Determination Of The Junction Surface recombination Velocity Limiting The Open Circuit (Sfoc) For A Bifacial Silicon Solar Cell Under External Electric Field.

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Abstract
In this paper, we study the influence of the electric field on the junction recombination velocity limiting the open circuit. The excess of minority carrier’s density in the base is determined from the continuity equation. The photovoltage and the open circuit voltage are derived from the excess minority carrier’s density. From the photovoltage study, the junction recombination velocity limiting the open circuit and the open circuit voltage are determined and studied for different values of electric field and simultaneous illumination mode.

Keywords: Solar Cell – Electric field – Junction recombination velocity – Open circuit voltage

I. Introduction
Photovoltaic conversion is a direct transformation of light energy into electrical energy through a device called solar cell. Because of their modest performance, many studies have been developed in order to improve their efficiency by different processes [1] and through different characterization techniques. The solar cell can be placed under static condition [2] and dynamic mode (transient and frequency) [3], then the electrical and recombination parameters [4-8] are deduced. As part this work, our contribution is to study the effect of polarization electric field on the junction surface recombination velocity limiting the open circuit through the open circuit voltage. The study will be done on the solar cell remained under simultaneous polychromatic illumination of the two sides.

II. Theory
In this study, we consider an n⁺-pp⁺ solar cell type [9], double side surface illuminated and under external polarization by applying a voltage. The effect of external electric field resulting from the polarization behavior of the charge carriers in the base is studied by help with the assumption of the quasi-neutral base (QNB) [10] theory’s. Figure 1 shows the structure of the solar cell depending on the model under study.
II.1. Détermination of the minority carrier’s density

The continuity equation for the excess minority carrier’s density photo-generated in the base under influence of the electric field is:

\[
\frac{\partial^2 \delta(x)}{\partial x^2} + \frac{\mu E}{D} \frac{\partial \delta(x)}{\partial x} + \frac{G(x)}{D} - \frac{\delta(x)}{L^2} = 0
\]

(1)

\(\delta(x)\) is the excess minority carriers density according to the depth \(x\) in the base of the solar cell, following the simultaneous double side surface illumination mode. 

\(E\) represents the electric field, \(D\) the diffusion coefficient, \(L\) the diffusion length, \(\mu\) the carrier mobility.

Posing in:

\[
L_E = \frac{\mu E L^2}{D}
\]

(2)

Equation (1) becomes:

\[
\frac{\partial^2 \delta(x)}{\partial x^2} + \frac{L_E}{L^2} \frac{\partial \delta(x)}{\partial x} + \frac{G(x)}{D} - \frac{\delta(x)}{L^2} = 0
\]

(3)
The expression of $G(x)$ depends on the $x$ depth of light absorption in the base and can be written in the form of the following equation [11].

$$G(x) = \sum_{i=1}^{3} a_i \cdot \left( e^{-b_i x} + e^{-b_i (H-x)} \right)$$  \hspace{1cm} (4)

The parameters $a_i$ and $b_i$ stem from the modeling of the incident illumination as defined by under A.M 1.5 condition [12].

$H$ is the thickness of the base.

Where, $a_1 = 6.13 \times 10^{20}$ cm$^{-3}$/s; $a_2 = 0.54 \times 10^{20}$ cm$^{-3}$/s; $a_3 = 0.0991 \times 10^{20}$ cm$^{-3}$/s; $b_1 = 6630$ cm$^{-1}$; $b_2 = 103$ cm$^{-1}$; $b_3 = 130$ cm$^{-1}$;

The solution $\delta(x)$ of the carriers’ diffusion equation (1) is obtained in the following forms:

$$\delta(x) = e^{\beta x} \cdot \left[ A \cdot ch(\phi \cdot x) + B \cdot sh(\phi \cdot x) \right] + \sum_{i=1}^{3} c_i \cdot \left( e^{-b_i x} + e^{-b_i (H-x)} \right)$$  \hspace{1cm} (5)

With the different coefficients expressed as:

$$\phi = \left( \frac{L_E^2 + 4 \cdot L_n^2}{2 \cdot L_n^2} \right)^{\frac{1}{2}}, \quad \beta = \frac{-L_E}{2 \cdot L_n^2}$$

$$c_i = \frac{a_i \cdot L_n^2}{D_n \cdot [L_n^2 \cdot b_i^2 \cdot L_E - L_E \cdot b_i - 1]}$$

The coefficients A and B are solved with the boundary conditions at the emitter – base junction and at the back surface of the cell [12, 13]:

- at the junction ($x=0$):

$$Sf = \left. \frac{D_n}{\delta(0)} \cdot \frac{\partial \delta(x)}{\partial x} \right|_{x=0}$$  \hspace{1cm} (6)

- at the back surface ($x=H$):

$$Sb = \left. \frac{D_n}{\delta(H)} \cdot \frac{\partial \delta(x)}{\partial x} \right|_{x=H}$$  \hspace{1cm} (7)

$Sf$ and $Sb$ are respectively the junction and back surface recombination velocity [10, 11].

We plot in figure 2, the minority carrier’s density versus base depth for different values of electric polarization field
II.2. Photovoltage

The expression of the photovoltage is obtained from the following relation

$$V_{ph} = V_T \ln\left(\frac{N_B}{n_i^2} \delta(0) + 1\right)$$

(8)

$V_T$ is the thermal voltage, $n_i$ the intrinsic carrier density at thermal equilibrium and $N_B$ the base doping density.

We plot in figure 3, the photovoltage versus junction recombination velocity.
II.2. Determination of the junction recombination velocity limiting the open circuit voltage

For low values of the junction recombination velocity, the photovoltage is maximum and constant. The excess minority carriers are then stored at the junction. Taking into account previous work [14] and keeping our interest in this flat part of the photovoltage curves, we can deduce the condition yielding the junction surface recombination limiting the open circuit voltage by the following equation.

\[ V_{ph}(S_f) - V_{oc} = 0 \]  \hspace{1cm} (9)

\[ V_{oc} = \lim_{S_f \to S_{oc}} V_{ph}(S_f) \]  \hspace{1cm} (10)

\[ S_{fco} = \frac{(D\beta E - F)(DbE e^{-gH}) + G - (G - D\beta E)(D\beta E - F)}{E(D\beta E - F)e^{-gH} + E(D\beta E e^{gH} + G)} \]  \hspace{1cm} (11)

\[ E = (Sb + D\beta)Sh(\phi, H) + D\phi Ch(\phi, H) \]  \hspace{1cm} (11-1)
We plot in Figure 4, the relative values of junction recombination velocity limiting the open circuit and the open circuit voltage versus the electric field

\[
F = \left[(Sb + D\beta)Ch(\phi, H) + D\phi Sh(\phi, H)\right]\phi D
\]

\[
(11-2)
\]

\[
G = \phi D(Sb + D\beta)e^{-H(\beta + h)}
\]

\[
(11-3)
\]

\[
Sb = \frac{\mu E D \phi Ch(\phi, H)}{D\phi Ch(\phi, H) - (\mu E + D)Sh(\phi, H)}
\]

\[
(11-4)
\]

We obtain the value of the electric field when the relative value of the open circuit voltage intercepts with the relative value of junction recombination velocity.

The values of the open circuit voltage and the recombination rate obtained are higher than those obtained for the illumination from the front side [15].
Conclusion

In this work, the excess of minority charge carriers density in the base is determined and its curve according the base depth for different values of electric field and for simultaneous illumination mode is presented. The excess of the photovoltage is deducted from that of minority carrier’s density and their profile depending the junction recombination velocity for different values the electric field and for proposed illumination mode. Thus, the junction recombination velocity limiting the open circuit voltage is determined for the solar cell under electric polarization.

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Concept Of Recombination Velocity S_{fsc} At The Junction Of A Bifacial Silicon Solar Cell, In Steady State, Initiating The Short-Circuit Condition

Junction recombination velocity induced open circuit voltage for a silicon solar cell under external electric field.