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Determination of the Series Resistance of a Series Vertical-Junction Silicon (N+/P/P+) Solar Cell under Polychromatic Illumination and Magnetic Field: Effect of Optimum Thickness

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Abstract

By solving the magneto-transport equation for excess minority charge carriers in the base of the series vertical-junction silicon cell, the phenomenological parameters of the cell can be determined from the boundary conditions. Photocurrent density and photovoltage are determined for each value of applied magnetic field and corresponding optimum thickness, to establish the current-voltage characteristic ($J_{ph}(Sf, Sb, z, B, Hop)$-$V_{ph}(Sf, Sb, z, B, Hop)$ of the silicon cell under polychromatic illumination. This study will make it possible to reduce the material used (by reducing the optimum thickness), which will help to lower prices. It will also enable us to reduce betting effects (lower series resistance), thereby boosting solar cell efficiency.

Keywords

Series Vertical Junction Silicon Cell, Static Regime, Magnetic Field, Optimum Thickness, Series Resistance

1. Introduction

To improve the quality of solar cells, several characterization techniques are used [1], depending on the operating regime established (static or dynamic regime) [2]-[7] in order to derive phenomenological parameters such as lifetime, mobility of minority carriers, diffusion length and coefficient, recombination velocities [1] [6]-[11] of minority carriers, as well as the electrical parameters of the solar cell, such as series and shunt resistances, capacitance and power [12]-[17].

In this work, we propose the determination of the series resistance of the N+/P/P+ silicon solar cell with vertical junctions [18]-[20] under polychromatic illumination in static regime placed in a magnetic field [3] [6] for different values of the optimum thickness of the base of the solar cell imposed by the magnetic field [21]-[24].

2. Theory

The structure of the series vertical-junction solar cell [18] [20] [25] [26] under polychromatic illumination and magnetic field is shown in **Figure 1** below.

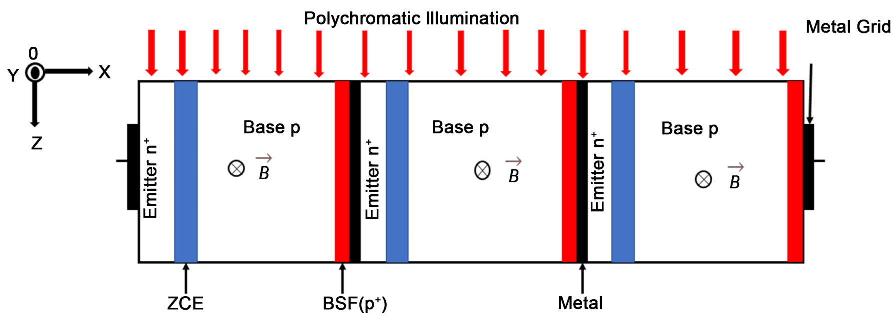

Figure 1. Series vertical-junction solar cell under polychromatic illumination and magnetic field.

Figure 2 shows a schematic diagram of a series of vertical junction solar cell units under polychromatic illumination and a magnetic field.

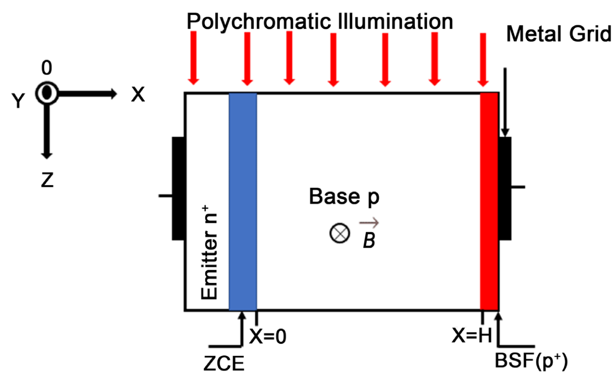

Figure 2. Series vertical junction solar cell unit under polychromatic illumination and magnetic field.

These parts are shown in following sections.

3. The n+ Type Transmitter

The thickness is small (0.5 to 1 μm), it is heavily doped with donor atoms (10^{17} to 10^{19} atoms per cm^3) and covered with a metallic contact which allows the photo-created electrical charges to be collected.

4. The p-Type Base

This part is relatively lightly doped (10^{15} to 10^{17} atoms per cm^3) in acceptor atoms. Its thickness is much greater than that of the transmitter. Being p-type (doped with acceptor atoms), this part of the structure presents a deficit of electrons (minority charge carriers in the base).

5. The Transmitter-Base Junction (Space Charge Zone)

Between the two zones of the two differently doped semiconductors (n-type emitter and the p-type base), there is a junction where a very intense electric field reigns allowing the separation of the electron-hole pairs photogenerated in the base arriving at this junction.

6. Continuity Equation

The phenomena of generation, diffusion and recombination of minority excess charge carriers in the base under magnetic field and polychromatic illumination are described by a so-called continuity equation. It is defined by the expression below.

$$D(B)\cdot\frac{\partial^2\delta(x)}{\partial x^2}-\frac{\delta(x)}{\tau}=-G(z) \tag{1}$$

$\delta(x)$ is the density of excess minority charge carriers photogenerated in the cell base.

$D(B)$ is the diffusion coefficient of electrons in the base in the presence of the magnetic field.

τ is the lifetime of the minority carriers in the base and is defined by the following Einstein relation:

$$\tau=\frac{L^2(B)}{D(B)} \tag{2}$$

$L(B)$ is the diffusion length of excess minority charge carriers in the base.

$D(B)$ is the diffusion coefficient of minority carriers in the base [3] [6] [23], it is defined by:

$$D(B)=\frac{D_0}{1+(\mu\cdot B)^2} \tag{3}$$

The expression for the generation ratio of minority carriers at depth z in the base is given by the following relation:

$$G(z)=n\times\sum_{i=1}^{3}\left(a_i\times\exp(-b_i\times z)\right) \tag{4}$$

With a_i et b_i tabulated coefficients of solar radiation and depend on the absorption coefficient of silicon with the wavelength [27]. It makes it possible to correlate the experimental illuminance level with the reference illuminance level taken under AM 1.5.

7. Solving the Continuity Equation

The expression for the continuity equation becomes:

$$\frac{\partial^2\delta(x,z,B)}{\partial x^2}-\frac{\delta(x,z,B)}{L^2(B)}+\frac{1}{D(B)}\times n\times\sum_{i=1}^{n}\left(a_i\times\exp(-b_i\times z)\right)=0 \tag{5}$$

The solution to this equation is in the following form:

$$\delta(x,z,B) = A(Sf,Sb,z,B)\cdot cosh\left(\frac{x}{L(B)}\right) + C(Sf,Sb,z,B)\cdot sinh\left(\frac{x}{L(B)}\right) + \sum_{i=1}^{3}\left(\frac{a_i \times L^2(B)}{D(B)} \times exp(-b_i(z))\right) \quad (6)$$

The coefficients $A(Sf,Sb,z,B)$ et $C(Sf,Sb,z,B)$ are determined from the boundary conditions.

8. Boundary Conditions

At the junction ($x = 0$):

$$\left.\frac{\partial\delta(x,z,B)}{\partial x}\right|_{x=0} = \left.\frac{Sf\cdot\delta(x,z,B)}{D(B)}\right|_{x=0} \quad (7)$$

Sf is the recombination velocity of minority charge carriers at the junction, imposed by the external charge, and reflects the flow of minority carriers through the junction [6] [9] [28] [29].

At the back surface ($x = H$):

$$\left.\frac{\partial\delta(x,z,B)}{\partial x}\right|_{x=H} = -\left.\frac{Sb\cdot\delta(x,z,B)}{D(B)}\right|_{x=H} \quad (8)$$

Sb is the recombination rate of excess minority charge carriers on the back of the cell [8]-[11] [29]. It characterizes the loss of carriers at the back of the cell. The existence of the backside electric field (BSF) enables photogenerated minority carriers to be returned from the backside (p/p+ junction) to the emitter-base junction to participate in the photocurrent.

9. Photocurrent Density and Photovoltage

The expression for photocurrent density is determined from the density of minority charge carriers using Fick's law. It is given by the following expression:

$$J_{ph}(Sf,Sb,z,B) = q\cdot D(B)\cdot\left.\frac{\partial\delta(x,z,B)}{\partial x}\right|_{x=0} \quad (9)$$

With q the elementary electric charge.

The expression for the photovoltage across the cell under illumination is given by Boltzmann's relation below.

$$V_{ph}(Sf,Sb,z,B) = \frac{Kb\cdot T}{q}\times\ln\left[\frac{Nb}{(n_i)^2}\cdot\delta(0,Sf,Sb,z,B,Hop)+1\right] \quad (10)$$

Kb is Boltzmann's constant, T is the absolute temperature, Nb is the doping rate in the base and n_i is the intrinsic electron concentration.

10. Technique for Determining the Recombination Velocity at the Junction Limiting the Open Circuit

Figure 3 shows the technique for determining the recombination velocity of minority carriers at the junction limiting the open circuit.

At low recombination velocities of minority carriers at the junction (*Sf*), the photovoltage is maximum and constant: this is the value of the open-circuit photovoltage. Referring to this part of the curve, the orthogonal projection of the point limiting the open circuit situation onto the x-axis gives the value of the minority carrier recombination velocity at the junction limiting the open circuit Sfco.

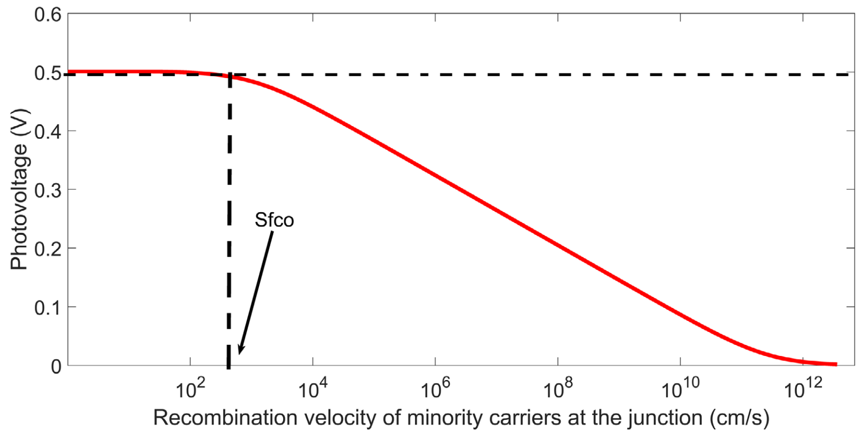

Figure 3. Photovoltage profile as a function of recombination rate at the junction ($\tau = 10^{-5}$ s; $\mu = 1350$ cm^2·V^{-1} s^{-1}).

11. Effect of the Magnetic Field and the Optimum Thickness of the Base on the Characteristic $J_{ph}(Sf, Sb, z, B, Hop)$-$V_{ph}(Sf, Sb, z, B, Hop)$

Figure 4 represents the profile of the J_{ph}- V_{ph} characteristic of the silicon solar cell under polychromatic illumination for different values of the magnetic field and different values of the optimum thickness of the base imposed by the magnetic field.

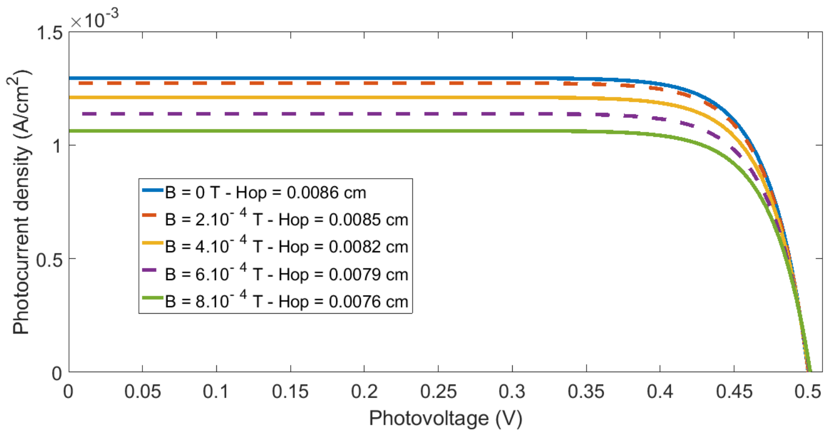

Figure 4. J_{ph}- V_{ph} characteristic of the solar cell for different values of the magnetic field and optimum thickness ($\tau = 10^{-5}$ s; $\mu = 1350$ cm^2·V^{-1} s^{-1}).

Figure 4 shows that the photocurrent density is maximum and constant at low values of the photovoltage, it corresponds to the short-circuit photocurrent density. When the photocurrent density decreases and tends towards a zero value, the photovoltage increases until it reaches a maximum value: this is the open circuit photovoltage.

We also note that the increase in the magnetic field and the optimum thickness imposed by the magnetic field lead to a reduction in the short-circuit photocurrent density, on the other hand, the open circuit photovoltage increases slightly.

12. Study of Series Resistance

Series resistance is a fundamental parameter which depends on the nature of the substrate, the temperature, the technology used and is very important for the quality of a solar cell. It should ideally be as low as possible to limit its influence on the current of the solar cell [12]-[14].

13. Electrical Model of the Open Circuit Solar Cell

To determine the series resistance R_s, we propose the equivalent electrical model of the silicon solar cell in open circuit (low values of Sf which correspond to the maximum value of the photovoltage). In **Figure 5**, in an open circuit situation (circled area), the photocurrent density characteristic as a function of the photovoltage is assumed to be an oblique line allowing the modeling of the solar cell as a voltage generator.

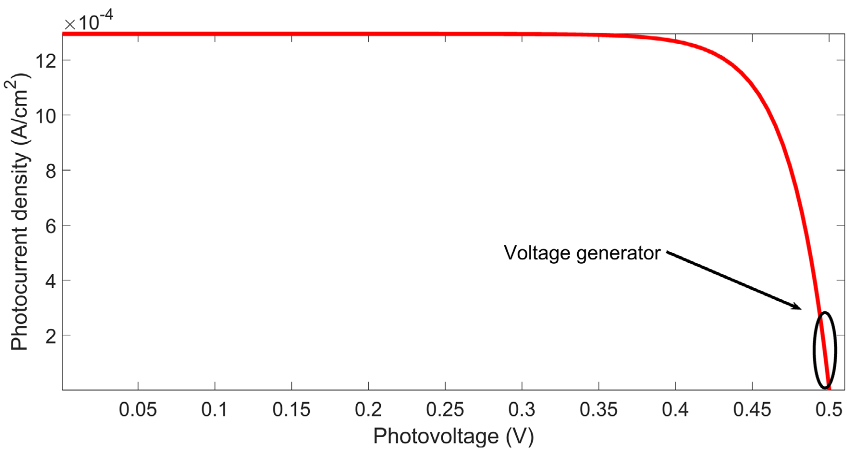

Figure 5. J_{ph}- V_{ph} characteristic.

The equivalent electrical diagram of the solar cell operating in an open circuit situation is shown in the figure below.

14. Expression of Series Resistance

The expression for the series resistance is obtained by applying the mesh law to the electrical circuit in **Figure 6** [30] [31]. It is given by the equation below.

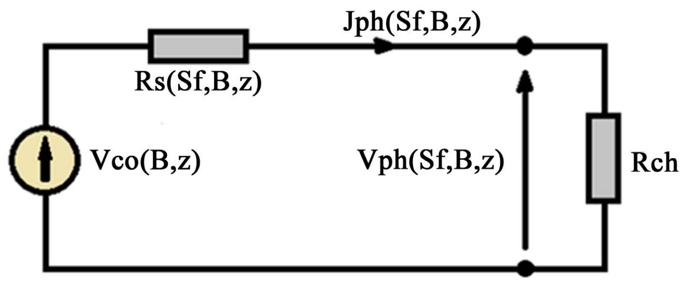

Figure 6. Equivalent electrical circuit of the solar cell in open circuit.

$$R_s\left(Sf, B, z\right) = \frac{V_{co}\left(B, z\right) - V_{ph}\left(Sf, B, z\right)}{J_{ph}\left(Sf, B, z\right)} \tag{11}$$

$V_{co}\left(B, z\right)$ is the open circuit voltage.

Figure 7 shows the evolution of the series resistance as a function of the recombination velocity of minority charge carriers at the junction for different values of the magnetic field and the corresponding optimum thickness.

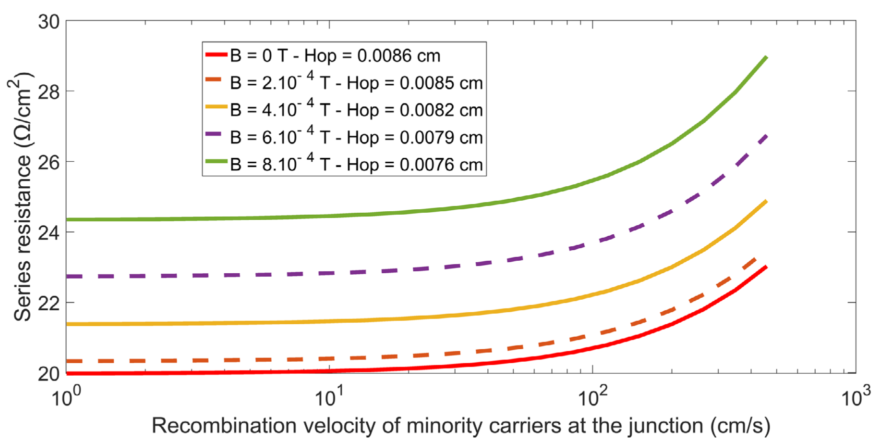

Figure 7. Profile of series resistance as a function of recombination velocity at the junction for different values of magnetic field and optimum thickness ($\tau = 10^{-5}$ s; $\mu = 1350$ cm^2·V^{-1} s^{-1}).

Figure 7 shows that whatever the value of the magnetic field, the series resistance increases with the velocity of recombination of the minority carriers at the *Sf* junction. As *Sf* increases, the quantity of excess minority charge carriers passing through the junction increases, causing the metal grid to heat up and the series resistance to increase with the recombination velocity at the junction.

Furthermore, we also see that when the magnetic field and the optimum thickness increase, the series resistance increases, whatever the value of the recombination velocity at the junction. The increase in series resistance with the magnetic field is due to the magnetoresistance effect.

($\tau = 10^{-5}$ s; $\mu = 1350$ cm^2·V^{-1} s^{-1}) gives some values of the series resistance obtained from the recombination velocity of the minority carriers at the junction limiting the open circuit for different values of the magnetic field and optimum thickness imposed on the magnetic field.

Table 1. Series resistance values for different values of magnetic field and optimum thickness.

B (10^{-4}T)	0	2	4	6	8
Hop (cm)	0.0086	0.0085	0.0082	0.0079	0.0076
Sf_{co} (cm/s)	400	350	200	150	130
R_s (Ω/cm^2)	22.5	22.8	23	24.15	25.78

Figure 8 shows the change in series resistance as a function of magnetic field. It can be seen that the series resistance increases with the magnetic field.

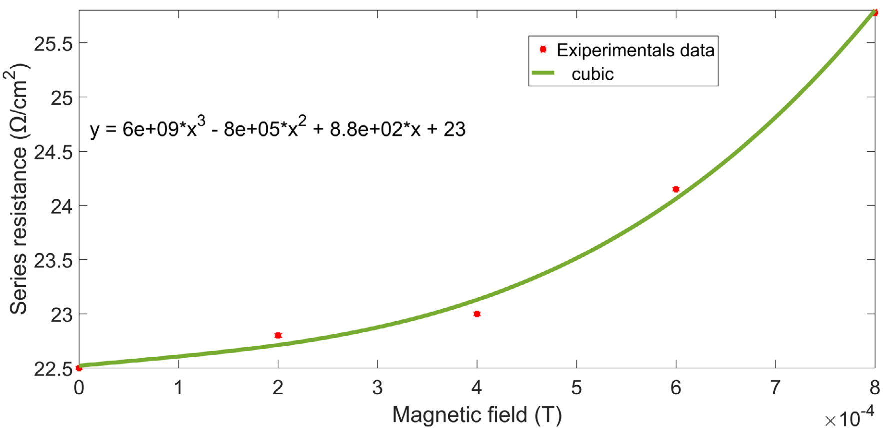

Figure 8. Profile of the series resistance as a function of the magnetic field.

The values in **Table 1** were used to plot the series resistance profile as a function of the optimum thickness of the cell base (**Figure 9**).

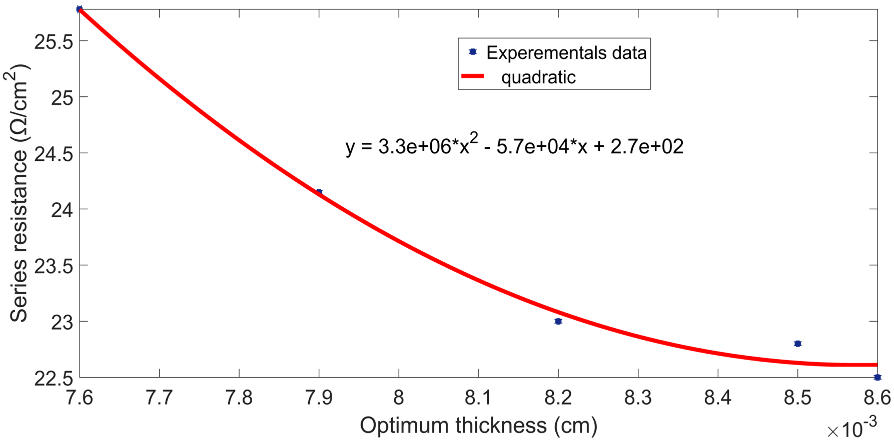

Figure 9. Profile of series resistance as a function of optimum base thickness.

Figure 9 shows that the series resistance decreases as the optimum thickness of the solar cell base increases. The mathematical correlation equation between series resistance and optimum thickness obtained from the curve in **Figure 9** is also shown in this figure.

15. Conclusion

The series resistance of the series vertical junction silicon solar cell in the static regime under polychromatic illumination and magnetic field, taking into account the optimum thickness of the base of the solar cell imposed by this magnetic field, is studied in this work. Using the boundary conditions, we first solve the diffusion equation for the minority carriers in the base, and then determine the photocurrent density and photovoltage. From the expressions for photocurrent density and photovoltage, the current-voltage characteristic of the solar cell under illumination and magnetic field conditions is presented, enabling the series resistance in the equivalent electrical circuit to be determined in an open-circuit situation. The profile of the series resistance as a function of the recombination velocity of the minority carriers at the junction for different values of the magnetic field and the corresponding optimum thickness is plotted to study the evolution of the series resistance as a function of the optimum thickness.

Notation List of All the Variables

Symbol	Physical size	Unit
x	Width of cell base	cm
z	Depth of cell base	cm
$G(z)$	Carrier generation ratio in the cell base	cm^{-3}/s
Nb	Base impurity doping ratio	cm^{-3}
n_i	Intrinsic density of minority carriers with $n_i = 10^{10}$	cm^{-3}
τ	Life of minority holders	s
B	Magnetic field	T
$\delta(x)$	Charge carrier density in the cell base	cm^{-3}
a_i	Tabulated solar radiation coefficient	cm^{-3}/s
b_i	Tabulated solar radiation coefficient	cm^{-1}
D	Diffusion coefficient	cm^2/s^{-1}
H	Thickness of the P-doped base	cm
L	Minority carrier diffusion length	cm
Sf	Recombination velocity of minority carriers at the junction	cm/s
T	Absolute temperature	K
Sb	Recombination velocity of minority carriers in the rear zone	cm/s
V_{ph}	Photovoltage	V
V_{co}	Open circuit voltage	V
V_T	Thermal voltage	V

Continued

Kb	Boltzmann coefficient	Sans unité
q	Elementary charge	C
J_{ph}	Photocurrent density	A/cm^2
R_s	Series resistance	Ω.cm^2
Sf_{co}	minority carrier recombination velocity at the junction limiting the open circuit Sf_{co}.	cm/s

Conflicts of Interest

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

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