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Influence of $CuInSe_2$ and $Cu(In,Ga)Se_2$ thin Layer Thickness on the Electric Parameters of the Solar Cell

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Abstract — In this paper we propose to study the effect of $CuInSe_2$ and $Cu(In, Ga)Se_2$ layers thickness on the electric parameters of the solar cells. The studied characteristics are resistance series Rs, resistance shunt Rsh, 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 $CuInSe_2$ to the base in $Cu(In,Ga)Se_2$. 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 $Cu(In, Ga)Se_2$ than for $CuInSe_2$. For the same thickness $Cu(In, Ga)Se_2$ presents better electric parameters than $CuInSe_2$.

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 $CuInSe_2$ and the Copper Indium Gallium Diselenide $Cu(In,Ga)Se_2$. 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.$CuInSe_2$ 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 $CuInSe_2$ semiconductor gap giving thus $Cu(In, Ga)Se_2$. In this paper we propose to study the effect of $CuInSe_2$ and $Cu(In, Ga)Se_2$ layers thickness on the electric parameters of the solar cells. The studied characteristics are resistance series Rs, resistance shunt Rsh, 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 $CuInSe_2$ and $Cu(In, Ga)Se_2$ 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 $CuInSe_2$ to the base in $Cu(In,Ga)Se_2$.

2. EXPERIMENTAL PROCESS

The $CuInSe_2$ and $Cu(In, Ga)Se_2$ 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 $CuInSe_2$ and $Cu(In, Ga)Se_2$ layers.

In this article we show the interest to make the transition from $CuInSe_2$ to $Cu(In,Ga)Se_2$ 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 micro-electronics 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 Rsh, 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 1000W.m $^{-2}$, the solar cell area at 1cm^2 and the ambient temperature at 300K.

3. 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

Material	Thickness (µm)	Jsc (mA.cm^{-2})	Voc (V)	Rs (Ohm.cm^2)	Rsh (Ohm.cm^2)	FF (%)	η (%)
$CuInSe_2$	1.0	31.2658	0.5009	0.007861	523.4	74.9857	11.7426
	1.5	31.6180	0.5029	0.01921	582.2	75.1845	11.9544
	2.0	31.7039	0.5035	0.03155	598.6	75.2062	12.0056
	2.5	31.7056	0.5037	0.03993	603.9	75.2091	12.0110
	3.0	31.6875	0.5037	0.04445	606.3	75.2101	12.0054
	3.5	31.6685	0.5038	0.04679	607.8	75.2104	11.9985
	4.0	31.6526	0.5038	0.04821	608.8	75.2102	11.9925
$Cu(In,Ga)Se_2$	1.0	36.3381	0.6271	0.002781	605.4	80.2725	18.2927
	1.5	36.6397	0.6333	0.01939	673.6	80.2499	18.6220
	2.0	36.7104	0.6352	0.03143	692.6	80.1958	18.6990
	2.5	36.7060	0.6356	0.03725	698.8	80.1785	18.7068
	3.0	36.6848	0.6357	0.03994	701.7	80.1745	18.6984
	3.5	36.6641	0.6358	0.04151	703.4	80.1736	18.6882
	4	36.6471	0.6358	0.04274	704.7	80.1730	18.6793

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 Jsc variation according to the absorber thickness

The short circuit current density Jsc 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 Jsc 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 1µm the short circuit current density Jsc is relatively weak, about 31.2658mA.cm $^{-2}$ for $CuInSe_2$ and 36.3381mA.cm $^{-2}$ for $Cu(In,Ga)Se_2$.

In fact for a real solar cell Jsc is expressed by the relation:

$$J_{cc} = J_{ph} - J_s\left[e^{\frac{qR_sJ_{cc}}{kT}} - 1\right] - \frac{R_sJ_{cc}}{R_{sh}} \qquad (1)$$

The increase thickness of the absorber is accompanied by a reduction in the term related to the dark current density $J_s\left[e^{\frac{qR_sJ_{cc}}{kT}} - 1\right]$,

which proves the increase of Jsc. When the absorber thickness passes from 2.5µm to 4µm we note a progressive slow reduction of Jsc. 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 2.5µm and it is more significant with $Cu(In, Ga)Se_2$ (36.7060 mA.cm $^{-2}$) that with $CuInSe_2$ (31.7056 mA.cm $^{-2}$).

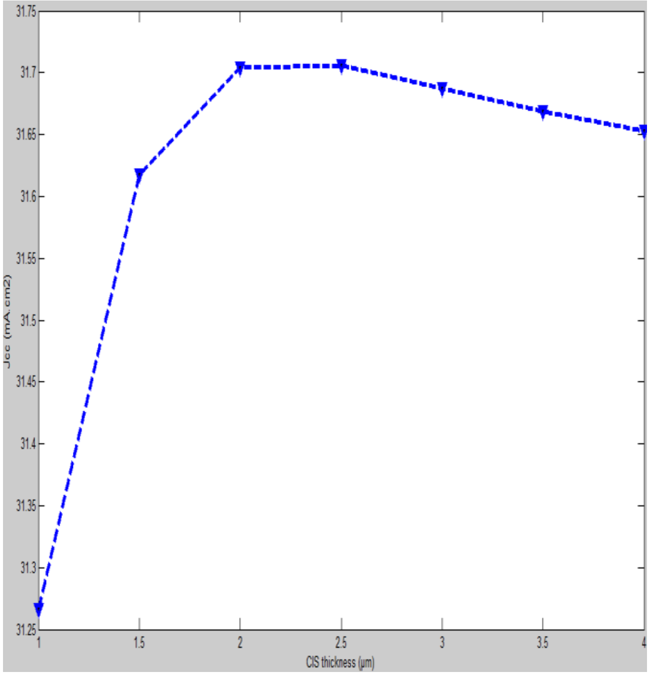

Fig.1: Short circuit current density Jsc variation according to the absorber thickness of $CuInSe_2$ thin film

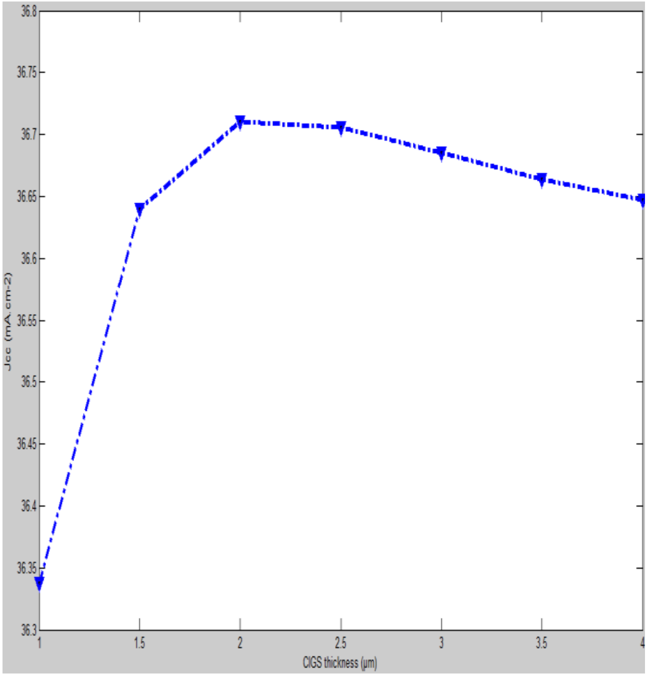

Fig.2: Short circuit current density Jsc variation according to the absorber thickness of $Cu(In,Ga)Se_2$ thin film

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 $CuInSe_2$ and $Cu(In, Ga)Se_2$ 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 $CuInSe_2$ and 0.6271V for $Cu(In, Ga)Se_2$. But it increases in a fastly with the absorber thickness until 2.5µm. From this value it evolves in a slower way.

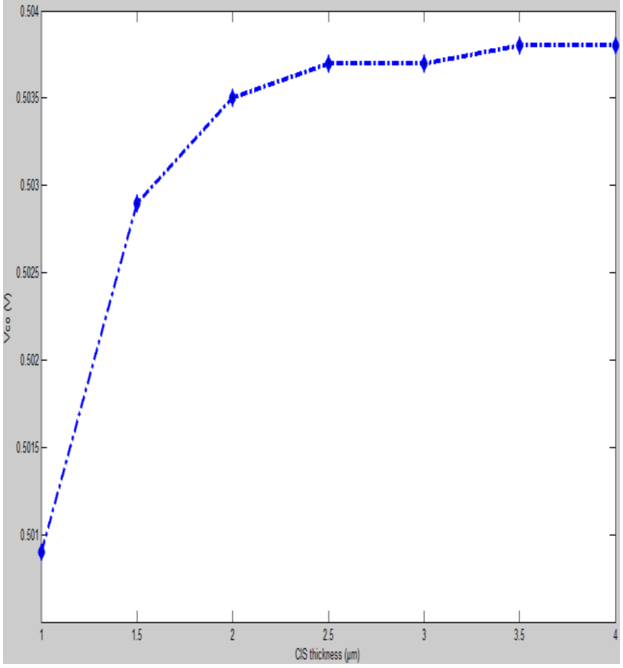

Fig.3: Open circuit voltage Voc variation according to the absorber thickness of $CuInSe_2$ thin film

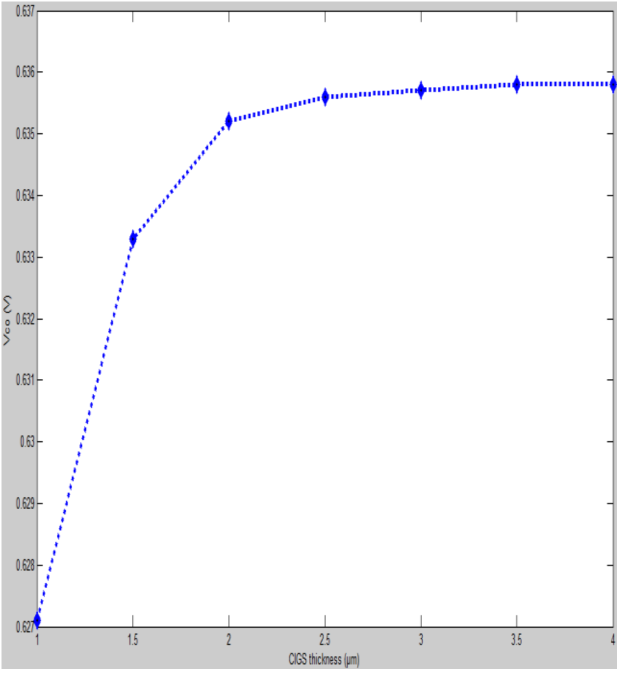

Fig.4: Open circuit voltage Voc variation according to the absorber thickness of $Cu(In,Ga)Se_2$ thin film

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

$$V_{co} = R_{sh}\left\{J_{ph} - J_{s}\left[e^{\frac{qV_{co}}{nk_BT}} - 1\right]\right\} \qquad (2)$$

The open circuit voltage is sensitive to resistance shunt Rsh and minority carrier's current Js. Resistance shunt doesn't stop increasing and we see that the open circuit voltage Vco grows too. The minority carriers current Js becomes significant starting from a thickness equal to 2.5µm causing then a reduction of the increasing swiftness of the open circuit voltage Voc. 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 Rs 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 Rs 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 Rs 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 1µm the resistance series Rs 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 Rs 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:

$$J_{cc} = \left[J_{ph} - J_s \left(e^{\frac{qJ_{cc}R_s}{nk_BT}} - 1 \right) \right] \left(1 - \frac{R_s}{R_{sh}} \right)$$

$$\text{however } R_s \prec\prec R_{sh} \qquad \Rightarrow \qquad \left(1 - \frac{R_s}{R_{sh}} \right) \approx 1 \qquad (3)$$

$$\Rightarrow \qquad J_{cc} = J_{ph} - J_s \left(e^{\frac{qJ_{cc}R_s}{nk_BT}} - 1 \right) \qquad (4)$$

$$\Rightarrow \qquad R_s = \frac{nk_BT}{qJ_{cc}} \ln\left(1 + \frac{J_{ph} - J_{cc}}{J_s} \right) \qquad (5)$$

We notice that resistance series is related to the short circuit current density. The Jsc 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 Rs according to 1/Jcc gives a resistance series smaller for Cu(In, Ga)Se_2 than for $CuInSe_2$.

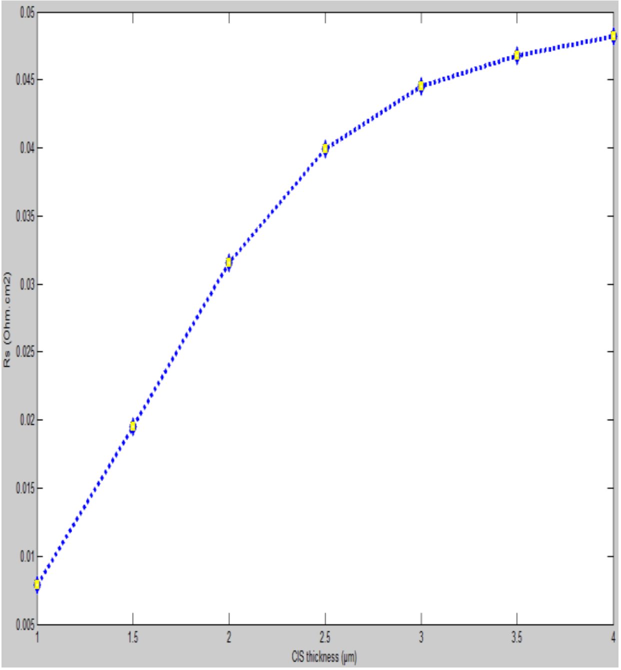

Fig.5: Resistance series Rs variation according to the absorber thickness of $CuInSe_2$ thin film

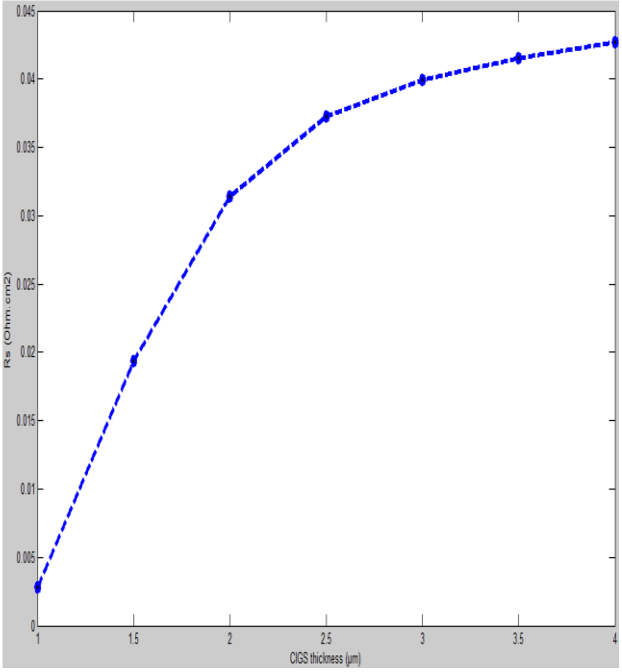

Fig.6: Resistance series Rs variation according to the absorber thickness of Cu(In,Ga)Se_2 thin film

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 $CuInSe_2$.

3.4. Resistance shunt variation according to the absorber thickness

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)

$$V_{co} = R_{sh}\left\{J_{ph} - J_s\left[e^{\frac{qV_{co}}{nk_BT}} - 1\right]\right\}$$

$$\Rightarrow \qquad R_{sh} = \frac{V_{co}}{J_{ph} - J_s\left(e^{\frac{qV_{co}}{nk_BT}} - 1\right)} \qquad (6)$$

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)Se2.

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$_2$.

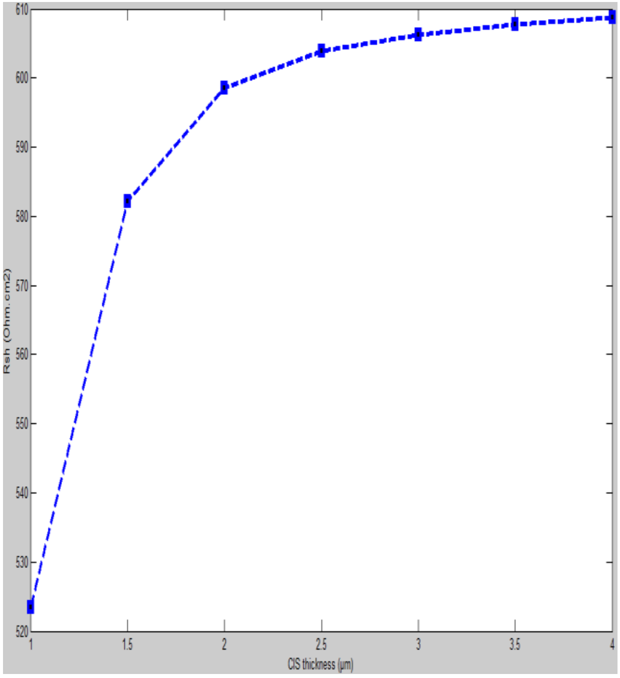

Figure 7 : Variation de la résistance shunt Rsh en fonction de l'épaisseur de la base en couche mince de CuInSe$_2$

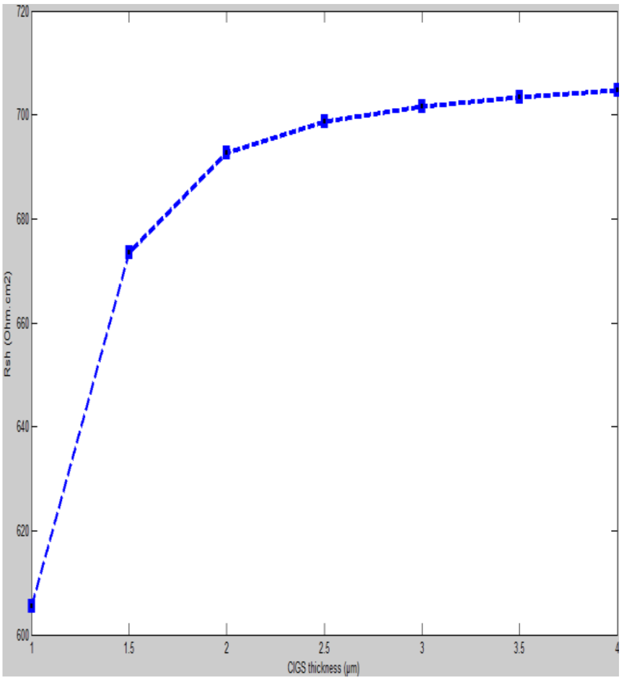

Figure 8 : Variation de la résistance shunt Rsh en fonction de l'épaisseur de la base en couche mince de Cu(In,Ga)Se$_2$

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.

$$FF = \frac{V_m I_m}{V_{co} I_{cc}} \qquad (7)$$

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.

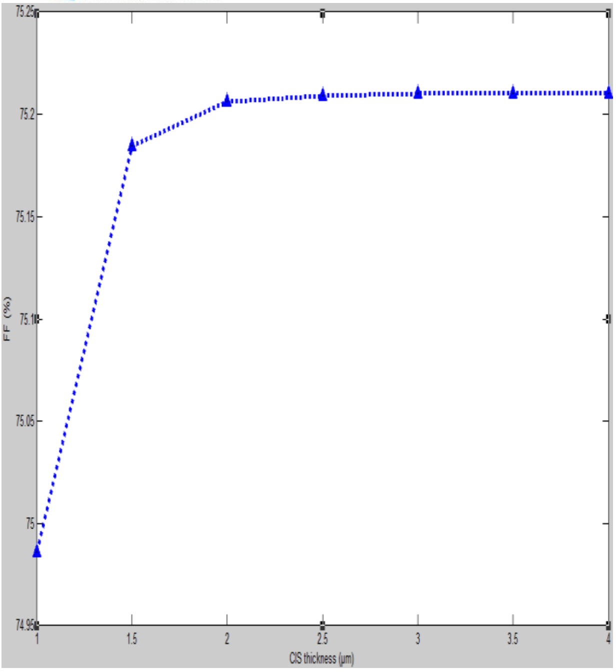

Fig.9: Form factor variation according to the absorber thickness of $CuInSe_2$

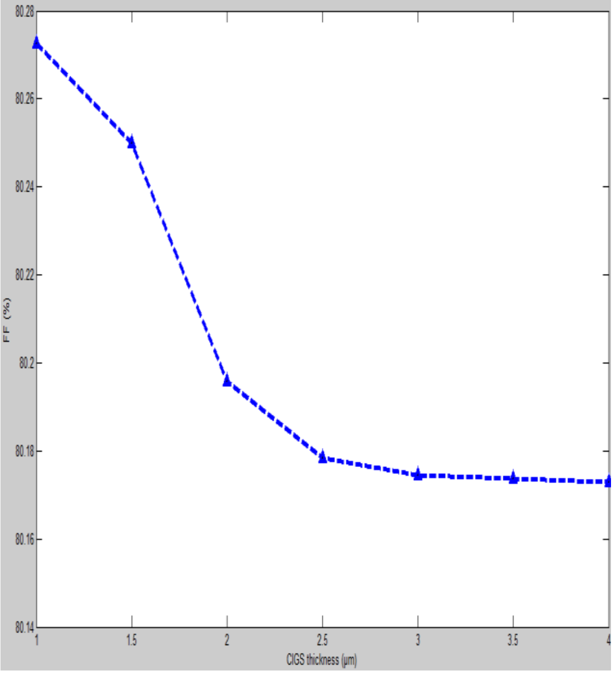

Fig.10: Form factor variation according to the absorber thickness of $Cu(In,Ga)Se_2$

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.

3.6. Conversion efficiency η 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.

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

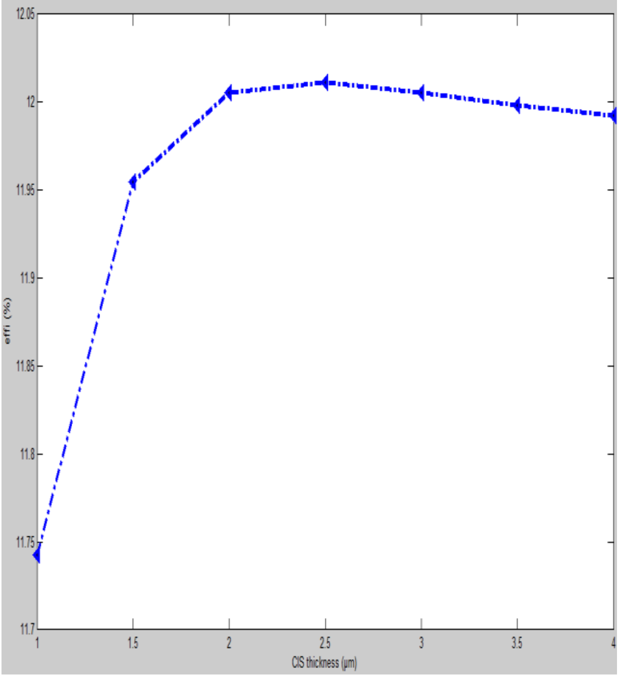

Fig.11: Conversion efficiency η according to the absorber thickness of the $CuInSe_2$ thin film

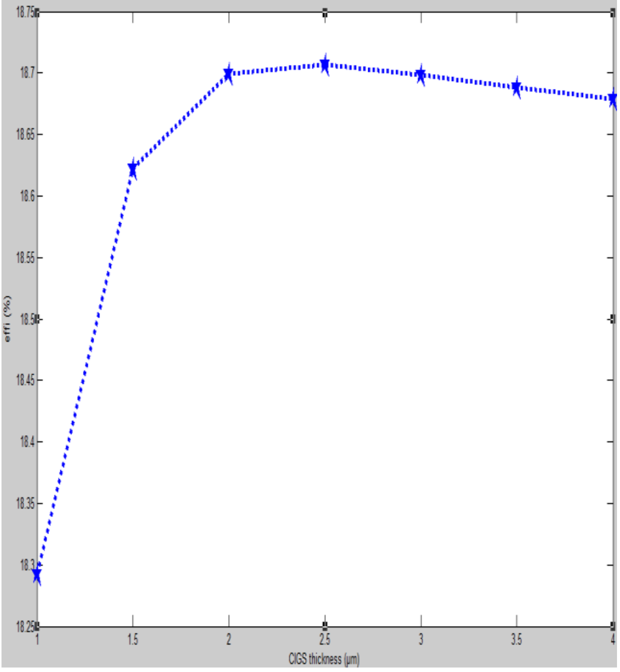

Fig.12: Conversion efficiency η according to the absorber thickness of the $Cu(In,Ga)Se_2$ thin film

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=603.9Ohm.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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