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Research Article

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Shunt resistance determination in a silicon solar cell under steady state: Effect of both illumination level and base thickness

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Abstract The excess minority carrier recombination velocity at both, the junction and back surfaces, is used to determine the optimum thickness of the base and the shunt resistance of the silicon solar cell, under steady state and with effect of the illumination level.

Keywords Silicon solar cell- Surface recombination velocity- Shunt resistance- low injection level

Introduction

The quality control of the solar cell aims to optimize the various steps of its manufacture [1,2]. The elaborate solar cell is subjected to different techniques for measuring electric current and voltage, under steady state [3,4] or dynamic regime (transient or frequency) operating modes [5,6].

The current-voltage characteristics (IV) of the solar cell under darkness [7] and under illumination [8] lead to the determination of parameters [9] such as the saturation current, the ideality factor, full factor. The equivalent electric parameters of the solar cell are, the resistances [10] series (Rs) [11] and shunt (Rsh) [7,12], which allow to appreciate the quality of the solar cell [13,14].

In this work, the electronic parameters, such as the excess minority carrier recombination velocity [15] in the bulk (τ) [16,17], at the emitter-base junction (Sf) [18-21] and on the back face (Sb) [21-26] of the thickness base (H) [27,28], are studied to extract the shunt resistance of the crystalline silicon solar cell as a function of the low level of injection of the expressed charge carriers, through the level of illumination [29,30].

Theoretical Study

a) Presentation of the solar cell

FIG. 1 represents a n^{+}-p-p^{+} silicon solar cell [16,31] under polychromatic illumination, by the emitter (n^{+}), through the collecting grids. The space charge region (SCR), in x = 0, constitutes the junction (n^{+}-p), allowing the separation of photogenerated electron-hole pairs. H is the solar cell base thickness. The rear face (p^{+}), in x = H, presents the zone where exists an electric field (Back surface Field), which allows the return of the minority carriers towards the junction [16, 22-24].

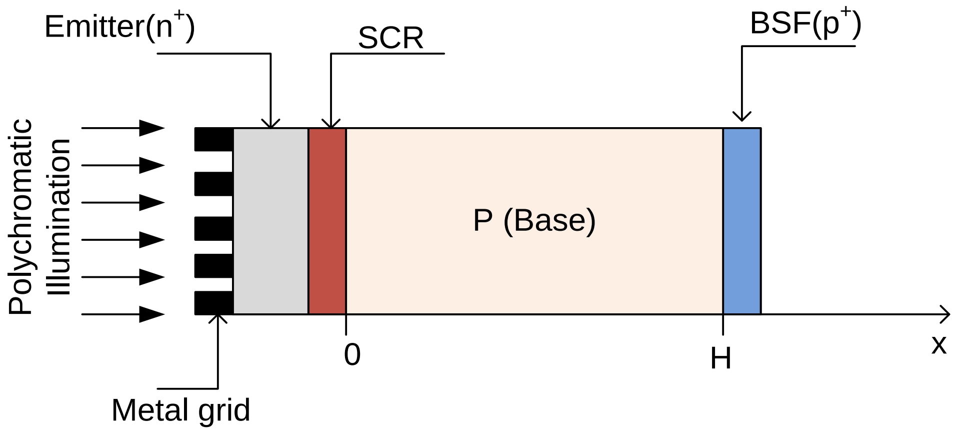

Figure 1: Structure of (n^+-p-p^+) silicon solar cell

b) Theory

When the solar cell is under illumination, the density δ (x) of the photo generated charge carriers in the base under weak injection, is governed by the following continuity equation.

$$D\frac{\partial^2\delta(x)}{\partial x^2}-\frac{\delta(x)}{\tau}=-G(x) \qquad 1$$

τ and D are respectively, the lifetime and the diffusion coefficient of the excess minority carrier in the base, connected by the Einstein's relation $L^2 = D\tau$,with L the excess minority carrier diffusion length. δ(x) is the excess minority carrier density in the base, produced by the generation rate, expressed by the following equation:

$$G(x)=n\sum_{i=1}^{3}a_i e^{-b_i x} \qquad 2$$

Where n is the number of sun or level of illumination. The coefficients a_i and b_i are obtained from the modeling of the radiation under A.M1,5 [32,33]. The excess minority carrier density expression in the base, is given by the resolution of the continuity equation and is written as:

$$\delta(x,Sf,n,H)=A(Sf,n,H)\cosh\left(\frac{x}{L}\right)+B(Sf,n,H)\sinh\left(\frac{x}{L}\right)+\sum_{i=1}^{3}K(n)e^{-b_i x} \qquad 3$$

$$K(n)=\sum_{i=1}^{3}\frac{n.a_i L^2}{D[1-(Lb_i)^2]} \qquad 4$$

c) Boundary conditions:

A and B are coefficients determined from the boundary conditions which respectively introduce the surface recombination velocities at the junction (Sf) and at the rear face (Sb).

i) At the junction x = 0 (SCR)

$$D.\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=0}=Sf\delta(x=0) \qquad 5$$

Sf indicates the velocity of passage of the charge carriers across the junction, to the emitter. This velocity of passage of the minority carrier is governed by the solar cell external charge resistance, which imposes the operating point [18,19]. Thus the charge carrier having crossed and not collected by the grid, constitute the losses which induce the shunt resistance [21,34,35].

ii) On the back side x = H

$$D\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=H}=-\mathrm{Sb}\delta(x=H) \qquad 6$$

Sb is the recombination velocity at the rear face of the minority carriers of charge in excess [16, 22, 36], in x = H, where exists a rear electric field (p / p^+, low-high junction), which returns the electrical charges, to the junction (SCR), to be collected. The first conventional solar cells did not have this technology, so the contact was ohmic, and Sb was very high.

Photocurrent

Fick's law allows us to obtain the expression of the photocurrent density. This expression is given by the following equation

$$Jph(Sf,n,H) = qD\left[\frac{B(Sf,n,H)}{L} - \sum_{i=1}^{n}((b_i)K(n))\right] \quad 7$$

Results and Discussions

Figure 2 gives the profile of the photocurrent density as a function of the excess minority carrier recombination velocityat the junction for different illumination level values.

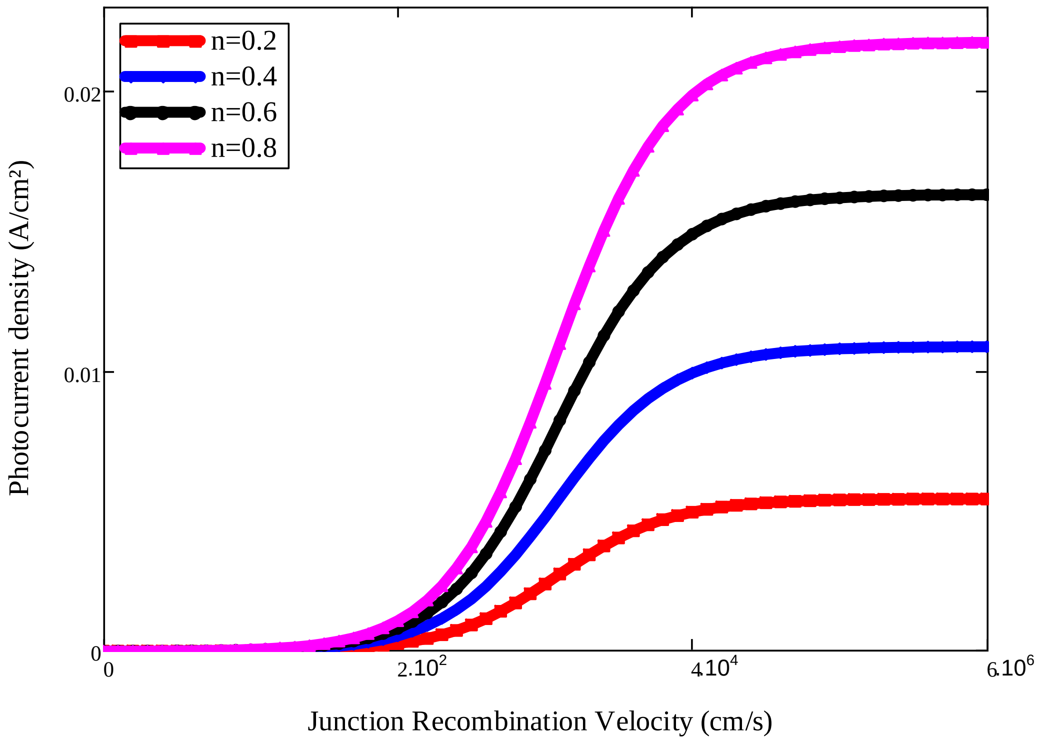

Figure 2: The profile of the photocurrent density as a function of the recombination velocity at the junction for different n illumination, D = 26cm^2/s, $\tau = 2.10^{-6}$ s. H = 0.015cm; Sb1(cm/s)

For Sf values less than 10^2 cm / s, the photocurrent is practically nil (depending on the level of illumination), which corresponds to an open circuit operating point of the solar cell. From 10^2cm / s to approximately 10^4 or 10^5cm / s, depending on the level of illumination, the photocurrent is increasing. Beyond 10^5cm / s, the photocurrent is practiced constant with Sf and corresponds to the short circuit current Jphsc, which is a bearing that increases with n, the illumination level.

Velocity of Recombination in Rear Face

Figure 2, indicates a plateau regardless of the sun number, thus the derivative of the expression of the photocurrent density relative to the recombination velocity, vanishes [19,22] and is therefore written as:

$$\frac{\partial Jp\,h(Sf,Sb,n,H)}{\partial Sf} = 0 \quad 8$$

The resolution of this equation leads to the following expressions Sb1 (H) and Sb2 (H) of the rear-end recombination velocity.
It then comes:

$$Sb1(H) = \sum_{i=1}^{3} \frac{D*\left[b_i\left(\cosh\left(\frac{H}{L}\right)-e^{-b_iH}\right)-\frac{1}{L}\sinh\left(\frac{H}{L}\right)\right]}{\cosh\left(\frac{H}{L}\right)-e^{-b_iH}-Lb_i\sinh\left(\frac{H}{L}\right)} \quad 9$$

$$Sb2(H) = -\frac{D}{L} * \tanh\left(\frac{H}{L}\right) \quad 10$$

Fig 3 gives the profile of the two recombination velocities at the rear face Sb1 and Sb2, as function of the solar cell base thickness.

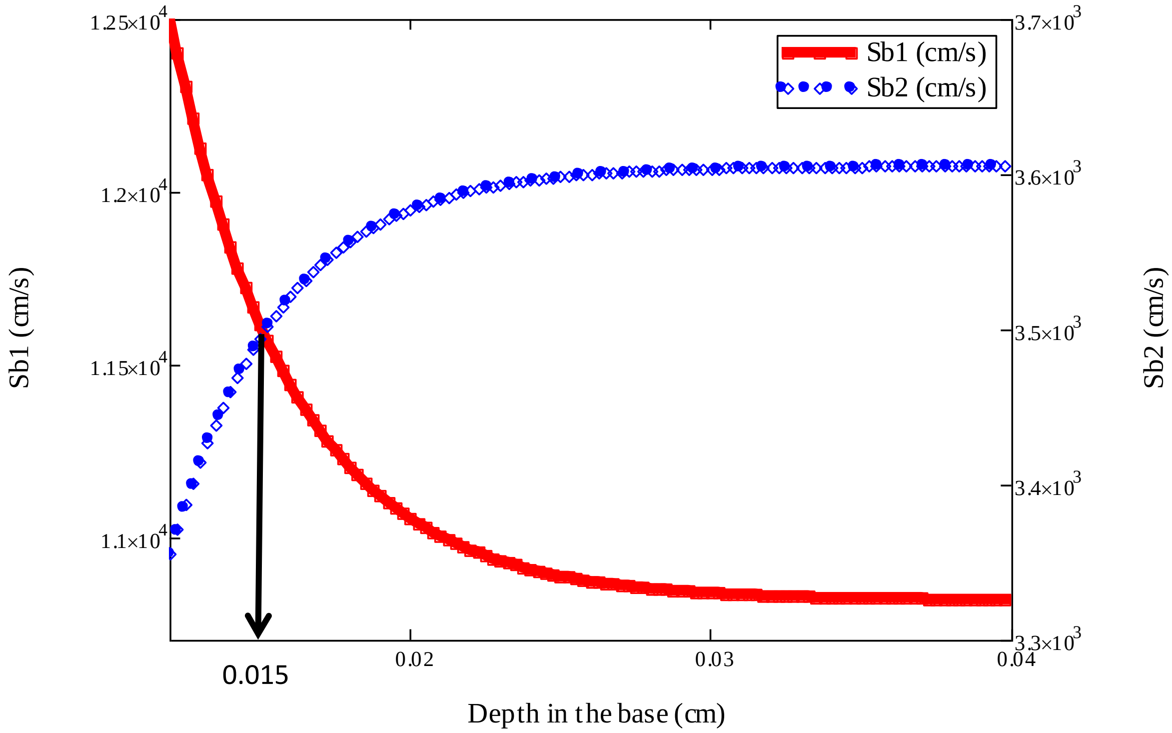

Figure 3: Back surface recombination velocities versus solar cell base thickness
$D = 26cm^2/s$, $\tau = 2.10^{-6}$ s

The intercept point of the two curves gives the optimum of the silicon solar cell base thickness having the specific electronic parameters (doping rate NB, D and τ) and optical (bi) contained in the expressions (9 and 10). The expression (9) at the low values of H, corresponds to the generation velocity (bi*D) and decreases with H, to tend towards the asymptote (Sb1), whereas the equation (10) corresponding to the intrinsic recombination velocity, independent of the optical parameter (bi) increases with H and reaches the asymptote (D / L) [23,37]

Expression of recombination velocity initiating the short circuit

The expression of the short-circuit obtained at the recombination velocity (Sfsc) value [38,39] is deduced trough out the conservation of photocurrent density Jph (Sf) for Sflarge values and the short circuit (Jphsc) photocurrent density given by the following relation:

$$Jph(Sf,n,H) - Jphsc(n,H) = 0 \quad 11$$

With

$$Jphsc(n,H) = \lim_{Sf \geq 6.10^5} Jph(Sf,n,H) \quad 12$$

Sf tends to5.10^6cm/s, corresponds to the velocity of the electron in the silicon material at room temperature [40]. Thus, the expression of Sfsc deduced, is given by the following equation:

$$Sf_{cc}(n,H) = \frac{K(n).X_3(H) - \frac{Sb^2(H)}{D}.X_4(H) - \frac{Sb^2(H)}{D.L}.X_5(H) + \frac{K(n)}{D}\sum_{i=1}^{3}\left(b_i - \frac{Sb(H)}{D}\right).e^{-b_i.H}.X_6(H)}{M_3(n,H)} \quad 13$$

$$M_3(n,H) = X_1(H) - X_2(n,H) \quad 14$$

$$X_1(H) = \frac{\cosh\left(\frac{H}{L}\right)\sinh\left(\frac{H}{L}\right)}{D^2L} + \frac{LSb(H).\sinh\left(\frac{H}{L}\right)}{D^2L} + \frac{Sb(H)\cosh^2\left(\frac{H}{L}\right)}{D^3} + 2\frac{(LSb^2(H))\cosh\left(\frac{H}{L}\right)}{D^3} \quad 15$$

$$X_2(n,H) = K(n)\frac{\sinh\left(\frac{H}{L}\right)\cosh\left(\frac{H}{L}\right)}{D^2L} - \left[\frac{Sb(H).\cosh^2\left(\frac{H}{L}\right)}{D^2} - \frac{\cosh\left(\frac{H}{L}\right)}{D^2}\sum_{i=1}^{3}\left[\left(b_i - \frac{Sb(H)}{D}\right)e^{-b_iH}\right]\right] \quad 16$$

$$X_3(H) = \sum_{i=1}^{3}\left[\frac{b_iSb(H)\cosh^2\left(\frac{H}{L}\right)}{D^2}\right] + \frac{\sinh^2\left(\frac{H}{L}\right)}{D^2L} + Sb(H)\frac{\cosh\left(\frac{H}{L}\right)\sinh\left(\frac{H}{L}\right)}{D^2L} - \sum_{i=1}^{3}\left[b_i\frac{\cosh\left(\frac{H}{L}\right)\sinh\left(\frac{H}{L}\right)}{DL}\right] + \frac{Sb(H)\sinh\left(\frac{H}{L}\right)}{D^2} \quad 17$$

$$X_4(H) = \sum_{i=1}^{3} b_i\left(\cosh\left(\frac{H}{L}\right) - \frac{\cosh^2\left(\frac{H}{L}\right)}{D}\right) - \frac{L\cosh\left(\frac{H}{L}\right)\sinh\left(\frac{H}{L}\right)}{D} \quad 18$$

$$X_5(H) = \sum_{i=1}^{3}(b_i)\sinh\left(\frac{H}{L}\right) - \cosh\left(\frac{H}{L}\right)\sinh\left(\frac{H}{L}\right) \quad 19$$

$$X_6(H) = \frac{\sinh\left(\frac{H}{L}\right)}{L} - Sb(H)\frac{\cosh\left(\frac{H}{L}\right) + L\sinh\left(\frac{H}{L}\right)}{D} \quad 20$$

Shunt Resistance

Phototension

The expression of the phototension is obtained using the Boltzmann relation.

This expression is given by the following relation

$$Vph(Sf,n,,H) = \frac{k_BT}{q}\ln\left[\frac{Nb}{(n0)^2}\delta(Sf,n,H)+1\right] \quad 21$$

Where, K_B is the Boltzmann constant, q is the elementary charge of the electron and T is the temperature. Nb is the solar cell base doping rate, n0 is the intrinsic density of minority charge carriers.

Experimental Shunt Resistance

Figure 5 represents the well-known (Jsc(Sf) -Vph(Sf)) electric characteristic of the solar cell under illumination.

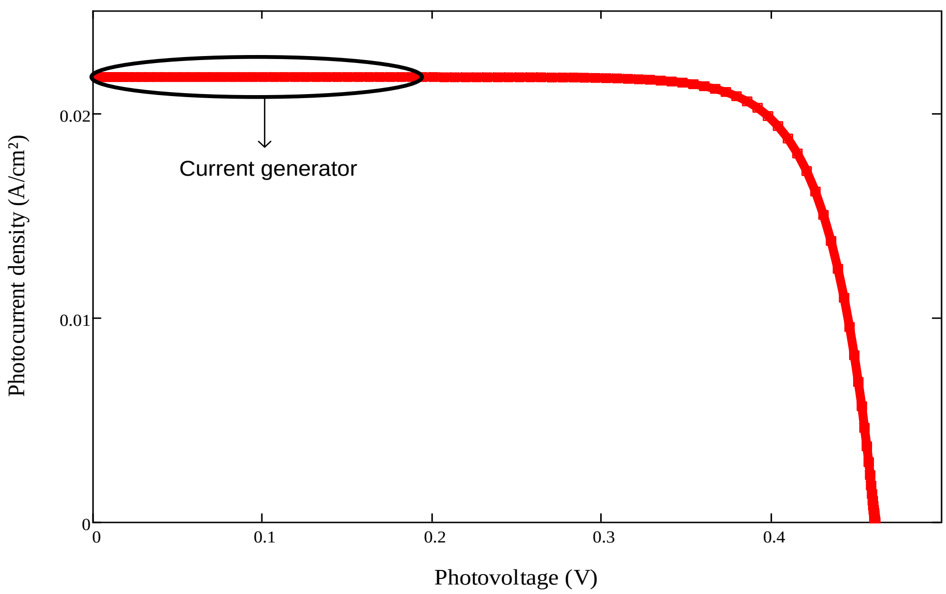

Figure 4: The photocurrent density as a function of the phototension.
$D = 26cm^2/s$, $\tau = 2.10^{-6}s$, n = 0.8, H =0.015cm

We will focus on the part of the characteristic, where the photocurrent density is maximum and constant and corresponds to the current generator [41,42]. The maximum photocurrent density represents the short-circuit photocurrent density (Figure 2). This current generator is modeled by an equivalent electrical circuit and is represented in Figure 5.

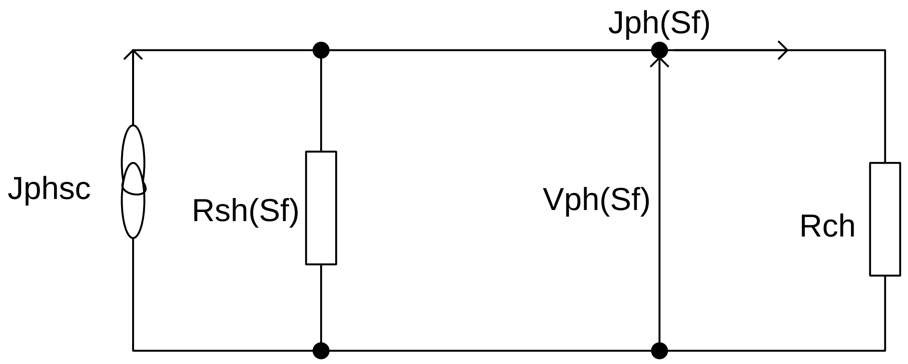

Figure 5: The equivalent electrical circuit of the solar cell under short circuit

Figure 5 gives the diagram of the equivalent electrical circuit of the short circuit solar cell.

Thus, the application of the law to the nodes and the mesh law on the electric circuit of Figure 5 makes it possible to deduce the expression of the shunt resistance, as dependent of the illumination level, the base thickness and the operating point (Sf).

$$R_{sh}(Sf,n,,H) = \frac{V_{ph}(Sf,n,H)}{Jph_{sc}(n,H) - Jph(Sf,n,H)} \quad 22$$

Figure 6 gives the profile of the calibration curve of the expression of the shunt resistance as a function of excess minority carrier recombination velocity at the junction, for different levels of illumination. The low levels of illumination show high shunt resistances compared to higher illumination (n < 1). Thus the charge carrier losses via the shunt resistor are greater at large illuminations.

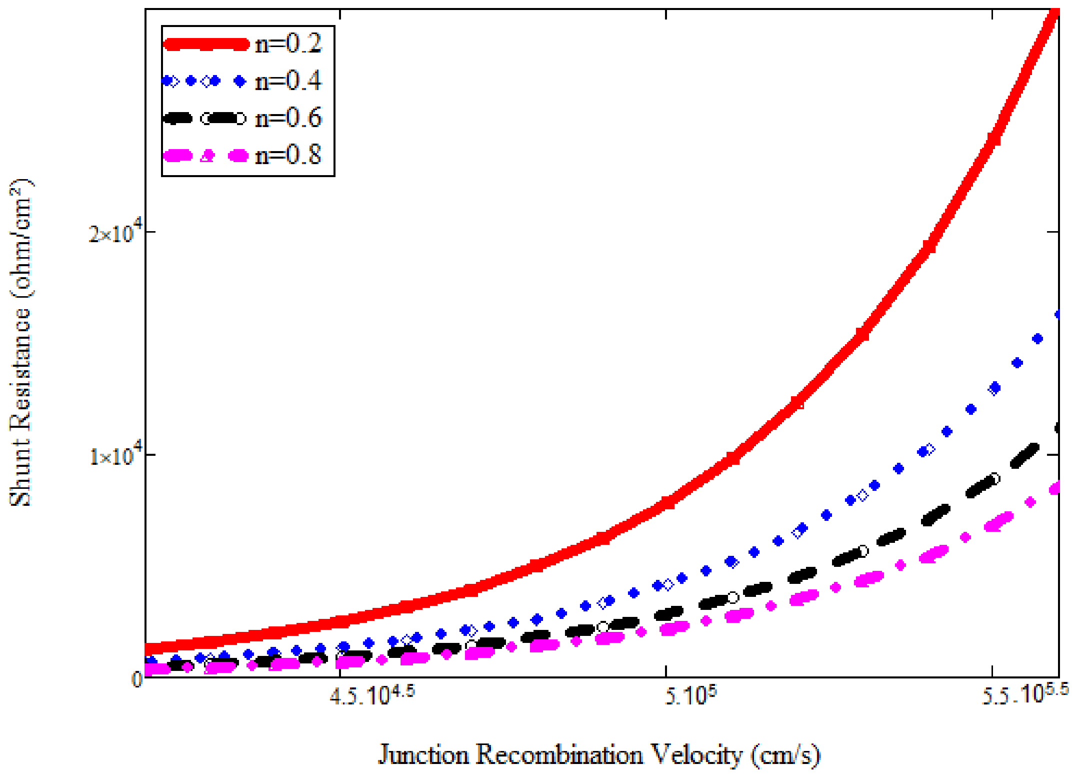

Figure 6: Shunt resistance calibration curve versus junction surface recombination velocity for different low illumination levels. D = 26cm^2/s, $\tau = 2.10^{-6}$ s. H = 0,013cm

Experimental determination technique of shunt resistance:

Figure 7 gives the technique of experimental determination of the shunt resistor, from the surface recombination velocity at the junction initiating the short circuit (Sfsc) in the solar cell, which intercepts the calibration curve to give an ordinate equal to the experimental shunt resistance (Rshex) [38, 39].

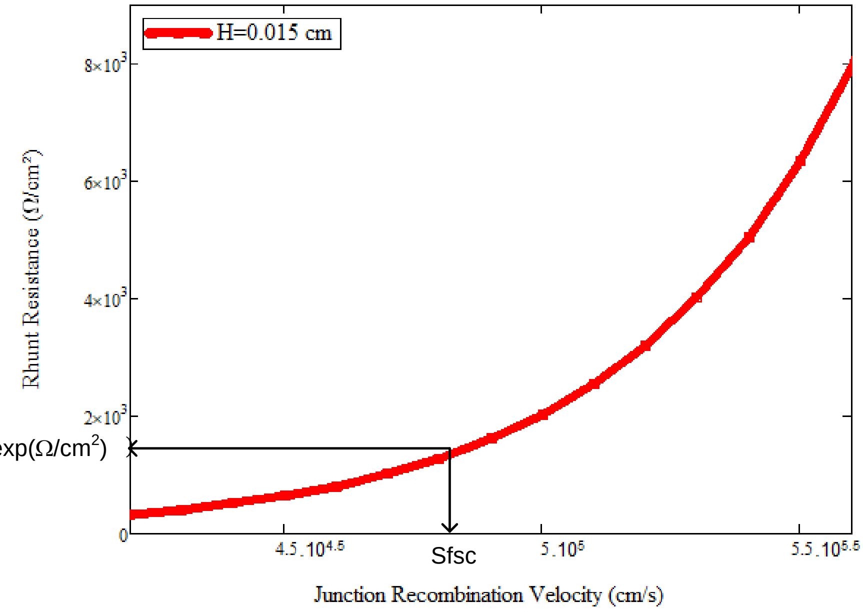

Figure 7: Calibration curve for the determination of the experimental shunt resistance

The values of the recombination velocitySfsc initiating the short circuit in the solar cell are obtained for each n illumination, and yield to the shunt resistors Rshex (Table.1).

Table 1: Rshexp values for different illumination level: Sfsc = 2.016 *10^5cm / s and H = 0.015cm

n	Rsh_{exp} ($\Omega.cm^2$)
0.2	3144.5
0.4	1658.8
0.6	1139.6
0.8	872.66

Figure 6 shows a linear relation between the inverse of the resistance Rshex and the low level n of illumination.

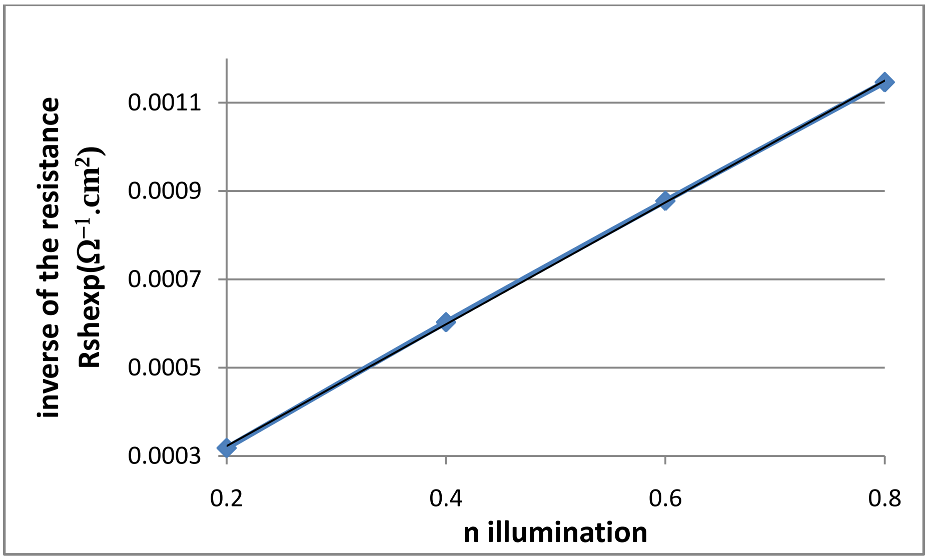

Figure 8: inverse of the experimental shunt resistance according to the number of suns

The equation obtained from the shunt resistance as a function of the low level of illumination is given by the following relation:

$$\frac{1}{Rshexp} = \alpha.n + \beta \quad (23)$$

With

$$\alpha = 14.10^{-4}\Omega^{-1}.cm^2 \quad (24)$$

and

$$\beta = 5.10^{-5}\Omega^{-1}.cm^2 \quad (25)$$

This technique can be widely applied to solar cell under different conditions, when Hopt is determinated in these cases [43-48].

Conclusion

In this work, the method of shunt resistance determination by the technique of the junction surface recombination velocity initiating the short circuit has been studied, taking into account, the effect of both, the illumination level and the solar cell base thickness under steady state,.

The study of the back surface recombination velocity of the excess minority carrier, through the two expressions obtained, leads to the optimum thickness of the base. The recombination on the rear face and the thickness of the base being tabulated.

The calibration curve of the shunt resistor Rsh as function of the excess minority carrier recombination velocity at the junction, is established for each low illumination level.

The junction surface recombination velocity initiating the short circuit is constant when the low level range of illumination. The shunt resistance decreases as the level of illumination of the base of the solar cell increases.

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