of electrons and the value of magnetic field applied.

The presence of the magnetic field in our model lead to a new values of carrier diffusion length (L^*) and carrier diffusion coefficient (D^*) which depend on magnetic field. θ is a coefficient which depend on magnetic field intensity.

$$g(x,y,z,t) = \begin{cases} n.\sum_{m=1}^{3} a_m \exp(-b_{m.}.z). & \text{if } t \le Te \\ 0 & \text{if } t > Te \end{cases} \quad (6)$$

In this expression of $g(x,y,z,t)$, n is called sun number and its expression is $n = \frac{I_{CCI}}{I_{CCO}}$; coefficients a_m and b_m are the tabulated values of the literature [13]

Equation (1) is solved with the following boundary conditions

At the junction (Z = 0).

$$\left.\frac{\partial\delta(x,y,z,t)}{\partial z}\right|_{z=0} = \frac{Sf}{D^*}\delta(x,y,0,t) \quad (7)$$

At the back face (Z = H).

$$\left.\frac{\partial\delta(x,y,z,t)}{\partial z}\right|_{z=H} = -\frac{Sb}{D^*}.\delta(x,y,H,t) \quad (8)$$

At the grain boundaries.

$$\left.\frac{\partial\delta(x,y,z,t)}{\partial x}\right|_{x=\pm a} = \pm\frac{S_{gx}}{D^*}.\delta(\mp a,y,z,t) \quad (9)$$

$$\left.\frac{\partial\delta(x,y,z,t)}{\partial y}\right|_{y=\pm b} = \pm\frac{S_{gy}}{D^*}.\delta(x,\mp b,z,t) \quad (10)$$

Where Sf and Sb are respectively the recombination velocity of minority carriers at surfaces $z = 0$, $z = H$

Sgx and Sgy are the recombination velocity of minority carriers in the grain boundaries respectively at coordinates $x = \pm a$ and $y = \pm b$

A general solution of equation (1) is given by expression (7) according to the author of the reference [14].

$$G = \sum_{i=1}^{+\infty}\sum_{j=1}^{+\infty}\sum_{k=1}^{+\infty} G_i.G_j.G_k \exp(-\beta^*.(t-t')) \quad (11)$$

With, $G_i = A_{k_i}^2 \cos(k_i x').\cos(k_i.x)$ (12)

$$G_j = A_{l_j}^2.\cos(l_j^*.y').\cos(l_j^*.y) \quad (13)$$

$$G_k = A_{\mu_k}^2.\cos(\mu_k.z'+\varphi_k).\cos(\mu_k.z+\varphi_k) \quad (14)$$

β^* and l_j^* are expressed by:

$$\beta^* = D^*.\left(k_i^2 + l_j^{\,2} + \mu_k^2 + \frac{1}{L^{*2}}\right) \quad (15)$$

$$l_j^* = \frac{l_j}{\sqrt{q}}$$

Where the parameters k_i l_j and μ_k are the eigenvalues obtained from the boundary conditions.

The quantities A_{l_i}, A_{l_j} and A_{μ_k} are obtained by normalizing G_i, G_j and G_k. φ_k is the initial phase and obtained by solving the following equation:

$$\tan(\mu_k.H + \varphi_k) = \frac{Sb}{\mu_k.D^*} \quad (16)$$

The transient voltage decay is defined by :

$$V(t) = V_T.\ln\left(1 + Fv(k_1, l_j^*, \mu_1).r.\exp\left(-\beta^*(t-Te)\right)\right) \quad (17)$$

In this expression, r is given by $r = \exp(\frac{\Delta V}{V_T}) - 1$

and $Fv(k_1, l_j^*, \mu_1)$, called reduced magnitude of transient voltage is defined by:

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$$Fv(k_1, l_1^*, \mu_1) = \frac{\Delta_0(0,0)}{\Delta(0,0)} \quad (18)$$

The quantities $\Delta_0(0,0)$ and $\Delta(0,0)$ are defined by:

$$\Delta_0(0,\ 0) = \int_{-a}^{a}\int_{-b}^{b} Z_{1,1,1}(x,y,0)dxdy \quad (19)$$

$$\Delta(0,\ 0) = \int_{-a}^{a}\int_{-b}^{b} d_{1,1,1}(x,y,0)dxdy \quad 20)$$

$Z_{1,1,1}(x,y,0)$ and $d_{1,1,1}(x,y,0)$ are respectively the spatial component of $\delta(x,y,z,t)$ and the minority carrier density during the phase of illumination.

The parameter l_1^* is defined by:

$$l_1^* = \frac{l_1}{\sqrt{\theta}} \quad (21)$$

According to expression (17), we notice two types of decays of $V(t)$:

- If $Fv(k_1,l_1,\mu_1).r.\exp\left(-\beta^*\left(t-Te\right)\right) \gg 1$ (22)

The time dependent tension is rewritten in the following way:

$$V(t) = V_T\left[-\beta^*(t-Te) + \ln\left\{Fv(k_1,l_1,\mu_1).r\right\}\right] \quad (23)$$

This is a linear function of the time with a negative slope: $-V_T.\beta^*$.

- If $Fv(k_1,l_1,\mu_1).r.\exp\left(-\beta^*\left(t-Te\right)\right) \ll 1$ (24)

In first order approximation of $Fc(k_1,l_1,\mu_1).r.\exp\left(-\beta^*\left(t-Te\right)\right)$, expression (12) allows to rewrite $V(t)$ in the form :

$$V(t) = V_T Fv(k_1,l_1,\mu_1).r.\exp\left(-\beta^*\left(t-Te\right)\right) \quad (25)$$

$V(t)$ is a time dependent decay exponential function

From the expression of β^*, we can write the minority carrier lifetime as the sum of two terms:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{1}{\tau_s} \quad (26)$$

Where τ_b is the bulk component and τ_s the surface component which is controlled by the recombination at the interfaces, the value of magnetic field and the base thickness of the cell.

III. Results and Tables

The transient voltage decay is obtained by the experimental setup that picture is shown on figure below:

It is composed of:

a mono-facial solar cell manufactured by MOTCH INDUSTRY; a power supply 0-12 V DC/6 V, 12 V AC**;** an Iron core, U-shaped, laminated; a digital teslameter 13610.93 1; a Hall probe; a pulse light source MINISTROB, PHYWE, model BOX-1203 BBE; a digital scope; TEKTRONIX, model TDS 210; a computer, Intel 586, 1GHz; a variable white light source and a variable resistance.The operating principle of this experimental system is the same described par Sam and al (2012)

The decay of voltage during the transient is recorded on the digital scope connected to the computer where are scored the data.

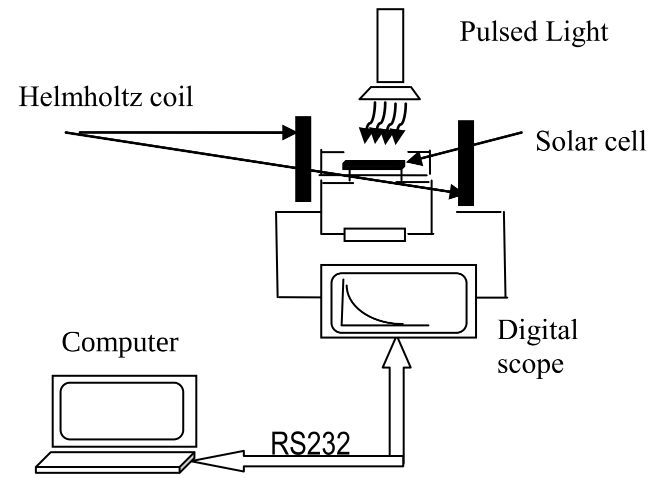

Figure 2: Experimental setup

The experimental value of reduced magnitude of transient voltage is given:

$$Fv_{\exp} = \frac{V(t' = 0)}{rV_T} \quad (27)$$

The couple $(t' = 0, V(t' = 0))$ is solution of equation:

$$V(t') = V_0 exp(-at') \quad (28)$$

$V(t')$ is given by the best fit of experimental points corresponding to an exponential decay from which τ_{eff} deduced.

The exponential fit of experimental points is obtained by equation:

$$\left[V(t') - V_{exp}\right] \rightarrow 0 \quad (29)$$

The error estimation is given by the correlation factor R^2 from the fit; t' = 0 is the beginning of the exponential part of $V(t)$ and $V(t' = 0)$ is the corresponding ordinate.

By identifying $V(t)$ to $V(t')$, we obtain:

$$a = b_{1,1,1}$$

$$V_0 = V_T Fv(k_1, l_1, \mu_1)$$

Using the hypothesis described by Sam and al [9] reduced magnitude of transient voltage is expressed as a function of k_1, l_1^* and μ_1 which are the fundamental eigenvalues defined below.

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So these parameters can be obtained by solving following equation:

$$Fv\left(k_1,\ l_1^*,\ \mu_1\right) = Fv_{\exp} \qquad (30)$$

The value of reduced magnitude $Fv\left(k_1,\ l_1^*,\ \mu_1\right)$ depend on the characteristics of grain and the value of magnetic field applied through k_1 l_1^* and μ_1 depend on the grain size grain boundary activities and the intensity value of magnetic field.

From analytical expression and the experimental value of Fv, we determine, using a reverse approach, the experimental value of the eigenvalue k_1, l_1^* and μ_1

After calculation of the remarkable points, the values of k_1, l_1^* and μ_1 are found by dichotomy. This dichotomy search is done using an iterative method of calculation based on NEWTON's algorithm. The incrementations are submitted to the test expressed by equation

$$\left|Fv\left(k_1,\ l_1^*,\ \mu_1\right) - Fv_{\exp}\right| \ \leq\ 10^{-6} \qquad (31)$$

On the figures 4 to 6 are presented for different values of magnetic field, the experimental curves of transient voltage.

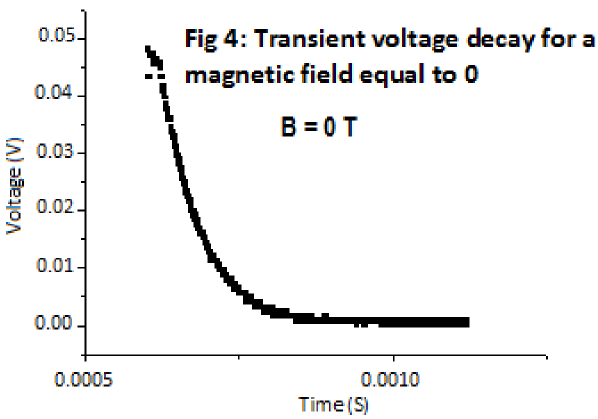

Fig 4: Transient voltage decay for a magnetic field equal to 0

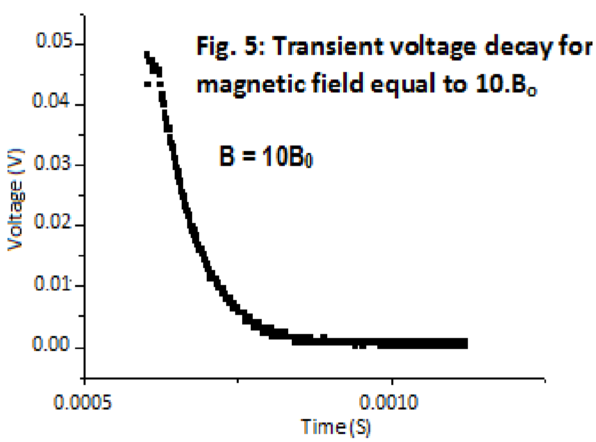

Fig. 5: Transient voltage decay for magnetic field equal to 10.B_o

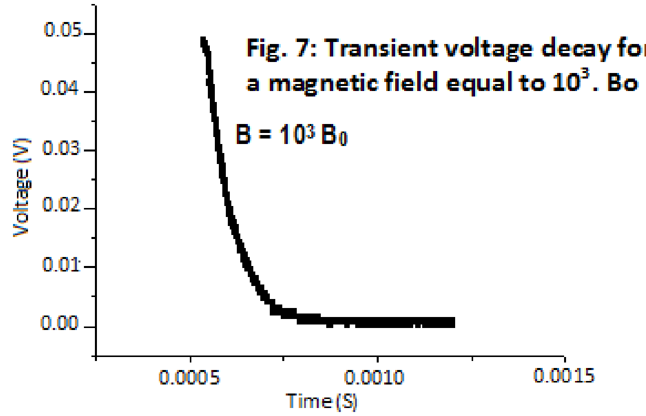

Fig. 7: Transient voltage decay for a magnetic field equal to 10^3. Bo

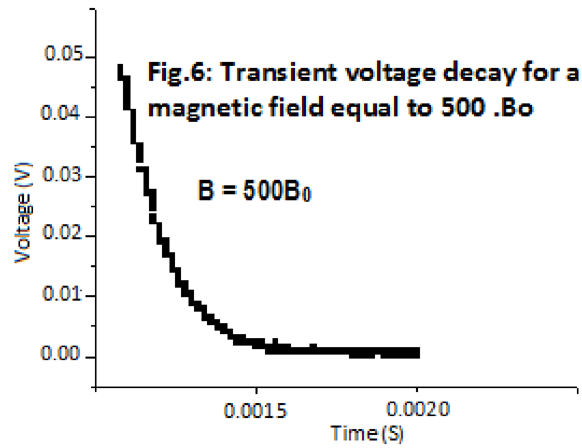

Fig.6: Transient voltage decay for a magnetic field equal to 500 .Bo

The solar cell used in our experiment has the following characteristics: H = 0, 02 cm; D = 26 cm^2/s i.e the same characteristics of those used in the references [9]

The values of τ_{eff} extracted from experimental curve are reported in **table 1**

Table 1 Values of effective bulk life time

B (Tesla)	0	B_0	10. B_0	500. B_0	10^3. B_0
$\tau_{eff}\,(s)$	44	43	43	35	25
$\tau_b\,(\mu s)$	4,2	4,2	4,2	3,9	3,5
R^2	0,98		0,97	0,96	0,96

The values of τ_{eff} obtained in this study diverge with those obtained in the literature except the case where B = 0

However, the magnetic field has substantially no effect on the bulk component of lifetime and we obtain the same values published in the literature [9]

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The experimental results shows that the effect of the magnetic field on the transient voltage is significant only when the values of the field are larger or equal to $500.B_0$. B_0 indicates the value of the horizontal component of the magnetic terrestrial field.

Comparing the numerical values of fundamental harmonics obtained in this study with those presented by Sam and al [9], and taking account that the bulk component is not depend to the magnetic field, we can conclude that the magnetic field changes only the cell interface states.

IV. Conclusion

In this paper, a three dimensional approach of electrons diffusion in the p region of a polycrystalline silicon solar cell is presented. The solar cell is submitted to an external magnetic field and illuminated by a pulsed light. The resolution of the time dependent and the three dimensional diffusion equation leads to new expressions of the transient voltage and the reduced amplitude of transient voltage. This last one term contains all the parameters characteristic of grain as the grain size, the interfaces state and magnetic field through the constraint coefficients at boundaries. By reconstructing the transient voltage curve from the experimental points recorded thanks to data acquisition software, we measured the experimental values of the reduced amplitude of transient voltage and the effective lifetime of the minority carriers. From these experimental values, the constraint coefficients at boundaries are computed using a reversed approach. The bulk lifetime is then deducted for many values of magnetic field

The values of bulk lifetime obtained in this study are been compared to those obtained from transient state under the same conditions without external magnetic field. This comparative study reveals a good agreement at low values of magnetic field and significant gap at high values of magnetic field. More precisely, the critical value of the magnetic field from which this gap is observed is 0.01 T

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