

Influence of the Magnetic Field and Optimum Base Thickness of a Series Vertical-Junction Silicon Solar Cell under Polychromatic Illumination and Magnetic Field on Capacitance: Determination of Transition and Dark Capacitances

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Abstract In this paper, we have studied the influence of the optimum thickness of the base of a series vertical-junction solar cell, under polychromatic illumination and magnetic field, on transition and dark capacitances. The expressions for minority carrier density, photovoltage, and capacitance are derived by solving the diffusion equation for minority carriers, based on boundary conditions involving recombination velocities at the junction (S_f) and in the back zone (S_b). The profile of capacitance versus photovoltage for each value of optimum thickness obtained from the magnetic field is then presented, in order to determine the value of transition and dark capacitances for each value of optimum thickness. The evolution of open-circuit photovoltage (V_{co}) as a function of magnetic field and optimum base thickness is described at the end.

Keywords: vertical junction silicon solar cell series, static regime, magnetic field, optimum thickness, capacity

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1. Introduction

In today's solar energy domain, the main focus of research is on increasing the efficiency of solar cells. For this reason, it is important to characterize solar cells to limit recombination in volume and surface area, and ultimately increase their capacity for better carrier collection. These recombination parameters can be studied under static or dynamic regime [1,2,3,4,5].

In this work, we study the effect of the magnetic field and the optimum thickness deduced from the magnetic field [4,6,7,8,9,10] on the capacitance of the series-connected vertical junction solar cell in static conditions, under polychromatic illumination [11,12,13].

2. Theory

2.1. Presentation of the Vertical-junction Silicon Solar Cell Series

The series vertical-junction solar cell is an assembly of

N+/P/P+ photovoltaic cells connected in series by a metal, with illumination parallel to the plane of the space charge zone. [13,14,15] (Figure 1).

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

The various parts of the series vertical junction silicon solar cell unit are:

The n+ -type emitter: it is thin (0.5-1 μ m), heavily doped with donor atoms (10^{17} to 10^{19} atoms per cm³) and covered with a metal contact that collects the photocreated electrical charges.

The p-type base: This part is relatively lightly doped (10^{15} to 10^{17} atoms per cm³) in acceptor atoms. Its thickness is much greater than that of the emitter. Being p-type (doped with acceptor atoms), this part of the structure has a deficit of electrons (minority charge carriers in the base).

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

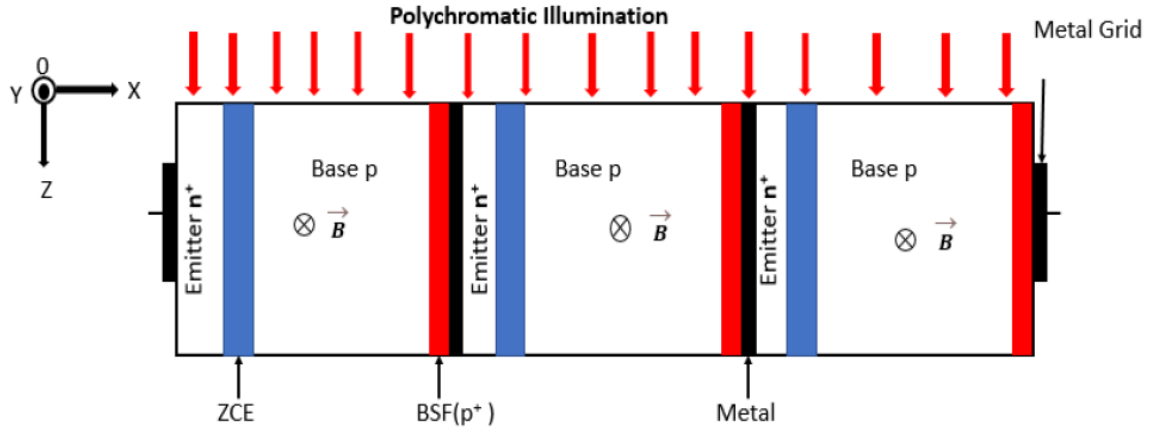


Figure 1. silicon solar cell with vertical junctions series under polychromatic illumination and magnetic field

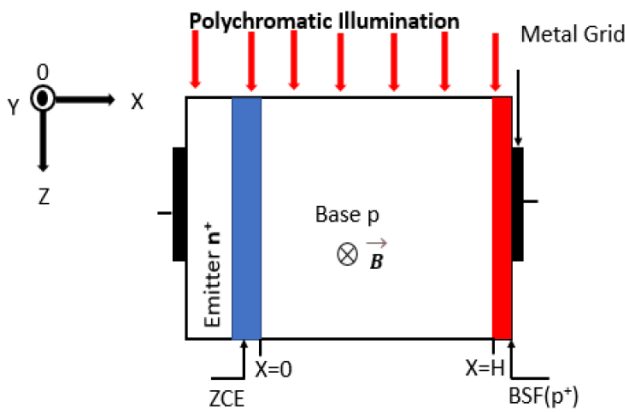


Figure 2. series vertical junction solar cell unit in magnetic field

2.2. Continuity Equation

Using magneto-transport theory, the continuity equation for the density of minority charge carriers photogenerated in the base of a series vertical junction solar cell under polychromatic illumination, magnetic field and static regime is written [4,6,11]:

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

$\delta(x)$ is the density of excess minority charge carriers photogenerated in the base of the solar cell. τ is the minority carrier lifetime in the base, defined by the Einstein relation:

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

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

$D(B)$ is the diffusion coefficient of minority carriers in the basis [4,6,9], it is defined by:

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

D_0 is the diffusion coefficient in the absence of the magnetic field, μ is the mobility of minority carriers

The expression for the generation rate of minority

carriers at depth z in the base is given by the following expression:

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

Where a_i and b_i are tabulated solar radiation coefficients and depend on the absorption coefficient of silicon with wavelength [16]. It correlates the experimental illuminance level with the reference illuminance level taken from AM 1.5.

Solving the continuity equation:

The expression for the continuity equation of comes from:

$$\frac{\partial^2 \delta(x,z,B)}{\partial x^2} - \frac{\delta(x,z,B)}{L^2(B)} + \frac{1}{D(B)} \times n \times \sum_{i=1}^3 (a_i \times \exp(-b_i \times z)) = 0 \quad (5)$$

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

Boundary conditions:

$$\text{At the junction (x=0): } \frac{\partial \delta(x,z,B)}{\partial x} \Big|_{x=0} = \frac{Sf \cdot \delta(x,z,B)}{D(B)} \Big|_{x=0} \quad (7)$$

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 [4,17,18,19].

$$\text{In the rear zone (x=H): } \frac{\partial \delta(x,z,B)}{\partial x} \Big|_{x=H} = -\frac{Sb \cdot \delta(x,z,B)}{D(B)} \Big|_{x=H} \quad (8)$$

Sb is the recombination velocity of the excess minority charge carriers in the rear zone of the solar cell [17,18,20,21,22]. It characterizes the loss of carriers in the rear zone. The existence of the backside electric field (BSF) enables photogenerated minority carriers from the backside zone (p/p+ junction) to be sent back to the emitter-base junction to participate in the photocurrent.

2.3. Photocurrent Density, Photovoltage and Capacitance

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:

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

q is elementary charge

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

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

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.

The space charge zone of a silicon solar cell between the emitter and the base can be likened to a planar capacitor whose capacitance is proportional to the junction area and inversely proportional to the extension of the space charge zone [23,24]. The capacitance is due to the diffusion of excess minority charge carriers across the junction. The expression for capacitance is given by the following relationship [23,25]:

$$C(Sf, Sb, z, B) = q \cdot \left. \frac{\partial \delta(x, z, B)}{\partial V_{ph}(Sf, Sb, z, B)} \right|_{x=0} \quad (11)$$

After calculating and developing this expression, we find:

$$C(Sf, Sb, z, B) = \frac{q \cdot (n_i)^2}{Nb \cdot V_T} + \frac{q \cdot \delta(0, z, B)}{V_T} \quad (12)$$

$V_T = \frac{K.T}{q}$ (12) is the thermal voltage.

3. Results and Discussions

Figure 3 shows the $J_{ph}(Sf, Sb, z, B, Hop) - V_{ph}(Sf, Sb, z, B, Hop)$ characteristic profile of the solar cell under polychromatic illumination for different values of the magnetic field and different values of the optimum thickness imposed by the magnetic field.

This profile was obtained by varying the minority carrier recombination velocity (Sf). At low values of Sf we have open-circuit photovoltage. At high values of the minority carrier recombination velocity (Sf), we obtain the short-circuit photocurrent density.

Figure 4 shows the capacitance profile as a function of the minority carrier recombination velocity at the junction for different magnetic field values corresponding to different values of the optimum solar cell base thickness.

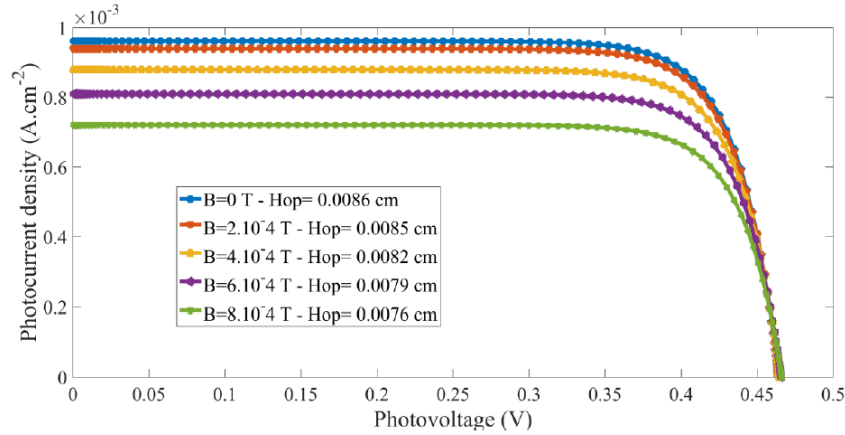


Figure 3. I-V characteristic of the solar cell for different magnetic field values ($\tau=10^{-5}$ s ; $\mu=1350$ cm² .V⁻¹ s⁻¹)

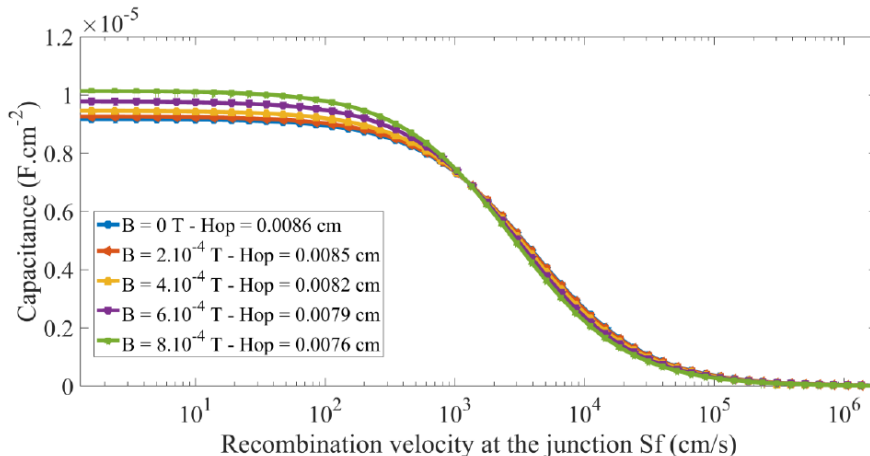


Figure 4. Capacitance profile as a function of carrier recombination velocity at the junction for different magnetic field values ($\tau=10^{-5}$ s ; $\mu=1350$ cm² .V⁻¹ s⁻¹)

In the vicinity of the open circuit, i.e. at low values of the minority carrier recombination velocity at the junction, the capacitance is at its maximum. This corresponds to a narrowing of the space charge zone. Excess photogenerated minority charge carriers are then stored close to the junction. At high junction recombination velocities (near the short circuit), the capacitance is very low. The space charge zone is enlarged. Indeed, as the junction recombination velocity tends towards its higher values, the flow of minority charge carriers across the junction increases, and the quantity of stored carriers in the vicinity of the junction decreases.

However, the capacitance in the vicinity of the open circuit increases with the magnetic field, but decreases slightly in the vicinity of the short circuit. This phenomenon is linked to the increase in the density of excess minority charge carriers near the junction due to the magnetic field.

3.1. Determining Transition Capacitance C_T

Figure 5 shows the evolution of capacitance as a function of photovoltage under the influence of the magnetic field and the corresponding optimum thickness.

The figure above (Figure 5) shows that capacitance is a linear function of photovoltage, with a strictly positive slope. This shows that capacitance increases with photovoltage.

The transition capacitance can be obtained from the ordinate at the origin. In this region, there are almost no free carriers.

It is also noted that the different curves obtained from

different values of the magnetic field and the corresponding optimum thickness have the same slope and therefore the same ordinate at the origin. It can be said that the transition capacitance does not depend on the value of the applied magnetic field.

The table below gives the values of transition capacitance, dark capacitance and open-circuit voltage for each value of the optimum thickness imposed by the applied magnetic field. These results are very similar to those of [26].

3.2. Determining Dark Capacitance

Dark capacitance is the capacitance recorded without illumination. It corresponds to zero photovoltage. Figure 6 shows the technique used to determine dark capacitance.

Figure 7 shows the evolution of open-circuit photovoltage as a function of magnetic field.

Figure 7 shows that the photovoltage of the open circuit increases as the magnetic field increases. This is because, as the magnetic field increases, the density of minority carriers near the junction increases.

Figure 8 shows the dark capacitance profile as a function of magnetic field.

Figure 9 shows the evolution of dark capacitance as a function of open-circuit photovoltage. The capacitance increases with increasing photovoltage.

The mathematical correlation equation is given by:

$$C_D = 3.7 \cdot 10^{-4} \times V_{OC} - 1.6 \cdot 10^{-4} \quad (13)$$

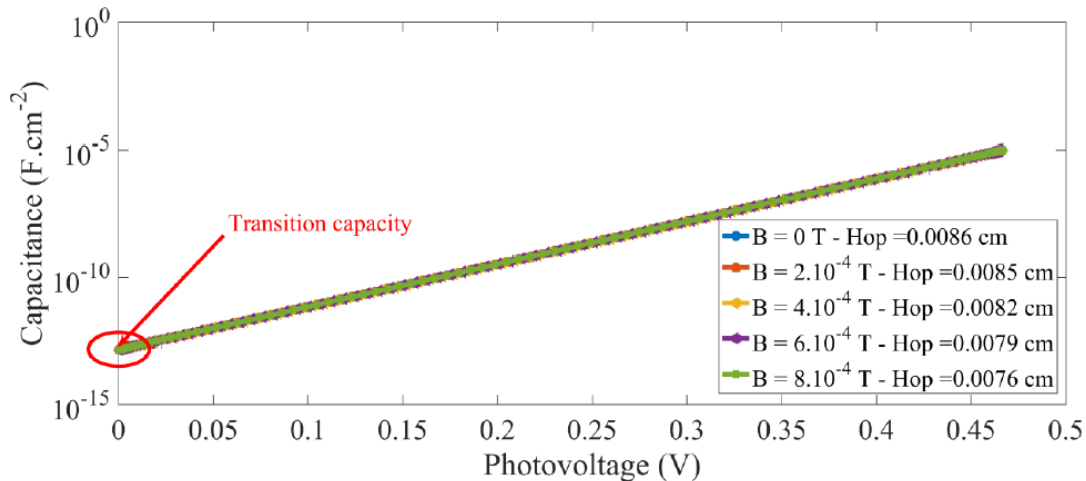


Figure 5. Capacitance profile as a function of photovoltage for various values of magnetic field and corresponding optimum thickness

Table 1. Values of transition capacitance, dark capacitance (C_D) and open-circuit voltage for each value of the optimum thickness imposed by the applied magnetic field

Magnetic field $B(10^{-4}T)$	0	2	4	6	8
Optimum Thickness $H_{OP}(cm)$	0,0086	0,0085	0,0082	0,0079	0,0076
Transition Capacitance C_T ($10^{-13}F/cm^2$)	1.484	1.484	1.484	1.484	1.484
Dark Capacitance $C_D(\mu F/cm^2)$	9.180	9.261	9.460	9.778	10.140
Open circuit voltage $V_{OC}(V)$	0.4642	0.4644	0.4650	0.4658	0.4668

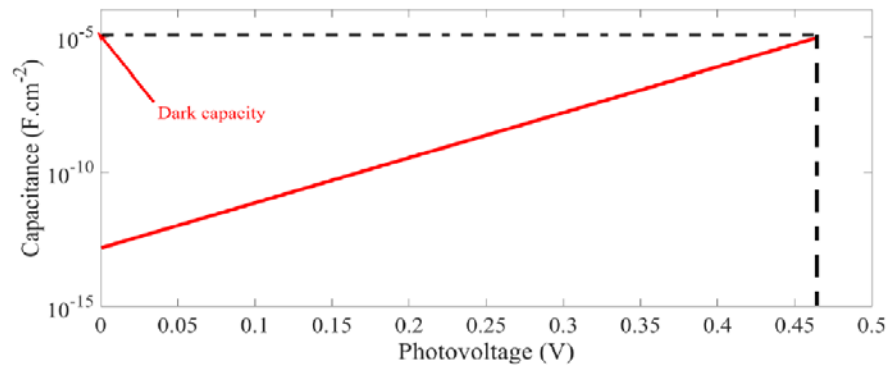


Figure 6. Technique used to determine dark capacitance

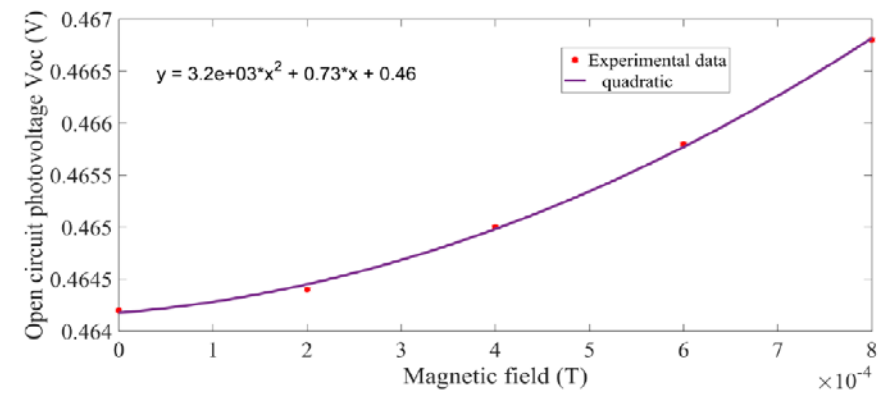


Figure 7. Open circuit photovoltage profile as a function of magnetic field

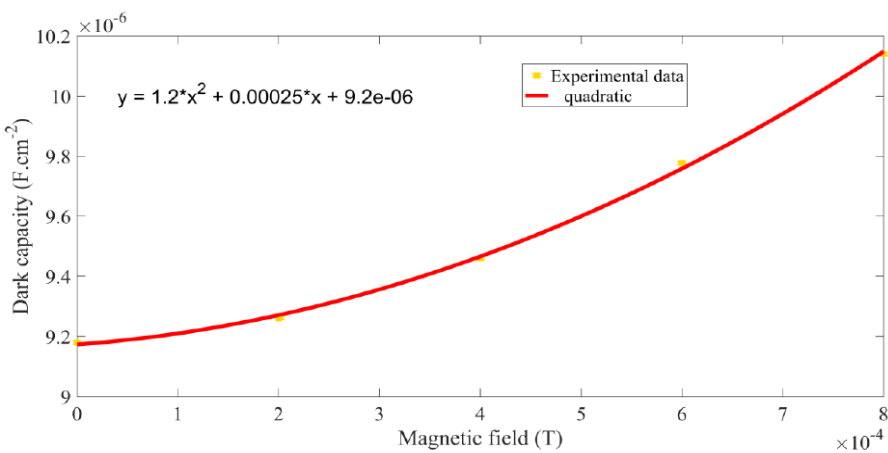


Figure 8. Profile of dark capacity as a function of magnetic field

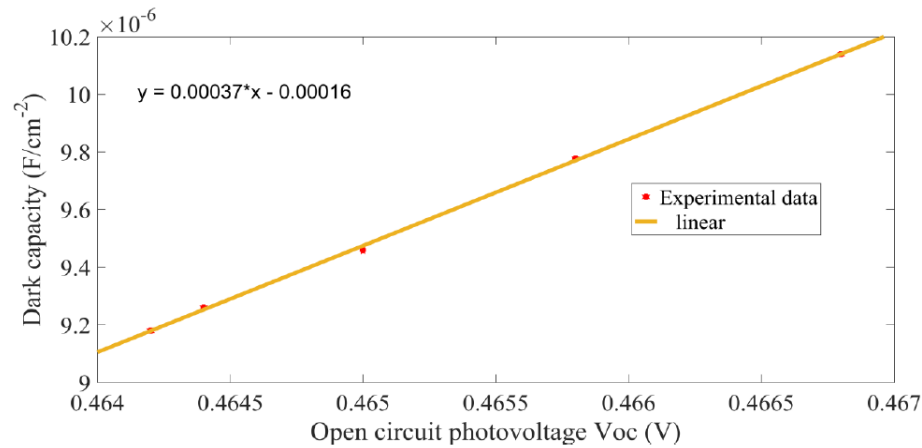


Figure 9. Dark capacity profile as a function of photovoltage

4. Conclusion

In this paper, the influence of the optimum base thickness (imposed by the applied magnetic field) on the capacitance of the series vertical-junction silicon solar cell under polychromatic illumination was studied. Expressions for photovoltage and capacitance, obtained by solving the continuity equation for the density of minority carriers in the base in the static regime, the evolution of capacitance as a function of the velocity of minority carriers at the junction and that of capacitance as a function of photovoltage have been studied for different values of magnetic field and corresponding optimum thickness. Figure 5 illustrates the determination of transition capacitance and open-circuit photovoltage, for each value of the optimum base thickness imposed by the magnetic field. The evolution of open-circuit photovoltage as a function of magnetic field and optimum base thickness has also been studied in this article.

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