

Research Article

The Effects of the Angle of Incidence and Gallium Doping Level on the Performance of a CIGS Solar Cell Studied Under Dynamic Frequency Under Monochromatic Illumination

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Abstract

This article presents a model for studying a basic CIGS solar cell in dynamic frequency mode under monochromatic illumination. The study begins by solving the differential equation that highlights the expression of minority carrier density, followed by those of photocurrent density, photovoltage, short-circuit photocurrent density, and open-circuit photovoltage. This work finalizes the identification and study of the expressions for the shape factor, power, and conversion efficiency of the photovoltaic cell. The study of the dynamic impedance of the basic CIGS solar cell using Bode and Nyquist diagrams is also developed in this work. Thus, we observe that an increase in the angle of incidence tends to decrease the power of the photovoltaic cell, the form factor, and the conversion efficiency. On the other hand, increasing the gallium doping rate tends to improve the cell's performance. Furthermore, the results obtained from the impedance study show the existence of two specific pulsation zones. The first zone $[0 \text{ rad/s}; 3.16 \cdot 10^7 \text{ rad/s}]$ where the modulus is a constant; this is the static regime. The second zone $]3.16 \cdot 10^7 \text{ rad/s}; 10^8 \text{ rad/s}]$ where the modulus increases; this is the dynamic regime. An increase in the angle of incidence with the dynamic impedance modulus is observed. Furthermore, the variation in the angle of incidence has no effect on the resonance frequency or phase. Furthermore, increasing the gallium doping level increases the dynamic resistance modulus. Subsequently, a slight decrease in the impedance phase is observed, synonymous with fluctuations in the pulse limiting the phase shift effects between the signal and the carriers produced. Finally, the Bode and Nyquist representations of the dynamic impedance show that inductive effects remain dominant.

Keywords

CIGS, Frequency Modulation, Incidence Angle, Gallium Doping, Bode Diagram, Nyquist Diagram

1. Introduction

Cu(In,Ga)Se_2 (CIGS) and related chalcopyrite compounds have attracted considerable interest for thin film photovoltaic

device on account of their high optical absorption coefficient and adjustable band gap, which makes it possible to achieve

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high conversion efficiency in CIGS solar cells. The best CIGS thin film solar cell has reached a confirmed conversion efficiency of about 20% under a solar spectrum of AM 1.5 G [1]. In addition, a simulation study on CIGS-based solar cells makes it possible to predict their performance. The CIGS-based solar cell model presented in this paper is therefore studied in dynamic frequency mode.

The solution of the differential equation used in this work highlighted the behavior of minority carriers and the density of minority carriers [1] and the diffusion of capacity [2]. The rest of the study led to the determination of the photocurrent density, the photovoltage, the short-circuit photocurrent density, and the open-circuit photovoltage.

This article continues the study of cell performance using Nyquist and Bode diagrams. To do this, the short-circuit photocurrent density is deduced from the photocurrent density m and the open-circuit photovoltage is deduced from the photovoltage. The ratio of the open-circuit photovoltage to the short-circuit photocurrent density will be the dynamic impedance of the photovoltaic cell and studied using Nyquist and Bode diagrams, highlighting the effects of the angle of incidence and the gallium doping rate [3].

After providing expressions for power, form factor, and efficiency, the article explains how the angle of incidence and gallium doping rate affect cell performance.

2. Theoretical Study

We consider a CIGS-based solar cells whose simplified structure is shown in Figure 1.

In this study, we will neglect the contribution of the emitter by focusing only on the bottom-up contribution. Under the effect of frequency-modulated monochromatic optical excitation, minority charge (electrons) carriers are generated in the absorbing layer of the solar cells. The continuity equation of the minority carriers in the x -axis base in frequency dynamic regime is of the form: [4, 5]

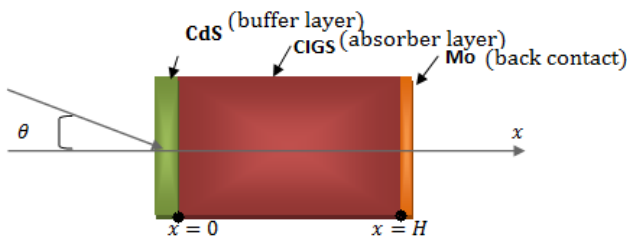


Figure 1. Simplified scheme of a one-dimensional CIGS-based solar cell.

Where θ is the angle of incidence, H is the thickness of the base.

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

With $D(\omega)$ the complex diffusion coefficient of minority carriers; $\delta(x, \theta, t)$ the density of minority carriers; $G(x, \theta, t)$ the generation rate of minority carriers [6, 7] and τ the average life of minority carriers θ angle of incidence; t is time.

The density and generation rate of minority carriers can be set respectively in the form [8, 9]:

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

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

Where $\delta(x, \theta)$ and $g(x, \theta)$ are the spatial component and $e^{(-i\omega t)}$ is the temporal component.

For illumination from the front face of the solar cell and depending on the angle of incidence, the spatial component of the generation rate is:

$$g(x, \theta) = \alpha(\lambda) \Phi(\lambda) (1 - R(\lambda)) \cos \theta e^{-\alpha(\lambda)x} \quad (4)$$

Where $\alpha(\lambda)$ is the absorption coefficient at the wavelength λ ; $R(\lambda)$ is the reflection coefficient of the material, $\Phi(\lambda)$ the incident photon flux, and θ the incidence angle.

By replacing equations (2), (3) and (4) in equation (1) we get:

$$\frac{\partial^2 \delta(x, \theta)}{\partial x^2} - \frac{\delta(x, \theta)}{L_\omega^2} + \frac{g(x, \theta)}{D_\omega} = 0 \quad (5)$$

with

$$L_\omega = L_0 \sqrt{\frac{(1-i\omega\tau)}{1+(\omega\tau)^2}} \quad (6)$$

L_0 intrinsic diffusion length

L_ω the complex diffusion length

The general solution of the preceding equation (5) is given by the relation (7).

$$\delta(x, \theta) = A \cosh\left(\frac{x}{L_\omega}\right) + B \sinh\left(\frac{x}{L_\omega}\right) - \frac{\alpha(\lambda) \Phi(\lambda) (1 - R(\lambda)) L_\omega^2 \cos \theta}{D_\omega (\alpha^2(\lambda) L_\omega^2 - 1)} e^{-\alpha(\lambda)x} \quad (7)$$

The constants A and B are determined from the following boundary conditions: [10]

At junction $x=0$:

$$\left. \frac{\partial \delta(x, \theta)}{\partial x} \right|_{x=0} = \frac{SF}{D_\omega} \delta(0, \theta) \quad (8)$$

on the rear face of the base ($x=H$):

$$\left. \frac{\partial \delta(x, \theta)}{\partial x} \right|_{x=H} = -\frac{SB}{D_\omega} \delta(H, \theta) \quad (9)$$

SF and SB denote the recombination speeds of the minority

load carriers at the junction and rear face of the base respectively.

The expression of minority carriers density is expressed as a function of the CIGS absorption coefficient. This coefficient depends on gallium doping and is given by:

$$\alpha(\lambda, X) = A \sqrt{\left(\frac{hc}{\lambda} - E_g(X)\right)} \quad (10)$$

with A (cm⁻¹ eV^{-1/2}) a constant [11].

$E_g(X)$ band gap of the CIGS base as a function of gallium doping level.

Note that: The ratio $X = \frac{[Ga]}{([In] + [Ga])}$ referred to in this article as the gallium doping level, determines the proportion of gallium atoms that replace indium atoms in the structure. The width of the CIGS band gap varies as a function of X between the values of pure CIS and pure CGS, according to the following empirical law [12]: $E_g(X) = 1,035 + 0,65X - 0,264X(1 - X)$.

Beyond the expressions of minority carriers density, photocurrent density and photovoltage are determined according to the angle of incidence of gallium doping rate, frequency and wavelength.

The photocurrent density is given by the following expression:

$$J(\lambda, \omega, SF, SB, \theta, X) = q \cdot D_{\omega} \cdot \left. \frac{\partial \delta(x, \lambda, \omega, SF, SB, \theta, X)}{\partial x} \right|_{x=0} \quad (11)$$

where q is the elementary charge.

λ , wavelength, ω , angular frequency, SF, recombination rate at the junction, SB, recombination rate at the rear surface, θ , angle of incidence, X, gallium doping concentration.

The short-circuit photocurrent density is obtained from the expression of the photocurrent density (11) by tending the recombination velocity at the SF junction towards a very large limit.

$$J(\lambda, \omega, SF, SB, \theta, X)|_{SF \rightarrow 5.10^5} \rightarrow J_{cc}(\lambda, \omega, SB, \theta, X) \quad (12)$$

From the excess minority carriers' density, we can deduce the photovoltage across the junction, according to the Boltzmann's relation as follow.

$$V(\lambda, \omega, SF, SB, \theta, X) = V_T \ln \left[\frac{Nb}{n_0} \delta(0, \lambda, \omega, SF, SB, \theta, X) + 1 \right] \quad (13)$$

with V_T the thermal voltage, Nb the base doping density, n_0 the intrinsic carriers' density.

λ , wavelength, ω , angular frequency, SF, recombination rate at the junction, SB, recombination rate at the rear surface, θ , angle of incidence, X, gallium doping concentration.

Thus, the open-circuit photovoltage will be deducted from the photovoltage by tending the recombination rate at the SF junction towards zero.

$$V(\lambda, \omega, SF, SB, \theta, X)|_{SF \rightarrow 0} \rightarrow V_{co}(\lambda, \omega, SB, \theta, X) \quad (14)$$

The impedance of the photovoltaic cell that will be the subject of our study is given by the following expression.

$$Z(\lambda, \omega, SF, SB, \theta, X) = \frac{V_{co}(\lambda, \omega, SF, SB, \theta, X)}{J_{cc}(\lambda, \omega, SF, SB, \theta, X)} \quad (15)$$

λ , wavelength, ω , angular frequency, SF, recombination rate at the junction, SB, recombination rate at the rear surface, θ , angle of incidence, X, gallium doping concentration.

This dynamic impedance of the photovoltaic cell will be studied using Nyquist and Bode diagrams. This will enable assessments to be made of the solar cell model.

Furthermore, the power supplied by the photovoltaic cell under monochromatic illumination of wavelength (λ_i) and for a given operating point at SF is expressed by the expression

$$P = I \cdot V_{ph} \quad (16)$$

avec

$$I = J_{ph} - Id \quad (17)$$

where Id is the diode current, J_{ph} photocurrent density

The FF form factor is the ratio between the maximum power supplied by the photovoltaic cell P_{max} and the product of the short-circuit current J_{cc} and the open-circuit voltage V_{co} (i.e., the maximum power of an ideal cell).

It is expressed by equation (18):

$$FF = \frac{P_{max}(\lambda, \omega, SB, SF, \theta, X)}{V_{co}(\lambda, \omega, SB, SF, \theta, X) \cdot J_{cc}(\lambda, \omega, SB, SF, \theta, X)} \quad (18)$$

λ , wavelength, ω , angular frequency, SF, recombination rate at the junction, SB, recombination rate at the rear surface, θ , angle of incidence, X, gallium doping concentration

Efficiency is the ratio of the maximum power delivered by the cell to the incident light power. Efficiency is given by equation (19):

$$\eta = \frac{P_{max}(\lambda, \omega, SB, SF, \theta, X)}{P_{in}(\lambda)} = FF \frac{V_{co} J_{cc}}{P_{in}(\lambda)} \quad (19)$$

Where $P_{in}(\lambda)$ is the incident power of light and is equal to solar power.

Subsequently, we will also study the effects of the angle of incidence and the gallium doping level on power, form factor, and efficiency.

3. Results and Discussions

3.1. Study of the Impedance Bode Diagram

The Bode diagram [13] is a method developed to simplify the obtaining of frequency response plots.

In our work, it is a question of adapting the Bode concept

to the plots of the amplitude of the impedance of the photopile and the phase of the impedance (in degrees) as a function of the logarithm of the pulsation.

3.1.1. Effect of the Angle of Incidence

Figure 2 shows the variation of the impedance modulus as a function of the logarithm of the pulsation, for different values of the incidence angle.

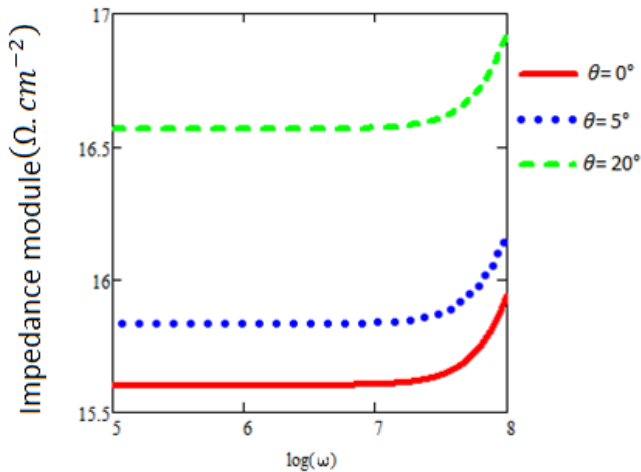


Figure 2. Impedance modulus as a function of the logarithm of the pulsation for different values of the incidence angle.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s};$$

$$\lambda = 0.6\mu\text{m}; X = 0,3$$

In this Figure 2, we distinguish two areas of dynamic impedance evolution:

- 1) the first zone corresponding to the pulsation interval $\left[0 \frac{\text{rad}}{\text{s}}; 3,16 \cdot 10^7 \text{ rad/s}\right]$: the impedance modulus remains constant; this is the quasi-static regime,
- 2) the second zone corresponding to the pulsation interval $\left[3,16 \cdot 10^7 \text{ rad/s}; 10^8\right]$ there is an increase in the impedance modulus with the logarithm of the pulsation; this is the dynamic regime.

In addition, Figure 2 shows that the dynamic impedance modulus increases with the incidence angle. But this variation in incidence angle does not affect the resonance pulse corresponding to the beginning of the variation of the impedance modulus with the pulse.

3.1.2. Effect of the Gallium Doping Rate on the Impedance Module

In Figure 3 we represent the impedance modulus as a function of the logarithm of the pulsation for different gallium doping rates.

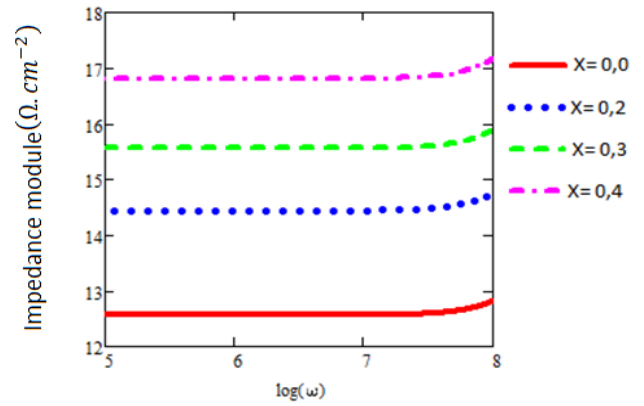


Figure 3. Impedance modulus as a function of the logarithm of the pulsation for different gallium doping rates.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s};$$

$$\lambda = 0.6\mu\text{m}; \theta = 0,0^\circ$$

In this Figure 3 we observe two pulsation zones: the pulsation range $\left[0 \frac{\text{rad}}{\text{s}}; 3,16 \cdot 10^7 \text{ rad/s}\right]$ where the modulus is a constant; it is the quasi-static regime and that $\left[3,16 \cdot 10^7 \text{ rad/s}; 10^8\right]$ where the modulus increases; it is the dynamic regime. It should be noted that the increase in the gallium doping rate increases the dynamic resistance without affecting the pulsation limiting the two zones.

3.2. Study of the Bode Diagram of the Impedance Phase

This involves representing the impedance phase as a function of the logarithm of the pulse in Figures 4 and 5.

3.2.1. Effect of the Angle of Incidence on the Impedance Phase

Figure 4 shows the variation of the impedance phase as a function of the logarithm of the pulsation for different values of the incidence angle.

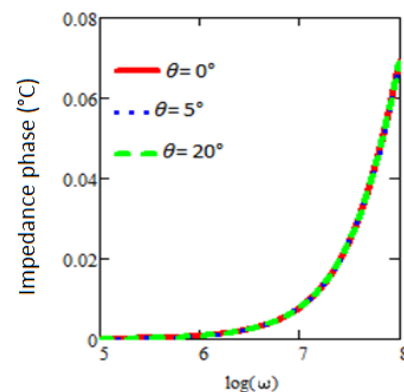


Figure 4. Impedance phase as a function of the logarithm of the pulsation for different values of the incidence angle.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s};$$

$$\lambda = 0,6\mu\text{m}; X = 0,3$$

Figure 4 illustrates the variation of the impedance phase as a function of the logarithm of the pulsation. Thus we distinguish in this graph two distinct domains. The first domain corresponds to pulsations lower than 10^6 rad/s where the phase is almost equal to zero. In this field there is no phase shift between the signal and the product carriers. The second part corresponds to pulsations higher than 10^6 rad/s , where we observe an increase in the phase with the pulsation. Thus there is a phase shift between the incident signal and the carriers produced. The observation of the Figure 4 indicates that the angle of incidence does not affect the phase, either the pulsation limiting the effects of the phase shift.

3.2.2. Effect of the Gallium Doping Rate on the Impedance Phase

Figure 5 shows the variation of the impedance phase as a function of the logarithm of the pulsation for different gallium doping rates.

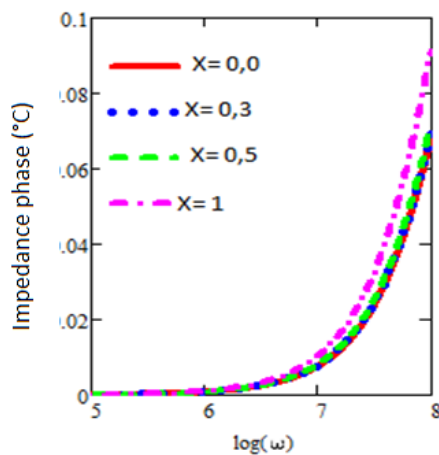


Figure 5. Impedance phase as a function of the logarithm of the pulsation for different gallium doping rates.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s};$$

$$\lambda = 0,6\mu\text{m}; \theta = 0,0^\circ$$

In this Figure 5 is presented the variation of the impedance phase as a function of the logarithm of the pulsation for different gallium doping rates. We also distinguish two areas. The first domain with pulsations lower than 10^6 rad/s ; the phase is almost null, there is no phase shift between the signal and the carriers produced. The second domain corresponds to pulsations higher than 10^6 rad/s . Here we observe an increase in the phase with the increase in pulsation, there is a phase shift between the incident signal and the carriers produced. Figure 5

also shows that the increase in the gallium doping rate increases the impedance phase. But also we are witnessing a slight decrease in the pulsation limiting the effects of phase shift between the signal and the carriers produced.

3.3. Study of the Nyquist Diagram of Impedance

The Nyquist diagram [13-15] is the representation of the imaginary part as a function of the real part of the complex impedance $Z(\lambda, SB, SF, \theta, X)$.

3.3.1. Effect of the Angle of Incidence

Figure 6 shows the Nyquist diagram of impedance with incidence angle effects.

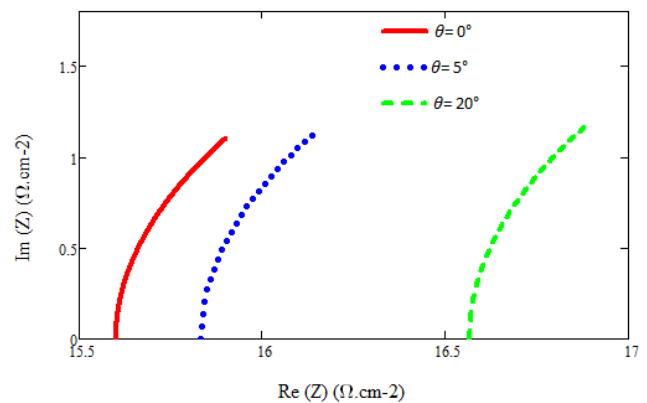


Figure 6. The imaginary part as a function of the real part of the impedance for different values of the incidence angle.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s};$$

$$\lambda = 0,6\mu\text{m}; X = 0,3$$

Figure 6 illustrates the variation of the Nyquist diagram with the effects of the incidence angle.

The Nyquist diagram of dynamic impedance shows us quadrants of circle. Thus the appearance of the curves shows the increase of the imaginary part with the increase of the real impedance bet according to the pulsation of the incident radiation.

In addition, Figure 6 shows that from the real part increases with the angle of incidence in the vicinity of zero pulsations, the maximum of the curves towards the high limit frequencies remains a constant regardless of the angle of incidence. Thus the radius of the quadrants of circle remains a constant.

3.3.2. Effect of the Gallium Doping Rate

Figure 7 shows the Nyquist diagram of impedance with the effects of gallium doping rate.

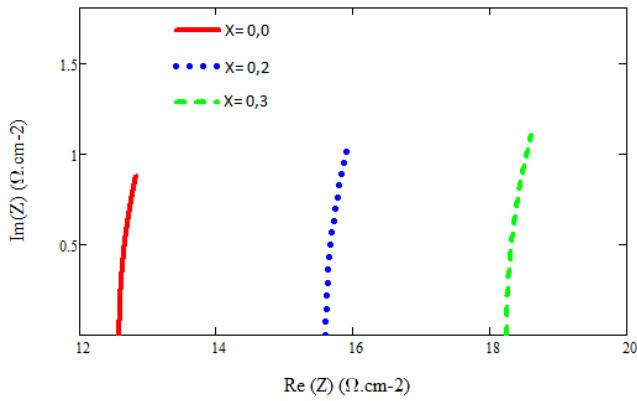


Figure 7. The imaginary part as a function of the real part of the impedance for different levels of gallium doping.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s};$$

$$\lambda = 0,6\mu\text{m}; \theta = 0,0^\circ$$

This **Figure 7** shows the variation of the imaginary part as a

function of the real part of the impedance for different levels of gallium doping. The Nyquist diagram of the dynamic impedance thus represented gives quadrants of circle. The appearance of the curves shows the increase of the imaginary part with the real impedance bet according to the pulsation of the incident radiation.

Subsequently all the curves show that the real part increases with the gallium doping rate in the vicinity of the zero pulsations. In addition, we observe that the maximum of the curves increases with the gallium doping rate towards the high limit frequencies. This shows the increase in the radii of these quadrants of circle. The effects of the gallium doping rate on this representation bodes well for a variation in shunt and series resistances with the gallium doping rate.

3.4. Study of the Power of the Photovoltaic Cell

3.4.1. Effect of the Angle of Incidence on Power

Figure 8 shows the variation in power as a function of photovoltage for different values of the angle of incidence.

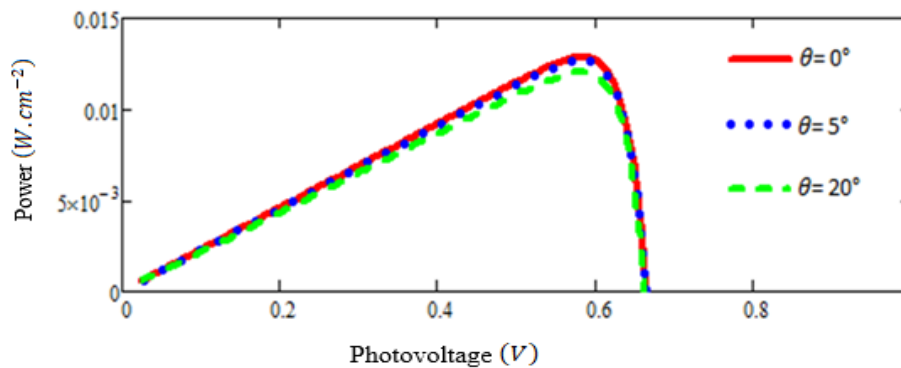


Figure 8. Module of the photovoltaic cell power as a function of the photovoltage for different values of the angle of incidence.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s};$$

$$\omega = 3.10^3 \text{ rad.s}^{-1}; \lambda = 0,6\mu\text{m}; X = 0,3$$

Figure 8 above shows that the electrical power module increases with photovoltage until it reaches its maximum value, which corresponds to the maximum operating point of the solar cell. From this value, the power gradually decreases and tends towards almost zero values when the photovoltage tends towards the open-circuit photovoltage value. In addition,

the power module decreases as the angle of incidence increases, highlighting the effects of attenuation of radiation intensity. Thus, increasing the angle of incidence reduces the cell's efficiency in capturing incident energy.

3.4.2. Effect of the Gallium Doping Rate on the Power

Figure 9 shows the variation in power as a function of photovoltage for different gallium doping levels.

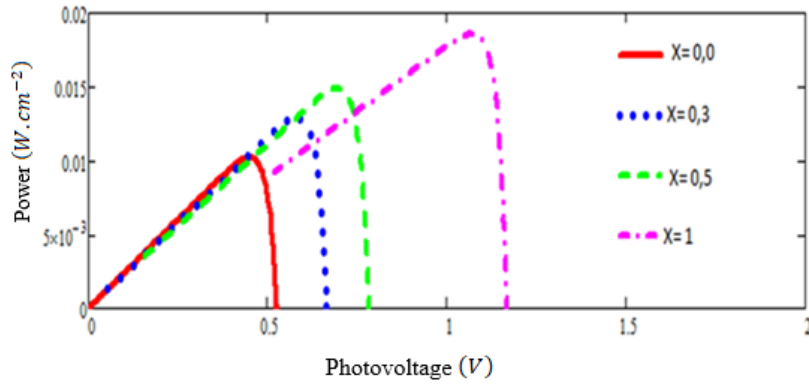


Figure 9. Variation of the power module as a function of the photovoltage for different values of the gallium doping rate.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s}; \omega = 3.10^3 \text{ rad.s}^{-1}; \lambda = 0,6\mu\text{m}; \theta = 0,0^\circ$$

In Figure 9, we observe the same trends for the four curves. An increase in the power module with photovoltage reaching its maximum value and then gradually decreasing towards zero. Furthermore, increasing the gallium doping results in an increase in power..

3.5. Study of the Form Factor of the Photovoltaic Cell

3.5.1. Effect of the Angle of Incidence on the Form Factor

Figure 10 shows the variation in the form factor as a function of the angle of incidence.

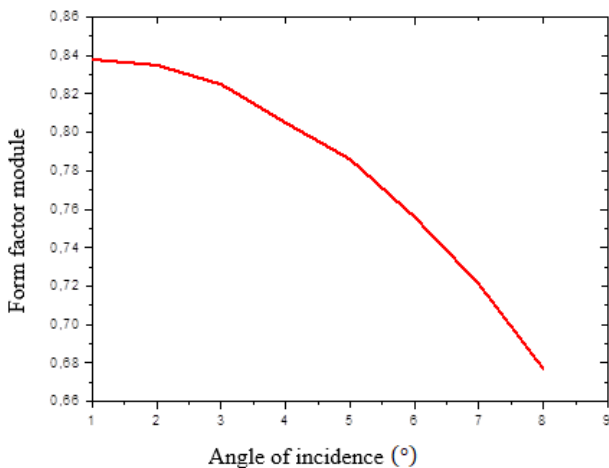


Figure 10. Form factor module as a function of the angle of incidence.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s};$$

$$\omega = 10^3 \text{ rad/s}; \lambda = 0.6\mu\text{m}; X = 0.3$$

Figure 10 shows the variation in the form factor modulus with the angle of incidence. We observe a decrease in the form factor as the angle of incidence increases. In fact, in the previous figure, we observed a decrease in the power modulus as the angle of incidence increased. These effects are reflected in the form factor.

3.5.2. Effect of the Gallium Doping Rate on the Form Factor

In Figure 11, we show the form factor module as a function of the gallium doping level.

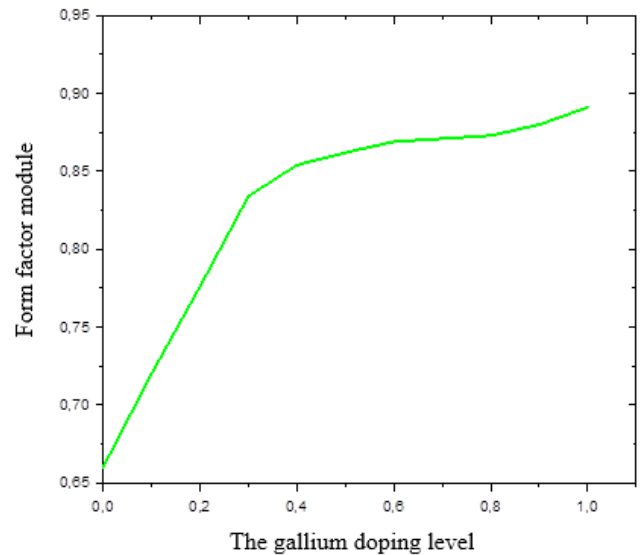


Figure 11. Variation in the modulus of the shape factor with the gallium doping level.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s};$$

$$\omega = 10^3 \text{ rad/s}; \lambda = 0,6\mu\text{m}; \theta = 0,0^\circ$$

Figure 11 illustrates the variation in the form factor with the doping level. We observe an increase in the form factor with

an increase in the gallium doping level. Two phases can be distinguished: the first, with a doping level between 0 and 0.3, shows an almost linear increase in the form factor, indicating a gradual improvement in the conductivity of the material and the quality of the contacts. The second phase, with a doping level above 0.3, shows a slight deterioration in the conductivity of the material..

3.6. Study of Photovoltaic Cell Efficiency

3.6.1. Study of the Effect of the Angle of Incidence on Photovoltaic Conversion Efficiency

In Figure 12, we show the variation in efficiency as a function of the angle of incidence.

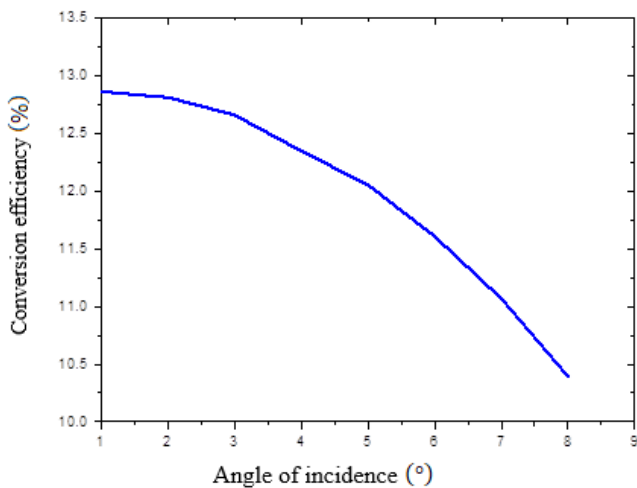


Figure 12. Photovoltaic conversion efficiency as a function of the angle of incidence.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s}; \omega = 10^3 \text{ rad/s}; \\ \lambda = 0,6\mu\text{m}; X = 0,3$$

Figure 12 illustrates the variation in solar cell efficiency as a function of the angle of incidence. We observe a decrease in efficiency as the angle of incidence increases. Similar to the decrease in power and form factor as the angle of incidence increases, we also see the same effects on efficiency. Indeed, a decrease in the angle of incidence is accompanied by a decrease in minority carriers and therefore a decrease in efficiency.

3.6.2. Effect of Gallium Doping Concentration on Photovoltaic Conversion Efficiency

Figure 13 shows the variation in the photovoltaic conversion efficiency of the cell with the gallium doping level.

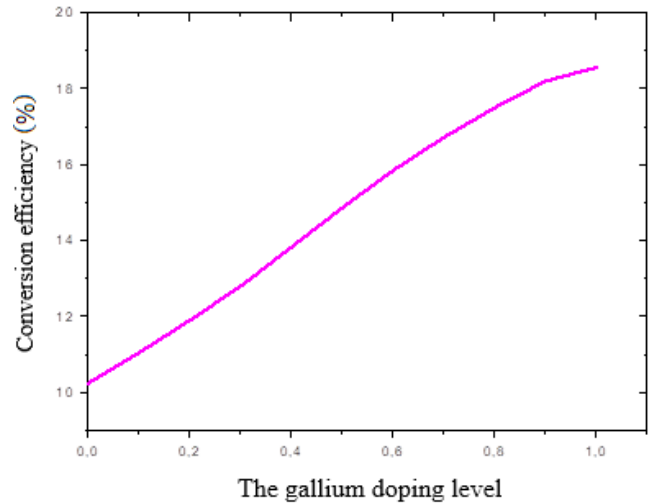


Figure 13. Variation in photovoltaic conversion efficiency with gallium doping level.

$$SF = 3.10^3 \text{ cm/s}; SB = 3.10^3 \text{ cm/s}; \omega = 10^3 \text{ rad/s}; \\ \lambda = 0,6\mu\text{m}; \theta = 0,0^\circ$$

Figure 13 above illustrates the evolution of photovoltaic conversion efficiency with gallium doping levels. Cell efficiency increases with gallium doping levels. Gallium doping therefore enhances cell performance.

4. Conclusion

The dynamic impedance of the CIGS-based solar cell was studied using Bode and Nyquist diagrams. The study shows characteristic areas of pulsation highlighting the dynamic range. These diagrams also allowed us to deduce the dominance of inductive effects in the cell. In addition, the effects of the angle of incidence and the gallium doping rate were also discussed. Furthermore, the effects of the gallium doping rate and the angle of incidence studied on the power, form factor, and efficiency of the CIGS-based solar cell show that increasing the angle of incidence decreases the cell's performance by reducing the power, form factor, and therefore the efficiency of the cell. However, increasing the doping rate improves cell performance, with an optimal rate of 0.3 being most noticeable in terms of form factor. This rate of 0.3 is consistent with most experimental results published in the field of CIGS cells, which show that the best yields are obtained with a gap of approximately 1.2 eV [16], corresponding to a Ga rate close to 30%.

Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

$\delta(x, \theta, t)$	density of minority carriers (cm^{-3})
J_{ph}	Photocurrent density module (A. cm^{-2})
J_{phcc}	short-circuit photocurrent density (A. cm^{-2})
ω	Angular frequency (rad. s^{-1})
λ	Wavelength (μm)
V_{ph}	Photovoltage Module (V)
V_{co}	Open-circuit photovoltage (V)
SF	Recombination Speed at the junction (cm. s^{-1})
SB	Recombination Speed at the rear face (cm. s^{-1})
X	Gallium doping rate
P	Solar cell power (W. cm^{-2})
FF	Form Factor (%)
η	Cell Efficiency (%)

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