

Research Article

Optimization of Performance in Thin-Film CIGS Solar Cells: Silvaco Simulation of Doping and Absorber Layer Thickness

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Abstract

This study investigates the effects of doping concentration and absorber layer thickness on the performance of Cu(In,Ga)Se₂ (CIGS) thin-film solar cells using detailed numerical simulations. The work focuses on identifying optimal design parameters to maximize power conversion efficiency by analyzing their influence on key device characteristics, including short-circuit current density, open-circuit voltage, and fill factor. The results indicate that the doping concentration critically impacts carrier transport and recombination dynamics. An optimal doping level of $6 \times 10^{16} \text{ cm}^{-3}$ enhances charge carrier collection, leading to simultaneous improvements in short-circuit current density, open-circuit voltage, and fill factor. Doping beyond this value increases series and shunt resistances, which reduces the efficiency gains, emphasizing the importance of precise doping control. The absorber layer thickness also plays a significant role in device performance. Increasing the thickness from 0.1 μm to 1 μm substantially improves photon absorption and carrier generation, resulting in a marked enhancement in efficiency. However, further increasing the thickness above 1 μm yields only marginal efficiency gains, as photon absorption reaches saturation and the recombination rate increases, highlighting the trade-off between absorption depth and minority carrier lifetime. Overall, the study demonstrates that careful optimization of both doping and absorber thickness is essential to achieving high-efficiency CIGS solar cells. Specifically, a doping concentration of $6 \times 10^{16} \text{ cm}^{-3}$ combined with an absorber thickness in the range of 0.1-1 μm provides the most favorable conditions for device performance. These findings offer practical guidelines for experimental fabrication and numerical optimization, contributing to the design of more efficient thin-film photovoltaic devices. The insights provided by this work can guide future research in enhancing the performance of CIGS solar cells and other related thin-film technologies.

Keywords

CIGS Solar Cells, Doping, Absorber Thickness, Efficiency, Short-Circuit Current, Open-Circuit Voltage, Fill Factor

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1. Introduction

CIGS is a material characterized by a direct optical bandgap, a high absorption coefficient in the visible range, and the ability to exhibit p-type conductivity without requiring external doping by impurities [1]. However, the development of CIGS-based solar cells is limited by the availability and high cost of elements like indium and gallium [2], highlighting the need to optimize the performance of electronic devices based on this material. The objective of this study is to analyze the impact of doping rate and the reduction of the absorber layer thickness on the performance of thin-film CIGS solar cells. To achieve this, we conducted a numerical simulation of a model solar cell using the ATLAS software from SILVACO [3].

The study is structured in two main parts: the first part covers the state of the art of the structural, optical, and electrical properties of thin-film CIGS layers, while the second part presents the principle of the numerical simulation performed with ATLAS, the structure of the studied solar cell, the properties of materials and defects, and the analysis of the results obtained.

2. Properties of CIGS Thin Films

2.1. Structural Properties

Copper indium diselenide (CuInSe_2), often referred to as CIS, crystallizes in the chalcopyrite phase, which is derived from the zinc blende structure of ZnS . The chalcopyrite structure of CIS is a tetragonal system composed of two face-centered cubic lattices that are stacked and offset by one-quarter of the diagonal. In this structure, each selenium (Se) atom is surrounded by two copper (Cu) atoms and two indium (In) atoms. Consequently, each cation (Cu^+ or In^{3+}) is surrounded by four selenium anions (Se^{4-}) [4].

By convention, the smaller edge is denoted as 'a' and the larger edge as 'c'. These are known as lattice parameters, with values reported in the literature as: $a = 5.782\text{\AA}$ and $c = 11.620\text{\AA}$. If the temperature exceeds 800°C , the anions move from their tetrahedral sites. In this case, the cations (Cu^+ and In^{3+}) randomly occupy cationic sites, forming tetrahedra whose centers are occupied by anions (Se^{4-}). As a result, the CIS structure transitions from the chalcopyrite phase to the sphalerite phase [5]. Both of these structures are illustrated in Figure 1 [6].

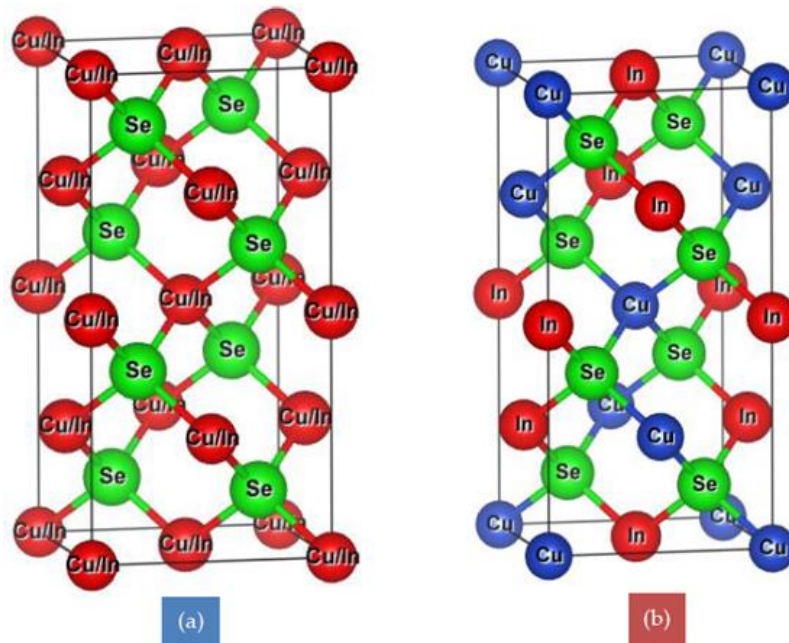


Figure 1. CIGS Structure (a): Sphalerite (b): Chalcopyrite.

Copper indium gallium diselenide ($\text{CuIn}_{1-x}\text{Ga}_x\text{Se}_2$), abbreviated as CIGS, also crystallizes in the chalcopyrite phase, similar to CIS, from which it is derived by partially substituting indium with gallium atoms. In the case of CIGS, the lattice parameters vary according to the gallium content, defined by $X = \text{Ga}/(\text{In} + \text{Ga})$, following the linear functions given by [7]:

$$a = 5.784 - 0.175x \quad (1)$$

$$c = 11.608 - 0.572x \quad (2)$$

Thus, the structure of CIGS is influenced by the gallium content and is often determined using X-ray diffraction. This technique is based on the principle of Rayleigh scattering, which produces alternating constructive and destructive interference. When the interference is constructive, the interplanar spacing can be calculated using Bragg's law:

$$2d_{hkl} \cdot \sin\theta = n \cdot \lambda \quad (3)$$

where d_{hkl} (cm) is the interplanar distance, θ (degrees) is the diffraction angle, n is the diffraction order, and λ (cm) is the wavelength of the X-ray beam.

The structure of CIGS is tetragonal ($\alpha = \beta = \gamma = \frac{\pi}{2}$ et $a = b \neq c$), and the lattice parameters (a and c) can be determined using the following relation:

$$\frac{1}{d_{hkl}^2} = \frac{h^2 + k^2}{a^2} + \frac{l^2}{c^2} \quad (4)$$

where h , k , and l are the Miller indices [8].

2.2. Optical Properties

CIGS is a direct bandgap semiconductor, with a high absorption coefficient in the visible and near-infrared range (105 cm^{-1}). It can be determined from the following relation:

$$\alpha = \frac{1}{d} \ln \left[\frac{(1-R)^2}{2T} + \sqrt{\frac{(1-R)^4}{2T^2} + R^2} \right] \quad (5)$$

where α (cm^{-1}) is the absorption coefficient, d (μm) is the layer thickness, R is the reflection coefficient, and T is the transmission coefficient [9].

Other studies show that the optical bandgap of such a semiconductor is related to its absorption coefficient by the relation:

$$(\alpha h\nu)^2 = A(h\nu - E_g) \quad (6)$$

where A ($J \cdot \text{cm}^{-2}$) is a proportionality constant, h ($J \cdot s$) is Planck's constant, ν (Hz) is the frequency, and E_g (eV) is the bandgap.

The optical bandgap of CIGS also depends on the gallium content, and it can be adjusted between 1.04 eV for CuInSe_2 and 1.68 eV for CuGaSe_2 . In several studies, it has been approximated by the following relation:

$$E_g = 1,04 + 0,64x - 0,15x(1 - x) \quad (7)$$

For CIGS-based solar cells, the best efficiencies have been obtained with an optical bandgap of around 1.2 eV, corresponding to an X value of about 0.3. However, theoretical predictions indicate that the optimal bandgap for this material is 1.5 eV, which would allow it to absorb a wider range of wavelengths from the solar spectrum and thus improve efficiency [10].

The optical bandgap of CIGS can be determined using UV-Visible spectroscopy. By analyzing the transmittance spectrum of CIGS, the $\alpha^2 = f(h\nu)$ curve can be plotted to deduce its optical bandgap E_g or the width of its forbidden band [11].

2.3. Electrical Properties

CIS can exhibit either n-type or p-type conductivity without external doping. This internal doping is due to the presence of intrinsic defects that depend on the composition, technique, and growth conditions of the material. The concentration of these defects is given by Neumann's relation:

$$N_{\text{def}} = N_0 \exp\left(-\frac{\Delta H_f}{KT}\right) \quad (8)$$

where ΔH_f (eV) is the formation enthalpy, K ($J \cdot s^{-1}$) is the Boltzmann constant, N_{def} (cm^{-3}) is the defect concentration at temperature T (K) and N_0 is a constant.

Deviations from the molecular and stoichiometric balance of valence are given by the relations:

$$\Delta X = \frac{[Cu]}{[In]} - 1 \quad (9)$$

$$\Delta Y = \frac{2[Se]}{[Cu]+3[In]} - 1 \quad (10)$$

where $[Cu]$, $[In]$ and $[Se]$ are the concentrations of Cu, In, and Se in CuInSe_2 [12].

Neumann established, based on the values and signs of ΔX and ΔY , a correlation between the composition of CIS and its conductivity. For polycrystalline films with small deviations from the ideal stoichiometry, p-type conduction is always observed. However, for single-crystal films, n-type conduction is observed for $\Delta X > 0$ and $\Delta Y < 0$, or $\Delta X < 0$ and $\Delta Y < 0$ with small deviations from the ideal stoichiometry [13].

Unlike CIS, which can be either n-type or p-type, thin-film CIGS is always p-type. This could be explained by the reduction of the formation energy of deep defects, such as CuIn and VCu, in the presence of gallium [14].

The electrical properties of CIGS thin films can be determined using the Hall effect measurement technique. This method involves applying a magnetic field perpendicular to the layer, generating an electric voltage called the Hall voltage. By measuring this Hall voltage for precise current and magnetic field values, the concentration of carriers (electrons and holes) and their mobility can be determined [15].

3. Numerical Simulation

3.1. Principle

The principle of numerical simulation for semiconductor-based devices relies on solving a set of fundamental equations. These equations, derived from Maxwell's equations, mainly include the Poisson equation, the continuity equations, and the transport equations. During this process, a simulator such as the ATLAS software calculates, at every point in space and at each instant, the carrier concentrations (electrons and holes) in the device, as well as the electrostatic potential.

i) Poisson's Equation

Poisson's equation relates the variations in electrostatic potential to the volumetric charge density, and is expressed as:

$$\Delta V + \frac{\rho}{\varepsilon} = 0 \quad (11)$$

where V is the electrostatic potential, ε is the dielectric permittivity, and ρ is the volumetric charge density.

ii) Continuity Equation

The continuity equations for electrons and holes are given by:

$$\frac{\partial n}{\partial t} = +\frac{1}{q} \text{div} \vec{J}_n + G_n - R_n \quad (12)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q} \text{div} \vec{J}_p + G_p - R_p \quad (13)$$

where, $\vec{J}_n$ and $\vec{J}_p$ represent the current density of electrons and holes, G_n and G_p are the generation rates of electrons and holes, while R_n and R_p are the recombination rates of electrons and holes.

In the steady state, the carrier concentration no longer depends on time, and the continuity equations become:

$$-\frac{1}{q} \text{div} \vec{J}_n = G_n - R_n \quad (14)$$

$$+\frac{1}{q} \text{div} \vec{J}_p = G_p - R_p \quad (15)$$

iii) Transport Equations

The transport equations, derived by approximating current densities using a drift-diffusion model based on Boltzmann transport theory, are given by the following relations:

$$\vec{J}_n = qn\mu_n \vec{E}_n + qD_n \nabla n \quad (16)$$

$$\vec{J}_p = qp\mu_p \vec{E}_p + qD_p \nabla p \quad (17)$$

where D_n is the electron diffusion coefficient and D_p is the hole diffusion coefficient, given by the Einstein relations:

$$D_n = \frac{KT}{q} \mu_n \quad (18)$$

$$D_p = \frac{KT}{q} \mu_p \quad (19)$$

with, μ_n being the electron mobility, μ_p the hole mobility, K the Boltzmann constant, and q the elementary charge.

The above equations are taken from the user manual of the ATLAS - SILVACO modeling and simulation software [16].

3.2. Simulation Structure and Parameters

In this work, an experimental CIGS thin-film solar cell was modeled and simulated using the ATLAS - SILVACO soft-

ware. The cell was fabricated by screen printing, and its structure is as follows: Pt-Al/ZnO/CdS/CIGS/Mo/PET [3].

To avoid shading effects that reduce illumination and thus efficiency, the Pt-Al grid was replaced by two aluminum contacts. Aluminum is a highly conductive, lightweight, and chemically stable metal, resistant to corrosion through the formation of a protective alumina (Al_2O_3) layer. This makes it a suitable material for photovoltaic applications such as CIGS thin-film solar cells [17].

The structure diagram is shown in Figure 2.

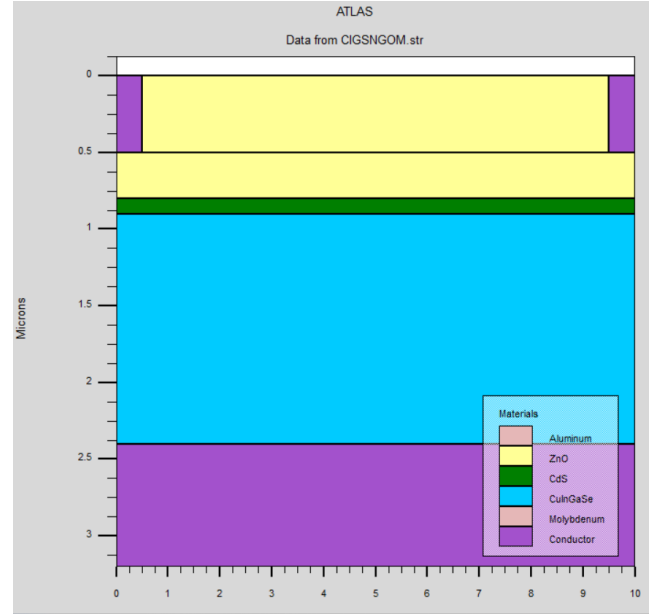


Figure 2. Schematic of the simulated structure.

The simulation parameters used in this study are derived from the literature, particularly from references [10, 18].

We used the following models in our simulation:

The Shockley-Read-Hall (SRH) recombination model for defects. In this model, the recombination rate for a trap i is given by:

$$R_{SRH,i} = \frac{pn - n_i^2}{\tau_n(p + n_i \exp \frac{E_i - E_t}{KT}) + \tau_p(n + n_i \exp \frac{E_t - E_i}{KT})} \quad (20)$$

where E_i is the Fermi energy level in the intrinsic semiconductor, τ_n is the electron lifetime and τ_p is the hole lifetime. These lifetimes are given by the following relations:

$$\tau_n = \frac{1}{\sigma_n v_{th} N_t} \quad (21)$$

$$\tau_p = \frac{1}{\sigma_p v_{th} N_t} \quad (22)$$

where σ_n and σ_p are the capture cross sections for electrons and holes by a trap i , v_{th} is the thermal velocity of carriers, and N_t is the trap density at an energy level E_t .

The model for recombination at interface and contact states: this is the recombination at the defects present at the CdS/CIGS interface and at the front and back contacts. It is modeled by a fixed recombination rate of 10^5 m/s in our study.

The defect density model: the materials used in our study contain a large number of defects. These donor state defects for CIGS and acceptor state defects for CdS and ZnO are modeled by a Gaussian distribution given by:

$$g_{GA}(E) = N_{GA} \exp \left[- \left[\frac{E_{GA} - E}{W_{GA}} \right]^2 \right] \quad (23)$$

$$g_{GD}(E) = N_{GD} \exp \left[- \left[\frac{E - E_{GD}}{W_{GD}} \right]^2 \right] \quad (24)$$

where N_{GA} and N_{GD} are the acceptor and donor defect state densities, E is the defect energy, W_{GA} and W_{GD} are the standard deviations, and, E_{GA} and E_{GD} are the Gaussian peak energies [10, 18].

Table 1. Material Properties.

Materials	CIGS	CdS	ZnO
Optical bandgap $E_{g300}(eV)$	1.2	2.4	3.3
Thickness $d(\mu m)$	1.5	0.1	0.8
Electron affinity $\chi(eV)$	4.8	4.5	4.1
Relative dielectric permittivity ϵ_r	13.6	10	9
Effective electron state density $N_{C300}(cm^{-3})$	2.2. e18	2.2. e18	2.2. e18
Effective hole state density $N_{V300}(cm^{-3})$	1.8.e19	1.8.e19	1.8.e19
Electron mobility $\mu_n(cm^2.V^{-1}.s^{-1})$	100	100	100
Hole mobility $\mu_p(cm^2.V^{-1}.s^{-1})$	25	25	25
Electron lifetime $\tau_n(s)$	1.e-7	1.e-7	1.e-7
Hole lifetime $\mu_p(s)$	1.e-7	1.e-7	1.e-7
Acceptor concentration $N_A(cm^{-3})$	2.e16		
Donor concentration (cm^{-3})		1.e18	1.e18

Table 2. Defect Properties.

Materials	CIGS	CdS	ZnO
Gaussian defect	$N_{DG} = 1.e14$	$N_{DA} = 1.e15$	$N_{DA} = 1.e15$
Standard deviation W_{GA} and $W_{GD}(eV)$	0.1	0.1	0.1
Peak energy E_{GA} and $E_{GD}(eV)$	0.6	1.2	1.65
Electron capture cross section $\sigma_n(cm^2)$	1.e-17	1.e-17	1.e-17
Hole capture cross section $\sigma_p(cm^2)$	1.e-15	1.e-15	1.e-15

4. Results and Discussion

4.1. Effect of Doping Rate in the Absorber Layer

i) Effect of the doping rate of the absorber layer on the

current-voltage characteristic

Figure 3 below shows the current density versus voltage characteristic for different doping values of the absorber layer.

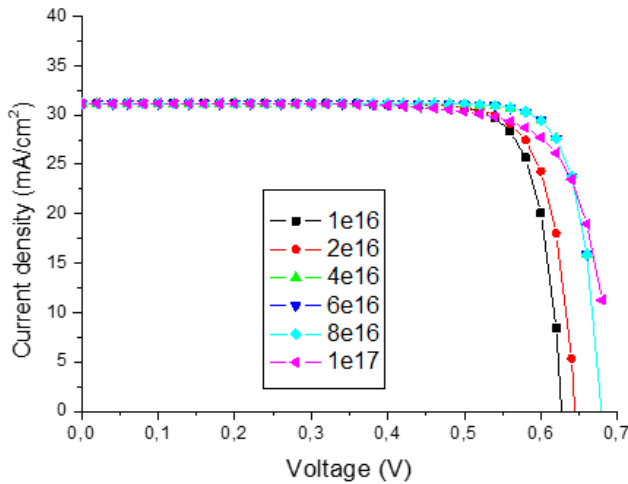


Figure 3. Current-voltage characteristic $J(V)$ for different doping rates of the CIGS absorber layer.

Figure 3 shows the $J(V)$ characteristics for different doping rates of the absorber layer. For $N_A = 4e16$ and $6e16 \text{ cm}^{-3}$ the characteristics are identical, as well as for $N_A = 8e16$ and $1e17 \text{ cm}^{-3}$. Aside from these two observations, we note that doping has almost no effect on the short-circuit current, but its influence is more pronounced on the open-circuit voltage, which increases with doping. To clarify these two effects further, we will next plot the current density and open-circuit voltage as a function of doping.

ii) *Effect of the doping rate of the absorber layer on the current density*

As mentioned in the previous paragraph, Figure 4 displays the short-circuit current density profile as a function of the doping rate of the absorber layer, in order to better observe its influence on the current density.

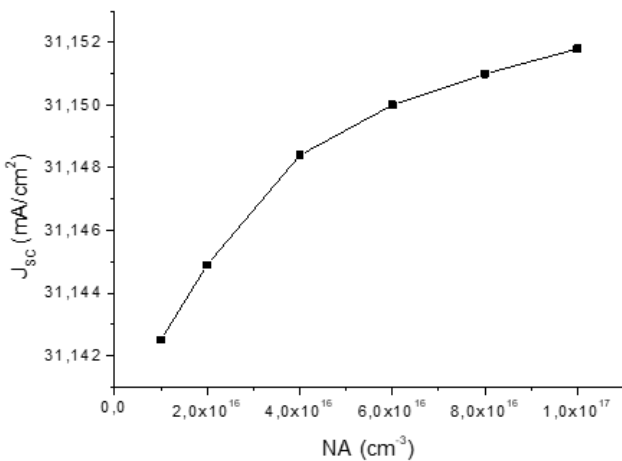


Figure 4. Short-circuit Current density as a function of the doping of the CIGS absorber layer.

Figure 4 shows that the current density increases from 31.1425 to 31.1518 mA/cm^2 when the doping rate of the

absorber layer changes from $1e16$ to $1e17$. Here, we observe a very slight increase in the short-circuit current density (J_{sc}) with doping ($+0,01 \text{ mA}/\text{cm}^2$ for a decade increase in doping). This can be explained by the behavior of the series resistance in the solar cell.

As the doping of the absorber layer increases, the carrier concentration in the material also increases, which could theoretically increase the photogenerated current, and therefore the short-circuit current density (J_{sc}). However, a higher doping concentration also leads to an increase in the series resistance of the cell, which is related to the material and contact resistance.

The series resistance, which is inversely proportional to the material's conductivity, is influenced by carrier mobility. At higher doping concentrations, although the carrier density increases, the carrier mobility tends to decrease due to increased collisions with defects and traps. This means that the material's conductivity may not increase proportionally with doping, and could even decrease, especially if additional defects are introduced.

Thus, the series resistance becomes more significant as the doping concentration increases, limiting the increase in J_{sc} . A high series resistance reduces the efficiency of carrier transport through the cell, preventing a significant increase in J_{sc} , despite a higher doping level [19].

In summary, the marginal increase in J_{sc} with increasing doping can be explained by the impact of series resistance, which, as it increases, limits current generation despite the increase in carrier density. This phenomenon emphasizes the importance of finding an optimal balance between doping, carrier mobility, and series resistance to maximize solar cell efficiency.

iii) *Effect of the doping rate of the absorber layer on the open-circuit voltage*

Figure 5 displays the open-circuit voltage profile as a function of the doping rate of the absorber layer.

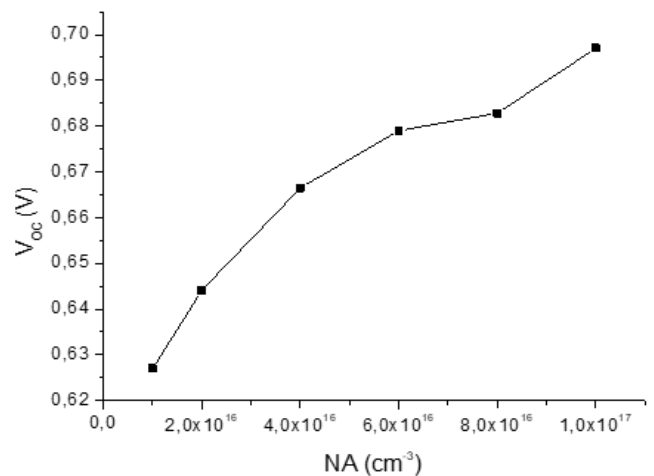


Figure 5. Open-circuit voltage as a function of the doping of the CIGS absorber layer.

Figure 5 shows that the open-circuit voltage increases from 0.6270 to 0.6970 V as the doping rate of the absorber layer increases from $1e16$ to $1e17$. In the same context, the open-circuit voltage (V_{OC}) increases by 0.07 V for a tenfold increase in the doping concentration of the absorber layer. This phenomenon can be explained by the combined effects of series resistance and the reduction in recombination with increasing doping.

The increase in open-circuit voltage with doping can mainly be attributed to a reduction in recombination losses, as well as to better carrier separation. However, this effect is counterbalanced by series resistance, although it has less impact on V_{OC} than on J_{SC} . Therefore, doping improves the cell's performance by increasing V_{OC} , but this must be balanced with the management of series resistance to optimize overall efficiency.

In addition to the series resistance, the shunt resistance plays an important role in the overall performance of the solar cell, especially in its effect on the open-circuit voltage (V_{OC}). The shunt resistance has a significant effect on the open-circuit voltage, particularly when it is low, as it causes current to bypass the active region of the solar cell, leading to energy losses and a reduction in V_{OC} . While doping can improve the open-circuit voltage by reducing recombination losses, it can also lead to a decrease in shunt resistance if it introduces defects. Therefore, optimizing both the doping concentration and the material quality to minimize shunt resistance is crucial for improving the overall efficiency of the solar cell [20].

In summary, shunt resistance and dopant concentration must be carefully managed to balance the effects on recombination and leakage currents, which ultimately determines the performance of the solar cell.

iv) *Effect of the doping rate of the absorber layer on the fill factor*

Figure 6 shows the profile of the fill factor as a function of the doping of the absorber layer.

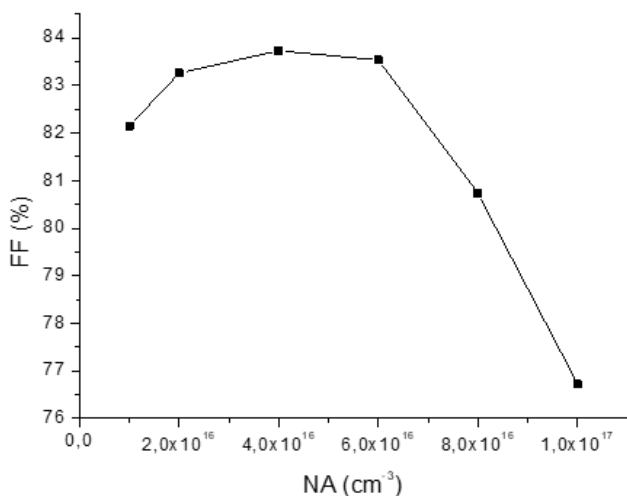


Figure 6. Fill factor as a function of the doping of the CIGS absorber layer.

Figure 6 shows that the fill factor (FF) increases from 82.1497 to 83.5307% as the doping rate of the absorber layer increases from $1e16$ to $6e16$ cm⁻³. This increase in the fill factor is mainly due to an improvement in carrier separation and a reduction in recombination losses, as indicated by the results observed for short-circuit current density (J_{SC}) and open-circuit voltage (V_{OC}). As doping increases, the carrier concentration in the absorber layer also increases, which theoretically enhances the photogenerated current, thus improving J_{SC} and increasing the fill factor. Moreover, the reduction of recombination losses and the improvement in carrier separation contribute to a positive effect on the fill factor, which is a key indicator of the overall efficiency of the cell.

However, the fill factor decreases from 83.5307 to 76.7180% as the current density increases from $6e16$ to $1e17$ cm⁻³, despite the increase in doping. This phenomenon is mainly linked to the increase in series resistance and shunt resistance. As doping concentration continues to rise, additional defects may be introduced into the material, which increases the shunt resistance, thereby reducing the efficiency of the cell. The increase in series resistance is also a limiting factor, as it reduces the efficiency of carrier transport through the cell, which can lower the overall performance, even if the current density increases.

In summary, while increasing doping improves carrier generation and increases the fill factor up to a certain point, excessive doping can introduce additional defects into the material, increasing both series and shunt resistances. This limits the positive impact of doping on performance, highlighting the importance of finding an optimal balance between carrier density, carrier mobility, and the resistances of the cell to maximize the fill factor and overall efficiency of the solar cell.

v) *Effect of the doping rate of the absorber layer on the efficiency*

Figure 7 shows the profile of the efficiency as a function of the doping of the absorber layer.

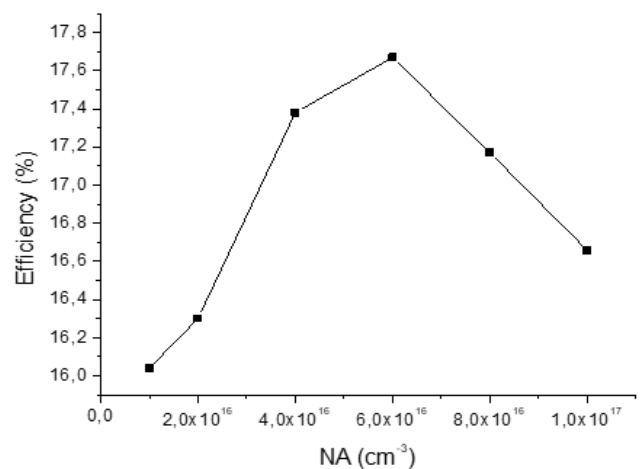


Figure 7. Efficiency as a function of the doping of the CIGS absorber layer.

Figure 7 shows that the efficiency increases from 16.04 to 17.67% as the doping rate of the absorber layer increases from 1×10^{16} to $6 \times 10^{16} \text{ cm}^{-3}$. However, the efficiency decreases from 17.67% to 16.66% when the doping rate of the absorber layer increases from 6×10^{16} to $1 \times 10^{17} \text{ cm}^{-3}$. This indicates that the optimal doping rate for the absorber layer is $6 \times 10^{16} \text{ cm}^{-3}$, which is consistent with existing theories on doping optimization for CIGS cells [21, 22].

In conclusion, the doping rate of the absorber layer significantly affects the performance of CIGS-based solar cells. The maximum efficiency of 17.67% is achieved with a doping rate of $6 \times 10^{16} \text{ cm}^{-3}$, as demonstrated in this study. This observation confirms the existence of an optimal doping level, beyond which further doping increases can lead to a decrease in efficiency due to increased recombination and higher series resistance.

In this first part, we studied the effect of the doping rate of the absorber layer on the performance of CIGS-based solar cells. The results show that doping has a significant impact on several key parameters, including short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), and fill factor (FF). We observed an increase in efficiency from 16.04% to 17.67% when the doping rate of the absorber layer increased from $1 \times 10^{16} \text{ cm}^{-3}$ to $6 \times 10^{16} \text{ cm}^{-3}$, with a slight decrease in efficiency when the doping rate reached $1 \times 10^{17} \text{ cm}^{-3}$. This behavior confirms that the optimal doping level for maximizing cell performance is $6 \times 10^{16} \text{ cm}^{-3}$, which aligns with existing theory.

The results highlight that, although increasing doping improves carrier generation and reduces recombination losses, excessively high doping can introduce additional defects, increasing both series and shunt resistances, thereby limiting performance gains.

In the next part of this study, we will examine the influence of the absorber layer thickness on the cell's performance, using the optimal doping rate found in this section, $6 \times 10^{16} \text{ cm}^{-3}$. This analysis will allow us to determine how the thickness of the layer, in interaction with the optimal doping rate, can further affect the overall performance of the solar cell.

4.2. Effect of the Thickness of the CIGS Absorber Layer on the Performance of the Cells

i) Effect of the thickness of the absorber layer on the current-voltage characteristic

Figure 8 below shows the current density versus voltage characteristic for different thickness of the CIGS absorber layer.

Figure 8 shows that the $J(V)$ characteristics are almost identical when the absorber layer thickness ranges from 0.3 to 3 μm . A slight shift in the curve is observed near the open-circuit voltage for an absorber layer thickness of 0.1 μm . To further analyze the influence of the absorber layer thickness, the profiles of short-circuit current density, open-circuit voltage, fill factor, and efficiency will be plotted in the following sections as a function of this layer thickness.

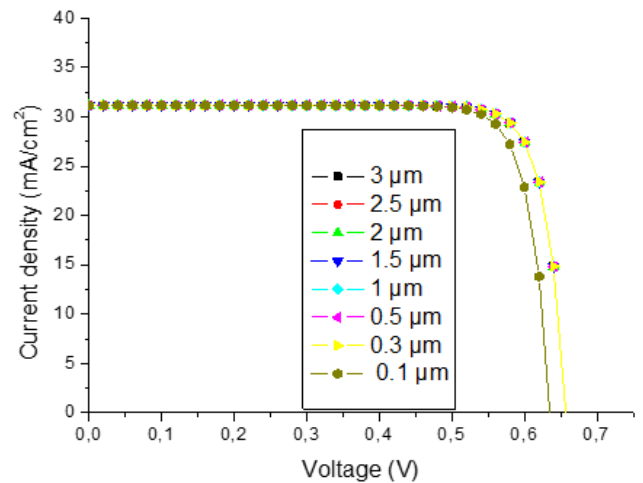


Figure 8. Current-voltage characteristic $J(V)$ for different thickness of the CIGS absorber layer.

ii) Effect of the absorber layer thickness on the Short-circuit current density

Figure 9 displays the short-circuit current density profile as a function of the thickness of the absorber layer.

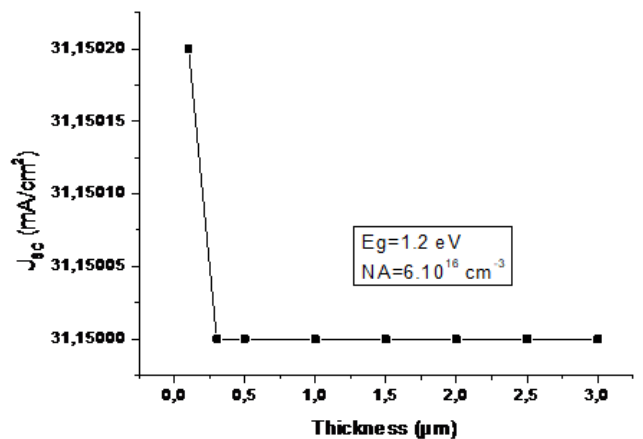


Figure 9. Short-circuit Current density as a function of the thickness of the CIGS absorber layer.

The short-circuit current density shows a slight decrease as the absorber layer thickness increases from 100 nm to 300 nm, which can be attributed to a reduction in the efficiency of carrier diffusion in the layer. However, beyond 300 nm, the current density remains constant up to 3 μm , suggesting that photon absorption reaches a saturation point, where further increases in layer thickness no longer significantly improve carrier generation. This behavior aligns with observations in the literature, where optimal absorber layer thicknesses exist, beyond which performance no longer increases.

iii) Effect of the absorber layer thickness on the open-circuit voltage

Figure 10 displays the open-circuit voltage profile as a

function of the thickness of the absorber layer.

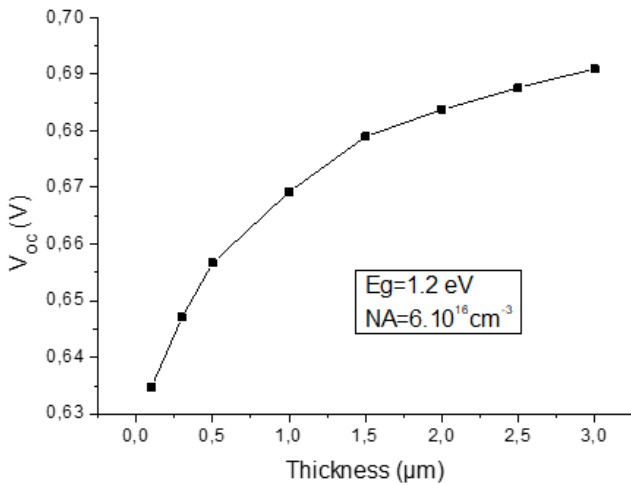


Figure 10. Open-circuit voltage as a function of the thickness of the CIGS absorber layer.

Figure 10 shows that as the absorber layer thickness decreases from 3 μm to 0.1 μm , the open-circuit voltage slightly decreases from 0.6910 V to 0.6348 V. This decrease in V_{oc} with the reduced absorber layer thickness, particularly below 0.3 μm , is mainly due to the reduction in the minority carrier diffusion length, which increases recombination and limits carrier generation. On the other hand, when the layer thickness increases from 0.1 μm to 3 μm , carrier generation increases due to improved photon absorption, leading to an increase in open-circuit voltage. This evolution highlights the trade-off between photon absorption and carrier recombination in absorber layers of different thicknesses.

iv) *Effect of the absorber layer thickness on the fill factor*

Figure 11 displays the fill factor profile as a function of the thickness of the absorber layer.

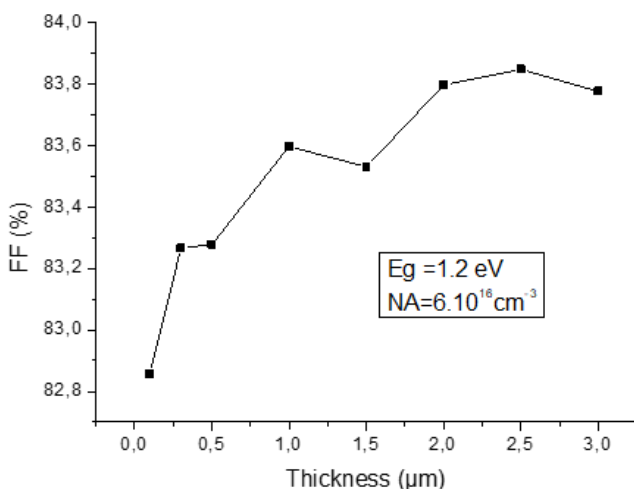


Figure 11. Fill factor as a function of the thickness of the CIGS absorber layer.

Figure 11 shows that as the absorber layer thickness increases from 0.5 μm to 3 μm , the fill factor (FF) increases slightly, from 83.2667% to 83.7763%. However, this increase is more significant when the absorber layer thickness changes from 0.1 μm to 0.5 μm . This trend can be explained by several factors related to the optimization of photon absorption and the reduction of recombination losses.

This analysis shows that increasing the absorber layer thickness improves the fill factor up to a certain thickness, after which the gains become marginal. The 0.1 to 0.5 μm range is therefore particularly optimal for maximizing carrier generation and reducing recombination losses, leading to a significant improvement in cell efficiency.

v) *Effect of the absorber layer thickness on the efficiency*

Figure 12 displays the efficiency profile as a function of the thickness of the absorber layer.

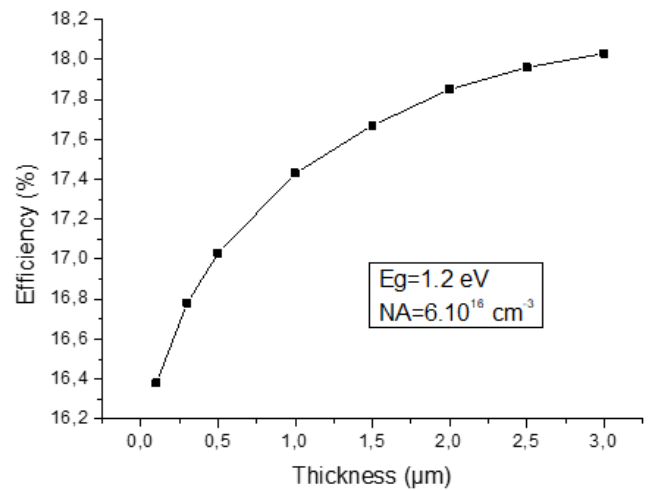


Figure 12. Efficiency as a function of the thickness of the CIGS absorber layer.

Figure 12 shows that when the absorber layer thickness increases from 1 μm to 3 μm , the efficiency increases slightly from 17.03% to 18.03%. However, when the absorber layer thickness increases from 0.1 μm to 1 μm , the increase in efficiency is more significant.

The increase in efficiency is more significant when the absorber layer thickness increases from 0.1 μm to 1 μm , as this optimizes photon absorption. Beyond 1 μm , absorption reaches a saturation point, and increasing the thickness has a more limited impact on efficiency.

In conclusion, while increasing the absorber layer thickness beyond 1 μm may have a limited effect on carrier generation, a thickness between 0.1 μm and 1 μm appears optimal for maximizing efficiency. This analysis provides valuable insights into the trade-off between carrier generation and recombination losses, paving the way for optimizing the layer thickness to enhance the overall performance of the solar cell.

5. Conclusion

This study analyzed the impact of doping and absorber layer thickness on the performance of CIGS solar cells. The optimal doping of $6 \times 10^{16} \text{ cm}^{-3}$ improves short-circuit current density, open-circuit voltage, and fill factor, but higher concentrations increase shunt and series resistance, limiting gains.

Regarding the absorber layer thickness, a thickness between $0.1 \mu\text{m}$ and $1 \mu\text{m}$ maximizes photon absorption and carrier generation, thereby increasing efficiency. Beyond $1 \mu\text{m}$, absorption reaches saturation, limiting further efficiency improvements.

In summary, optimal management of doping and absorber layer thickness is essential to maximize the efficiency of CIGS solar cells. The results of this study provide a solid foundation for the design and optimization of these cells.

Abbreviations

ATLAS	Advanced Technology for Large Area Simulation (logiciel de simulation TCAD de SILVACO)
CdS	Cadmium Sulfide
CIGS	Copper Indium Gallium Selenide
CIS	Copper Indium Selenide
FF	Fill Factor
J(V)	Current-Voltage Characteristic
J_{sc}	Short-Circuit Current Density
Mo	Molybdenum
N_A	Acceptor Concentration
N_C	Effective Density of States in the Conduction Band
N_V	Effective Density of States in the Valence Band
PET	Polyethylene Terephthalate (Plastic Substrate)
Pt-Al	Platinum-Aluminum (Metal Grid/Contact)
R_{SH}	Shunt Resistance
R_S	Series Resistance
Se	Selenium
SRH	Shockley-Read-Hall (Recombination Model)
V_{oc}	Open-Circuit Voltage
ZnO	Zinc Oxide

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Conflicts of Interest

The authors declare no conflicts of interest.

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