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Research Article

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Dynamic Series Resistance of an (n+/p/p+) Silicon Solar Cell, (p) Base Thickness Optimized Under Polychromatic Illumination in Frequency Modulation

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Abstract: The dynamic series resistance of an (n+p/p+) silicon solar cell, under polychromatic illumination in frequency modulation, is determined from its calibration curve as a function of minority carriers recombination velocity at the junction. It is then modelled and expressed according to the (p) base thickness optimum previously determined and adapted for each modulation frequency.

Keywords: Silicon solar cell- Ac base optimum thickness-Ac Recombination Velocity-Ac Series resistances

1. Introduction

The series resistance [1-5] of the solar cell [6-9] is an important parameter that influences the performance obtained from its characteristic [10-16], under darkness and illumination. It can be established according to different regimes, static or dynamic, taking into account environmental conditions, by theoretical determination or by experimental measurement of the photocurrent density (Jph) and the tension (Vph). The parameters of the electrical model [17-26] equivalent to the solar cell depending on the regime, such as series and shunt resistances, capacitance, self-inductance, are obtained by several techniques [17-26]. Thus the other electrical parameters [27-30], such as power, fill factor, and efficiency, can then be deduced.

This present modeling work aims to determine the dynamic series resistance of the photocell (n+/p/p+) to silicon, taking into account the phenomelogical parameters [31-43] of the material, as well as the base optimum thickness [44-47], under the influence of the modulation frequency [34, 42, 44-49] of the polychromatic illumination incident on the (n+) face.

To do this, the solution of the diffusion equation relating to the density of the minority charge carriers in the base in the dynamic regime [41, 49] is carried out with the boundary conditions at the junction (n+/p) and the rear face (n/p+), respectively at x= 0 and x= H. These limits are characterized by the recombination velocities [5, 27-39, 44-47] of the minority charge carriers, respectively (Sf) at the junction and (Sb) at the rear face.

Both ac expressions of the photocurrent density and the tension are inferred from the ac minority carrier's density. They are correlated by (Sf) the minority carriers' recombination velocity, at the junction to produce the $\left(\boldsymbol{J_{ph}}(S_F)-\boldsymbol{V_{ph}}(S_F),\ \right)$ [35-39] representations of the characteristic. From the electrical equivalent model of the solar cell as a voltage source, the expression of the dynamic series resistance $(\boldsymbol{R_s}[\boldsymbol{H_{opt}}(\boldsymbol{\omega}), S_F])$, is then established and it calibration curve versus (S_F) is produced, for different optimized base $(\boldsymbol{H_{opt}}(\boldsymbol{\omega}))$thicknesses [45, 46], imposed by $(\boldsymbol{\omega})$ the frequencies of modulation of the incident illumination.

I Theory

a) Presentation of the solar cell

The (n+-p-p+) silicon solar cell [6, 28, 44-46] studied is front illuminated by the (n+) face with a polychromatic light in frequency modulation. The structure of the solar cell under consideration is represented and described in Figure 1.

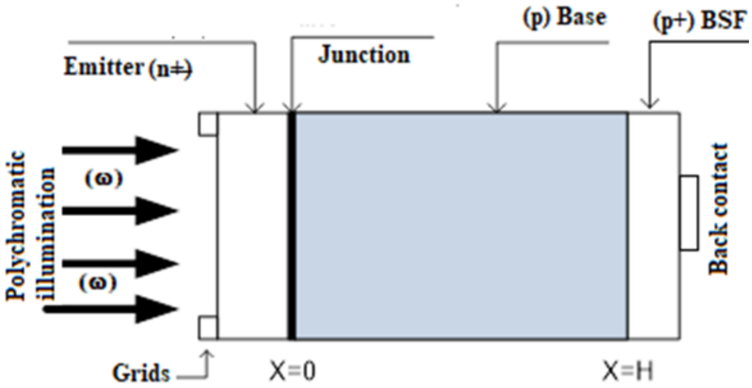

Figure 1: (n^+-p-p^+) solar cell structure diagram

b) Ac continuity equation relative to minority carriers density

The continuity equation relative to $\boldsymbol{\delta(x, \omega, t)}$ the density of minority excess carriers in the base of the solar cell under, polychromatic illumination in frequency modulation$(\boldsymbol{\omega})$, by the (n+) face, is given by the following relation[34, 48, 49]

$$D\frac{\partial^2\delta(x,\omega,t)}{\partial x^2} - \frac{\delta(x,\omega,t)}{\tau} = \frac{\partial\delta(x,\omega,t)}{\partial t} - G(x,\omega,t) \quad \textbf{(1)}$$

$\delta(x,\omega,t)$, D is the dynamic density of the charge carriers at the x-coordinate x and at time t:

$$\delta(x,\omega,t) = \delta(x)e^{i\omega t} \quad \textbf{(2)}$$

With $\delta(x)$ is the spatial component of the carrier density, and $e^{i\omega t}$, is the time component:

$G(x,t)$, is the dynamic generation rate of the carriers at x-coordinate x and time t; written as:

$$G(x,\omega,t) = g(x)e^{i\omega t} \quad \textbf{(3)}$$

Ou g(x) is the spatial component of the minority carriers generation rate at the x-coordinate x [50], and $e^{i\omega t}$, is the time component

$$g(x) = \sum_{i=1}^{3} a_i e^{-b_i x} \quad \textbf{(4)}$$

By replacing each quantity of the **equations. 2** and **3**, by their expressions in **equation. 1**, we obtain:

$$\frac{\partial^2\delta(x,\omega)}{\partial x^2} - \frac{\delta(x,\omega)}{L^2(\omega)} = -\frac{g(x)}{D(\omega)} \quad \textbf{(5)}$$

$D(\omega)$, is the minority carriers' dynamic diffusion coefficient, expressed as:

$$D(\omega) = D_0 \times \left(\frac{1 - j\cdot\omega^2\cdot\tau^2}{1 + (\omega\cdot\tau)^2}\right) \quad \textbf{(6)}$$

$$L(\omega) = \sqrt{\frac{D(\omega)\cdot\tau}{1 + j\omega\tau}} \quad \textbf{(7)}$$

(D_0) and (τ) are respectively the minority carriers diffusion coefficient and lifetime in the base of the steady-state solar cell. In the dynamic frequency regime, both, the minority carriers diffusion coefficient and length (**equations 6 and 7**) are complex quantities ($j^2 = -1$) that vary as a function of the modulation frequency [34, 42, 44-49].

The solution of the continuity equation (**Eq. 5**) is in the form:

$$\delta(x,\omega) = A ch\left(\frac{x}{L(\omega)}\right) + B sh\left(\frac{x}{L(\omega)}\right) + \sum_{i=1}^{3} c_i e^{-b_i x} \quad \textbf{(8)}$$

The coefficients A and B are determined from the boundary conditions of the (p) base, which are:

-At the junction$(n^+ - p)$:

$$\left.\frac{\partial\delta(x,\omega,S_f)}{\partial x}\right|_{x=0} = \frac{S_f}{D(\omega)}\delta(0,\omega,S_f) \quad \textbf{(9)}$$

-At the back surface$(p - p^+)$:

$$\left.\frac{\partial\delta(x,H,\omega,S_b)}{\partial x}\right|_{x=H} = -\frac{S_b}{D(\omega)}\delta(H,\omega,S_b) \quad \textbf{(10)}$$

$\mathbf{S_f}$ **and** $\mathbf{S_b}$ are respectively the minority carriers recombination velocity at the junction [5, 27, 33-39] and at the rear surface [35-38, 44-47] of the solar cell

c) Expression of the Ac density of photocurrent and the Ac voltage

Previous studies [28, 29, 44-46] have shown that photocurrent density and voltage are related by ((S_F) minority carrier's recombination velocity at the junction. By varying the latter, the set of points $\left(\boldsymbol{V_{ph}}(S_F),\ \boldsymbol{J_{ph}}(S_F)\right)$ on the current-voltage characteristic of the solar cell, is defined. The concept of minority carrier's recombination velocity at the junction makes it possible to describe the solar cell operating point in relation with the external charge, regardless of the operating regime. These previous studies have given the expressions of both, the voltage and the photocurrent density for the solar cell by the following equations:

The **equation. 9**, leads to the following expression of the photocurrent density:

$$\boldsymbol{J_{ph}\left(S_f,\omega,H,S_b\right) = S_f q \sum_{i=1}^{3} C_i \left\{\left(\frac{e^{-b_i H}\left(b_i-\frac{S_b}{D(\omega)}\right)+K_1-b_i L(\omega)K_2}{\left(K_1+\frac{L(\omega)S_f}{D(\omega)}K_2\right)}\right)\right\}} \quad \textbf{(11)}$$

Voltage, taking into account equation (8) through Boltzmann's law, leads to:

$$\boldsymbol{V_{ph}\left(S_f,S_b,\omega,H\right) = V_T \ln\left(\frac{N}{n_i^2}\left[\sum_{i=1}^{3} C_i \left\{\frac{e^{-b_i H}\left(b_i-\frac{S_b}{D(\omega)}\right)-L(\omega)K_2 b_i+K_1}{\left(K_1+\frac{L(\omega)S_f}{D(\omega)}K_2\right)}\right\}\right]+1\right)} \quad \textbf{(12)}$$

$$\boldsymbol{n_i = A\cdot T^{\frac{3}{2}}\cdot exp\left(-\frac{E_g}{2\cdot K\cdot T}\right)} \quad \textbf{(13)}$$

A : est une constante $\left(\boldsymbol{A = 3.87\ \cdot 10^{16}\ Cm^{-3}\cdot K^{-\frac{3}{2}}}\right)$

$\boldsymbol{n_i}$ **:** is intrinsic minority carriers' density.

N_b : is base doping rate

V_T : is thermal tension

k : is Boltzmann constant ($k = 1.38 * 10^{-23} JK^{-1}$)

T : is the temperature

q : is elementary charge ($q = 1.6\ 10^{-19} C$)

2. Dynamic Series Resistance Determination

The dynamic series resistance $\boldsymbol{R_s[H_{opt}(\omega)]}$ comes from the resistivity of the material used, the metal contacts and the collection grid. It is opposed to the dynamic diffusion of the carriers to be collected as an output current at the junction. A high dynamic series resistance decreases the flow of electrons that pass through the junction, thus decreasing the quality of the solar cell. Consequently, a solar cell is all the more efficient the lower its dynamic series resistance.

The solar cell current-voltage characteristics have a quasi-vertical part in the vicinity of the open-circuit voltage [28, 29, 39, 42,], for each modulation frequency (ω). We can therefore deduce that under this operating condition, the solar cell behaves as a constant voltage generator in series with the dynamic series resistance.

Thus, applying the law of lattices on the circuit, we obtain the expression of the dynamic series resistance by the relation:

$$R_s\left(S_f,S_b,\omega,H\right) = \frac{V_{phco}(\omega,S_{fco},S_b,H)-V_{ph}(S_f,S_b,\omega,H)}{J_{ph}(S_f,S_b,\omega,H)} \quad \textbf{(14)}$$

The dynamic series resistance ($R_s\left(S_f,S_b,\omega,H\right)$), the voltage ($V_{ph}\left(S_f,S_b,\omega,H\right)$) and the photocurrent density ($J_{ph}\left(S_f,S_b,\omega,H\right)$) are all dependent of, minority carriers' recombination velocity at the junction and on the back side, the modulation frequency as well as the thickness of the base.

The open circuit voltage $\left(\boldsymbol{V_{phco}\left(S_{fco},\omega,S_b,H\right)}\right)$ is obtained for a minority recombination velocity value at the junction less than '$\boldsymbol{S_{fco}}$, which is challenged from the relationship:

$$V_{ph}\left(S_f,S_b,\omega,H\right) - V_{co}\left(S_{fco},S_b,\omega,H\right) = 0 \quad \textbf{(15)}$$

The solution of which can be obtained graphically, from the calibration curve of the voltage versus (S_f) [31, 38, 40-43], $i.e.: V_{ph} = f\left(S_f\right)$

i) Determination of S_{fco} the minority carriers' recombination velocity limiting the open circuit

For each optimum thickness $H_{opt}(\omega)$ [45]obtained with a given modulation frequency, by use of **equation. 15**, we produce the corresponding S_{fco}values in **Table 1**.

Table 1: Optimum thickness $H_{opt}(\omega)$inducing (S_{fco}) a recombination velocity at the junction for (ω) the modulation frequency

		(n+-p-p+) silicon solar cell	
ω $(rad \cdot s^{-1})$	$D(\omega)$ $(cm^2 \cdot s^{-1})$	Hopt (cm) [45]	S_{fco} $(10^2 cm \cdot s^{-1})$
10^2	35	0.0113	1.95
10^3	34.9965	0.0113	1.93
10^4	34.6552	0.0112	1.84
$2 \cdot 10^4$	33.6808	0.0109	1.79
$3 \cdot 10^4$	32.2399	0.0105	1.67
$4 \cdot 10^4$	30.5562	0.0101	1.60
$5 \cdot 10^4$	28.8617	0.0095	1.52
$6 \cdot 10^4$	27.3522	0.0091	1.46
$7 \cdot 10^4$	26.1583	0.0085	1.41
$8 \cdot 10^4$	25.3380	0.0081	1.39
$9 \cdot 10^4$	24.8847	0.0076	1.35
10^5	24.7487	0.0074	1.32

From the values in table 1 we represent in the figure 2, (S_{fco}) versusH_{opt} (ω).

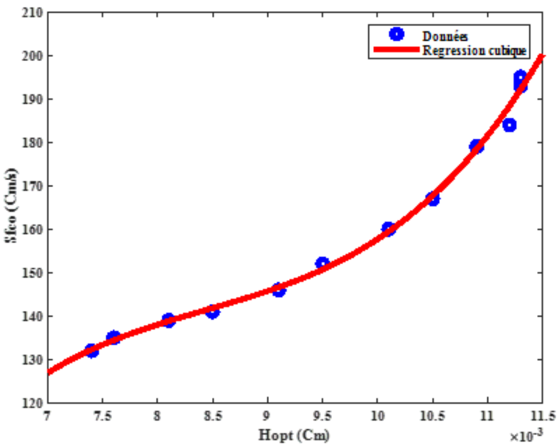

Figure. 2: Plot of (S_{fco}) versus H_{opt} (ω)

We observe that (S_{fco}) increases with the optimum thickness $H_{opt}(\omega)$ according to following **equation (16)**:

$$Sf_{co}(Hopt) = 1.273 \cdot 10^9 \cdot Hopt^3 - 3.224 \cdot 10^7 \cdot Hopt^2 + 2.796 \cdot 10^5 \cdot Hopt - 687.1 \quad \textbf{(16)}$$

For each optimum thickness $H_{opt}(\omega)$ associated with a modulation frequency, we determine the corresponding (S_{fco}) values which then allow us by help of **equation. 14,** to deduce the dynamic series resistance 〖 $R_s[H_{opt}(\omega)]$ value.

ii) Determination of $R_s[H_{opt}(\omega)]$ the dynamic series resistance

We then represent in **Figure (3)** the profile of the dynamic series resistance 〖$R_s[H_{opt}(\omega)]$ depending on the optimum thickness$H_{opt}(\omega)$.

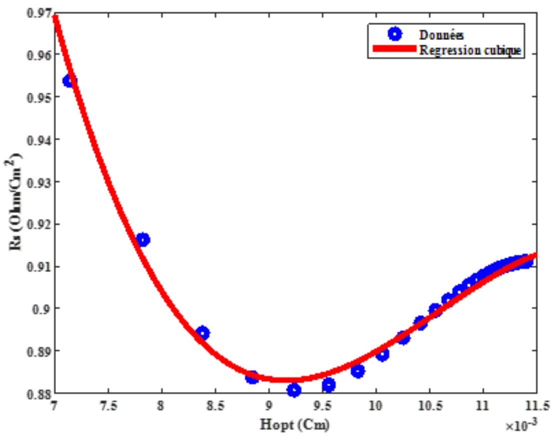

Figure 3: Plot of dynamic series resistance versus H_{opt} (ω)

The relation reflecting the variation of the dynamic series resistance as a function of the optimum thickness $\boldsymbol{H_{opt}(\omega)}$ is given by **equation (17).**

$$R_s(Hopt) = -2.891 \cdot 10^6 \cdot Hopt^3 + 9.168 \cdot 10^4 \cdot Hopt^2 - 951.9\, Hopt + 4.132 \qquad \textbf{(17)}$$

In **figure. 3,** the dynamic series resistance decreases with the optimum thickness $\boldsymbol{H_{opt}(D(\omega))}$ to reach a minimum in the vicinity of $(\boldsymbol{D(\omega)}) = \boldsymbol{26cm^2/s}$ corresponding to the low values of the diffusion coefficient $(\boldsymbol{D(\omega)})$, obtained for the large values of the frequency of modulation $(\boldsymbol{\omega})$ (**tableau. 1**).

3. Conclusion

This study used the phenomelogical parameters of the silicon material, in the (n+/p/p+) solar cell, under polychromatic illumination in frequency modulation, to determine the dynamic series resistance, as a function of the optimum dynamic thickness of the base (p). To do this, this study used the concept of the minority carriers' recombination velocity at the junction, limiting the open circuit, in the model of the electrical equivalent circuit of the illuminated solar cell. The modeled expression of the dynamic series resistance is proposed

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