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Modeling Study of N^+/P Solar Cell Resistances from Single I-V Characteristic Curve Considering the Junction Recombination Velocity (Sf)

[1,2]S. Mbodji, [3]I. Ly, [4]H. L. Diallo, [1]M.M. Dione, [1]O. Diasse and [1]G. Sissoko
[1]Laboratoire des Semi-conducteurs ET d'Energie Solaire, Département de Physique, Faculté des Sciences ET Techniques, Université Cheikh Anta Diop, Dakar, Senegal
[2]Section de Physique, UFR SATIC, Université de Bambey, Sénégal, BP 30 Bambey-Sénégal
[3]Ecole Polytechnique de Thiès, Thiès, Sénégal
[4]UFR SET, Université de Thiès, Thiès, Sénégal

Abstract: This study presents a new technic based on the junction recombination velocity (Sf) for the evaluation of the series and shunt resistances. Associating Sf and Sb, the back surface recombination velocity, we resolved the continuity equation in the base of the solar cell under monochromatic illumination and plotted I-V and P-V curves. Using single I-V curve, two equivalent electric circuits of the solar are proposed and lead to expressions of R_s and R_{sh}. Computations of Rs and Rsh and comparison with published data are given.

Key words: Grain boundary recombination velocity, grain size, junction recombination velocity, series resistance, shunt resistance

INTRODUCTION

Our study, is based on the junction recombination velocity Sf (Mbodji *et al*., 2010; Diallo *et al*., 2008; Sissoko *et al*., 1998) which is associated to the well known back side recombination velocity Sb (Madougou *et al*., 2007a, b; Sissoko et al., 1998; Dugas, 1994) and uses a 3D model of a polycrystalline solar cell which takes into account the existence of grain size g and grain boundary recombination velocity Sgb.

Sf appears as an effective characteristics of the junction and is related to the solar cell technological parameters (base doping, base width) and to the operating conditions (junction polarization). Sf quantifies how the excess carriers flow through the junction in actual operating conditions and then Sf characterizes the junction as an active interface (Mbodji *et al*., 2010; Diallo *et al*., 2008; Sissoko *et al*., 1998). When Sf tends to zero, there is no current flows through the junction so carriers are stored on both sides of the junction: that is open circuit state of an ideal cell. In a non ideal cell (real case with losses at the junction), there is a very small current flowing through the junction, which means that an internal load exists in the solar cell: that is the shunt resistance R_{sh} of the cell. This shunt resistance induces an intrinsic junction recombination velocity Sf0 (Barro *et al*., 2008; Diallo *et al*., 2008; Deme *et al*., 2010) which depends only on the intrinsic parameters of the photovoltaic cell. So Sf stands for the sum of two terms: Sf0 the intrinsic part imposed by the shunt resistance and Sf_j which is related to the current flow and imposed by an external load and defines the operating point of the cell Sf (Mbodji *et al*., 2010; Diallo *et al*., 2008; Sissoko *et al*., 1998). In our study of modeling, we set $Sf = Sf0+Sf_j$ with $Sf_j = 10^j$ and $j>0$.

Keeping the series resistance R_s as low as possible is of paramount importance because its increase causes power loss due mainly to a decrease of short-circuit current density (I_{sh}), open circuit velocity (V_{oc}), maximum power (P_m), fill factor (FF) and conversion efficiency (h) of the solar cell (Bashahu and Habyarimana, 1995; Pysch *et al*., 2007).

Contrarily to the series resistance R_s, the shunt resistance R_{sh} must be higher to avoid current loss at the junction (Bouzidi *et al*., 2007) diminishing the photocurrent and hence the solar cell performance.

These two parameters (R_s, R_{sh}) must be determined as accurately and robustly as possible to get a reliable characterization in both industrial production for quality control and also solar cell development labs.

In this way, many methods based on experimental conditions (Bashahu and Habyarimana, 1995), number of diodes quoted in the solar cell model (Bashahu and Habyarimana, 1995), simultaneous determination of the other parameters or not and assumptions such as constant ideality factor or not and infinite or finite shunt resistance (Bashahu and Habyarimana, 1995), have been developed.

In this study, we resolved the three dimensional continuity equations, and calculated the photocurrent

Corresponding Author: S. Mbodji, Laboratoire des Semi-conducteurs ET d'Energie Solaire, Département de Physique, Faculté des Sciences ET Techniques, Université Cheikh Anta Diop, Dakar, Senegal

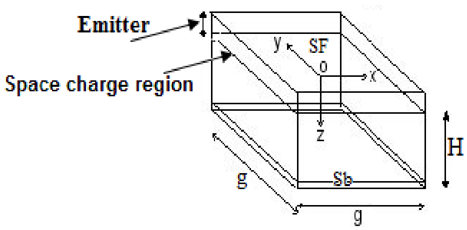


Fig. 1: Isolated grain

density (I) and photovoltage (V). Curves of I-V and P-V characteristics are plotted and from the single I-V curve, two equivalents electric circuit of the solar cell, in open circuit and short circuit, are proposed, allowing us to deduce R_s and R_{sh}.

THEORY

Excess minority carriers density: We consider an N^+-P polycrystalline solar cell which is a fibrously oriented columnar and an isolated grain represented in Fig .1

The excess minority carrier distribution $\delta(x, y, z)$ in the solar cell base is expressed as (Dugas, 1994; Dieng *et al*., 2011):

$$\delta(x,y,z) = \sum_{k}^{\infty}\sum_{j}^{\infty}\left[\begin{array}{l} A_{kj}.ch\left(\dfrac{z}{L_{kj}}\right) + B_{kj}.sh\left(\dfrac{z}{L_{kj}}\right) \\ -\dfrac{16.L_{kj}^2.\sin\left(\frac{g.c_k}{2}\right).\sin\left(\frac{g.c_j}{2}\right)}{D\cdot c_k\cdot c_j\cdot F_{kj}}\cdot G(z)\end{array}\right] \cdot\cos(x\cdot c_k)\cdot\cos(y\cdot c_j) \quad (1)$$

D and L are respectively, the excess minority carrier diffusion constant and effective diffusion length.

G(z) is a position dependent carrier generation rate and can be written as (Sissoko *et al*., 1998):

$$G(z) = \alpha.I_0.(1-R).\exp(-\alpha.z) \quad (2)$$

α and R are the absorption and reflexion coefficients of light associated to the wavelength λ (Green and Keevers, 1995), I_0 is the incident photon flux (Green and Keevers, 1995).

From transcendental Eq. (3) and (4), obtained using boundary conditions at the contact of two grains, we determine c_k and c_j (Goyal, 2007; Dieng *et al*., 2011):

$$\tan\left(\frac{ck.g}{2}\right) = \frac{Sgb}{ck.D} \quad (3)$$

and

$$\tan\left(\frac{cj.g}{2}\right) = \frac{Sgb}{cj.D} \quad (4)$$

Constants A_{kj} and B_{kj} are determined using the boundary conditions defined at the junction and at the back side of the solar cell (Mbodji *et al*., 2010; Dieng *et al*., 2011):

- At the junction (N^+-P interface (z = 0)):

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

- At the back surface (z = H):

$$D\cdot\left.\frac{\partial Z_{kj}(z)}{\partial z}\right|_{z=H} = -Sb\cdot Z_{kj}(H) \quad (6)$$

Photocurrent density: The photocurrent density I at the junction of solar cell is obtained from the excess minority carriers density as follows (Diallo *et al*., 2008; Madougou *et al*., 2007a):

$$I(g,Sgb,\lambda,Sb,Sf) = q.D.\left.\frac{\partial\delta(x,y,z)}{\partial z}\right|_{z=0} \quad (7)$$

D is a constant defined above and $q = 1.6.10^{-19}$ C.

Photovoltage: By means of Boltzmann's relation, the photovoltage V can be expressed as (El-Adawi and Al-Nuaim, 2002):

$$V(g,Sgb,\lambda,Sb,Sf) = V_T.Log\left[N_B\cdot\frac{\delta(g,Sgb,\lambda,Sb,Sf,z=0)}{n_i^2}+1\right] \quad (8)$$

where, $V_T = K.T/q = 0.026$ V is the thermal voltage at T = 300 K, n_i the intrinsic carriers density and N_B the base doping density.

RESULTS AND DISCUSSION

I-V and P-V characteristics: By means of the junction recombination velocity Sf, which varies from 0 to Sf = 1.5×10^6 m/s (Barro *et al*., 2008), we plotted in Fig. 2 and 3 the I-V characteristic curves.

Figure 2 is the plot of the I-V characteristics for various grain boundary recombination velocities Sgb with fixed values of wavelength (λ = 800 nm) and grain size (g = 40 mm).

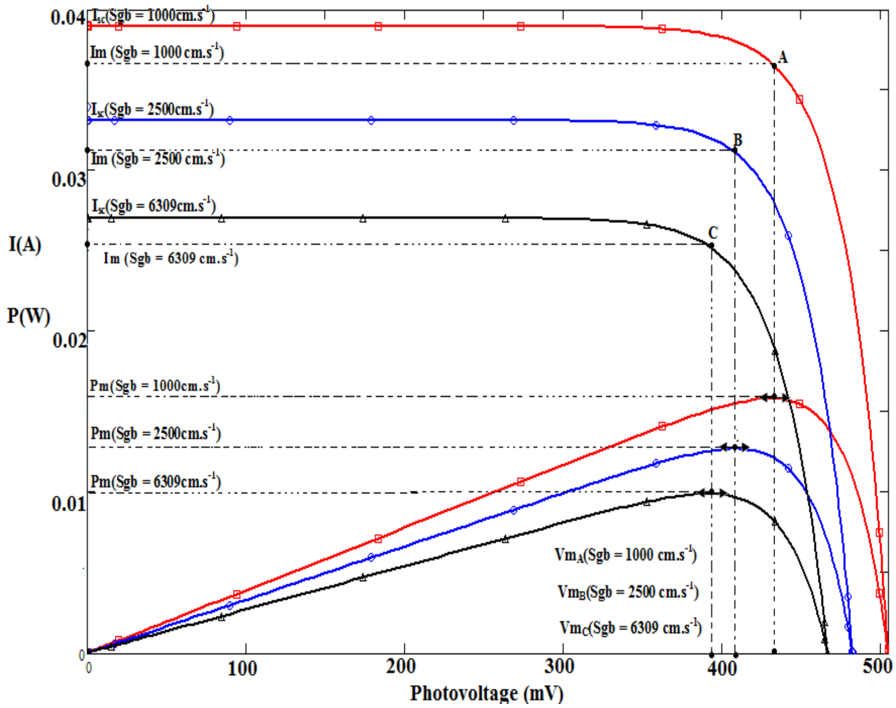


Fig. 2: Power- Photovoltage (P-V) and Photocurrent - Photovoltage (I-V) characteristics for various grain boundary recombination velocity Sgb(cm/s); g = 40 mm and λ = 800 nm.

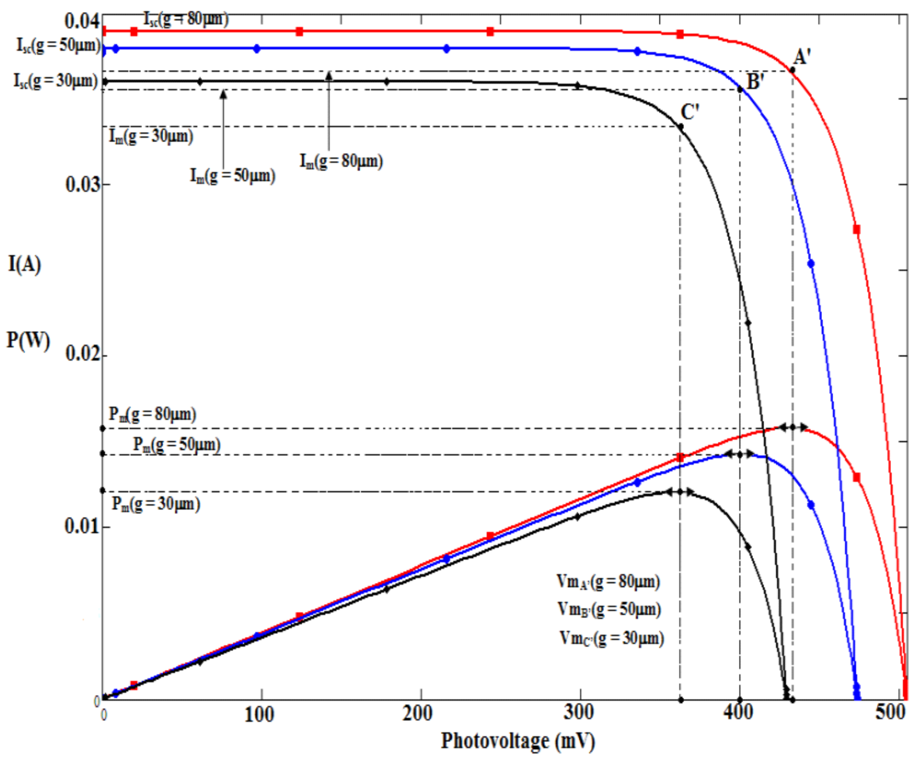


Fig. 3: Power- Photovoltage (P-V) and Photocurrent - Photovoltage (I-V) characteristics for various grain size g (cm/s); Sgb = 1000 cm/s; λ = 800 nm

Grain size's influence on I- V characteristic when wavelength (λ = 800 nm) and grain boundary recombination velocity (Sgb = 10^3 cm/s) are fixed values, is plotted in Fig. 3.

Varying the junction recombination velocity, meaning changing external load, I-V plots give as seen by (El-Adawi and Al-Nuaim, 2002) three points: the short circuit photocurrent I_{sc}, the open-circuit photovoltage V_{oc} and the "knees" (A, B, C, A′, B′ and C′) of the I-V plot. These three parameters are affected by grain size and grain boundaries recombination velocity.

The short circuit photocurrent is constant for Sf > 10^4 cm/s (Barro *et al*., 2008), and we show that, it depends on the considered two parameters (g, Sgb). It decreases with grain boundary recombination velocity but increases with the grain size of the solar cell.

The open circuit photovolage $V_{oc,}$ valuable for Sf < 10^2 cm/s (Barro *et al*., 2008), occurs on a point of the curves where the photocurrent is zero. As the short circuit photocurrent, the open circuit photovoltage decreases with grain boundary recombination velocity and increases with the grain size.

We also noted that the shape of the I-V has the same evolution of I_{sc} and V_{co} when we change parameters.

The junction of solar cell in real operating point is a plane capacitor with two identical plane electrodes separated by a thickness Z_0 (Mbodji *et al*., 2010). The effect of grain size on this thickness is clear demonstrated (Mbodji *et al*., 2010) when this parameter increases. Authors showed that, increasing of grain size leads to the decrease of the space allowing high electrons' flow rate crossing the junction, corresponding to an increase of the photocurrent and the efficiency of the solar cell.

But, when the grain boundary recombination velocity increases, the thickness of the junction is enlarged but decreases with this parameter (Sgb) and electrons which cross the junction are light (Mbodji *et al*., 2010).

The fill factor which is the ration of the peak power ($I_m.V_m$) to the product $I_{SC}.V_{OC}$ (Chegaar *et al*., 2001) is one of the main significant values when determining the efficiency of the solar cell. Thus, it depends on the short circuit photocurrent I_{sc}, the open circuit photovoltage V_{co}, the maximum power point P_m.

Each I-V curves is characterized by a point named "knee" (El-Adawi and Al-Nuaim, 2002) which has I_m and V_m as coordinates. The product of I_m and V_m gives the peack power $P_m = I_m.V_m$.

We note that the coordinates of the knee, the peak power, the open circuit voltage and the short circuit photocurrent increase and decrease with grain size and grain boundary recombination velocity, respectively. These results confirm works, done by Mbodji *et al*. (2010) and Deme *et al*. (2010), which study the solar cell performance evaluating the extension region of the junction

Determination of series and shunt resistances: Series and shunt resistances are electrical parameters and their determination can be done by using many methods (Bashahu and Habyarimana, 1995; Bouzidi *et al*., 2007; El-Adawi and Al-Nuaim, 2002).

The series resistance is caused by the movement of electrons through the emitter and base of the solar cell, the contact resistance between the metal contact and the silicon and the resistance of metal grids at the front and the rear of the solar cell (Bashahu and Habyarimana, 1995; Bouzidi *et al*., 2007; El-Adawi and Al-Nuaim, 2002).

The shunt resistance is due to manufacturing defects and also lightly by poor solar cell design. It corresponds to an alternate current path for the photocurrent (Bashahu and Habyarimana, 1995; Bouzidi *et al*., 2007; El-Adawi and Al-Nuaim, 2002).

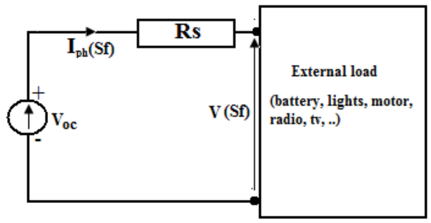
In a constant illumination level, i.e., one I-V curve supposing one diode model and neglecting R_{sh} effect, one can use the method of the slope at (V_{oc}, 0) point, the maximum power point method, the area and the generalized area methods (Bashahu and Habyarimana, 1995; Pysch *et al*., 2007).

Near the short-circuit, the slope of I-V curve permits to determine the shunt resistance (Bouzidi *et al*., 2007). Some authors use the interdependence between R_s and R_{sh} to calculate each of them (El-Adawi and Al-Nuaim, 2002).

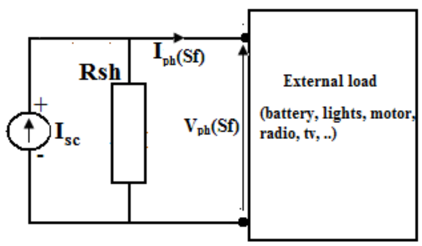
In our study, knowing that power loss due to R_s and R_{sh} is most significant in upper voltage part at V_{oc} and lower voltage at I_{sc} (Bashahu and Habyarimana, 1995; Bouzidi *et al*., 2007; El-Adawi and Al-Nuaim, 2002) respectively, we use the open circuit (Barro *et al*., 2008; Madougou *et al*., 2007b; Diallo *et al*., 2008) and short circuit zones (Barro *et al*., 2008; Madougou *et al*., 2007b; Diallo *et al*., 2008) of I-V characteristic and propose two circuits for the solar cell and calculating R_s and R_{sh}.

Hence, we present in Fig. 4a, the solar cell as photovoltage generator (open circuit zone) in series with the series resistance and the external load and in Fig. 4b, the solar cell is in parallel with the shunt resistance (short circuit zone) which illustrated the diversion of the current at the junction.

Using Fig. 4a and b, the series resistance and the shunt resistance are then defined by Eq. (9) and (10), respectively:



(a)



(b)

Fig. 4: Equivalent electric circuit of the solar cell, (a) solar cell is a voltage generator; (b) solar cell is a current generator

$$R_S(g,Sgb,\lambda,Sf) = \frac{V_{oc}(g,Sgb,\lambda) - V(g,Sgb,\lambda,Sf)}{I(g,Sgb,\lambda,Sf)} \quad (9)$$

and

$$R_{sh}(g,Sgb,\lambda,Sf) = \frac{V(g,Sgb,\lambda,Sf)}{I_{sc}(g,Sgb,\lambda) - I(g,Sgb,\lambda,Sf)} \quad (10)$$

R_s depends on open circuit voltage V_{oc} at any operating points for Sf<10^2cm/s (Barro *et al*., 2008; Diallo *et al*., 2008; Chegaar *et al*., 2001) and the photocurrent. R_{sh} depends on V, I and I_{sc} for Sf>10^4 cm/s (Barro *et al*., 2008; Diallo *et al*., 2008; Chegaar *et al*., 2001).

Compared to Bashahu and Habyarimana (1995) and Bouzidi *et al*. (2007) methods where R_s and R_{sh} are calculated using single I-V curve, our relation results from equivalent electric circuits of the solar cell deduced from I-V curve.

In our model of circuit there aren't diodes as it is seen in model of one diode (Chegaar *et al*., 2001) or two diodes (Singal, 1981), usually used in the establishment of R_s and R_{sh}.

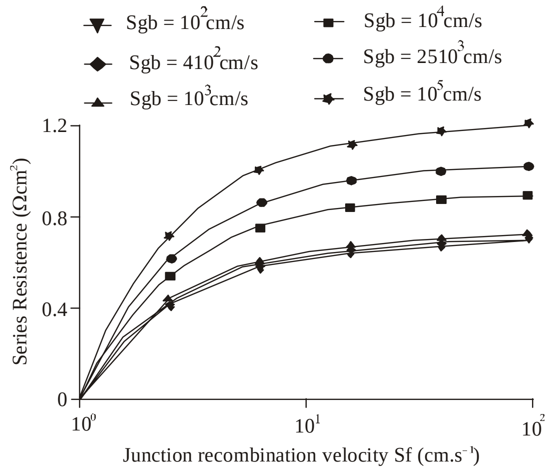


Fig. 5: Series resistance versus junction recombination velocity; g = 90 mm; λ = 800 nm

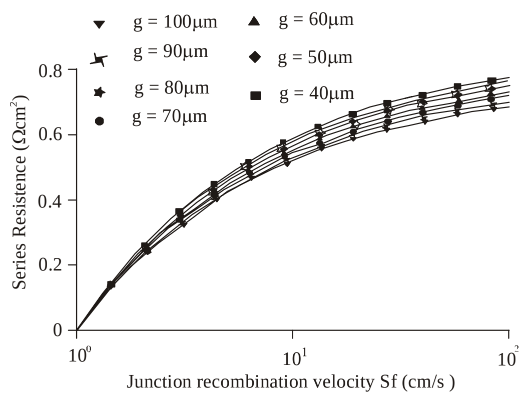


Fig. 6: Series resistance versus junction recombination velocity; Sgb = 25.10^2 cm/s; λ = 800 nm

The curves of the series resistance versus the junction recombination velocity are plotted in Fig. 5 when the grain boundary recombination velocity varies and in Fig. 6 when the grain size changes.

Figure 5 and 6 show that the series resistance depends also on junction recombination velocity (Sf), grain size (g) and grain boundary recombination velocity (Sgb). Series resistance increases with Sf and with grain boundary recombination velocity and decreases with grain size.

Our method assesses the values of series resistance, which lie in the following interval [0, 1.25] Ω.cm^2. It is accurate to (Bashahu and Habyarimana, 1995), which presents values of R_s ranging from 0 to 1600 Ω.cm^2.

The decrease of the series resistance with grain size is explained by the reduction of losses in grain boundary and the decrease of the thickness of the junction (Mbodji

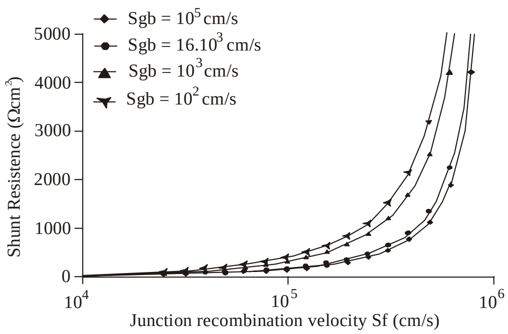


Fig. 7: Shunt resistance versus junction recombination velocity; g = 90 mm; λ = 800 nm

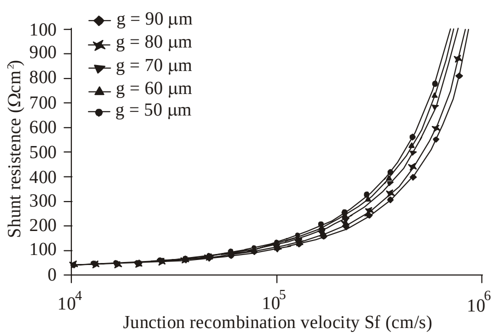


Fig. 8: Shunt resistance versus junction recombination velocity; Sgb = 10^3 cm/s; λ = 800 nm

et al., 2010; Deme *et al*., 2010) which lead to an increase of photocurrent and efficiency as shown by (Diallo *et al*., 2008). The study of the effect of the grain boundary recombination velocity on the series resistance shows in Fig. 5 that there are many losses in grain boundary, the thickness of the junction solar increases leading to a little crossing of electrons on the junction and the low photocurrent and efficiency (Mbodji *et al*., 2010; Deme *et al*., 2010).

Increase of Sf corresponds to an increase of the crossing of electrons at the junction (Barro *et al*., 2008; Madougou *et al*., 2007a; Diallo *et al*., 2008) leading to heat the metal grids in the front and the rear sides of the solar cell.The dependence of the shunt resistance on both the junction recombination velocity and grain boundary recombination velocity is plotted in Fig. 7, for g = 90 μm; λ = 800 nm. Figure 8 shows plot of the shunt resistance of the solar cell versus both Sf and g for Sgb = 10^3 cm/s and λ = 800 nm.

It is noted that, the shunt resistance increases with Sf meaning that, the photocurrent increases with Sf as shown by (Barro *et al*., 2008; Madougou *et al*., 2007a; Diallo *et al*., 2008) because the space charge region is enlarged regarding an increase of the crossing of the electrons of the junction (Mbodji *et al*., 2010; Deme *et al*., 2010).

In the increase of grain size and grain boundary recombination velocity we note that the shunt resistance increases and decreases, respectively. The grain size g increases the effect on R_{sh} and allows then much photocurrent and more efficiency of the solar cell. Grain boundary recombination velocity's increase corresponds to a decrease of R_{sh} and then we note a severe effect on current through the shunt resistance. This leads to a reduction of a photocurrent and the efficiency.

Our study gives higher values of R_{sh}, in accordance to those in the literature (Bashahu and Habyarimana, 1995; Singal, 1981) which, because R_{sh} has high values, neglected its effects (Bashahu and Habyarimana, 1995; Singal, 1981).

CONCLUSION

Using both the junction and back surface recombination velocities, the diffusion continuity equation, in a 3D model, is resolved by taking into account grain size and grain boundary recombination velocity effects.

Varying Sf from 0 to 1.5×10^6 cm/s, we plotted I-V and P-V characteristic curves. From single I-V curve, we proposed two equivalent electric circuits: the first, for low values of Sf (Sf < 10^2 cm/s) and the second for near the short circuit (Sf >10^4 cm/s).

The series resistance is determined by means of our first equivalent electric circuit where the solar cell is functioning as a voltage generator and the shunt resistance is calculated with the second circuit in which the solar cell is considered as a current generator.

R_s and R_{sh} are determined independently from Sf and showed that electron's flow increases with Sf, corresponding to an increase of photocurrent and metal grids in the front and the rear sides of the solar cell warmed.

It is shown that R_s and R_{sh} decrease and increase, respectively with grain size (g) and as conversion efficiency decreases depending on grain boundary recombination velocity (Sgb), R_s and R_{sh} increase and decrease, respectively with Sgb.

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