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A Steady-State Spectral Response and Quantum Efficiency Determination of a Bifacial Silicon Solar Cell under Monochromatic Illumination and Constant Magnetic Field Effects by Using the Photoconductivity Method

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Abstract In this work, a theoretical approach of the effects of wavelength and applied magnetic field on the spectral response and quantum efficiency of a bifacial silicon solar cell, is made. For this, the continuity equation relative to the photogenerated minority carriers in the base of the solar cell, in steady-state, is used. The resolution of this equation allowed us to determine the minority carriers' density according to the wavelength, the magnetic field and the junction recombination velocity. Based on the expression of minority carriers' density, we obtained the photoconductivity, the photocurrent density from which the spectral response and the quantum efficiency have been established according to the excitation and phenomenological parameters of the solar cell. We found that, as the magnetic field increases, both the spectral response and quantum efficiency decrease; this situation shows a degradation of the intrinsic properties of the solar cell.

Keywords: *bifacial solar cell, photoconductivity, spectral response, quantum efficiency, magnetic field, wavelength*

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1. Introduction

Photovoltaic energy, a part of renewable energy sources, produced by the solar panels, is a particular interest to overcome environmental problems (greenhouse effects, climate change etc.) and the growing energy demands of the world's population. However, this solar energy depends on weather conditions, installation technique of PV panels and their energy conversion efficiency, the nature of the solar cells that are used and the manufacturing technology [1]. Therefore, several techniques and methods have been developed for the characterization of solar cells in order to improve the electrical, electronic, phenomenological parameters and the energy conversion efficiency of these cells. Thus, the photoconductivity [2-20], the spectral response [21] and the quantum efficiency [22-33] are widely used as characterization techniques. Furthermore, these authors Andrés Cuevas et al. [34] and Vasiliki Paraskeva et al. [35] have used respectively photoconductivity on the 'emitters' layers of solar cells and the effects of the shunt resistances of germanium multi-junction solar cells to measure their quantum efficiencies. Also, Giorgio Bardizza et al. [36] and Mauro Pravettoni et al. [37] have characterized dye-sensitive solar cells (DSSC) in frequency modulation and concentrated crystalline solar cells using the spectral response technique, respectively. For Baishali Talukdar et al. [38], the shading effect of several cells is shown on spectral response and quantum efficiency.

In this paper, we carry out a theoretical study of the wavelength and applied magnetic field effects on the spectral response and quantum efficiency of a silicon solar cell. We show how some properties of the solar cell, are degraded with the magnetic field.

2. Theory

A bifacial silicon solar cell of a n+-p-p+ type [39-43], is used in a one-dimension following the x-axis that corresponds to the incident illumination. The expression of the photoconductivity is given by [44]:

$$\sigma_{ph} = \frac{q\mu_o\delta_n}{\left(1+\mu_o^2 B^2\right)} \qquad (1)$$

with:

$$\mu_o = \frac{q\tau_n}{m} \qquad (2)$$

where: μ_o is the static mobility of electrons in the base without an applied magnetic field; q, τ_n and m are respectively the elementary charge, the average lifetime and the effective mass of electrons in the base; δ_n is the excess minority carriers' density in the base.

In steady-state, excess minority carriers flow is governed by the continuity equation:

$$D_n \frac{\partial^2\delta_n}{\partial x^2} - \frac{\delta_n}{\tau_n} = -G \qquad (3)$$

With D_n being the minority carriers diffusion coefficient given by:

$$D_n = \frac{D_o}{1+\mu_o^2 B^2} \qquad (4)$$

Where D_o is the minority carriers diffusion coefficient without magnetic field; G is the minority carriers generation rate [45, 46] at position *x*, whose expression is:

$$G = \alpha(\lambda)\phi(\lambda)\left(1-R(\lambda)\right)e^{-\alpha(\lambda)x} \qquad (5)$$

Where the parameters $\alpha(\lambda)$, $R(\lambda)$ and $\phi(\lambda)$ are respectively the absorption coefficient, the reflection coefficient and the incident photons flux at wavelength λ.

A solution of equation (3) is given by:

$$\delta_n = Ae^{-\frac{x}{L_n}} + Ce^{\frac{x}{L_n}} - \frac{\alpha(\lambda)L_n^2\phi\left(1-R(\lambda)\right)e^{-\alpha(\lambda)x}}{D_n\left(\alpha(\lambda)^2 L_n^2 - 1\right)} \qquad (6)$$

with:

$$L_n = \sqrt{D_n\tau_n} \text{ and } \left(\alpha(\lambda)^2 L_n^2 - 1\right) \neq 0 \qquad (7)$$

Where L_n is the minority carriers diffusion length in the base.

To obtain the complete expression of the minority carriers' density, we have to determine the coefficients A and C by using the following boundary conditions [46,47]:

- at the junction (x = 0)

$$D_n \cdot \left.\frac{\partial\delta_n}{\partial x}\right|_{x=0} = Sf \cdot \left.\delta_n\right|_{x=0} \qquad (8)$$

- at the back side (x = H)

$$D_n \cdot \left.\frac{\partial\delta_n}{\partial x}\right|_{x=H} = -Sb \cdot \left.\delta_n\right|_{x=H} \qquad (9)$$

Where *Sf* and *Sb* are respectively junction recombination velocity and back surface recombination velocity. The recombination velocity *Sf* is the sum of the junction recombination velocity due to the external load that defines the solar cell operating point and the intrinsic junction recombination velocity that materializes an effective recombination velocity of the minority carriers at the emitter-base interface.

For the discussion of the results in this work, we neglect the effective recombinations of the minority carriers at the emitter-base interface by setting the junction recombination velocity $Sf = 5.10^5\ cm.s^{-1}$ and minimize the minority carriers losses at the rear side, with a back surface recombination velocity $Sb = 200\ cm.s^{-1}$.

3. Expression of the Photocurrent Density

The photocurrent density is determined according to the photoconductivity. Its expression is given by equation (10):

$$J_{ph} = \frac{1}{\gamma}\left(\sigma_{ph} - \beta\left(e^{-\alpha(\lambda)H} - 1\right)\right) \qquad (10)$$

Where γ is a coefficient that depends on geometrical parameters of the solar cell and the nature of the incident illumination; β a coefficient which expression is:

$$\beta = \frac{q\mu_o\phi(\lambda)\left(1-R(\lambda)\right)L_n{}^2}{D_o\left(\alpha(\lambda)^2 L_n^2 - 1\right)} \qquad (11)$$

4. Expressions of the Spectral Response and the Quantum Efficiency

The spectral response (SR) is the ratio of photocurrent density J_{ph} to incident power P_i. Its expression is given by [48,49]:

$$SR = \frac{J_{ph}}{P_i} \qquad (12)$$

with:

$$P_i = \frac{hC}{\lambda}\phi_i \qquad (13)$$

where ϕ_i is the incident photons flux ($\phi(\lambda)$), *h* is the Planck's constant and C the light celerity in the vacuum.

Substituting equations (10) and (13) into equation (12), we get:

$$SR = \frac{\lambda}{\gamma hC(\lambda)}\left[\sigma_{ph} - \beta\left(e^{-\alpha(\lambda)H} - 1\right)\right] \qquad (14)$$

On the one hand, from the relationship between spectral response and external quantum efficiency (EQE) [50,51,52] in equation (15):

$$SR = \frac{q\lambda}{hC} EQE \qquad (15)$$

the external quantum and internal quantum (IQE) on the other hand in equation (16):

$$EQE = \left(1 - R(\lambda)\right) IQE \qquad (16)$$

We deduce the following equation:

$$SR = \frac{q\lambda}{hC}\left(1 - R(\lambda)\right) IQE \qquad (17)$$

Through equations (15), (16) and (17), the quantum efficiency, which can vary with the photoconductivity, also depends on the wavelength and the applied magnetic field.

We present, in the following discussion, some results from these different relationships that are obtained above and consider a constant charge across the solar cell.

5. Results and Discussion

5.1. Profile of the Spectral Response (SR)

In figure 1, we represent the spectral response according to the wavelength for different values of the magnetic field:

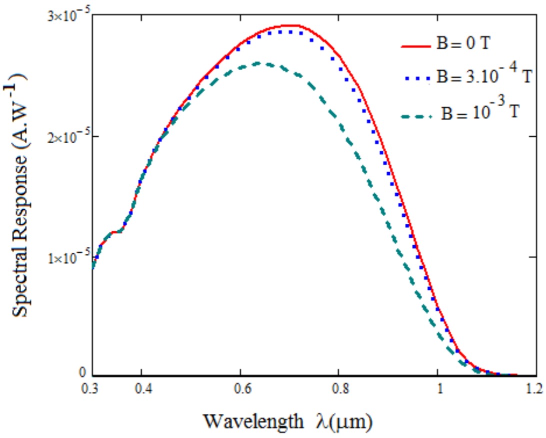

Figure 1. Spectral response versus wavelength for different magnetic field values

In figure 1, the spectral response is given according to the wavelength for different values of the magnetic field. We get three curves that have the same behaviour. For a given curve, the spectral response increases with the wavelength until reaching a maximum value $SR_{max}(\lambda_L)$ where λ_L is a corresponding limit wavelength. From this maximum value, the spectral response decreases with the wavelength. In the interval of wavelength [0.3µm; λ_L], the increase in spectral response is due to that of photoconductivity [20] which corresponds to a significant absorptivity of the base of the solar cell; what implies a good sensitivity of this cell. However, in the interval of wavelength]λ_L; 1.2µm], the spectral response decreases; this leads to a decrease in the sensitivity of the solar cell since the photoconductivity also decreases in the base.

In the table below, we give a few values of SR_{max} and λ_L.

From the table, for $SR_{max} = 2.8.10^{-5}$ A.W^{-1} and $SR_{max} = 2.7.10^{-5}$ A.W^{-1}, we get the same value of $\lambda_L = 0.7$µm when the magnetic field values are respectively B = 0 T and B = 3.10^{-4} T. For a magnetic field B = 10^{-3} T, we have $SR_{max} = 2.5.10^{-5}$ A.W^{-1} and $\lambda_L = 0.64$µm. The variation of $\Delta\lambda_l$ between the values $\lambda_L = 0.64$µm for B = 10^{-3} T and $\lambda_L = 0.7$µm for B = 0 T, and then that of ΔSR_{max} between the values $SR_{max} = 2.5.10^{-5}$ A.W^{-1} and $SR_{max} = 2.8.10^{-5}$ A.W^{-1}, give respectively $\Delta\lambda_L = -0.06$µm and $\Delta SR_{max} = -0.3.\ 10^{-5}$ A.W^{-1}. These negative variations show a wavelength shift towards short wavelength and a decrease of the maximum spectral response; this leads to a narrowing of the solar cell sensitivity range when the magnetic field increases.

Table. A Few values of SR_{max} and λ_L for different magnetic fields

B(T)	0	3.10^{-4}	10^{-3}
λ_L (µm)	0.7	0.7	0.64
SR_{max} (A.W^{-1})	$2.8.10^{-5}$	$2.7.10^{-5}$	$2.5.10^{-5}$

5.2. Profiles of the Quantum Efficiencies

In figure 2-a, the external quantum efficiency is represented according to the wavelength for different magnetic field:

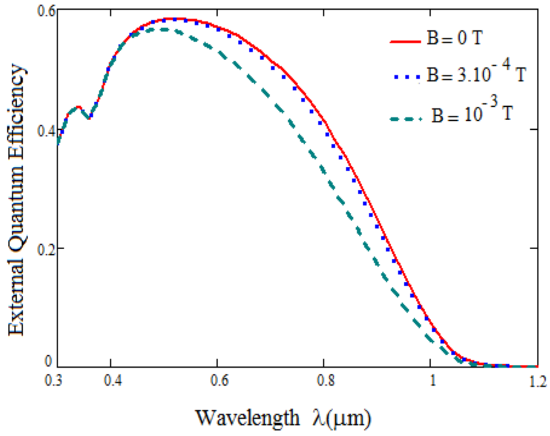

Figure 2-a. External quantum efficiency versus wavelength for different magnetic field values

At the figure 2-a above, the three curves of external quantum efficiency according to the wavelength, present the same behaviour for the different magnetic field values. For a given curve, the maximum of the external quantum efficiency is localized in the visible wavelength domain. We obtained three maximum values of the external quantum efficiency: i) the first $EQE_{max1} = 0.422$ corresponds to a wavelength $\lambda_1 = 0.34$µm for the three magnetic field values; ii) the second $EQE_{max2} = 0.565$ to a wavelength $\lambda_2 = 0.52$µm for B = 0 T and B = 3.10^{-4} T; iii) the third $EQE_{max3} = 0.555$ to a wavelength $\lambda_2 = 0.48$µm for B = 10^{-3} T. Beyond these maximum values, the external quantum efficiency decreases when the wavelength increases since the absorption of the incident photons becomes feeble in the base depth of the solar cell. From the wavelength $\lambda = 0.455$µm, the amplitude of the external quantum efficiency decreases with the increase of the magnetic field.

After studying the external quantum efficiency, we represent, now, in figure 2-b, the internal quantum efficiency according to the wavelength for different magnetic field values:

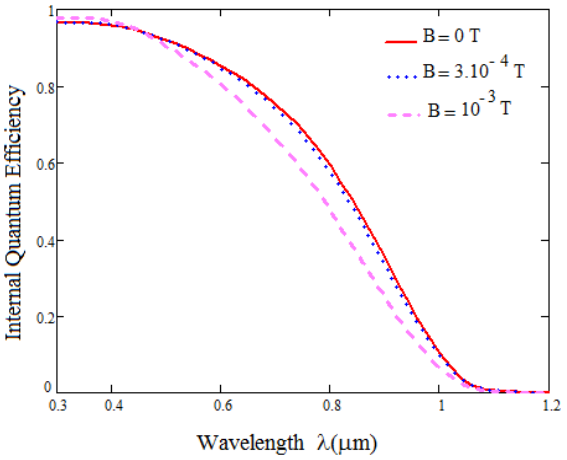

Figure 2-b. Internal quantum efficiency versus wavelength for different magnetic field values

At the Figure 2-b, the internal quantum efficiency decreases with the wavelength for the three represented curves. For short wavelengths corresponding to high energies of incident photons, the internal quantum efficiency is at its maximum: the photons are strongly absorbed by a certain thickness in the front face of the solar cell. The maximum value IQE_{max} = 0.978 of the internal quantum efficiency, is obtained at the wavelength λ = 0.30μm. As the wavelength increases, the photon absorption gradually decreases and the base of the solar cell becomes especially transparent of the long wavelengths. The increase of the magnetic field leads to a decrease in the amplitude of the internal quantum efficiency.

The profile of the quantum efficiency (external and internal), according to the wavelength, without an applied magnetic field, is shown in Figure 2-c:

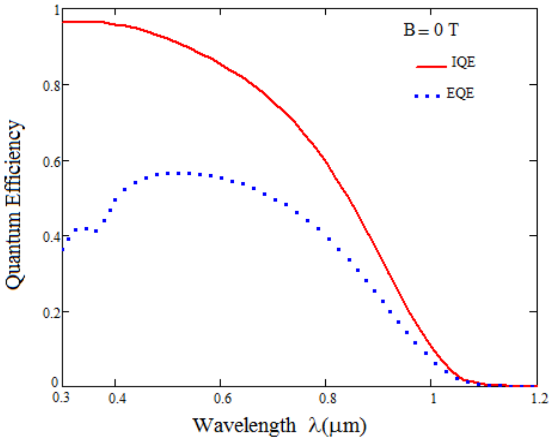

Figure 2-c. Quantum efficiency versus wavelength without an applied magnetic field

In figure 2-c, we represent both quantum efficiencies curves, without a magnetic field, according to the wavelength. A comparison of these curves, shows a clear difference between the values EQE_{max2} = 0.565 and IQE_{max} = 0.978. From the wavelength λ = 0.30μm to that of up to a slightly higher value than λ = 1μm, the internal quantum efficiency remains higher than the external quantum efficiency. At long wavelengths, the decrease of the quantum efficiency can be linked to a probable recombination of photogenerated minority carriers in the bulk of the base. For wavelengths λ > 1μm, the low quantum efficiency corresponds to a very weak absorption of the incident photons by the base of the solar cell since there is no more photogenerated minority carriers.

5.3. Comparative Profiles of the Spectral Response and the External Quantum Efficiency

The spectral response and the external quantum efficiency, according to the wavelength, without an applied magnetic field, are represented in Figure 3:

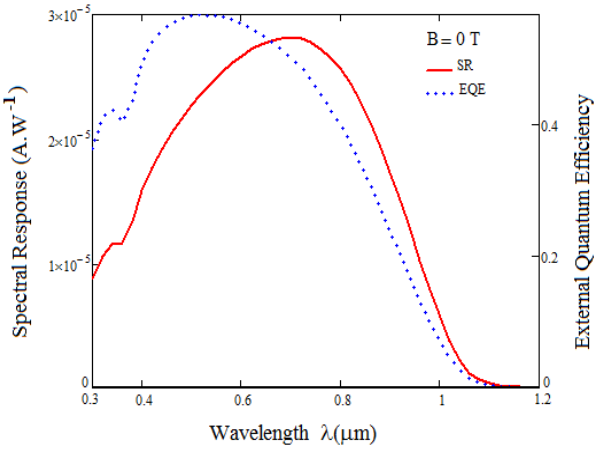

Figure 3. Spectral response and external quantum efficiency versus wavelength, without an applied magnetic field

In Figure 3, the two curves representing the spectral response and the external quantum efficiency according to the wavelength, have the same behaviour. However, the maximums of the spectral response $SR_{max} = 2.8.10^{-5}$ $A.W^{-1}$ and the external quantum efficiency EQE_{max2} = 0.565, correspond respectively to wavelengths λ_1 and λ_2 which all are defined in the visible domain. Thus, we determine the wavelength interval [0.4μm; 0.8μm] where the maximum values of the spectral response and the external quantum efficiency are founded.

6. Conclusion

From the relationships that are established between the studied quantities, we analyzed the effects of the wavelength and the magnetic field on the spectral response and the quantum efficiency. Some specific wavelengths for different magnetic fields, corresponding to the maximum spectral response and quantum efficiency values, were determined. It is noted, from these profiles, that the increase of the magnetic field leads to a narrowing of the sensitivity range of the solar cell and that the specific wavelengths are in the visible domain.

It should be reminded that, in this work, we fixed the junction and the rear side recombination velocities and then neglected the contribution of the solar cell emitter. In addition, for a future work, we will be able to take into account of the influence of junction and the rear side recombination velocities on the spectral response and quantum efficiency in order to determine phenomenological parameters of the solar cell.

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