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The influence of the type and the thickness of the window layer on the electric parameters of the $Cu(In,Ga)Se_2$ thin film solar cell

[1]A. K. Ehemba, [2]M. Dieng, [3]D. Diallo, [4]I. Wade, [5]M. Socé
Laboratory of Semiconductors and Solar Energy, Physics Department, Faculty of Science and Technology
University Cheikh Anta Diop – Dakar – SENEGAL

ABSTRACT
In this paper we study the influence of the window layer on the electric parameters of the solar cell. We carry out the simulation of a solar cell of type window layer / transmitter layer (CdS) / absorber ($CuInGaSe_2$).We vary the nature of the window layer by using intrinsic Zinc Oxide (i-ZnO), the Zinc Oxide doped N (n-ZnO), the Tin Dioxide (SnO2) and the Indium Transparent Oxide (ITO). A variation of the thickness of each one of these windows layers enable us to study the behavior of the macroscopic electric parameters (Voc, Jsc, FF, η) and external quantum efficiency EQE. A solar cell efficiency of about 16.6% is obtained with the n-ZnO, which makes it the best candidate. The SnO_2 also allow us to reach a significant external quantum efficiency of about 93.85% for a thickness of 0.01µm only.

Keywords *- external quantum efficiency EQE, ITO, i-ZnO, macroscopic electric parameters, n-ZnO, SnO_2, solar cell, window layer.*

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I. INTRODUCTION

As indicated by its name, the window layer plays an optical window function in the cell. It is a material doped N with a significant transmission coefficient of about 80%.The window layer, which must have a good conductivity, can also be used like front metal contact. Its choice must take to account the bandgap which influences its transparency and the doping which influences its conductivity.

In this paper we study the influence of this window layer on the electric parameters of Cu(In, Ga)Se_2 thin film solar cell. However various types of window layer are studied with variable thicknesses. The studied characteristics are the characteristic current-voltage (J-V), the open circuit voltage Voc, the short-circuit current density Jsc, the form factor FF, the efficiency η, the maximum power point voltage V_MPP, the maximum power point current density J_MPP and the quantum efficiency QE. This work would enable us to take note of best materials to be used like window layer and their optimal thickness. The materials used are the intrinsic Zinc Oxide (i-ZnO), the doped N Zinc Oxide (n-ZnO), the Indium Transparent Oxide (ITO) and the Tin Dioxide (SnO2).

II. EXPERIMENTAL PROCESS

The $Cu(In,Ga)Se_2$ solar cells are very effective with a controlled technology. We carry out the simulation of this solar cell using SCAPS-1D. This last is a software of one-dimensional numeric simulation, developed at the ELIS laboratory of Gent University (Belgium) by Marc Burgelman et al..[1]-[2]

Studies already carried out in our laboratory enabled us to find a thickness optimal of the base in Cu(In, Ga)Se_2 of 2.5µm.[3]

This enables us to simulate a simple solar cell of type *"window layer/emitter CdS (0.5µm)/base Cu(In, Ga)Se_2 (2.5µm)"* to study the influence of the window layer on the electric parameters. The experimental conditions are an ambient temperature of 300K, a low resistance series, a resistance shunt ` infinite' compared to resistance series, under a spectrum of illumination of AM_1.5 and an incident light power of $1000W.m^{-2}$.

We vary the window layers and for each type of window layer we fix thicknesses going from 0.02µm to 0.1µm. For each thickness we study the current-voltage characteristic (J-V) and we define the macroscopic electric parameters (Voc, Jsc, FF, η, V_MPP, J_MPP). To elucidate the phenomena of transmittance and reflectance we study for each type and for each thickness of window layer the quantum efficiency QE.

III. RESULTS AND DISCUSSIONS

III.1 Influence of the type and thickness of the window layer on macroscopic electric parameters Vco, Jcc, FF, η, V_MPP and J_MPP of the solar cell.

III.1.1 Influence of the thickness of the i-ZnO window layer on the macroscopic electric parameters of the solar cell

The intrinsic Zinc Oxide i-ZnO is a candidate very much used like window layer. [4]
It is a Transparent Conducting Oxide TCO with a gap of 3.4eV. It presents good optoelectronic properties with a transparency higher than 80% and an electric conductivity higher than $10^3 \Omega.cm^{-1}$.[5]
The Table 1 gives us the macroscopic electric parameters derived from the J-V characteristics with various thicknesses of i-ZnO.
Tab.1: Macroscopic electric parameters of the solar cell with i-ZnO window layer at various thicknesses

i-ZnO thickness (µm)	Vco (V)	Jsc (mA.cm^{-2})	FF (%)	η (%)	V_MPP (V)	J_MPP (mA.cm^{-2})
0.02	0.612440	33.9413	77.7803	16.1682	0.520723	31.0496
0.04	0.612421	33.9088	77.7329	16.1424	0.520449	31.0163
0.06	0.612400	33.8791	77.7439	16.1300	0.520410	30.9947
0.08	0.612381	33.8522	77.7547	16.1189	0.520410	30.9734
0.1	0.612364	33.8279	77.7634	16.1087	0.520410	30.9538

For i-ZnO thicknesses varying from 0.02µm to 0.1µm we notice a very weak decreasing of the Vco and V_MPP voltages. Also for Jsc and J_MPP current densities the decreasing is weak but more significant than that of the Vco and V_MPP voltages. In fact the thickness of the i-ZnO window layer affects more the current densities than the voltages.The form factor FF is significant for all thicknesses and also decreases very slightly. The cell efficiency η varies from 16.1682% to 16.1087%.The i-ZnO presents a better efficiency when it is finest (0.02µm).

III.1.2 Influence of the thickness of the n-ZnO window layer on the macroscopic electric parameters of the solar cell

The n-ZnO is different from the i-ZnO in view of the conductivity. The n-ZnO is doped N and this doping changes the physical properties of the layer with a gap which decreases (3.3eV), the dielectric permittivity is equal to 9 and the shallow uniform donnor density is equal to $10^{18}cm^{-3}$. Various publications are already carried out with the n-ZnO.[6]-[7]
The table 2 gives us the macroscopic electric parameters derived from the J-V characteristics with various n-ZnO thicknesses.

Tab.2: Macroscopic electric parameters of the solar cell with n-ZnO window layer at various thicknesses

n-ZnO thicknesses (µm)	Vco (V)	Jsc (mA.cm^{-2})	FF (%)	η (%)	V_MPP (V)	J_MPP (mA.cm^{-2})
0.02	0.612400	33.9736	79.7921	16.6011	0.528105	31.4352
0.04	0.612279	33.8271	79.8022	16.5283	0.527988	31.3043
0.06	0.612180	33.7031	79.8229	16.4694	0.527910	31.1973
0.08	0.612104	33.6046	79.8434	16.4234	0.527871	31.1125
0.1	0.612044	33.5283	79.8603	16.3880	0.527793	31.0501

We always note the same variations as previously. The Voc and V_MPP voltages decrease slightly with the n-ZnO thickness whereas the Jsc and J_MPP current densities decrease more quickly and go from $33.9736mA.cm^{-2}$ and $31.4352mA.cm^{-2}$ to $33.5283mA.cm^{-2}$ and $31.0501mA.cm^{-2}$ respectively. The form factor FF is the only parameter which increases with the thickness of the window layer. Indeed the expression of the form factor is

$$FF = \frac{V_{MPP} \times J_{MPP}}{V_{OC} \times J_{SC}} \quad (1)$$

For a solar cell with an n-ZnO window layer, the product $V_{MPP} \times J_{MPP}$ increases more quickly than the product $V_{OC} \times J_{SC}$.

III.1.3 Influence of the thickness of the SnO_2 window layer on the macroscopic electric parameters of the solar cell.

The SnO_2 is also a TCO like ZnO. It has a bandgap of about 3.6eV and a dielectric permittivity is equal to 9. It is doped N with a shallow uniform donor density equal to 10^7cm^{-3}. The SnO_2 is also used in many works too. [8] - [9]

The table 3 presents the macroscopic electric parameters of the solar cell according to the thickness of the SnO_2 window layer.

Tab.3: Macroscopic electric parameters of the solar cell with SnO_2 window layer at various thicknesses

SnO_2 thickness (µm)	Voc (V)	Jsc ($mA.cm^{-2}$)	FF (%)	η (%)	V_MPP (V)	J_MPP ($mA.cm^{-2}$)
0.02	0.613292	34.1955	77.3264	16.2167	0.511348	31.7137
0.04	0.613342	34.2759	78.0073	16.3993	0.514980	31.8446
0.06	0.613344	34.3168	78.3092	16.4825	0.516699	31.8997
0.08	0.613324	34.3242	78.4808	16.5217	0.517715	31.9126
0.1	0.613295	34.3134	78.5586	16.5321	0.518145	31.9063

We note a weak increase in the Voc and V_MPP voltages according to the increase thickness of the layer SnO_2 window layer. The open circuit voltage decreases starting from 0.08µm SnO_2 thickness. The Jsc and J_MPP current densities increase according to the SnO_2 thickness. We notice that they decrease too starting from 0.08µm. These decreases result in the fact that we move away from the ideal thickness of the SnO_2 window layer. Nevertheless until an SnO_2 thickness of 0.1µm, these decreases don't affect yet the cell quality since the form factor FF and the efficiency η continue their increase with the thickness. We note FF_{max}=78.5586% and $η_{max}$=16.5321% for an optimal SnO_2 thickness of 0.1µm.

III.1.4 Influence of the thickness of the ITO window layer on the macroscopic electric parameters of the solar cell.

The Indium Tin Oxide ITO is a thin film which presents effective electrical and optical properties which make it competitive compared with Transparent Conducting Oxides. It has a gap of about 3.6eV and is doped N with a shallow uniform donor density of $10^{20}cm^{-3}$.[10]-[11]

The table 4 gives us the macroscopic electric parameters of the solar cell in with an ITO window layer at various thicknesses.

Tab. 4 : Macroscopic electric parameters of the solar cell with ITO window layer at various thicknesses

ITO thickness (µm)	Voc (V)	Jsc ($mA.cm^{-2}$)	FF (%)	η (%)	V_MPP (V)	J_MPP ($mA.cm^{-2}$)
0.02	0.616503	33.7038	63.7110	13.2382	0.438730	30.1739
0.04	0.616395	33.6724	63.7304	13.2275	0.438730	30.1496
0.06	0.616341	33.6566	63.7400	13.2222	0.438730	30.1374
0.08	0.616313	33.6483	63.7449	13.2194	0.438730	30.1309
0.1	0.616298	33.6438	63.7476	13.2178	0.438730	30.1274

We notice that the open circuit voltage Voc is more significant than with the use of the TCO and it slightly also decreases with the thickness. The maximum power point voltage V_MPP is not affected by the thickness variation of the ITO and remains equal to 0.438730V.The Jsc and J_MPP current densities decrease with the ITO thickness but remain less significant as in the case of the use of a TCO. The form factor FF remains significant but also decreases with the ITO thickness passing from 63.7110% to 63.7476%. Compared with the use of the TCO, there is a less significant cell efficiency which remains competitive considering the accessible process manufacturing of ITO. The conversion efficiency also decreases with the ITO thickness.

III.2 The current voltage characteristic J-V of the cell for the various types of windows layers.

The Fig.1 shows us the J-V characteristics of the cells for the various types of window layers which are i-ZnO, n-ZnO, SnO_2 and ITO. For each one of these window layers we represent the J-V characteristic of the cell with their optimal thickness. This enables us to note the differences in characteristic with the use of these windows layers.

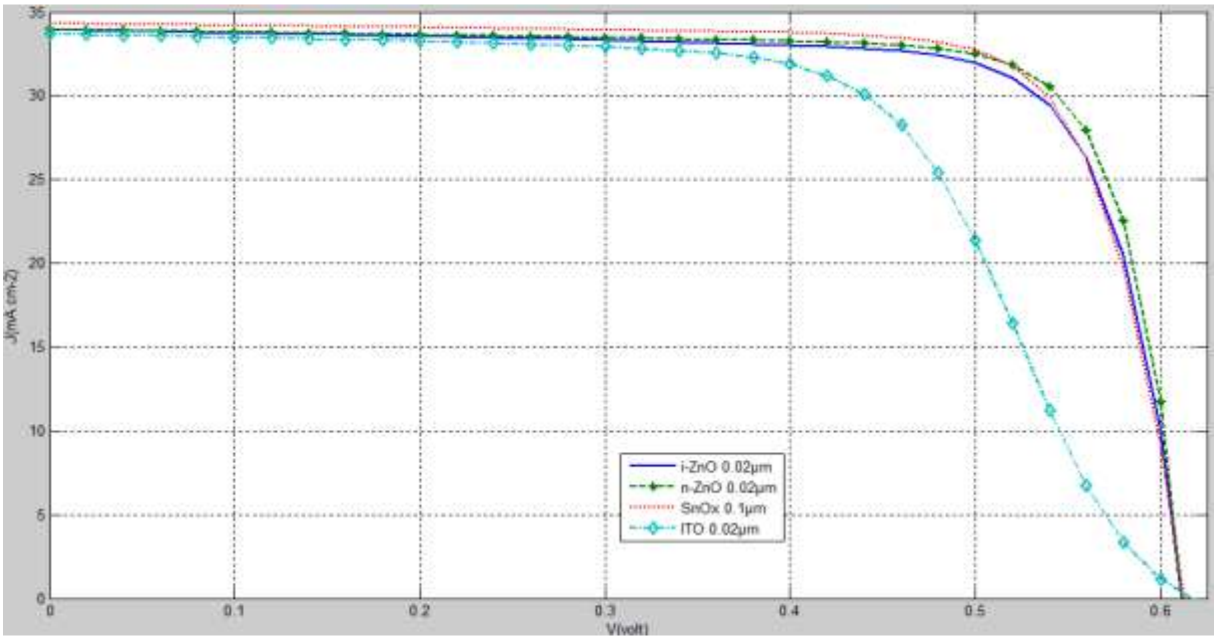

Fig.1: J-V characteristics of the cells according to the type of the used window layer

We notice that the window layers have a net influence on the electric parameters of the cell. The short circuit current density Jsc is more affected than the open circuit voltage Vco. These characteristics are convergent with the established search results. The use of the TCO gives very close characteristics whereas that of the ITO presents a maximum power point less low.

III.3 Influence of the type and the thickness of the window layer on the quantum efficiency

The Quantum Efficiency QE, also called spectral response, makes it possible to do without the studies of transmittance and reflectance. It is of two types:

- The external quantum efficiency EQE which is the ratio of the number of charge carriers collected on the incident photon number.
- The internal quantum efficiency IQE which is the ratio of the number of charge carriers collected on the number of photons really absorbed.

We are interested in our work by the external quantum efficiency. We study the spectral response for wavelengths going from 300nm to 900nm which relates a part of the field of UV radiations (300nm-400nm), the visible domain (400nm-800nm) and IR radiations (800nm-900nm).

III.3.1 Influence of the i-ZnO window layer thickness on the quantum efficiency

The Fig.2 gives us the variation of the spectral response according to the thickness of the i-ZnO window layer.

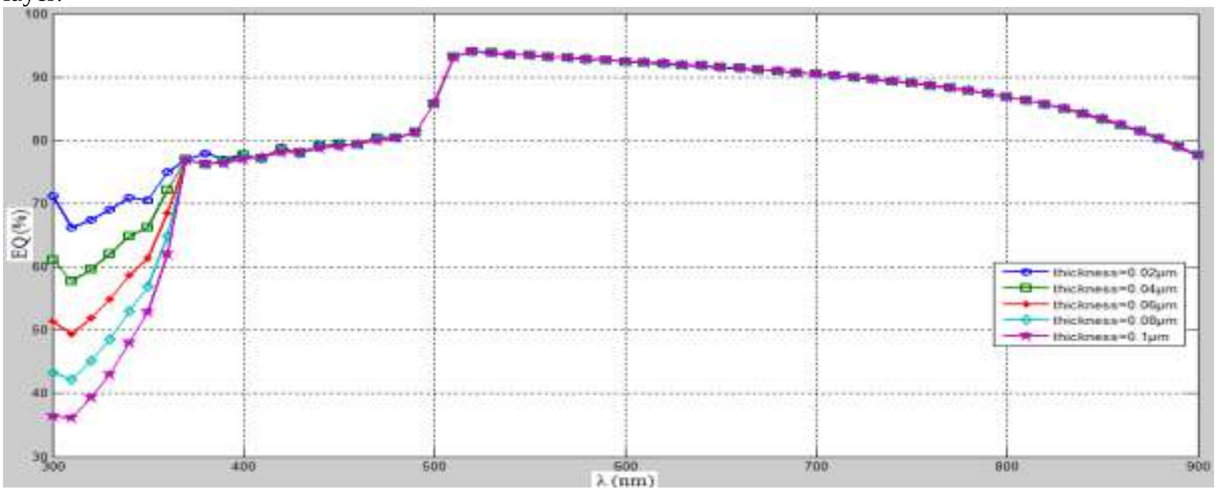

Fig.2: Variation of the quantum efficiency according to the window layer i-ZnO thickness.

For a wavelength λ=300nm, the spectral response is already significant; it is 71.221% for an i-ZnO thickness of 0.02µm. This spectral response decreases with the thickness up to 36.404% for i-ZnO window layer of 0.1µm. The quantum efficiencies vary in the same proportions with the wavelength increase. We however note a small fall until 320nm due to the importance of the reflectance. From this value the spectral responses increase because of the importance of transmittance. The Quantum efficiency is strongly affected by the thickness of the window layer until 370nm. Between 370nm and 480nm the spectral reponses are very close. Beyond 480nm the i-ZnO window layer thickness doesn't affect any more the quantum efficiency which reaches a maximum of 94.054%. This wavelength characterizes the maximum power point and for wavelengths higher than 480nm the spectral answer drops slightly.

III.3.2 Influence of the n-ZnO window layer thickness on the quantum efficiency

The Fig.3 gives us the variation of the spectral response according to the thickness of the n-ZnO window layer.

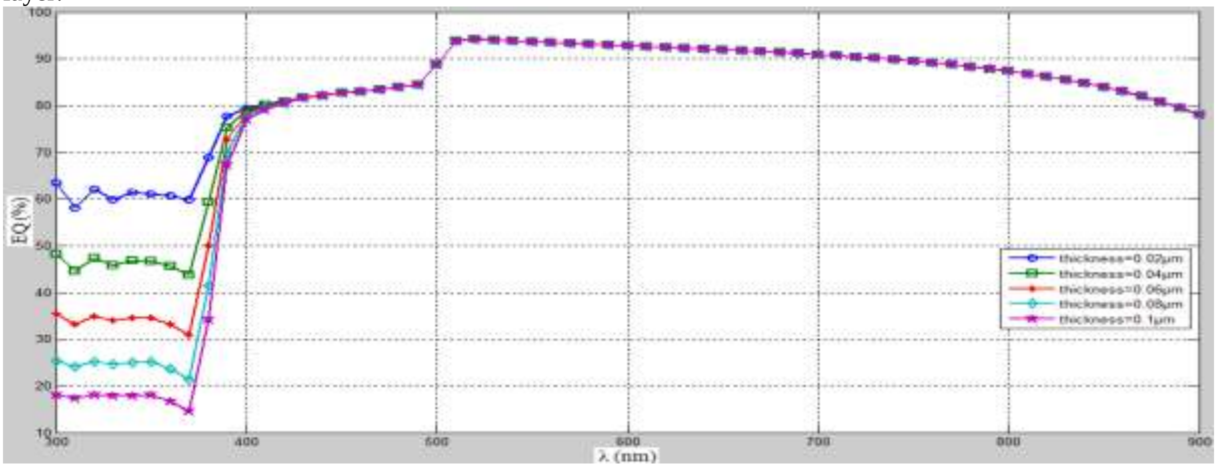

Fig.3: Variation of the quantum efficiency according to the window layer n-ZnO thickness.

The doping of intrinsic ZnO has a remarkable impact on the spectral response. Indeed for a wavelength of 300nm the quantum efficiency is less significant than with the i-ZnO. It is 63.501% and falls to 18.076% if the window layer thickness passes from 0.02µm to 0.1µm. The spectral responses variations have the same proportions until a wavelength of 370nm. We notice that the thickness of the window layer influences quantum efficiency clearly. On the wavelength ranges going from 300nm to 370nm the reflectance and transmittance phenomena are worth what explains the constancy of the spectral response. From this value the spectral response becomes significant and the influence of the window thickness decreases. This influence is not noticed any more starting from 430nm. Quantum efficiency evolves to a maximum value of 94.275% for a wavelength of 520nm whereas it was 94.054% with the i-ZnO. This light improvement of the spectral response results in an increase in the conversion efficiency.

III.3.3 Influence of the SnO_2 window layer thickness on the quantum efficiency

The Fig.4 gives us the variation of the spectral response according to the thickness of the SnO_2 window layer.

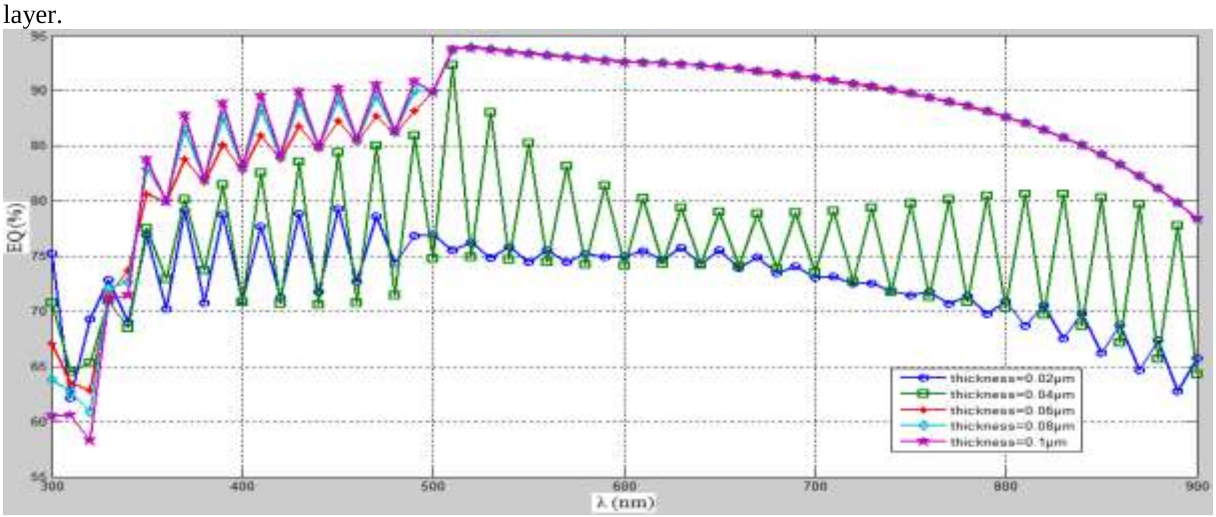

Fig.4: Variation of the quantum efficiency according to the SnO_2 window layer thickness.

The use of SnO_2 window layer gives us a spectral response not very common for wavelengths going from 300nm to 900nm.This is due to the fact that the spectral response borders its maximum on the wavelength range. The fluctuations give, for a wavelength of 520nm, the quantum efficiencies maxima according to the thickness of SnO_2. For thicknesses from 0.06µm to 0.1µm we note a maximum quantum efficiency of 93.856%.The SnO_2 thickness has a greater influence on the spectral response for values from 0.02µm to 0.04µm. Indeed the phenomena of transmittance are more significant for thicknesses from 0.06µm to 0.1µm.

III.3.1 Influence of the ITO window layer thickness on the external quantum efficiency EQE

The figure 5 presents the spectral response of the cell with an ITO window layer.

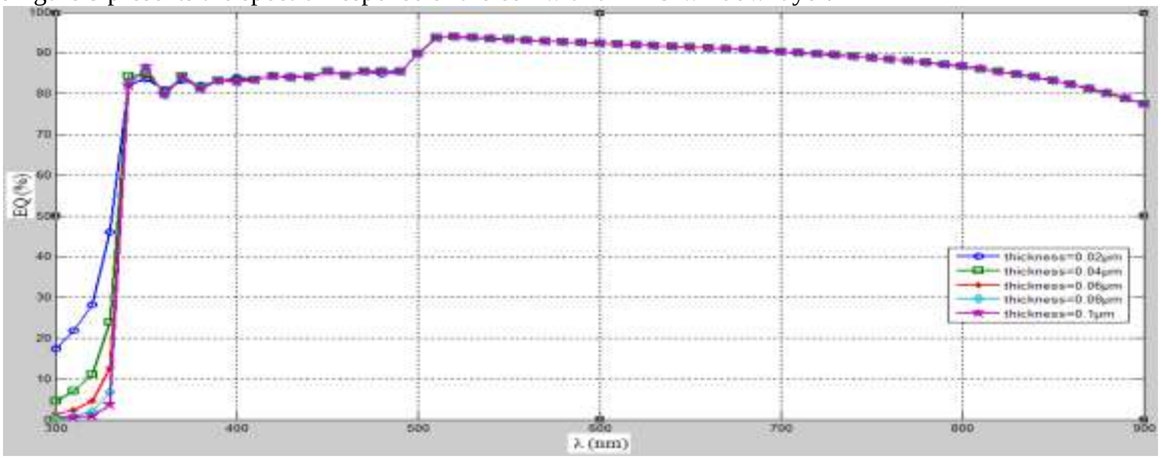

Fig. 5: Variation of the external quantum efficiency according to the ITO window layer thickness

For wavelengths of 300nm we have weak spectral response compared to the preceding cases of use of ITO. We just have a spectral response of 17.426% for a window layer of 0.02µm which regresses up to 0.35594% for 0.1µm. the ITO presents a very good transmittance which results in the fast improvement due the spectral answer. The influence of the thickness of the window layer on quantum efficiency is noted until 340nm, wavelength from which the variations of quantum efficiency become identical. We note quasi a constancy of the spectral response until 490nm for all the thicknesses. From this value the thickness of the window layer does not affect any more the spectral answer and this one reached a maximum of 93.948% for a wavelength of 520nm.

CONCLUSION

This work shows us that the best candidate for window layer is the Zinc Oxide doped N (n-ZnO) which presents a maximum conversion efficiency of 16.6011% for a thickness of 0.02µm. Nevertheless the use of the Tin dioxide SnO2 is very significant but for a thickness of 0.1µm one notes a conversion efficiency of 16.5321%.
Compared to the spectral response we note that SnO2 presents the most interesting quantum efficiency which is 93.856% for a wavelength 520nm. As for the n-ZnO, we obtained a maximum quantum efficiency of 92.275% for a wavelength of 520nm. the use of n-ZnO or SnO2 window layers gives to remarkable effectiveness.The choice between the two materials is done compared to the prospective results.

REFERENCES

[1] M. Burgelmann, P. Nollet, and S. Degrave, Modelling polycristalline semiconductor solar cell, *Thin Soli Films* 362, 2000, 527-532.
[2] M. Burgelmann and Jonas Merlin, Analysis of graded band gap solar cells with SCAPS, *23rd European Photovoltaic Solar Energy Conference,*Valencia, September 2008.
[3] A. K. Ehemba, M. Dieng, and al., Influence of $CuInSe_2$ and $Cu(In,Ga)Se_2$ thin layer thickness on the electric parameters on the solar cell, *Current Trends in Technology and Science,* 04(03), 2015, 531-545.
[4] S. Ishizuka, and K. Sakurai, Fabrication of wide-gap $Cu(In_{1-X},Gas_X)Se_2$ thin films solar cells: a study of the correlation of cell performance with highly resistive i-ZnO layer thikness, *Solar Energy Materials and Solar Cells,* 87(4), 2005, 541-548.
[5] Subba Ramaiah Kodigala, $Cu(In,Ga)Se_2$ Based Thin Film Solarr, in Elsevier, *Fabrication and properties of window layer thin film solar cell*, 2010, 393-504.
[6] L. Stolt, J. Hedström, and al., $ZnO/CdS/CuInSe_2$ thin film solar cell with improved performance, *Applied Physics Letters,* 62, 1993, 597.
[7] O. Horomichi, M. Hiroshi, and al., Fabrication and characterization of heteroepitaxial p-n junction diode composed of wide-gap oxide semiconductors $p\text{-}ZnRh^2O^4/n\text{-}ZnO$, *Aplplied Physics Letters,* 82(05), 2003, 823-825.
[8] S. Belgacem and R. Bennaceur, SnO_2 and $CuInSe_2$ airless spray thin film properties, *Rev. Phys.(Paris),* 25, 1990, 1245-1258.
[9] R. Outemzabet, N. Kesri, Elaboration and characterization of SnO_2/Si(PS) structure, *Phys. Chem. News,* 6, 2002, 59-62.
[10] R. A. Joshi, V. S. Taur, and R. Sharma, Polymer impinged $CdS/CuInSe_2$ solar cell, *Solar Energy,* 86, 2012, 301-306.
[11] A. K. Ehemba, M. Dieng, and al., Minority carriers' diffusion length determination in thin films $CuInSe_2$ solar cells electrodeposited on flexible substrate in Kapton, *International Journal of Innovative Science, Engineering & Technology,* 02(01), 2015, 302-307.