Impact of the Thickness and the Index of the Anti-Reflecting Coating on the Macroscopic Electric Parameters of the Cu(In,Ga)Se2 Thin Film Solar Cell

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Abstract

In this article we are interested by the decreasing of the front surface reflection of a Cu(In, Ga)Se_2 thin film solar cell. For that we use an antireflective coating (ARC) in Zinc Oxide to form the ZnO/CdS interface. This layer plays as well the role of windows layer. We improved the electric parameters by using a thickness of antireflective coating of 105nm which gives a short circuit current density of 0.023mA.cm $^{-2}$, an open circuit voltage of 0.828V and a maximum power of 0.01858mW. The study carried on the index of refraction of the ARC gives an optimal index of 1.676.We find with this value a short-circuit current density of 0.0267mA.cm $^{-2}$, an open circuit voltage of 0.829V and a maximum power of 0.01915mW.The solar cell with an antireflective coating, wich has a thickness of 105nm and an index of 1.676, gives us a maximum quantum efficiency of 88.28% for an incidental wavelength of 0.7µm. the use of the ARC with an optimal thickness and an ideal index improves the performances of the solar cell.

Keywords: Antireflective coating, ZnO, electric parameters, EQE, Cu(In,Ga)Se_2 thin film.

Introduction

The performances of the photovoltaic solar cells depend on several more or less complex factors that the researchers try everyday to optimize. These factors are either internal in the cell or external. They unceasingly search to improve the efficiency of the cell while by the development [1]-[2], the cell technology [3], and the parameters of use of the cell [4]-[5]. Our research searches to improve the macroscopic electric parameters of thin film solar cells by the rates of doping of the layers [6], the thickness of the layers [7], the recombinations [8], and the optical effects. In this article we are interested by the decreasing of the front reflection of a Cu(In, Ga)Se_2 thin film solar cell. We use an antireflective coating in Zinc Oxide to form the ZnO/CdS interface. Indeed the ARC increases the transmission of incidental beam. However the antireflective coatings the most used in the bibliography are the Silicon Oxide SiO, the Silicon nitride SiN, the Dioxide Titanium TiO2 and the TCO [9]- [10]. Our ARC is deposited on a CdS buffer layer as presented by figure 1.

A correct operation of the antireflective coating depends of two principal parameters which are the thickness of the ARC and the refractive indexes of the medium, the ARC and the buffer layer. The ideal thickness of the ARC to be used is proportional to the wavelength of the incidental beam. It is calculated by the relation:

$$d_{ZnO} = \frac{\lambda}{4n_{ZnO}} \quad (1)$$

d_{ZnO} is the thickness of the ARC, n_{ZnO} its index and λ incidental wavelength.

In the same way the ideal index of the ARC depends on the index of the incidental medium and the index of the buffer layer; and it can be evaluated while applying:

$$n_{ZnO} = \sqrt{n_{Cds} \times n_0} \qquad (2)$$

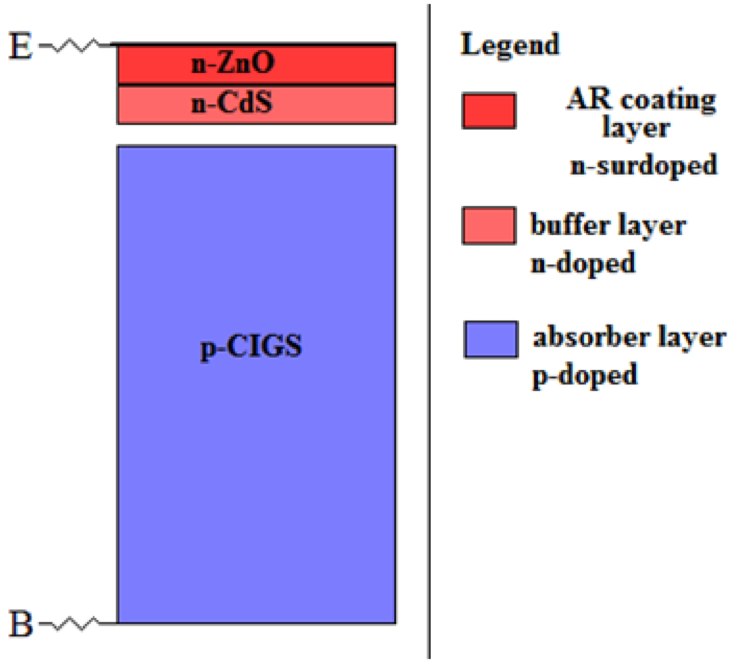

Figure 1: schematic device

However the use of the cells takes place for a broad range wavelength going from the ultraviolet range to the near infrared range. We propose in the first part of our work to find the thickness optimal of the ARC which gives the best electric parameters.

The index of ZnO varies according to the Dispersion Formula:

$$n^2 = 2.81418 + \frac{0.87968\lambda^2}{\lambda^2 - 0.3042^2} - 0.00711\lambda^2 \qquad (3)$$

For a maximum transmission, we study in the second part of our work the effect of the variation of the ARC index on the electric parameters of the cell. We use a broad range of incidental wavelengths going from 300nm to 1200nm with a constant incidental power of 0.1W.cm^{-2} and under a standard illumination of AM1.5.The studied electric parameters are the short circuit current density Jsc, the open circuit voltage Voc, the maximum power Pm of the cell and the external quantum efficiency EQE.

Materials and Methods

Our working method is based on three steps. The first step corresponds to the resolution of the fundamental equations which govern the physical phenomena which intervene in the solar cell. These equations correspond:

with the density of the charge carriers (electrons and holes) : $\begin{cases} J_n = \mu_n n \nabla E_{Fn} \\ J_p = \mu_p p \nabla E_{Fp} \end{cases}$ (4)

the exponential approximation of Boltzmann for the function of Fermi distribution:

$$\begin{cases} n = N_C e^{-(E_c - E_{Fn})/kT} \\ p = N_V e^{-(E_{Fp} - E_V)/kT} \end{cases} \qquad (5)$$

transport equations: $\overrightarrow{J_p} = -eD_p \vec{\nabla} p - ep\mu_p \vec{\nabla} V + p\mu_p kT \vec{\nabla}(n_{ie} L_n)$ *(6)*

$$\overrightarrow{J_n} = eD_n \vec{\nabla} n - en\mu_n \vec{\nabla} V - n\mu_n kT \vec{\nabla}(n_{ie} L_n) \quad (7)$$

This mathematical base extends until the determination of the macroscopic electric parameters.

In the second step of our work, to check the convergence of the mathematical results, we carry out a simulation using the PC1D. It is a quasi one-dimensional program conceived to simulate solar cells and able to solve the nonlinear coupled equations which control the physical phenomena of the studied device. It is a software developed at the University South Wales of Sydney in Australia and distributed by Photovoltaics Special Research Center. The PC1D makes it possible to approach complex studies such as the strong rates of doping, high levels of injection, the no plane structures and the transients [11]-[12]. However it is a software used especially for the crystalline structures in particular containing Silicon. We adapted it to the cells Cu(In,Ga)Se_2 thin film solar cell. The Table 1 presents the properties of materials used for simulation.

Table 1 : Physical parameters of materials

	n-ZnO	n-CdS	p-Cu(In,Ga)Se2
Thickness (μm)	0.05	0.05	2.5
Dielectric constant	10	13.6	13.6
Band gap (eV)	3.3	2.4	1.2
Intrinsic. Conc. At 300K (cm^{-3})	1.99×10^{-9}	0.04353	5.232×10^{8}
Refractive index	3.45	3.45	3.45
P-type background doping (cm^{-3})	10^{18}	10^{17}	2×10^{16}
1^{st} front diffusion N-type (cm^{-3})	6×10^{19}	10^{18}	2×10^{16}

The third step of our work corresponds to obtaining the characteristics treated with Matlab for more convergence. It is visualization and computation software, whose basic entities are matrices. MATLAB is an abbreviation of Matrix Laboratory. It is a language interpreted which proposes facilities of programming and visualization, as well as a great number of functions carrying out various numerical methods [13]-[14].

These three stages enabled us to study the influence of the thickness of the antireflective coating and its refractive index on the macroscopic electric parameters of the cell.

Results and discussion

We start by showing at figure 2 the current density-voltage characteristic and power maximum-voltage characteristic of the studied cell without ARC. The characteristics attest us the conventional performances of the cell which operates like a rectifier. We have a short circuit current density $|J_{sc}|$= 0.032mA.cm^{-2}, an open circuit voltage of 0.83V, and a maximum power of 0.023mW.

Influence of the thickness of the ARC on the macroscopic electric parameters of the cell

Variation of the short circuit current density according to the thickness of the ARC

The short-circuit current density is the current per unit of area delivered by the cell when it does not deliver any voltage. It is a quantifiable physical parameter using the expression:

$$J_{sc} = J_{ph} - J_s\left[e^{\frac{qV}{kT}} - 1\right] \qquad (8)$$

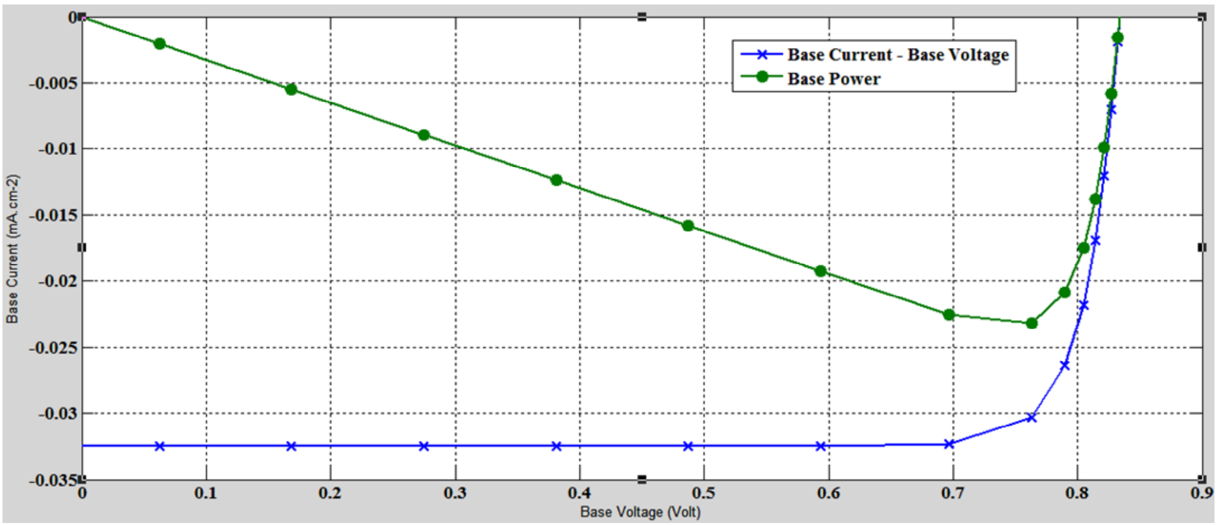

Figure 2: current density-voltage and maximum of power-voltage characteristics of the CIGS thin film solar cell without ARC.

The Figure 3 shows us the variation of the short circuit current density of the cell according to the thickness of the ARC in ZnO deposited on the CdS buffer layer. The device being a rectifier, we note a negative current density, which for more convenience will be taken in absolute value. For a thickness from 0nm to 200nm we have an improvement of Jsc which is followed by a clear reduction. When we consider a thickness of the ARC which varies between 80 and 120nm, we approach the ideal thickness for an optimal short circuit current density. We find a maximum Jsc of $0.026 mA.cm^{-2}$ for a thickness of 105nm.This behavior of the short circuit current density is explained by its proportionality with incidental beam. The antireflective coating increases transmitted beam. When the ideal thickness is exceeded the transmission gets weaker because the significant thickness of the ARC of the cell constitutes a barrier to the diffusion of incidental wavelengths. What explains the decrease of Jsc. Compared to the minority carriers it is noted that for a thickness of 105nm, they have more the possibility of crossing the junction to be collected. When the thickness of the ARC increases, the carriers lifetime does not enable them to cross the junction to be collected, they recombine.

Variation of the open circuit voltage according to the thickness of the ARC

When the solar device does not deliver any more current, it delivers a voltage called open circuit voltage which is quantified using the expression:

$$V_{oc} = \left(\frac{kT}{q}\right)\log\left(1 + \frac{J_{sc}}{J_s}\right) \qquad (9)$$

The Voc results from the fundamental equation of voltage delivered by the photovoltaic cell:

$$V = \left(\frac{kT}{q}\right)\log\left(1 + \frac{J_{ph} - J}{J_S}\right) - R_s J \qquad (10)$$

Jph is the density of photocurrent, *Js* saturation current density, *J* current density at the boundaries of the circuit of use and *Rs* series resistance. The Figure 4 gives the variation of the open circuit voltage according to the thickness of the ARC. The open circuit characteristic for a thickness of the ARC going from 0 to 200nm shows also an ideal thickness. The latter is elucidated by considering a thickness going of 80nm with 120nm.The Voc is maximum and is equal to 0.828V for a thickness of 105nm. Indeed the increase in transmitted beam increase the number of carriers photocreated. The number of minority carriers stored to the junction of the cell increases from where the increase of the open circuit voltage. The same phenomenon noted with the short circuit current density makes also decrease the open circuit voltage.

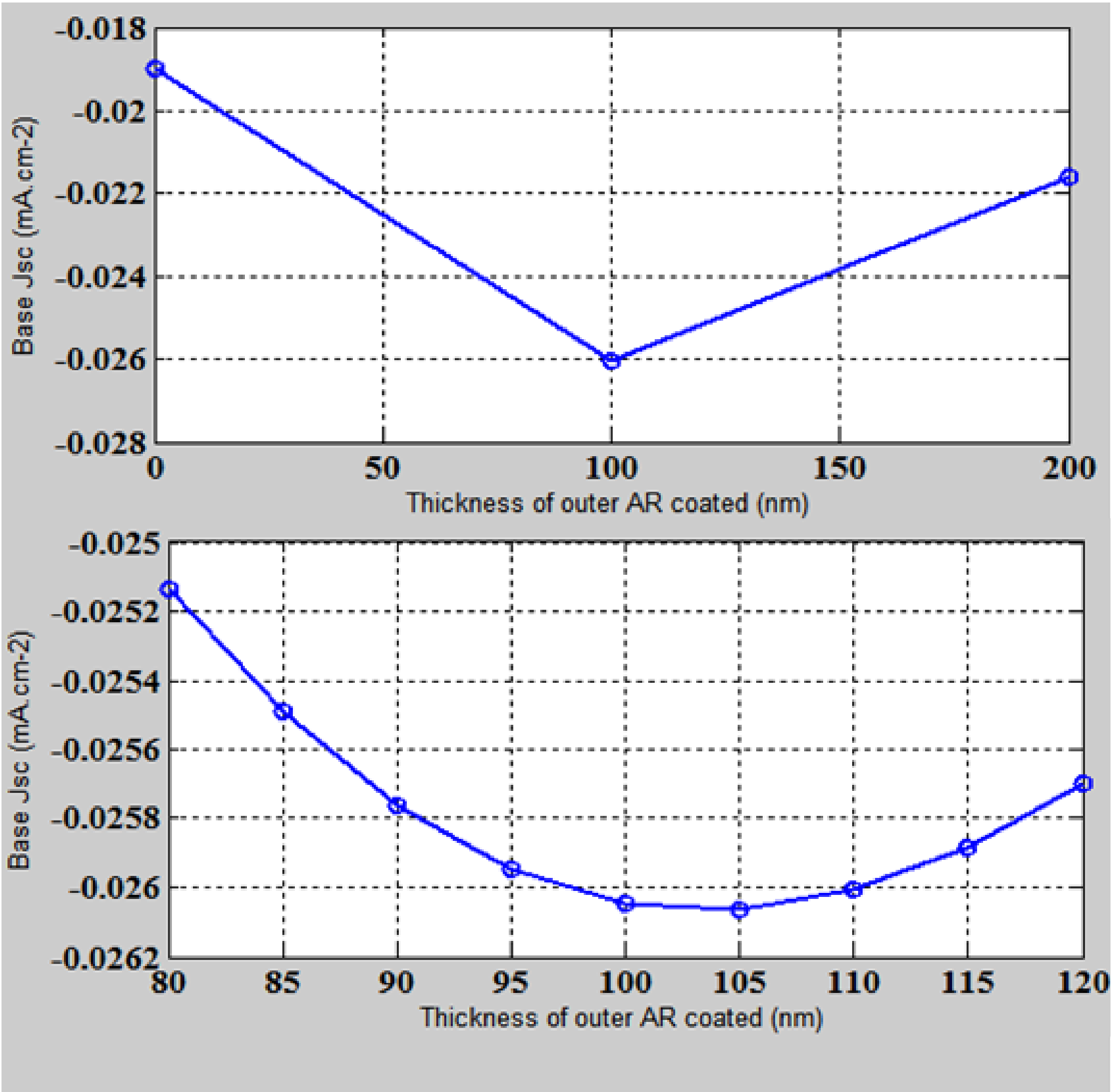

Figure 3: Variation of the short circuit current density according to the thickness of the ARC

Variation of the maximum power Pm of the solar cell according to the thickness of the ARC

The power of the device is evaluated by making the product of the delivered voltage and the delivered current intensity. To give the maximum power we make the product of the maximum current density, for a cell thickness of 1cm2, and the maximum voltage delivered.

$P_m = J_m \times V_m$ (11)

The figure 5 presents the variation of this maximum power according to the thickness of the antireflective coating deposited on the CdS buffer layer. In accordance with the variations of the open circuit voltage and of the short circuit current density we note a peak of maximum power of 0.01858mW for the optimal thickness of 105nm.

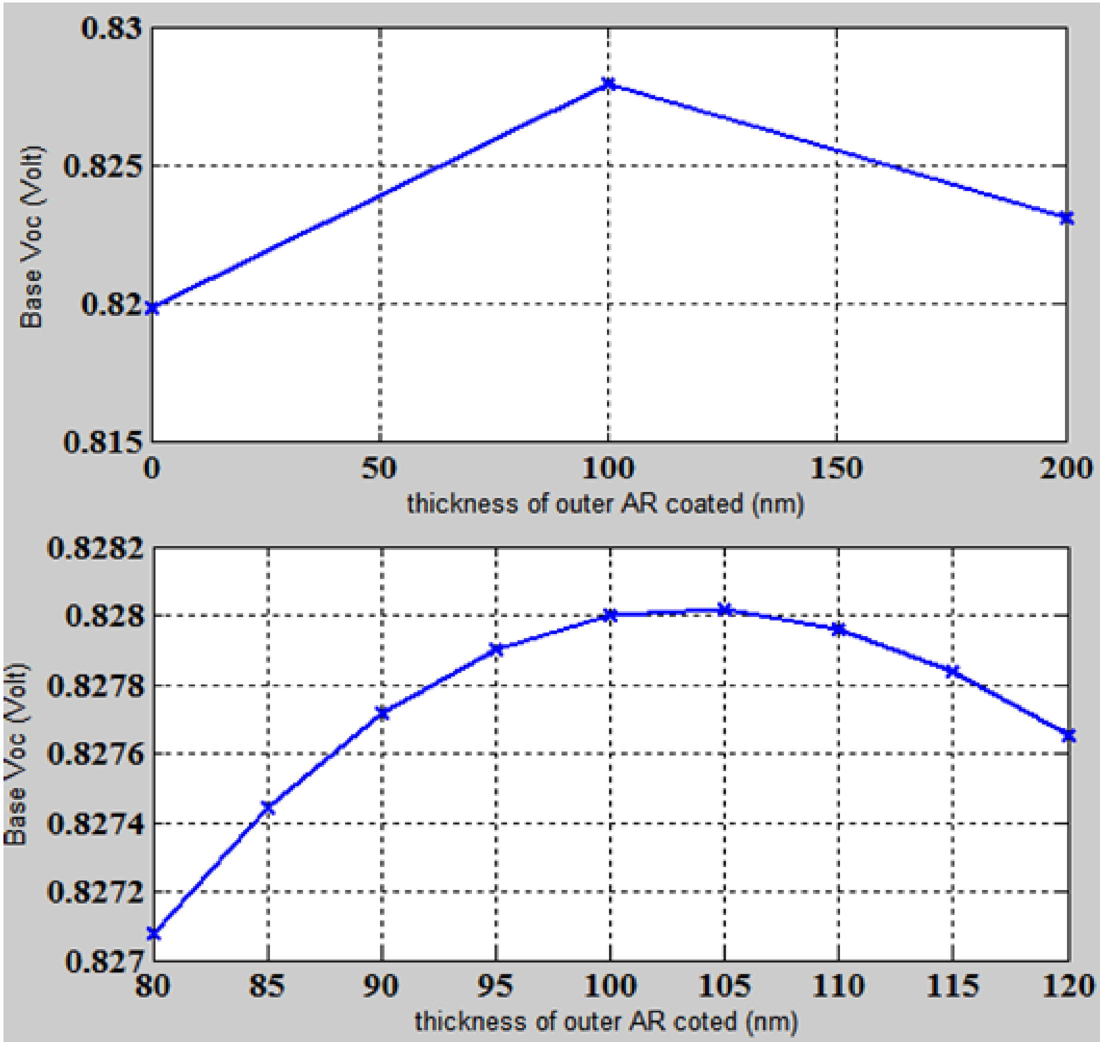

Figure 4: Variation of the open circuit voltage Voc according to the thickness of the ARC

This first part of our work indicates to us an optimal thickness of 105nm.The performances of the ARC depending on the refractive index of ZnO, we approach in the second part of work the influence of this index on the electric parameters of the cell.

The Influence of the ARC index on the macroscopic electric parameters of the cell

The index of refraction varies according to the incidental wavelength according to the formula of dispersion (3).To take into account the possible values of the index of the anti-reflecting layer we use a beach of values going from 1.3 to 2.75.

Variation of the short circuit current density Jsc according to the ARC index

The figure 6 gives us the characteristics of the short circuit current density Jsc according to the ARC index. For indices going from 1.3 to 2.75 we note a preferential index. The characteristic obtained with indices going of 1.46 to 1.78 enables us to locate the optimal index which is equal to 1.676. This index gives a short-circuit current density $|J_{sc}|$= 0.02692mA.cm^{-2}. Indeed transmitted beam is more significant for this index, which corresponds to a more significant creation of minority carriers. The number of carriers crossing the junction to be to collected increases the Jsc.

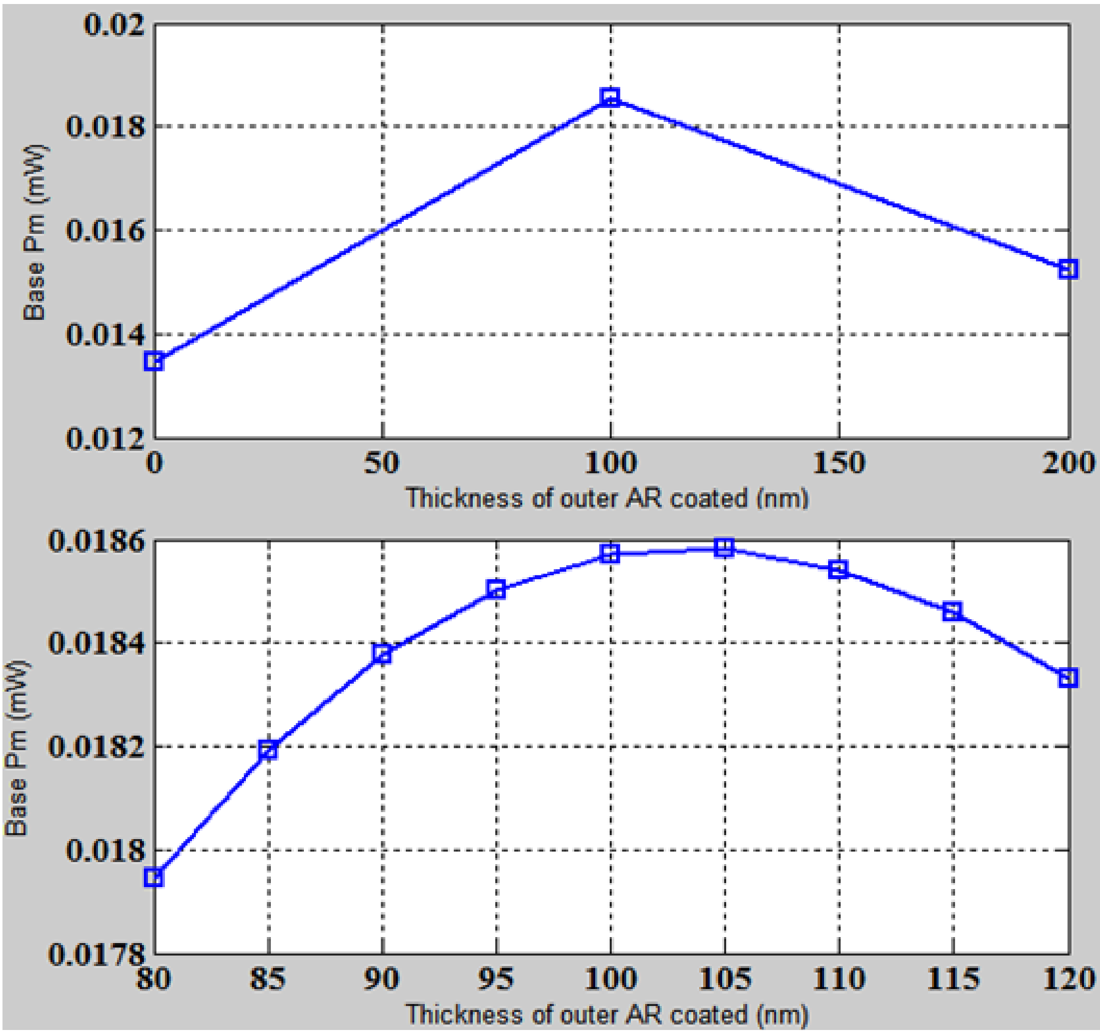

Figure 5: Variation of the maximum power Pm of the cell according to the thickness of the ARC

Variation of the open circuit voltage Voc according to the ARC index.

The figure 7 shows us the behavior of the open circuit voltage according to the ARC index. We note for a range of indices going from 1.3 to 2.75, an optimal index. With the characteristic which corresponds to the indices going from 1.46 to 1.78, we note an open circuit voltage maximum equal to 0.8289V for n=1.676. This index gives a maximum transmission which increases the number of minority carriers stored at the junction. This explains the increase in Voc. When this index exceeds 1.676 transmitted beam is reduced and is accompanied by a fall of the open circuit voltage.

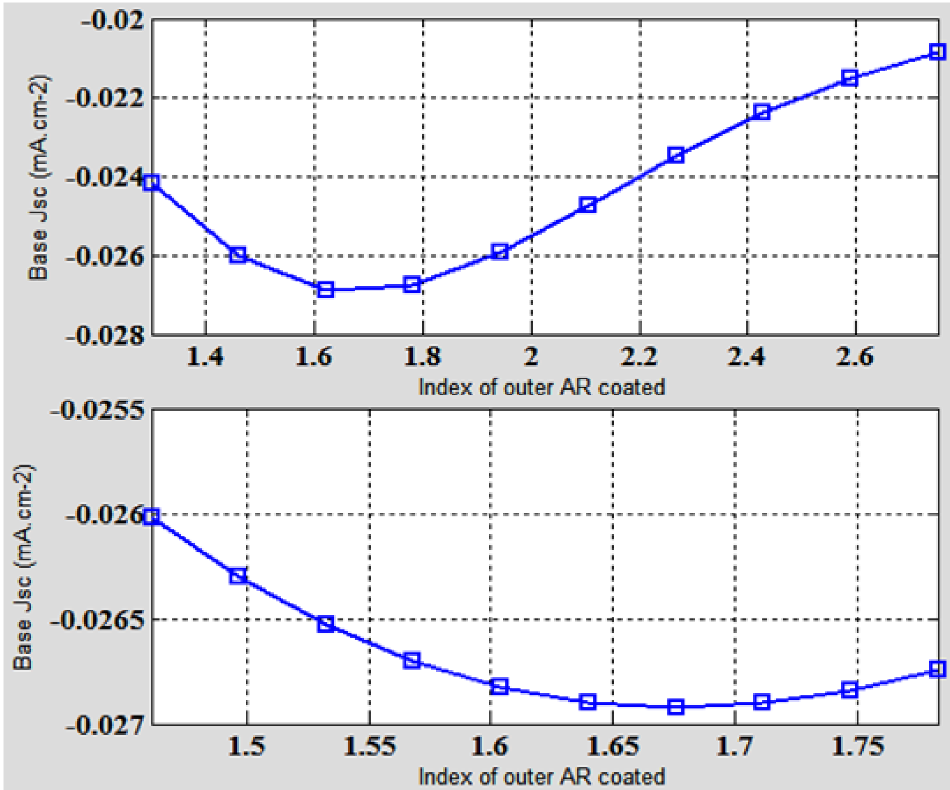

Figure 6: Variation of the short circuit current density Jsc according to the ARC index.

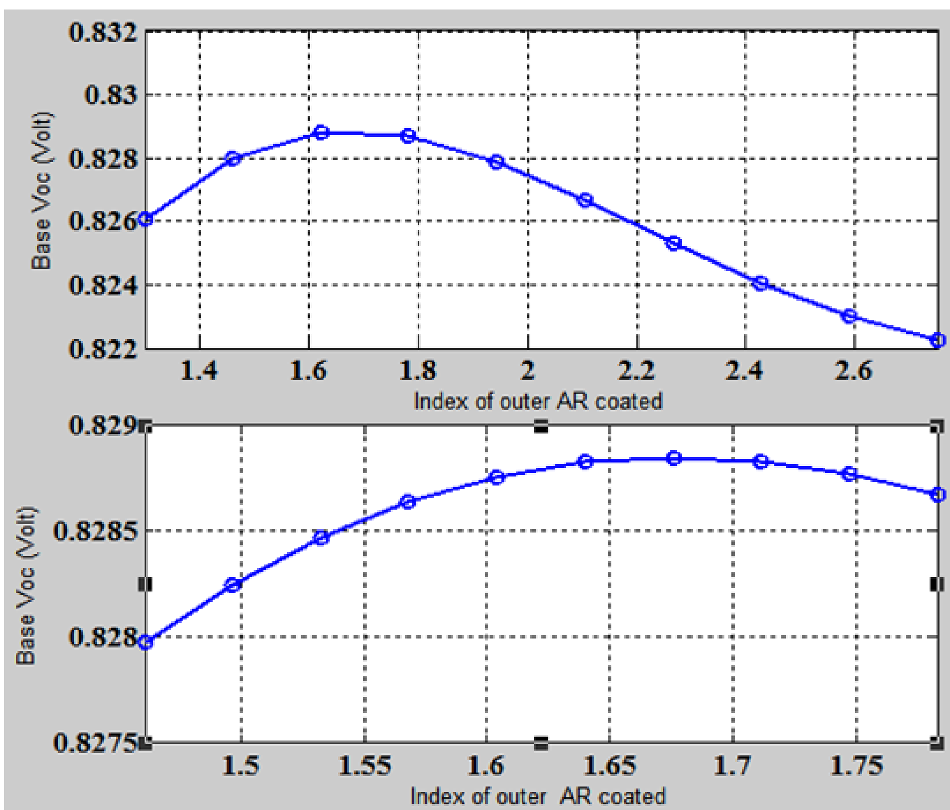

Figure 7: Variation of the open circuit voltage Voc according to the ARC index

Variation of the maximum power Pm of the cell according to the ARC index

The figure 8 gives us the variation of the maximum power of the solar cell according to the ARC index. By analogy with the variations of the short circuit current density Jsc and the open circuit voltage Voc, we could predict an optimal maximum power of 0.01915mW for an ARC index of 1.676. This value is also related to the maximum transmission which gives a greater number of photocreated minority carriers.

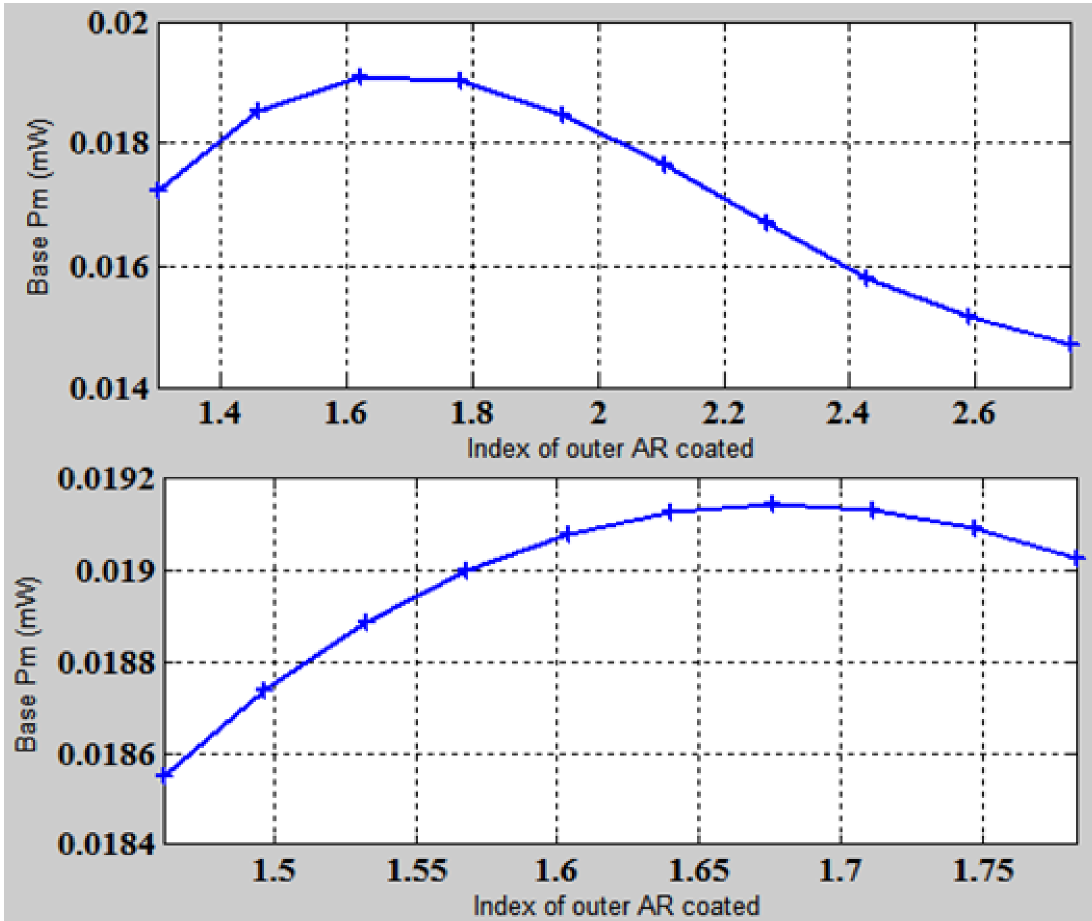

Figure 8: Variation of the maximum power Pm of the cell according to the ARC index

The second part of our study enables us to affirm that the performances of the cell are better for an ARC index of 1.676.We show in the last part some characteristics of the cell with an antireflective coating thickness of 105nm with an index of 1.676.

Characteristics of the Cu(In,Ga)Se$_2$ thin film solar cell with an antireflective coating thickness of 105nm and an index of 1.676

Characteristics density of current-tension-power

The characteristic obtained attests the rectifier character of the cell. Compared to the characteristic of figure 2, we note a net improvement of the electric parameters. The short circuit current density is equal to 0.02692mA.cm^{-2}, the open circuit voltage is 0.8321V and the maximum power of the cell is of 0.019mW.The performances of the cell are then satisfactory.

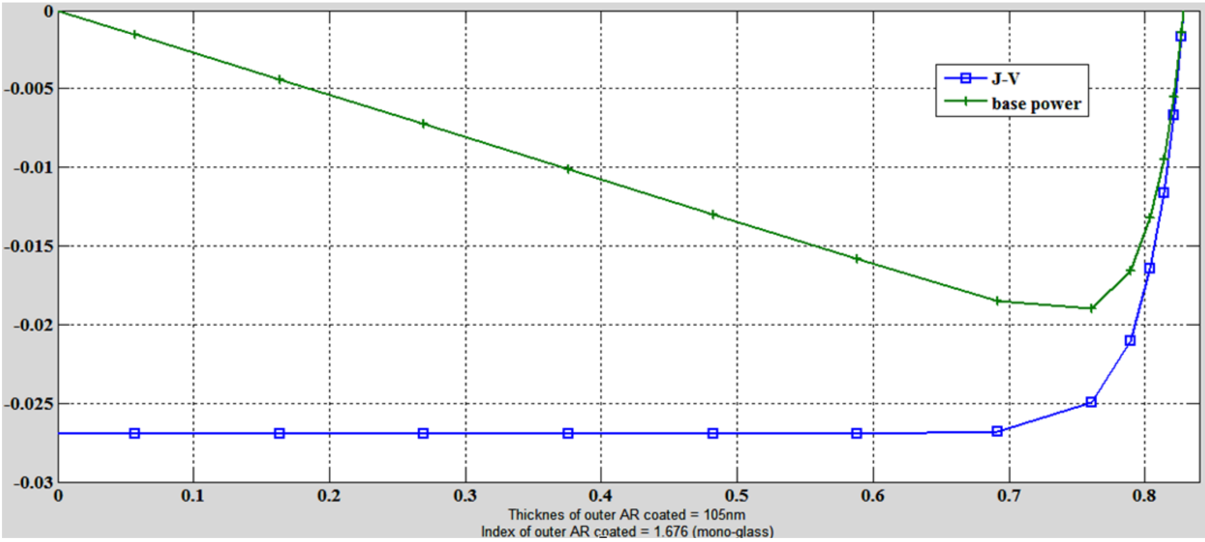

Figure 9: Characteristics density of current-tension-power of the cell with an ARC thickness of 105nm and a refractive index n=1.676.

Characteristic of the external quantum efficiency EQE.

The external quantum efficiency EQE is the ratio of the number of carriers collected on the number of incidental photons. It gives an idea of the spectral response of the device according to the various incidental wavelengths. We use a constant illumination of $0.1W.cm^{-2}$, and incidental wavelengths going from 300nm to 1200nm thus covering the Ultraviolet range, the Visible range and the near infrared range. The figure 10 presents to us the variation of the EQE of the cell with an ARC thickness of 105nm and an index of 1.676.The maximum absorption area extends on both sides of the visible range. The response is higher than 40% in the ultraviolet range. It reaches a maximum value of 88.28% for an incidental wavelength of 700nm which corresponds to energy of 1.77eV.This value is cancelled in the near infrared because the incidental wavelengths are accompanied by energy weaker than the optical gap of the absorber in Cu(In, Ga)Se_2.

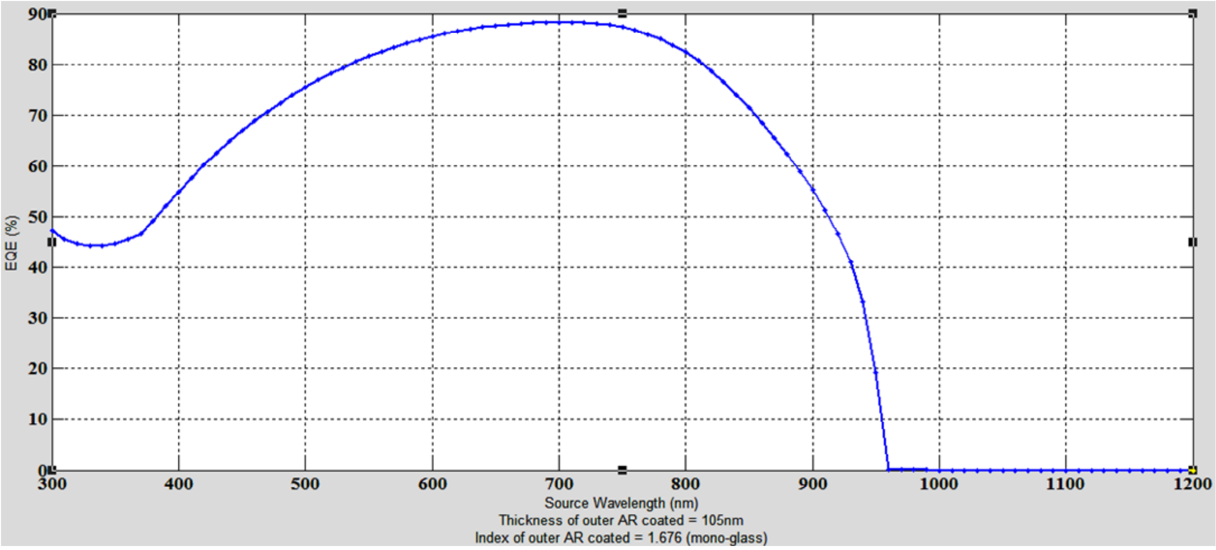

Figure 10: Variation of the external quantum efficiency EQE of the cell with an ARC thickness of 105nm and index n=1.676

Conclusion

This work falls under the prospect to improve the Cu(In, Ga)Se2 thin film solar cell by using an antireflective coating in ZnO. This layer plays also the role of window layer. We improved the electric parameters by using an arc thickness of 105nm which gives short circuit current density of 0.023mA.cm^{-2}, an open circuit voltage of 0.828V and a maximum power of 0.01858mW. The study based on the refractive index of the ARC gives an optimal index of 1.676.We find with this value a short circuit current density of 0.0267mA.cm^{-2}, an open circuit voltage of 0.829V and a maximum power of 0.01915mW.The solar cell with an ARC, which forms the ZnO/CdS interface, with a thickness of 105nm and an index of 1.676, gives us a maximum quantum efficiency of 88.28% for an incidental wavelength of 0.7µm.

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