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Recombination Parameters Measurement of Silicon Solar Cell Under Constant White Bias Light With Incident Angle

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Abstract - The motivation of this work has been to extend the concept of junction and back surface recombination velocity Sf and Sb on a silicon solar cell under white bias illumination for minority carrier's recombination measurement and under various incident angle θ. The photocurrent density Jph is presented as a calibrated function, diffusion length dependent, it intercepts with the experimental short circuit current density J_{SCexp} obtained from an automatic characterization device, at the effective minority carries diffusion length L value. Also the intrinsic junction surface recombination velocity Sf0 is determinated from effective diffusion length.

Keywords - Silicon solar cell- recombination velocity-diffusion length-Incident angle.

INTRODUCTION

Many methods have been developed for determining lifetime, diffusion length and back surface recombination velocity of minority carriers in the base of solar cell. Steady methods, as photo response **[1],** were widely used for such parameters determination. The method could be subjected to limited wavelengths range condition **[3].** Constant flux method as surface voltage **[3]** requires several assumptions which must be valid in order to measure the diffusion length. Transient methods **[4-5]**, were performed and used either removable excitation (light or electrical) or removable charge under constant illumination. Impedance effects have been observed in solar cell response so that the electronic parameters deduced from the device could be strongly influenced.

Our main analysis is based on phenomenological parameters describing generation-diffusion and recombination processes that take place in solar cell under constant composite light illumination and for different incident angle values. A theoretical expression of the photocurrent density Jph is presented as a calibrated function, diffusion length depending of incident angle values, it intercepts with the experimental short circuit current density Jsc_{exp}, at the effective minority carrier diffusion length L value. The effective diffusion length will be determinate from photocurrent variation versus diffusion length. And the junction intrinsic recombination velocity S_{F0} is obtained from Leff.

The method proposed in this work considers the solar cell under a real operating condition, for various incident angle values **[6-7-8]**.

I. THEORY

In this study, we use a silicon solar cell under a given incident angle θ.

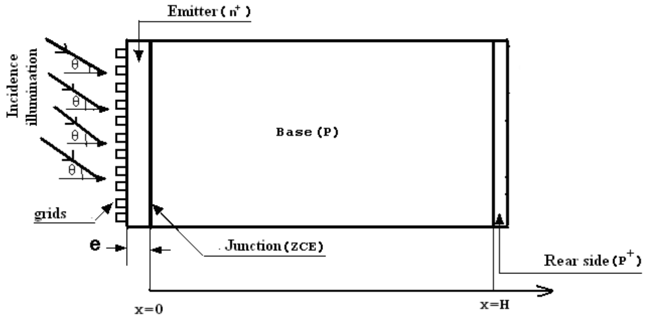

***Figure1**: schematic structure of a silicon solar cell*

We consider a dominated base silicon solar cell n^+pp^+ **[9].** The continuity equation for the excess minority carrier density $\delta(x)$ under steady state.

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

Where D and L respectively are the minority carriers diffusion constant and diffusion length. The distance x is measured from the edge of the depletion layer in the base. The generation rate is expressed by the following relation:

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

Where a_i and b_i are coefficients from modeling of the generation rate over all the radiations in solar spectrum under A.M1.5.

Table1 : coefficients ai and bi values**[11]**

i	a_i	b_i
1	$6{,}13.10^{20}$ $cm^{-3}.s^{-1}$	6630 cm^{-1}
2	$0{,}54.10^{20}$ $cm^{-3}.s^{-1}$	10^3 cm^{-1}
3	$0{,}0991.10^{20}$ $cm^{-3}.s^{-1}$	130 cm^{-1}

Equation (1) is solved with following boundary conditions at the two edges:

- the junction interface at x = 0

$$\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=0} = \frac{S_f}{D}\cdot\delta(0) \qquad (3)$$

- the rear side at x = H

$$\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=H} = -\frac{S_b}{D}\cdot\delta(H) \qquad (4)$$

Where Sf and Sb are respectively the excess minority carriers' recombination velocities related to the back-surface and to the junction of the solar cell.

For the junction surface recombination velocity Sf, we have two terms: the intrinsic recombination velocity Sf_0 related to the junction and the recombination velocity Sf (load) imposed by the resistance load **[3-10]**. Sf= Sf0(Leff) +Sf(load)

The steady state solution for minority carrier density can be expressed as.

$$\delta(x) = A\cdot\cosh\left(\frac{x}{L}\right) + B\cdot\sinh\left(\frac{x}{L}\right) - \frac{1}{D}\cdot\cos(\theta)\cdot\sum_{i=1}^{3} a_i\cdot e^{-b_i\cdot H}\cdot\left(b_i^{\,2} - \frac{1}{L^2}\right)^{-1} \qquad (5)$$

Coefficients A and B can be determined through the boundary conditions.

On Figure 1, we give profile of minority carrier's density versus base depth for various incident angles in short circuit condition:

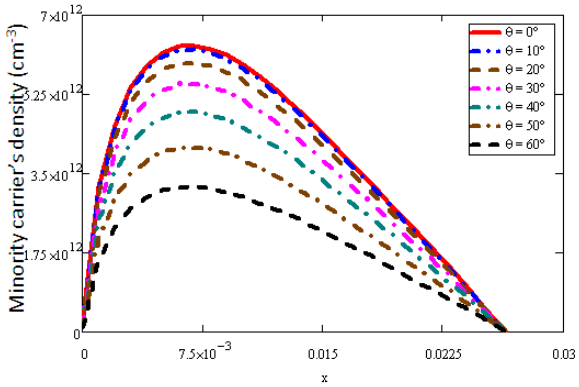

Figure 2: *Excess minority carrier's density versus base depth*

H = 0.03 cm L=0.01cm, $S_f = 6.10^6\,cm.s^{-1}$ *and* $S_b = 3.10^3\,cm.s^{-1}$

Figure 2 shows that pour chaque valeur de teta, la densité des porteurs diminue en profondeur dans la base.

II. Photocurrent

The photocurrent density expression is written as:

$$J_{ph} = q\cdot D\cdot\left.\frac{\partial\delta(x)}{\partial x}\right|_{x=0} \qquad (6)$$

Replacing δ(x) in equation 6, we obtain the following expression:

$$J_{ph} = q.\frac{D}{L}\cdot\cos(\theta)\cdot\sum_{i=1}^{3} K_i.Sf\,\frac{(b_i.D - Sb).e^{-b_i.H} + X - L.b_i.Y}{\frac{D}{L}.X + Sf.Y} \qquad (7)$$

With

$$X = \frac{D}{L}\cdot\sinh\left(\frac{H}{L}\right) + Sb.\cosh\left(\frac{H}{L}\right) \qquad (8)$$

$$Y = \frac{D}{L}\cdot\cosh\left(\frac{H}{L}\right) + Sb.\sinh\left(\frac{H}{L}\right) \qquad (9)$$

We present in figure 3 the photocurrent density versus junction surface recombination velocity for different incident angle values **[10-13-14]**.

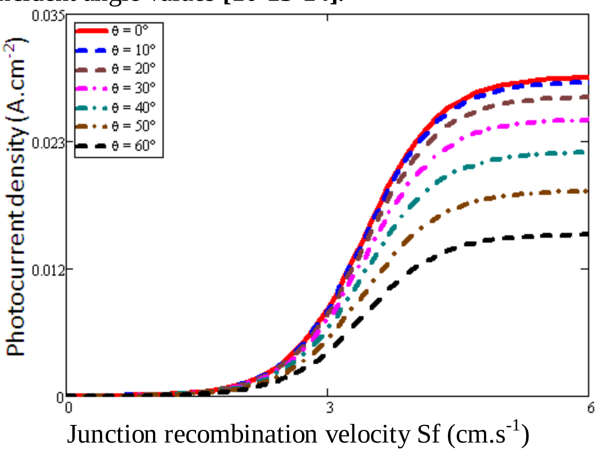

Figure 3: *Photocurrent density versus Junction surface recombination velocity*

H = 0.03 cm, L = 0.01 cm. Sb = $3.10^3 cm.s^{-1}$

For high *Sf* values, the photocurrent density *Jph* is a horizontal line which gives the short circuit current density *Jsc*. For low *Sf* values, *Jph* is zero and confirms that any charge carrier crosses the junction that corresponds to the open circuit condition.

II.1 Base recombination velocity

From figure 3, the photocurrent is constant for large Sf values, we then write:

$$\left[\frac{\partial J_{ph}}{\partial Sf}\right] = 0 \qquad (10)$$

Solving equation (10) leads to the back surface recombination velocity expressed as diffusion length dependent.

$$Sb(L) = \frac{D}{L}.\sum_{i=1}^{3}\frac{L.b_i\left(e^{-b_i.H} - \cosh\left(\frac{H}{L}\right)\right) + \sinh\left(\frac{H}{L}\right)}{L.b_i.\sinh\left(\frac{H}{L}\right) - \cosh\left(\frac{H}{L}\right) + e^{-b_i.H}} \qquad (11)$$

Introducing Sb (L) in the expression of the photocurrent density and taking Sf value very large, we obtain an expression of the short circuit current density both diffusion length and incident angle dependent, while optical (bi) and geometrical(H) parameters remained constant.

$$Jsc(L,\theta) = q.\frac{D}{L}\cdot\cos(\theta)\sum_{i=1}^{3} K_i.\frac{(b_i.D - Sb(L)).e^{-b_i.H} + X - L.b_i.Y}{Y} \qquad (12)$$

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We present in figure 4 the short circuit current density versus diffusion length for different incident angle values.

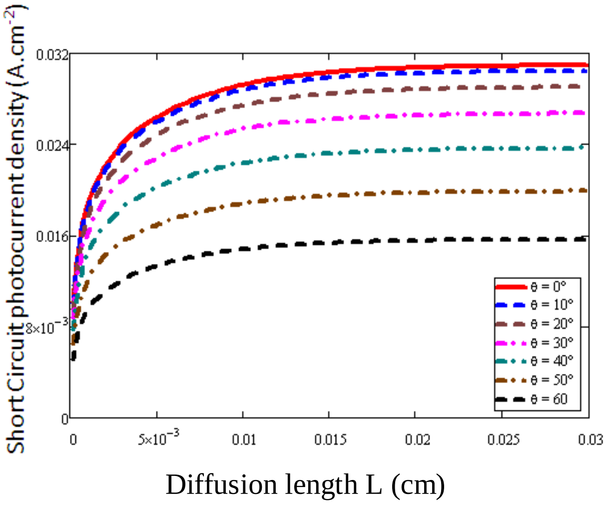

Figure 4: *Profile of Short Circuit photocurrent density versus diffusion length for different incident angle values, H = 0.03 cm,* $S_f = 6.10^6 cm.s^{-1}$

Figure 4 shows that for each incident angle, the short circuit photocurrent density increases, and is constant for high diffusion length values .

II.2 Effective diffusion length determination

The method used the calibrated short circuit photocurrent density and the experimental one Jsc_{exp} plots versus the diffusion length while the incident angle value is constant .We obtain the value of the effective minority carrier's diffusion length when the experimental short circuit current density Jsc_{exp} intercepts with the calibrated function Jsc(L) (Figure 5) **[15]**. Then for each incident angle, the effective diffusion length is then extracted.

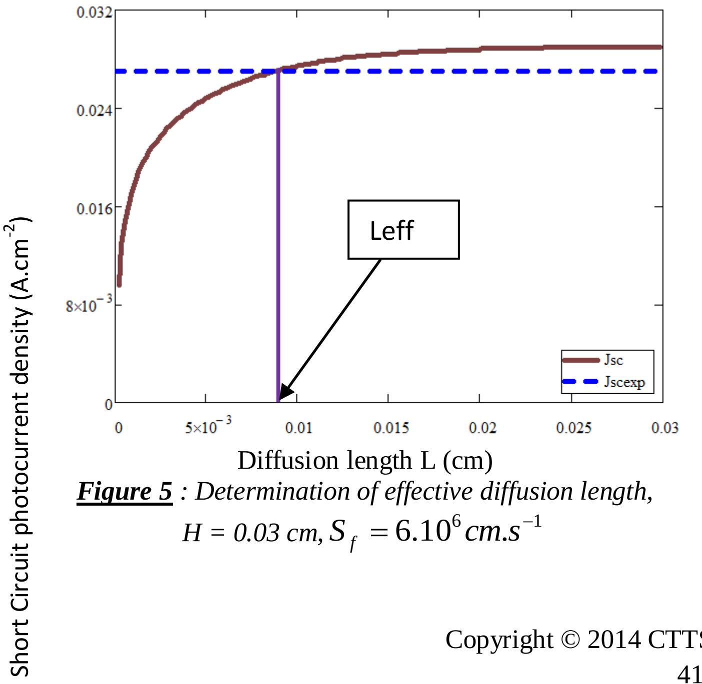

Figure 5 *: Determination of effective diffusion length, H = 0.03 cm,* $S_f = 6.10^6 cm.s^{-1}$

II.3 The junction intrinsic recombination velocity:

Figure 6 represents the evolution of the current density as a function of the base recombination velocity for different incident angle values.

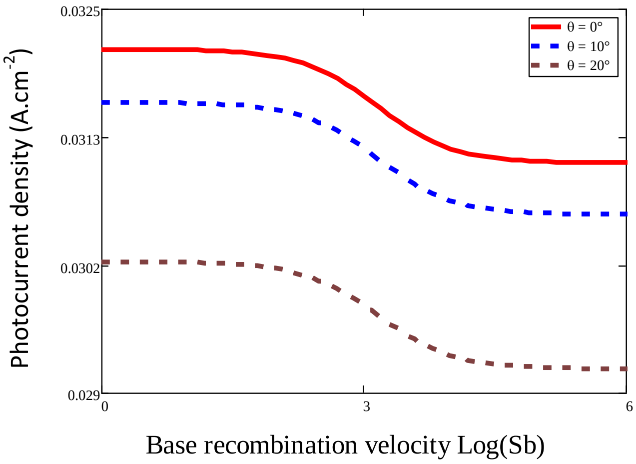

Figure 6: *variation of the photocurrent density versus base recombination velocity*
L=0.02 cm, $S_f = 6.10^6 cm.s^{-1}$

The following curbe (Figure 6) shows the variation of the photocurrent density versus base recombination velocity for differents incident angle values. The photocurrent density is a decreasing function of the base recombination velocity. Either the photocurrent density decreases for high values of incident angle θ.

For a given operating point, there is a slight variation of the current density as a function of base recombination velocity.

We obtain greater values of photocurrent density for low Sb values: it is the case of backfield solar cells (BSF). For large Sb values, the photocurrent density is less important: it is the conventional case of ohmic solar cells **[16]**.

As the photocurrent density *Jph* remains constant for certain Sb values, we can write:

$$\left[\frac{\partial J_{ph}}{\partial Sb}\right] = 0 \qquad (13)$$

From this equation, we then extract the expression of the junction recombination velocity depending only to the diffusion length.

$$Sf(L) = \frac{D}{L}.\sum_{i=1}^{3}\frac{b_i.e^{-b_i.H} + \frac{1}{L}.\sinh\left(\frac{H}{L}\right) - b_i.\cosh\left(\frac{H}{L}\right)}{\frac{1}{L}.e^{-b_i.H} + \left(b_i.\sinh\left(\frac{H}{L}\right) - \frac{1}{L}.\cosh\left(\frac{H}{L}\right)\right)} \qquad (14)$$

Replacing the diffusion length L by Leff, we obtain

$$Sf(Leff) = Sf_0 \qquad (15)$$

EXPERIMENTAL STUDY

Figure 7 present the experimental set up **[8]**.

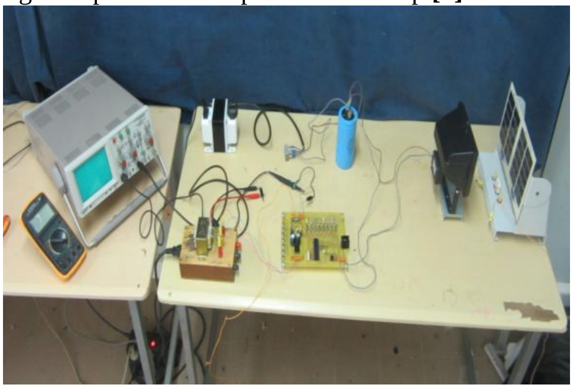

Figure 6: *Experimental device for acquisition*

For θ = 20°, we obtained the following curve with the analog oscilloscope (Figure 8).

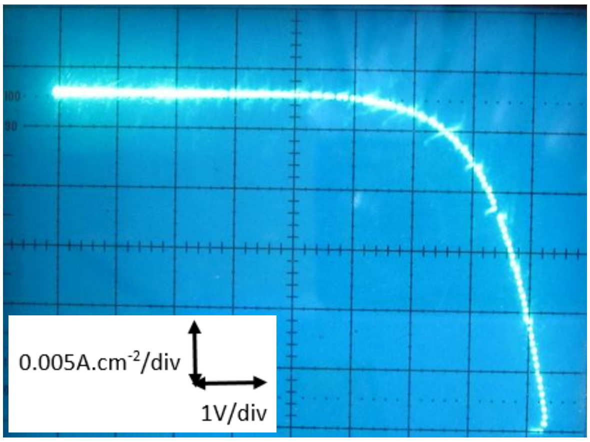

Figure 8: *I-V Characteristic for θ = 20°*
From the I-V caracteristic we can extract the expérimental short-circuit photocurrent density.

III. EXPERIMENTAL RESULTS

The table below shows the results obtained from the experimental set up for an automatic characterization of the solar cell under several incident angle values. This table shows for each value of θ, the density of short circuit current, the effective diffusion length, the base recombination velocity and the intrinsic recombination velocity.

Table 2: Recombination parameters

θ (°)	0	10	20	30	40	50	60
Jsc_{exp}(10^{-3}A.cm^{-2})	28.5	28	27	25	22.5	19	15
Leff (µm)	83.7	85.6	89.4	93.2	106.5	112.2	110
Sb (10^3cm/s)	9.361	9.159	8.781	8.436	7.436	7.086	6.875
Sf_0 (10^5cm/s)	2.026	2.026	2.026	2.025	2.024	2.024	2.023

On the above table, it should be noted that when the incident angle θ increases, the Jsc_{exp} decreases, and the carrier diffusion length increases. This means that for high incident angle, the solar cell is exposed to bad lighting conditions.

CONCLUSION

The method proposed in this work considers the solar cell under a real operating condition. By help of the phenomenological parameters such as bulk and surface recombination velocity, the behaviour of an illuminated cell can be well described through the photocurrent, for all incident angles.
From calibrated photocurrent density as a function of diffusion length. We have extended the technics for bulk and surface recombination velocity determination in a silicon solar cell since the experimental short circuit current for each incident angle is known.

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