3D determination of the minority carrier lifetime and the p-n junction recombination velocity of a polycrystalline silicon solar cell

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Abstract. This work presents a theoretical and experimental transient tri-dimensional study conducted for the determination of the bulk component of the minority carrier lifetime and the p-n junction recombination velocity of a bifacial polycrystalline silicon solar cell. The theoretical analysis is based on the columnar model of the grains in the polycrystalline silicon solar cell. The boundaries conditions are defined in order to use Green's function to solve the three-dimensional diffusion equation. This leads to a new expression of the transient photovoltage. The value of the constraint coefficients at interfaces of the grain are computed while those of the effective minority carrier lifetime τ_{eff} is extracted from the experimental curve of transient voltage. The bulk lifetime and the p-n junction recombination velocity are deduced and have been compared to those obtained from transient state by one-dimensional modelling of carrier's diffusion. This comparative study permitted us to show grain effects on the lifetime and consequently the inadequacy of one-dimensional modelling of carrier's diffusion in the polycrystalline silicon solar cells.

1. Introduction

The minority carrier's lifetime and the p-n junction recombination velocity are two important recombination parameters that affect strongly the efficiency of the solar cells. It is the reason why many techniques have been developed, especially dynamic methods, in order to determine these parameters [1, 2]. But these methods developed in different laboratories often lead to overestimated or underestimated values [3]. This is probably due to the fact that the one-dimensional model is not appropriate to describe the diffusion of carriers because it does not take into account 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 [4]. In these conditions, the one-dimensional model is not appropriate to describe the diffusion of carriers. So the purpose of this work is to develop mathematical solutions of the time dependent and three-dimensional diffusion equation for minority carriers in the base of a polycrystalline p-n junction solar cell and to propose a new experimental procedure to measure minority carriers' lifetime and p-n junction recombination velocity by photovoltage decay analysis. In this study, mathematical approach in 3D description of carriers' diffusion is based on the following hypothesis [5]:

- The surfaces between two adjacent grains and perpendicular to the junction are characterized by the same carrier recombination processes evaluated by a grain boundary recombination velocity Sg
- The electric field of crystal lattice is negligible
- Only the contribution of the base in the processes of generation is considered

2. Theoretical analysis

Polycrystalline devices contain many grains randomly oriented or relatively ordered. In order to do the modeling of the processes of generation, diffusion and recombination, the polycrystalline solar cell will be considered as a regular array of many units cells connected in parallel with dimensions 2a, 2b and H (figure 1). This modeling of polycrystalline solar cell structure was described in detail by the authors of references [5, 6, and 7]. On these hypotheses, the properties of polycrystalline solar cell can be described by a study of generation, diffusion and recombination processes only in one grain.
Figure 1 shows the theoretical model for a grain taken as a unit cell inside the sample and the Cartesian coordinates used to solve the diffusion equation.

For simplicity it is considered a square section for the grain (i.e. grain size $Xg = 2a = 2b$).

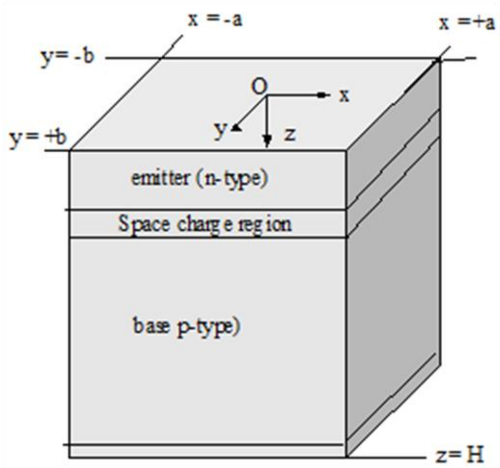

Figure 1. Theoretical model of grain

When the cell is submitted to a multispectral flash illumination on its surface defined by $z = 0$, the excess minority carrier density $\delta(x, y, z, t)$ in the base region is governed by the inhomogeneous partial diffusion equation of the form:

$$\frac{\partial\delta(x,y,z,t)}{\partial t} - D.\left[\vec{\nabla}^2\delta(x,y,z,t) - \frac{\delta(x,y,z,t}{L^2}\right] = g(x,y,z,t) \qquad (1)$$

The generation rate $g(x,y,z,t)$ is governed by equations:

$$g(x,y,z,t) = \begin{cases} \sum_{m=1}^{3} \mathrm{a}_m.\exp(-\mathrm{b}_{m.}.z) & \text{if} \quad 0 \le t \le Te \\ \\ 0 & \text{if} \quad t > Te \end{cases} \qquad (2)$$

The coefficients a_m and b_m are the modeling coefficients of AM1.5 solar spectrum. These coefficients were evaluated by [8]; D and L are respectively the diffusion coefficient and the diffusion length of the carriers; Te is the duration of the flash illumination.

The differential equation defined at (1) is integrated with the following boundary conditions:

- at p-n junction defined by z = 0

$$\left.\frac{\partial\delta(x,y,z,t)}{\partial z}\right|_{z=0} = \frac{Sf}{D}\delta(x,y,0,t) \tag{3}$$

- at back surface defined by $z = H$

$$\left.\frac{\partial\delta(x,y,z,t)}{\partial z}\right|_{z=H} = -\frac{Sb}{D}.\delta(x,y,H,t) \tag{4}$$

- at surfaces limited by $x = \pm a$ and $y = \pm b$

$$\left.\frac{\partial\delta(x,y,z,t)}{\partial x}\right|_{x=\pm a} = \mp\frac{Sg}{D}.\delta(\mp a,y,z,t) \tag{5}$$

$$\left.\frac{\partial\delta(x,y,z,t)}{\partial y}\right|_{y=\pm b} = \mp\frac{Sg}{D}.\delta(x,\mp b,z,t) \tag{6}$$

Sf, *Sb* and *Sg* are the recombination velocity of minority carriers respectively at surfaces $z = 0$, $z = \mathrm{H}$ and $x = \pm a$ (or $y = \pm b$); a, b and H are the grain sizes as indicated on figure 1.

The transient voltage decay is defined by equation (7):

$$V(t) = V_T.\ln\left\{1 + Fc(k_1,l_1,\mu_1)q\exp\left[-\beta_{1,1,1}(t\text{-}Te)\right]\right\} \tag{7}$$

where $Fc(k_1,\ l_1,\mu_1)$ is the reduced magnitude of transient voltage defined by :

$$Fc(k_1,l_1,\mu_1) = \frac{X0_{1,1,1}}{X1_{1,1,1}} \tag{8}$$

The value of this function depends on the characteristics of the cell.

The quantities $X0_{1,1,1}$, $X1_{1,1,1}$, q and $\beta_{1,1,1}$ are giving by :

$$X0_{1,1,1} = \int_{-a}^{a}\int_{-b}^{b} Z_{1,1,1,}(x,y,0)\,\mathrm{d}x\mathrm{d}y \tag{9}$$

$$X1_{1,1,1} = \int_{-a}^{a}\int_{-b}^{b} \delta_{1,1,1}(x,y,0)\,\mathrm{d}x\mathrm{d}y \tag{10}$$

$$q = \exp(\Delta V) - 1 \tag{11}$$

$$\beta_{1,1,1} = D.\left(k_1^2 + l_1^2 + \mu_1^2 + \frac{1}{L^2}\right) \tag{12}$$

$Z_{1,1,1}(x,y,0)$ and $\delta_{1,1,1}(x,y,0)$ are respectively the spatial component of $\delta(x,y,z,t)$ and the minority carriers density during the phase of illumination. The parameters k_1, l_1 and μ_1 are the fundamental eigenvalues obtained from the boundary conditions.

These parameters depend only on the grain sizes and the grain boundary recombination activities. Expression (7) leads to predict two type of transient voltage decay: linear and exponential decay. To understand the role that the grain play in limiting the solar cell efficiency, the concept of effective minority carrier lifetime used in the case of polycrystalline silicon solar is introduced. The effective minority carrier lifetime is given by:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_s} + \frac{1}{\tau_b} \tag{13}$$

where τ_b is the bulk lifetime and τ_s is the surface component which is controlled by the grain boundary recombination velocity and the grain size through k_1 and l_1, the base thickness, the back and p-n junction surfaces recombination velocity through μ_1. Then the surface lifetime can be expressed as:

$$\frac{1}{\tau_s} = D.\left(k_1^2 + l_1^2 + \mu_1^2\right) \quad (14)$$

3. Experimental details

The experimental setup is presented on figure 2. It is composed of : a bifacial solar cell of MOTECH INDUSTRIES; 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.

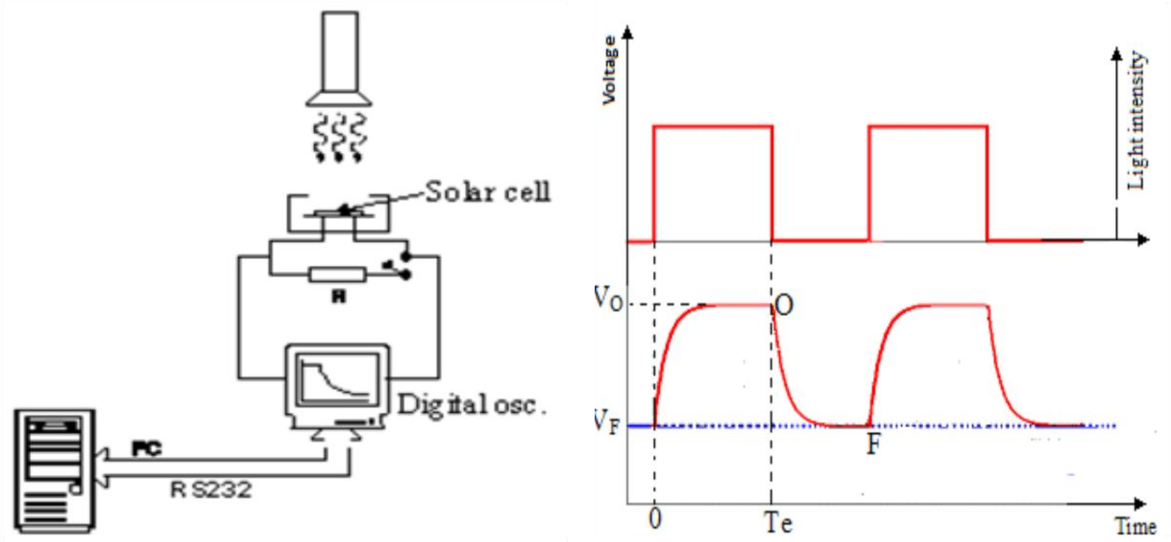

Figure 2. Experimental setup and operating mode

At time t = 0, the cell is illuminated with the multispectral flash which establishes a steady state characterized by the potential V^F corresponding to an operating point called *F* (figure2). At *t* = *Te* the flash is abruptly cut off. The voltage V^F drops from V^F to V^0 corresponding to a new operating point denoted O. The decay of voltage from V^F to V^o is recorded on a digital scope connected to a computer via a RS-232 cable. Experimental data are stored in the computer to be used later for the reconstruction of the signal response of the solar cell and analysis.

Let *t' = 0* be the time of beginning of the exponential part of *V(t)*. At this time corresponds the ordinate *V(t' = 0)*. The couple *(t' = 0, V (t' = 0))* is solution of the equation:

$$V(t') = V_T.Fc(k_1, l_1, \mu_1)q\exp\left(-\beta_{1,1,1}.t'\right) \quad (15)$$

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

$$\left[V\left(t'\right) - V_{exp}\right] \to 0 \quad (16)$$

The other experimental points not fulfilling the condition defined by (16) are not solutions of equation (15) and are therefore taken out of the fit. The error estimation is given by the correlation factor R^2 obtained from the fit.

The experimental value of $Fc(k_1,\ l_1,\ \mu_1)$, the reduced magnitude of transient voltage, is then obtained by:

$$Fc(k_1,\ l_1,\ \mu_1) = \frac{V(t'=0)}{q.V_T} \tag{17}$$

$V(t'=0)$ is as defined above; q is deduced from expression (11) using ΔV defined by: $\Delta V = V_O - V_F$. The values of $V(t'=0^+)$ and q lead to the experimental value of reduced magnitude of transient voltage: Fc_{exp}. The diffusion coefficient D for silicon is a function of dopant density N_B and expressed as:

$$D = V_T.\frac{1350}{\left[1+\dfrac{81.N_B}{N_B+3,2.10^{18}}\right]^{\frac{1}{2}}} \tag{18}$$

The diffusion length can be expressed as function of D, τ_{eff}, k_1, l_1 and μ_1 by

$$L = \left[\frac{D.\tau_{eff}}{1-D.\tau_{eff}.\left(k_{1,\alpha}^2+l_{1,\alpha}^2+\mu_{1,\alpha}^2\right)}\right]^{\frac{1}{2}} \tag{19}$$

The boundary conditions at p-n junction surface and back surface allow to express Sf as:

$$Sf = -\mu_1 D\tan\left[\tan^{-1}\left(\frac{Sb}{\mu_1 D}\right)-\mu_1 H\right] \tag{20}$$

Likewise, with grain boundary conditions, the common value of the laterals size of grain can be expressed as function of *Sg*. The value of grain boundary recombination velocity Sg evaluated by optical scanning allows us to express *Sg* as:

$$Sg = Sg_m = m\times 10^4\ cm/s \tag{21}$$

where *m* is a real >1.

These expressions allow to write $Fc(k_1,l_1,\mu_1)$ as a function of parameters N_B, *H*, *Sb* , *m* and τ_{eff}. As *H, D, Sb,* and τ_{eff} are known, therefore, the analytical expression of the function $Fc(k_1,l_1,\mu_1)$ is completely described by the parameter m.

The hypothesis of square section of grains leads to $k_1 = l_1$. In these conditions, reduced magnitude of transient voltage is expressed as only a function of k_1 and μ_1. So these parameters can be obtained by solving equation (22)

$$Fc_m(k_1,\mu_1) = Fc_{exp} \tag{22}$$

A homemade software allows us to get the experimental values of constraints coefficients k_1 and μ_1 After calculation of the remarkable points, the values of k_1, μ_1 and m are found by dichotomy. This dichotomic search is done using an iterative method of calculation based on NEWTON's algorithm. The incrementations are submitted to the inequality expressed by equation (23):

$$\left|Fc_m(k_1,\ l_1,\ \mu_1)-\frac{V(t'=0^+)}{q.V_T}\right| \le 10^{-6} \tag{23}$$

The surface lifetime is calculated using expression (14) and the bulk lifetime is deduced from the equation (13). Likewise Sf is obtained by means of expression (20).

On figure 4 to figure 6 are presented experimental curves of transient voltage and their fit.

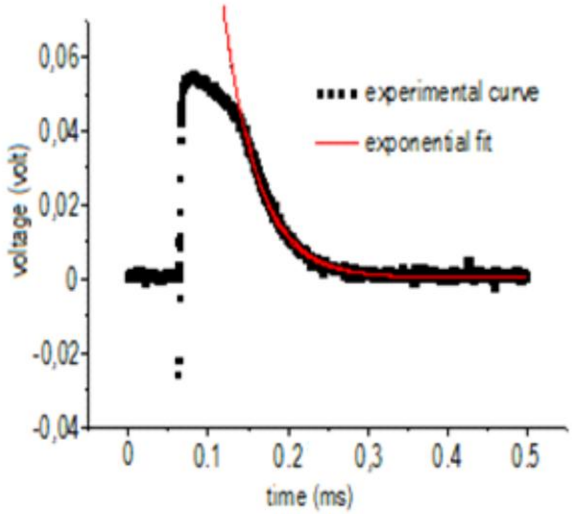

Figure 3. Transient voltage decay for load R = 0,7kΩ

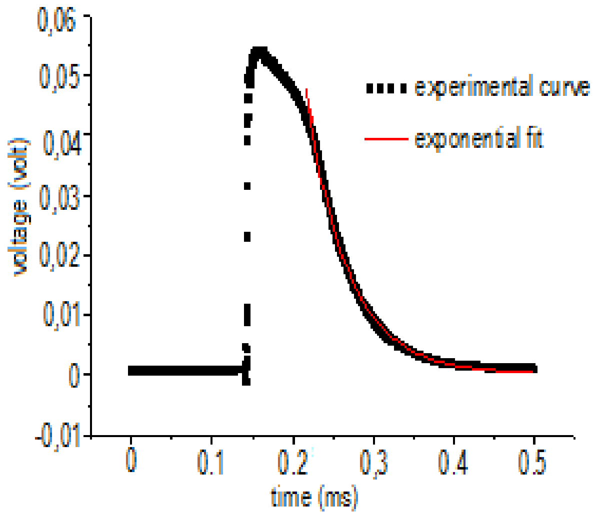

Figure 4. Transient voltage decay for load R=1kΩ

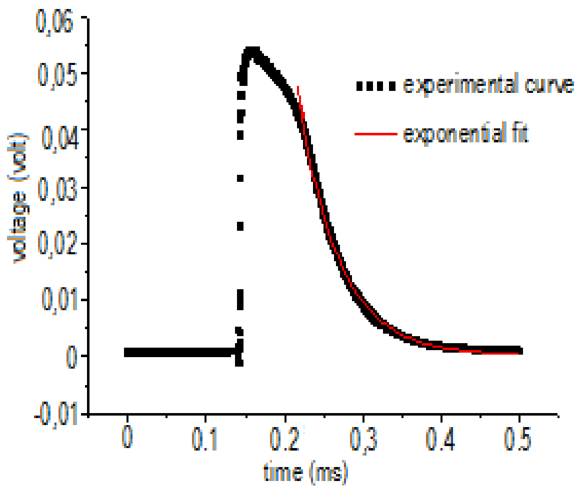

Figure 5. Transient voltage decay and corresponding exponential fit; R =1,5kΩ

Technique described above leads to the results presented on the table 1. The solar cell used in our experiment has the following characteristics: H = 0,02 cm ; D=26 cm^2/s.

Table 1. Lifetime and p-n junction surface velocity for different values of load

	τ_b(µs)	τ_{eff}(µs)	Sf(cm/s)	R^2
R=0.7kΩ	10,9	9,3	1.2.10^4	0,98
R=1kΩ	4	40	1.10^3	0,95
R=1.5k Ω	4,3	43	900	0,91

A similar procedure as described in this paper based on one-dimensional model of carrier diffusion and developed by the author of the reference [9] leads to the same values of τ_{eff} . However, a profound disagreement is revealed on the value of bulk component of lifetime τ_b.

Even if the appearance of interference impedances during the transient state disrupts the measured values, this disagreement can't be justified only by the effects of interference impedances. This disagreement can be explained by the lateral diffusion of minority [10].

Indeed, by superimposing the expression of bulk lifetime τ obtained by one- dimensional modeling to those established in this study, we obtain through the three dimensional analysis of carrier diffusion, the expression:

$$\frac{1}{\tau_b}-\frac{1}{\tau}=\omega_0^2-D\left(k_1^2+l_1^2+\mu_1^2\right) \tag{24}$$

The constants ω_0 and μ_1 are controlled by the same parameters i.e. *Sf*, *Sb* and *H*. Then it occurs

$$\frac{1}{\tau_b}-\frac{1}{\tau}\simeq -2D\mathrm{k}_1^2 \tag{25}$$

With the experimental value of, k_1 the part of grains activity on the disagreement of experimental values of bulk lifetime obtained by one and three-dimensional analysis of carrier diffusion can be expressed. This contribution of grains can be estimated by the value of coefficient η defined:

$$\eta=\left|\frac{-2Dk_1^2}{\frac{1}{\tau_b}-\frac{1}{\tau}}\right| \tag{26}$$

The difference between the experimental value of bulk lifetime obtained in this study and those published by the authors of the reference [9] leads to a value of η greater than 0, 9.

4. Conclusion

In this 3 D study, we have presented a new mathematical description of carrier's diffusion as well as a new experimental procedure for minority carrier lifetime and p-n junction recombination velocity determination. This study led us to establish a new expression of transient voltage containing all the characteristic parameters of the geometrical grains and their interface states.

With a classic experimental setup allowing the observation of the transient state, we have reconstituted on computer and analyzed the response of cell submitted to a multispectral flash illumination. The treatment of transient voltage decay curve reconstituted from data acquisition allowed us to obtain the value of reduced magnitude of transient voltage as well as the effective minority carrier lifetime. The eigenvalues, solution of equations expressing the cell's boundary constraints are then calculated by software program based on NEWTON's algorithm. The values of bulk lifetime and p-n junction recombination velocity are then deduced.

The experimental results obtained reveal a profound disagreement with those obtained on the same cell by one-dimensional modeling. Using the experimental values of coefficients k_1 and l_1, we have demonstrated that the disagreement observed is due to the fact that we take into account the lateral diffusion of minority carrier. This analysis highlights the part of grains effect in indetermination of the bulk lifetime of carriers and the shortcoming of one-dimensional model in the description of polycrystalline silicon wafers.

The experimental results also showed that the values of the effective lifetime increases with the value of load. This increase may be related to the capacitance of the PV modules which manifests itself at proximity of open circuit conditions. During the experimental operations, it appeared that the value of bulk lifetime can be stabilized by increasing the illumination level. This observation will be examined in details in the future by a global increase of injection level.

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