Influence of CuInSe₂ and Cu(In,Ga)Se₂ thin layer thickness on the Electric Parameters of the Solar Cell

Alain Kassine EHEMBA (ehembaalain@yahoo.fr), Moustapha DIENG, Demba DIALLO, Mamour SOCE, Djibril WADE

Laboratory of Semiconductors and Solar Energy, Physics Department, Faculty of Science and Technology University Cheikh Anta Diop – Dakar – SENEGAL

Abstract — In this paper we propose to study the effect of CuInSe₂ and Cu(In, Ga)Se₂ layers thickness on the electric parameters of the solar cells. The studied characteristics are resistance series Rs, resistance shunt Rs, the short circuit current density Jsc, the open circuit voltage Voc, the form factor FF and the conversion efficiency η. We operate the characterization of these cells by using the wxAMPS (Analysis of Microelectronic and Photonic Structures) and Matlab which are recognized characterization softwares. This study enables us to take note on the one hand adequate thickness of thin film which would give a more powerful cell and on the other hand the capital interest to pass from the base in CuInSe₂ to the base in Cu(In,Ga)Se₂. We find that the electric parameters of the cell vary according to the thickness of the base and that the suitable thickness is 2.5µm as well for Cu(In, Ga)Se₂ than for CuInSe₂. For the same thickness Cu(In, Ga)Se₂ presents better electric parameters than CuInSe₂.

Keyword — absorber layer thickness, CuInSe₂, Cu(In,Ga)Se₂, electric parameters, Matlab, wxAMPS

1. INTRODUCTION
The chalcopyrite path takes its industrial take-off today. It presents the most significant efficiencies prospects among the thin layers. The chalcopyrite ternary compounds which can play the role of absorber are mainly the Copper Indium Diselenide CuInSe₂ and the Copper Indium Gallium Diselenide Cu(In,Ga)Se₂. These two films have optical absorption coefficients which enable them to absorb a broad range of the solar spectrum with very fine thicknesses, and thus few materials.CuInSe₂ is the most promising material of the ternary compounds and we even undertook his development on flexible substrates such as Kapton. [1] But its forbidden band limits the open circuit voltage and thus the cell efficiency. However one often adds to its structure Gallium (Ga) atoms which replace Indium (In) atoms widening the CuInSe₂ semiconductor gap giving thus Cu(In, Ga)Se₂. In this paper we propose to study the effect of CuInSe₂ and Cu(In, Ga)Se₂ layers thickness on the electric parameters of the solar cells. The studied characteristics are resistance series Rs, resistance shunt Rs, the short circuit current density Jsc, the open circuit voltage Voc, the form factor FF and the conversion efficiency η.

We find in the bibliography CuInSe₂ and Cu(In, Ga)Se₂ thin films solar cells with good optoelectronics, morphological and structural properties.[2]-[4] We operate the characterization of these cells by using the wxAMPS (Analysis of Microelectronic and Photonic Structures) and Matlab which are recognized characterization softwares. This study enables us to take note on the one hand adequate thickness of thin film which would give a more powerful cell and on the other hand the capital interest to pass from the base in CuInSe₂ to the base in Cu(In,Ga)Se₂.

2. EXPERIMENTAL PROCESS
The CuInSe₂ and Cu(In, Ga)Se₂ thin films are known as being semiconductors with the good physicochemical properties. In fact they present good optical properties enabling them to absorb a broad range of the solar spectrum, good structural properties which confer to them the aptitudes of a chalcopyrite compound and good morphological properties which facilitate their adhesion on other layers. Their elaboration can be carried out by using several methods divided into Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD).[5]-[8] The obtained results during ages made it possible to fix all physicochemical parameters of the CuInSe₂ and Cu(In, Ga)Se₂ layers. In this article we show the interest to make the transition from CuInSe₂ to Cu(In,Ga)Se₂ by studying the influence from their thicknesses on the electric parameters. With this intention we used the wxAMPS software which is a data-processing tool for characterization with recognized and proven results. It makes it possible to carry out the one-dimensional analysis of the microelectronics and photonic structures. The software was developed in 1997 by Fonash et al.[9]-[10] The modeled cell configuration is:

ZnO Window layer (0.75µm)
CdS Transmitter layer (0.5µm)
(CIS or CIGS) Absorber layer (of 1µm with 4µm)
The results obtained are treated with Matlab. This last one is a tool for characterization which gives us the characteristics of resistance series Rs, resistance shunt Rs, the open circuit voltage Voc, the short circuit current density Jsc, the form factor FF and the conversion efficiency η variation according to the thickness of the thin film. Matlab is used in search with proven results. [11]-[12]
These electric parameters characterize the photovoltaic solar cell and make it possible to judge its efficiency. To study the absorber thickness influence on the solar cell we base our analysis on these macroscopic electric parameters.

In order to standardize the experimental conditions we use the conditions standards AM 1.5, the intensity of illumination is fixed at 1000 W.m\(^{-2}\), the solar cell area at 1 cm\(^2\) and the ambient temperature at 300K.

### RESULTS AND DISCUSSION

The modeling carried out using the AMPS enabled us to find precise values of the electric parameters studied. Indeed we held account for each layer of the electric and optical properties, the defects, and the recombination band-to-band and even of the edge grid. The results obtained are recapitulated in Table 1.

**Table 1 : Results of the electric parameters obtained by simulation with the wxAMPS**

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (μm)</th>
<th>Jsc (mA.cm(^{-2}))</th>
<th>Voc (V)</th>
<th>Rs (Ohm.cm(^2))</th>
<th>Rsh (Ohm.cm(^2))</th>
<th>FF (%)</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuInSe(_2)</td>
<td>1.0</td>
<td>31.2658</td>
<td>0.5009</td>
<td>0.007861</td>
<td>523.4</td>
<td>74.9857</td>
<td>11.7426</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>31.6180</td>
<td>0.5029</td>
<td>0.01921</td>
<td>582.2</td>
<td>75.1845</td>
<td>11.9544</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>31.7039</td>
<td>0.5035</td>
<td>0.03155</td>
<td>598.6</td>
<td>75.2062</td>
<td>12.0056</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>31.7056</td>
<td>0.5037</td>
<td>0.03993</td>
<td>603.9</td>
<td>75.2091</td>
<td>12.0110</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>31.6875</td>
<td>0.5038</td>
<td>0.04679</td>
<td>607.8</td>
<td>75.2104</td>
<td>11.9985</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>31.6685</td>
<td>0.5038</td>
<td>0.04445</td>
<td>608.8</td>
<td>75.2102</td>
<td>11.9925</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>31.6526</td>
<td>0.5038</td>
<td>0.04821</td>
<td>608.8</td>
<td>75.2102</td>
<td>11.9925</td>
</tr>
<tr>
<td>Cu(In,Ga)Se(_2)</td>
<td>1.0</td>
<td>36.3381</td>
<td>0.6271</td>
<td>0.002781</td>
<td>605.4</td>
<td>80.2725</td>
<td>18.2927</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>36.6397</td>
<td>0.6333</td>
<td>0.01939</td>
<td>673.6</td>
<td>80.2499</td>
<td>18.6220</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>36.7104</td>
<td>0.6352</td>
<td>0.03143</td>
<td>692.6</td>
<td>80.1958</td>
<td>18.6990</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>36.7060</td>
<td>0.6356</td>
<td>0.03725</td>
<td>698.8</td>
<td>80.1785</td>
<td>18.7068</td>
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<tr>
<td></td>
<td>3.0</td>
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<td>0.6357</td>
<td>0.03994</td>
<td>701.7</td>
<td>80.1745</td>
<td>18.6984</td>
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<tr>
<td></td>
<td>3.5</td>
<td>36.6641</td>
<td>0.6358</td>
<td>0.04151</td>
<td>703.4</td>
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<td>18.6882</td>
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<tr>
<td></td>
<td>4.0</td>
<td>36.6471</td>
<td>0.6358</td>
<td>0.04274</td>
<td>704.7</td>
<td>80.1730</td>
<td>18.6793</td>
</tr>
</tbody>
</table>

For better determining the variations of these electric parameters according to the thickness of the absorbing layer and material, we use Matlab which enables us to trace the discussed characteristics.

#### 3.1. The Short circuit current density J\(_{sc}\) variation according to the absorber thickness

The short circuit current density J\(_{sc}\) expressed in mA.cm\(^{-2}\) is the current density which circulates in the cell under illumination and without applied voltage.

The Fig. 1 and 2 show the variation of the short current density J\(_{sc}\) according to the thickness of the CuInSe\(_2\) and Cu(In,Ga)Se\(_2\) respectively. We note that the two curves have the same profile. For a thickness of 1 µm the short circuit current density J\(_{sc}\) is relatively weak, about 31.2658 mA.cm\(^{-2}\) for CuInSe\(_2\) and 36.3381 mA.cm\(^{-2}\) for Cu(In,Ga)Se\(_2\).

In fact for a real solar cell J\(_{sc}\) is expressed by the relation:

\[
J_{cc} = J_{ph} - J_s \left[ e^{\frac{qR_sJ_{cc}}{nKT}} - 1 \right] - \frac{R_sJ_{cc}}{R_{sh}}
\]

where \(J_{ph}\) is the photo-generated current, \(J_s\) is the saturation current, \(q\) is the electronic charge, \(n\) is the ideality factor, \(K\) is the Boltzmann constant, \(T\) is the absolute temperature, \(R_s\) is the series resistance, \(R_{sh}\) is the shunt resistance.

The increase thickness of the absorber is accompanied by a reduction in the term related to the dark current density

\[
J_s \left[ e^{\frac{qR_sJ_{cc}}{nKT}} - 1 \right]
\]

which proves the increase of J\(_{sc}\). When the absorber thickness passes from 2.5 µm to 4 µm we note a progressive slow reduction of J\(_{sc}\). This is due to the resistivity increase of the layers which increases resistance series Rs. The greatest current density is then obtained for an absorber thickness of 2.5 µm and it is more significant with Cu(In, Ga)Se\(_2\) (36.7060 mA.cm\(^{-2}\)) than with CuInSe\(_2\) (31.7056 mA.cm\(^{-2}\)).
Fig. 1: Short circuit current density Jsc variation according to the absorber thickness of CuInSe\textsubscript{2} thin film

Fig. 2: Short circuit current density Jsc variation according to the absorber thickness of Cu(In,Ga)Se\textsubscript{2} thin film

3.2. Open circuit voltage Vco variation according to the absorber thickness

The open circuit voltage Vco expressed in Volt (V) is the solar cell voltage when no current circulates in the device.

The Fig. 3 and 4 show the open circuit voltage Vco according to the thickness of the absorber thin film of CuInSe\textsubscript{2} and Cu(In, Ga)Se\textsubscript{2} respectively. We note again two curves with the same profile. For an absorber thickness of 1µm we note that the open circuit voltage Vco is 0.5009V for CuInSe\textsubscript{2} and 0.6271V for Cu(In, Ga)Se\textsubscript{2}. But it increases in a fastly with the absorber thickness until 2.5µm. From this value it evolves in a slower way.

Fig. 3: Open circuit voltage Vco variation according to the absorber thickness of CuInSe\textsubscript{2} thin film

Fig. 4: Open circuit voltage Vco variation according to the absorber thickness of Cu(In,Ga)Se\textsubscript{2} thin film

In fact the open circuit voltage Vco is evaluated while applying:

\[
V_{co} = R_{ph} \left( J_{ph} - J_0 \left[ \frac{q V_{co}}{e kT} - 1 \right] \right) \quad (2)
\]
The open circuit voltage is sensitive to resistance shunt \( R_{sh} \) and minority carrier’s current \( J_s \). Resistance shunt doesn’t stop increasing and we see that the open circuit voltage \( V_{oc} \) grows too. The minority carriers current \( J_s \) becomes significant starting from a thickness equal to 2.5\( \mu \text{m} \) causing then a reduction of the increasing swiftness of the open circuit voltage \( V_{oc} \). We find a maximum open circuit voltage tension equals to 0.6358V with Cu(In, Ga)Se\(_2\) whereas for CuInSe\(_2\) it has a maximum value of 0.5038V.

### 3.3. Resistance series \( R_s \) variation according to the absorber thickness

The electrodes resistivity and the metal-semiconductor interfaces resistivity added to the ohmic losses due to the resistivity of the various layers and the side surface of the junction, generate a resistance series \( R_s \) considerable compared to the bulk resistance. This resistance is expressed in Ohm.cm\(^2\). It must be very weak for an ideal cell.

The Fig. 4 and 5 show the resistance series \( R_s \) variation according to the absorber thickness in thin film of CuInSe\(_2\) and Cu(In,Ga)Se\(_2\) respectively. As for the preceding curves we note the same profile for the two materials. For an absorber thickness of 1\( \mu \text{m} \) the resistance series \( R_s \) is very low; it is equal to 0.007861 Ohm.cm\(^2\) for CuInSe\(_2\) and 0.002781 Ohm.cm\(^2\) for Cu(In, Ga)Se\(_2\). When one varies the absorber thickness the resistances series \( R_s \) increase but that of the cell containing CuInSe\(_2\) varies more quickly than that of the cell containing Cu(In, Ga)Se\(_2\).

In fact the equation (1) gives:

\[
J_{cc} = \left[ J_{ph} - J_s \left( \frac{q\tau_{ph}R_i}{n_b\mu_b} - 1 \right) \right] \left( 1 - \frac{R_s}{R_{sh}} \right)
\]

however \( R_s \ll R_{sh} \) \( \Rightarrow \) 

\[
1 - \frac{R_s}{R_{sh}} \approx 1
\]

\[
J_{cc} = J_{ph} - J_s \left( \frac{q\tau_{ph}R_i}{n_b\mu_b} - 1 \right)
\]

\[
R_s = \frac{n\tau_{ph}T}{qJ_{cc}} \ln \left( 1 + \frac{J_{ph} - J_{cc}}{J_s} \right)
\]

We notice that resistance series is related to the short circuit current density. The \( J_{sc} \) being more significant for the Cu(In, Ga)Se\(_2\) thin film solar cell than for the CuInSe\(_2\) thin film solar cell, the decrease of the resistance series \( R_s \) according to 1/J\(_{cc}\) gives a resistance series smaller for Cu(In, Ga)Se\(_2\) than for CuInSe\(_2\).

### 3.4. Resistance shunt variation according to the absorber thickness

It explains the fact that maximum resistance series for CuInSe\(_2\) is equal to 0.04821 Ohm.cm\(^2\) and 0.04274 Ohm.cm\(^2\) for Cu(In,Ga)Se\(_2\). For an ideal cell resistance series must be null. There we find once again moreover one advantage of Cu(In, Ga)Se\(_2\) compared to CuInSe\(_2\).
The Resistance shunt Rsh characterizes the leakage currents. It is also expressed in Ohm.cm$^2$. For an ideal cell resistance shunt must tend towards the infinite one.

The fig. 7 and 8 show the resistance shunt variation according to the absorber thickness in CuInSe$_2$ and Cu(In, Ga)Se$_2$ thin films respectively. We always notes the same profile for the two curves. For an absorber thickness of 1µm, resistance shunt already reaches, in the two cells, a very large value compared the resistance series: for CuInSe$_2$ there is a resistance shunt of 523.4 Ohm.cm$^2$ and for Cu(In, Ga)Se$_2$ there is Rsh=605.4 Ohm.cm$^2$. These values evolve with the thickness of the base.

We have at the equation (2)

$$V_{co} = R_{sh} \left( J_{ph} - J_s \left( \frac{qV_o}{ek_BT} - 1 \right) \right)$$

$$\Rightarrow R_{sh} = \frac{V_{co}}{J_{ph} - J_s \left( \frac{qV_o}{ek_BT} - 1 \right)}$$

The resistance shunt variation has the same profile as the open circuit voltage according to the absorber thickness. We obtain a maximum resistance shunt of 608.8 Ohm.cm$^2$ for CuInSe$_2$ and 704.7 Ohm.cm$^2$ for Cu(In, Ga)Se$_2$.

We mention that the ideal cell has a resistance series null and an "infinite" resistance shunt. This ideal cell characteristic shows us that Cu(In,Ga)Se$_2$ approaches more the ideal than CuInSe$_2$.

3.5. Form factor FF variation according to the absorber thickness

The form factor FF is equal to the ratio of the product of maximum voltage Vm and the maximum current Im on the product of the open circuit voltage Vco and the short circuit current Icc.

$$FF = \frac{V_m I_m}{V_{co} I_{cc}}$$

The form factor FF is expressed in %. More it is large more the conversion efficiency is significant.

The Fig. 9 and 10 give the form factor variation according to the absorber thickness CuInSe$_2$ and Cu(In,Ga)Se$_2$ thin films respectively. We notice two different profiles.

For the cell in CuInSe$_2$ thin film, the form factor evolves such a function affine with a positive coefficient between 1 and 2µm of CuInSe$_2$. From 2µm the form factor increases slightly with the increase of the absorber thickness.

For the cell in Cu(In,Ga)Se$_2$ thin film, the form factor is more significant for low absorber thicknesses. It decreases until an absorber thickness of 2µm then varies slightly starting from this value. In fact Cu(In, Ga)Se$_2$ has a better conversion efficiency for low thicknesses, which explains its significant form factor.

If we compare the results of the Cu(In, Ga)Se$_2$ thin film with those of the CuInSe$_2$ thin film we note that the form factor remains more significant for the Cu(In, Ga)Se$_2$ than for the CuInSe$_2$ for all absorber thickness.
3.6. Conversion efficiency $\eta$ variation according to the absorber thickness

The conversion efficiency is the relationship between the maximum power delivered by the cell and the power of the incident light.

$$\eta = \frac{FF \times V_{co} \times I_{cc}}{P_{in}}$$  \hspace{1cm} (8)

For the cell in Cu(In,Ga)Se$_2$ the form factor varies between 80.1730\% and 80.2725\% whereas for the cell in CuInSe$_2$ it varies between 74.9857\% and 75.2102\%. Cu(In,Ga)Se$_2$ has a better conversion efficiency.
The Fig. 11 and 12 give the variation of the conversion efficiency of the cell according to the absorber thickness for the cells into CuInSe$_2$ and Cu(In, Ga)Se$_2$ thin film respectively. The two curves present the same profile. For a thickness of 1µm the cells reach already efficiencies of 11.7426% for CuInSe$_2$ and 18.2927% for Cu(In,Ga)Se$_2$. These values evolve fastly with the absorber thickness up to 12.0110% for CuInSe$_2$ and 18.7068% for Cu(In,Ga)Se$_2$ with an absorber thickness of 2.5µm. From this value the efficiency decreases slightly with the absorber thickness. We note that Cu(In,Ga)Se$_2$ presents the best cell efficiency with the same absorber thickness.

CONCLUSION
This study enabled us to define the electric parameters of CuInSe$_2$ and Cu(In, Ga)Se$_2$ thin film solar cells. We can conclude that the electric parameters of the cell vary according to the thickness of the base and that the suitable thickness is 2.5µm as well for Cu(In, Ga)Se$_2$ than for CuInSe$_2$.

In fact for CuInSe$_2$ we obtained with an absorber thickness 2.5µm: Jsc=36.7060 mA.cm$^{-2}$, Voc=0.5037V, Rs=0.03993Ohm.cm$^2$, Rsh=603.90hm.cm$^2$, FF=75.2091% and η=18.7068%.

For Cu(In,Ga)Se$_2$ with the same thickness of 2.5µm we have: Jsc=36.7060 mA.cm$^{-2}$, Voc=0.635V, Rs=0.03725 Ohm.cm$^2$, Rsh=698.8 Ohm.cm$^2$, FF=80.1785% and η=18.7068%.

For the same thickness Cu(In, Ga)Se$_2$ presents better electric parameters than CuInSe$_2$.

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