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Study of the Electrical Parameters of a Silicon Solar Cell ($n^+/p/p^+$) under the Effect of Temperature by Optimization of the Base Thickness and the Doping Rate

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Abstract

In this work, we propose an approach to model the basic parameters of a silicon solar cell ($n^+/p/p^+$) by optimizing the doping rate and the thickness of the base using Matlab Simulink. This technique applies to electrical parameters such as the short-circuit current (J_{cc}) and the open-circuit voltage (V_{co}). These parameters are mainly related to the variations in the doping rate and the thickness of the solar cell. So, optimizing these parameters could offer the possibility of better taking into account the influence of temperature and improving the quality of the solar cell. This technique consists of determining the optimum thickness and the optimum doping rate. And this allowed us to observe using graphs the behavior of the solar cell under different values of temperature.

Keywords

Solar Cell, Doping Rate, Temperature, Thickness

1. Introduction

The performance of a solar cell depends on several parameters, mainly its manufacturing technique and operating conditions [1]-[3]. Previous studies have been done on the limiting and evolving parameters of the solar cell in order to increase the photoconversion efficiency. Some researchers have used optimization techniques for the thickness [4]-[8] of the base and others have optimized the doping rate [8] [9] of the solar cell. Furthermore, the optimization of these parameters is of capital importance in the manufacture of solar cells in order to reduce not only the amount of usable material but also to improve photoconversion efficiency. However, these studies have limitations because the conversion efficiency is always low.

Thus, in order to deepen the research, we propose an approach to modeling the parameters of the silicon solar cell by optimizing the base thickness and the doping rate using Matlab Simulink to improve the photoconversion efficiency.

This empirical study involves the resolution of the continuity equation, allowing us to determine the expression of the density of minority charge carriers in the base or from which we deduce the expressions of the photocurrent density (J_{ph}) and the photovoltage (V_{ph}).

Our methodology consists of first identifying all the mathematical equations concerning this work. Then optimize the doping rate and the base thickness from the short-circuit current density (J_{cc}) and the open-circuit voltage (V_{co}). These optimum values allow us to graphically model the temperature variation on the basic parameters of the solar cell, and this led us to present the simulation results with different temperature values in a table.

2. Theoretical Study

2.1. Presentation of the Photocell

The photovoltaic cell considered is of type ($n^+/p/p^+$) [10] [11] and its structure is presented in Figure 1, where H and x represent respectively the thickness and the depth of the base of the photovoltaic cell. This depth is measured from the emitter-base junction ($x = 0$) to the back surface ($x = H$).

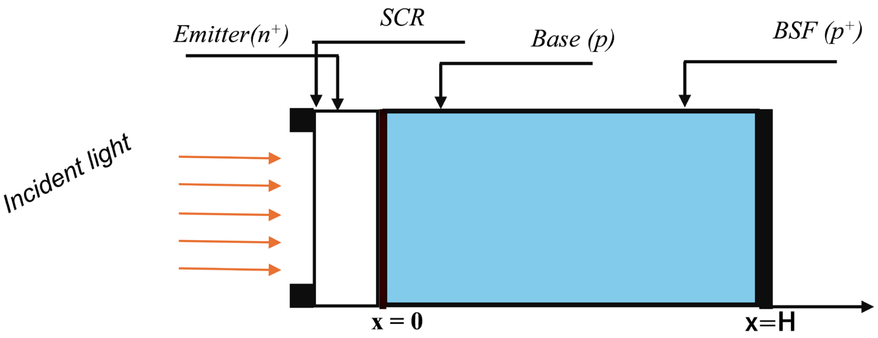

Figure 1. Structure of n^+-p-p^+ type of solar cell.

2.2. Continuity Equation and Boundary Conditions

- **Continuity equation**

When the photocell is under optical or electrical excitation, charge carriers are generated in the base. These carriers cross the space charge region where they participate in the external current, or undergo recombination due to defects related to the manufacture of silicon. Taking into account the phenomena of generation, diffusion and recombination in the solar cell, the continuity equation of the density of minority charge carriers in frequency modulation is given by:

$$\frac{\partial^2 \delta(x,t)}{\partial x^2} - \frac{1}{D(T,N_b)} \frac{\delta(x,t)}{\partial t} - \frac{\partial \delta(x,t)}{D(T,N_b) \times \tau} = -\frac{G(x,t)}{D(T,N_b)} \tag{1}$$

$G(x,t)$ and $\delta(x,t)$ [12] are, respectively, the overall generation rate and the density of minority charge carriers in the base as a function of depth (x) and time (t):

$$\delta(x,t) = \delta(x) \times \mathrm{e}^{i\omega t} \text{ et } G(x,t) = g(x) \times \mathrm{e}^{i\omega t} \tag{2}$$

This rate of generation of charge carriers varies according to the mode of illumination and for our case study, it is given by:

$$g(x) = n \cdot \sum_{i=1}^{3} a_i \cdot \mathrm{e}^{-b_i x} \tag{3}$$

a_i and b_i are tabulated coefficients of solar radiation and depend on the absorption coefficient of silicon with wavelengths under AM 1.5 [13].

n: is a parameter called (number of suns) level of solar radiation. It allows to correlate the level of experimental lighting to the level of reference lighting taken under AM 1.5.

x: represents the depth of the base of the solar cell measured from the emitting junction ($x = 0$) to the back face ($x = H$).

By inserting Equation (2) into Equation (1), we obtain the following relation:

$$\frac{\partial^2 \delta(x)}{\partial x^2} - \frac{1}{L(Nb,T)^2} \cdot \delta(x) = -\frac{g(x)}{D(Nb,T)} \tag{4}$$

- $D(Nb,T)$: represents the diffusion coefficient of electrons generated in the base of a photocell at temperature (T) depending on the Nb doping. It is given by the following relation:

$$D(Nb,T) = \frac{D(T)}{\sqrt{1 + 81 \cdot \frac{Nb}{Nb + 3.2^{18}}}} \ \mathrm{cm}^2/\mathrm{s} \tag{5}$$

$L(Nb,T)$: is the diffusion length of excess minority carriers depending on the temperature and the doping rate. It is given by the following expression:

$$L(Nb,T) = \sqrt{D(Nb,T) \cdot \tau(Nb)} \ \mathrm{cm} \tag{6}$$

With

$$\tau(Nb) = \frac{12}{1 + \frac{Nb}{5 \times 10^{16}}} \ \mu\mathrm{s} \tag{7}$$

(Nb) denotes the average lifetime of excess minority carriers corresponding to the average time taken by a minority carrier before succumbing to recombination, it is given by [14]:

$$\delta(x,Nb,T) = Ach\left(\frac{x}{L(Nb,T)}\right) + Ash\left(\frac{x}{L(Nb,T)}\right) - \sum_{i=1}^{3} \beta_i \cdot \mathrm{e}^{-b_i x} \tag{8}$$

The constants A and B are determined from the boundary conditions at the junction and the back face [15].

- **Boundary Conditions**

At the junction: $x = 0$

$$\left.\frac{\delta(x, Nb, T)}{\partial x}\right|_{x=0} = \frac{Sf}{D(Nb, T)}\delta(0, Nb, T) \tag{11}$$

At the rear face: $x = H$

$$\left.\frac{\delta(x, Nb, T)}{\partial x}\right|_{x=H} = -\frac{Sb}{D(Nb, T)}\delta(H, Nb, T) \tag{12}$$

The parameters Sf and Sb represent the recombination rates at the junction and at the back face [16] [17]. The recombination rate Sf is equal to the sum of the recombination rate $Sf_j = j \times 10^j$ cm/s due to the external charge and the intrinsic recombination rate Sf_0 which is an effective recombination rate at the emitter-base interface.

2.3. Short Circuit Photocurrent Density (J_{cc})

The short-circuit photocurrent density (J_{cc}) is obtained from the photocurrent density for large values of the recombination velocity at the junction ($Sf \geq 10^6$ cm/s).

It is given:

$$J_{CC}(Nb, T) = \lim_{Sf \geq 10^6 \text{cm/s}} J_{ph}(Sf, Nb, T) \tag{13}$$

After calculation, the expression for the short-circuit photocurrent density of a photocell when illuminated from the front face is given by the relation (14):

$$J_{CC}(Nb, T, H) = q \cdot D \sum_{i=1}^{3} \beta_i \frac{L(Db - Sb)\left[\cosh\left(\frac{H}{L}\right) - \mathrm{e}^{-bH}\right] + \left(bSbL^2 - D\right)\sinh\left(\frac{H}{L}\right)}{L^2 \cdot Sb \sinh\left(\frac{H}{L}\right) + DL\cosh\left(\frac{H}{L}\right)} \tag{14}$$

Avec $L = L(Nb, T)$ et $D = D(Nb, T)$.

2.4. Open Circuit Voltage

It represents the maximum voltage at the terminals of the solar cell, for zero current. It is obtained by calculating the limit of the photovoltage when the recombination speed at the junction (Sf) tends towards zero.

$$V_{co}(Nb, T, H) = \lim_{Sf \to 0} V_{ph}(Nb, T, H) \tag{15}$$

2.5. Form Factor

The form factor FF, also called curve factor or filling factor, is defined as the ratio between the maximum power and the product ($J_{cc} \times V_{co}$); from which it is given by the relation:

$$FF = \frac{P_m}{J_{cc} \times V_{co}} \tag{16}$$

This factor shows the deviation of the current-voltage curve from a rectangle that corresponds to the ideal solar cell.

2.6. Conversion Efficiency *η*

Conversion efficiency is the most important parameter in the solar cell. It expresses the ability of the cell to efficiently convert photons of incident light into electric current. It is defined as the ratio between the maximum power delivered by the cell and the power of the solar radiation reaching the cell.

$$\eta = \frac{P_m}{P_{in}} = \frac{FF \cdot V_{CO} \cdot J_{cc}}{P_{in}} \tag{17}$$

This efficiency can be improved by increasing the form factor, short-circuit current and open-circuit voltage. At constant temperature and illumination, the efficiency of a solar cell depends on the load in the electrical circuit.

3. Effect of Doping Rate on Open Circuit Voltage and Short Circuit Current

In **Figure 2**, we plot the open circuit voltage and short circuit current as a function of the base doping rate.

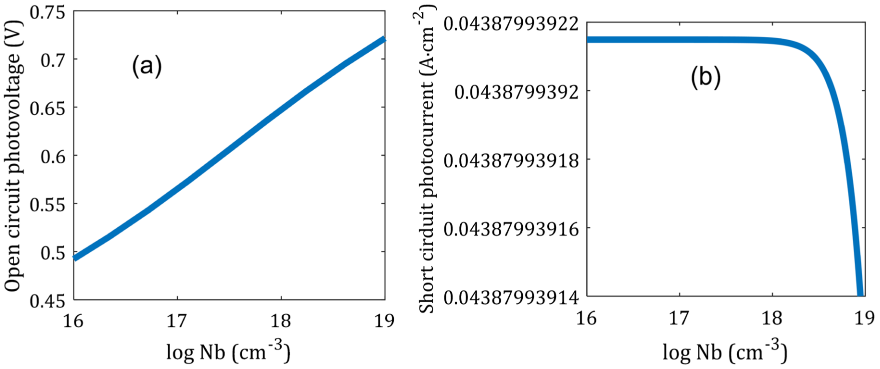

Figure 2. Open circuit voltage (a) and short circuit current (b) as a function of the logarithm of the base doping rate at $T = 300$ K.

It is evident from these experiments that a high doping rate leads to an increase in the open circuit voltage. While the short-circuit current decreases at high doping rates (for $Nb \geq 10^{18}$ cm^{-3}). This decrease in the short-circuit current is due to the increase in the resistivity of the base which decreases the diffusion length and the mobility of the minority carriers.

This result shows that a high doping rate decreases the effective diffusion coefficient, the diffusion length and the lifetime of minority carriers and limits the short-circuit current. Then, a reasoned decrease in the doping rate seems a solution to limit recombination losses.

Moreover, when the base doping rate increases, the width of the space charge zone decreases and consequently fewer carriers cross the junction of the solar cell leading to an increase in the open circuit voltage.

The increase in the open circuit voltage and the decrease in the short-circuit current as a function of the base doping rate shows that there is a point from which the power is maximum.

Then, the base doping rate is a judicious choice to obtain a good photoconversion efficiency.

For a rigorous choice, we determine from **Figure 3** and **Figure 4** the optimal doping rate and the optimal thickness through the short-circuit current and the open-circuit voltage.

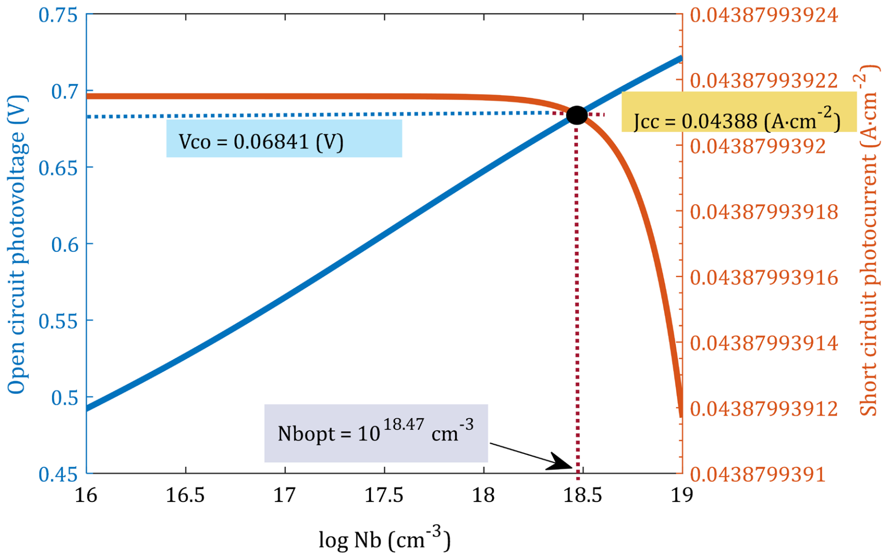

Figure 3. Determination of the optimum doping rate at $T = 300$ K.

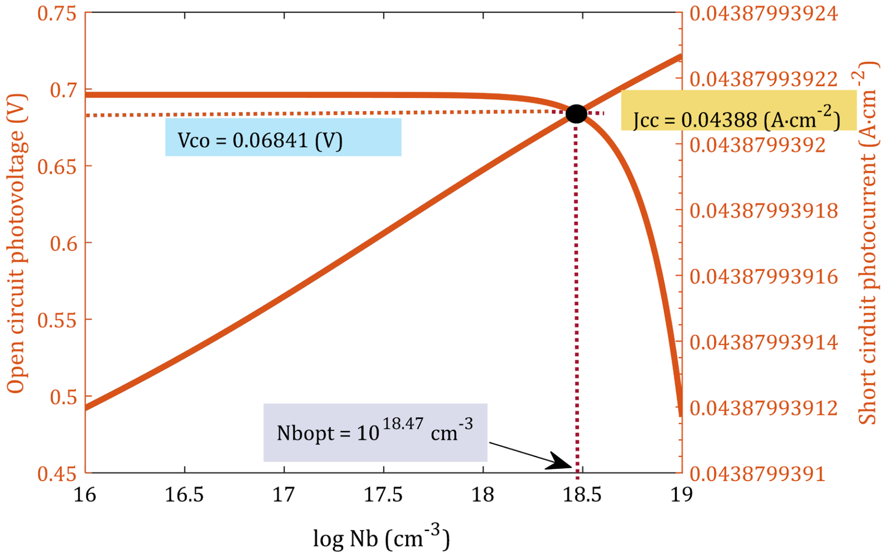

Figure 4. Determination of the optimum thickness at $T = 300$ K.

4. Determination of the Doping Rate and the Optimum Thickness According to the Open Circuit Layout and the Short-Circuit Current

Figure 3 and **Figure 4** represent respectively the determination of the optimum doping rate (Nbopt) and that of the optimum thickness (Hopt).

We note that the optimum doping rate is obtained at $10^{18.47}$ cm^{-3} and the base thickness is optimal at 223 µm. Under this condition, the short-circuit current (J_{cc}) has a value of 0.4388 A·cm^{-2} and the open-circuit voltage $V_{co} = 0.68$ V.

5. Modeling the Influence of Temperature on the Photocell

The following **Figure 5** represents the open circuit voltage, the short circuit current, the form factor, and the conversion efficiency as a function of temperature and at optimized thickness and doping rate values.

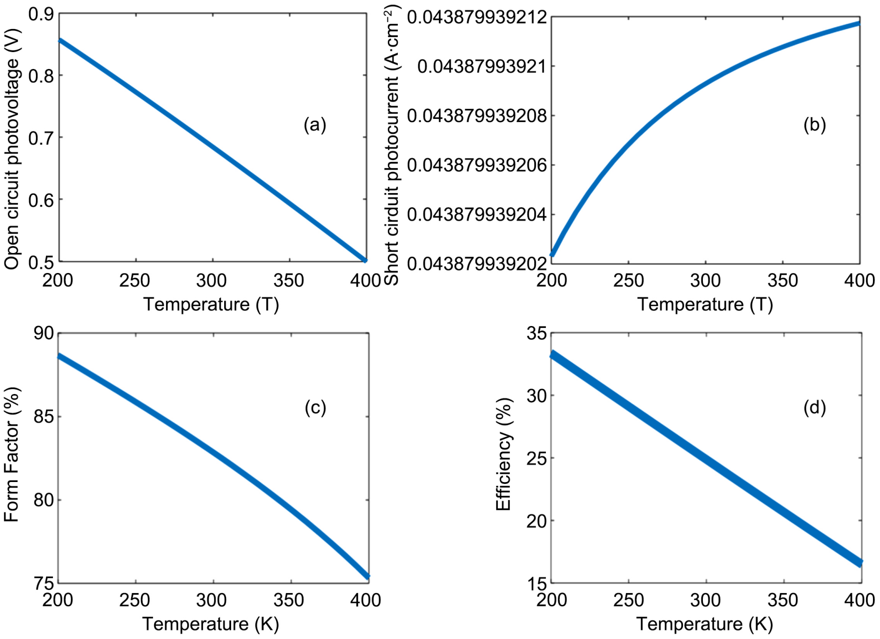

Figure 5. Effect of temperature on (a) V_{co}, (b) J_{cc}, (c) FF and (d) η Avec $Nb = 10^{18.47}$ cm^{-3} et $H = 223$ µm.

It appears from these representations that the short-circuit current (J_{cc}) increases as a function of temperature. Even more, the open circuit voltage decreases as the temperature increases.

Indeed, a high temperature degrades the intrinsic properties of the solar cell, subsequently leading to a decrease in the parallel resistance and consequently a decrease in the FF as well as the V_{co}. Therefore, we conclude that the open circuit voltage degrades linearly with the increase in temperature.

Both the form factor and the efficiency are sensitive to increasing temperature. To demonstrate this, we represent in **Table 1** the values of V_{co}, J_{cc}, FF and η as a function of temperature under a doping condition $Nb = 10^{18.47}$ cm^{-3}.

Table 1. Simulation results with different temperature values.

Température	**200**	**250**	**300**	**340**	**360**	**380**
Nb (cm^{-3})	$10^{18.47}$	$10^{18.47}$	$10^{18.47}$	$10^{18.47}$	$10^{18.47}$	$10^{18.47}$
H (µm)	223	223	223	223	223	223
V_{co} (V)	0.8574	0.7725	0.6842	0.6115	0.5744	0.5371
J_{cc} (A/cm^2)	0.043871	0.043872	0.043873	0.04375	0.04376	0.04378
FF (%)	88.67	85.87	82.84	80.15	78.67	77.07
η (%)	**33.36**	**19.11**	**24.87**	**21.5**	**19.83**	**18.16**

From the results obtained in this table, we notice that the short-circuit current is not very sensitive to the increase in the base temperature. We also note that the best efficiencies are obtained at low temperatures. Therefore, we can conclude that, when the temperature increases, the emitted phonons heat the crystal lattice, thus causing a progressive loss of energy of the carriers.

6. Conclusion

This study showed the importance of the doping rate and the base thickness in the study of the solar cell in order to optimize the conversion efficiency. For our case study with Matlab Simulink, the doping rate and the base thickness of the (p) type are respectively optimal at $10^{18.47}$ cm^{-3} et à 223 µm. In addition, in the study of the influence of temperature, we noticed that the increase of the temperature in the base of the solar cell promotes an increasingly degradation of the open-circuit voltage and a slight increase of the short-circuit current.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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