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Study of the Consequences of the Front External Reflection on the Electric Parameters of a Thin Film Cu (In,Ga) Se_2 Solar Cell

Alain Kassine Ehemba*, Ibrahima Wade, Mouhamadou M. Soce, Djimba Niane and Moustapha Dieng
Laboratory of Semiconductors and Solar Energy, Faculty of Science and Technology, Cheikh Anta Diop University of Dakar, Dakar, Senegal
ehembaalain@yahoo.fr

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Abstract

We study in this paper the effect of the front external reflection of incidental photons on the electric parameters such as the open circuit voltage Voc, the short circuit current density Jsc, the maximum power Pm of the cell and external quantum efficiency EQE. The optimization of these parameters makes it possible to improve the performances of the solar cell of type n-ZnO/n-CdS/p-Cu (In, Ga) Se_2. We use a broad range of reflection going from 0%, use of ideal anti-reflecting layer, to a reflection of 80% which corresponds to a very weak absorption. We note that with the use of an "ideal" anti-reflecting layer, we obtained a short circuit current density of 0.0325mA.cm^{-2}, an open circuit voltage of 0,8337V, a maximum power of cell of 0.0233mW and a maximum value of the external quantum efficiency of 99.29%. However these physical parameters are deeply affected by the external front reflection. All the physical parameters studied decrease considerably. We find for a front reflection of 80%, a short circuit current density of 0.0065mA.cm^{-2}, an open circuit voltage of 0,7923V, a maximum power of cell of 0.0045mW and a maximum value of the external quantum efficiency of 19.86%.

Keywords: Front external reflection, Cu (In,Ga) Se_2, PC1D, electric parameters, EQE, IQE.

Introduction

The performances of a silicon or thin film solar cell depend not only on the internal parameters of the cell but also of the external use parameters of use of the cell. Our studies were initially based on the improvement of the performances of the cell by optimizing its internal parameters such as the donors doping density, the acceptors defects, the atomic ratios of concentrations of the base, and others[1-4]. Then we were interested in optimization of the external parameters of use of the solar cell such as the temperature of use[5,6]. The losses by reflection can be related to two principal parameters: i. The internal factors of which mainly the refractive index of the material which is equal to 3.45 in this study. That is to say approximately 30% of the incidental light is considered. ii. The external factors which can either attenuate this reflection by the use of anti-reflecting layer, or to increase this reflection by decreasing the absorption of the incidental light beam (case of dust).

We study the effect of the external front. However we use a broad range of reflection coefficients going from 0% to 80% to take into account all these parameters. We study the impact of the front external reflection on the electric parameters such as the short circuit current density Jsc, the open circuit voltage Voc, the maximum power of the cell Pm and the external quantum efficiency EQE. The optimization of these parameters makes it possible to improve the performances of the cell. The study is based on a cell of n-ZnO/n-CdS/p-CIGS type as Figure-1 indicates it.

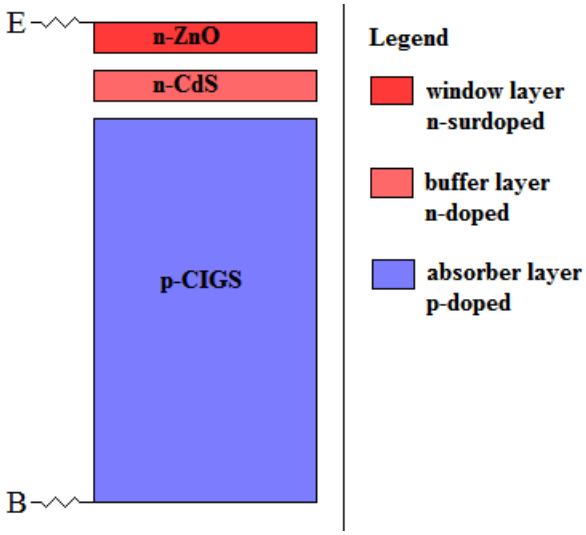

Figure-1
Device schematic

Materials and Methods

In the bibliography, front external reflection studies were carried out but they were based more particularly on the properties of material used like anti-reflecting layer such as ZnO, or on the metal contacts which can play a role of reflectors[7,8]. This front reflection can indeed be due to intrinsic natural factors with materials or to external factors. All these factors contribute to the increase of the reflection decreasing consequently the absorption of the incidental photons.

Our study will relate not on the causes of the front external reflection but to their effects on the electric parameters of the cell. The reflection coefficients vary from 0% to 80%, a range of relatively large value to take into account all the factors that are likely to increase the reflection. However they carried out works concern three phases.

The first phase of our studies relate to the handling of the fundamental equations which govern the operation of a cell and utilizing the optical effects. These equations leave the equation of Poisson, the equations of continuity and the transport equations. We had to develop these equations before[9].

The relation 1 shows the Poisson's equation with εs the dielectric permittivity of the semiconductor and the density of space charge ρ:

$$\nabla^2 V = -\frac{\rho}{\varepsilon_S} \quad (1)$$

The relations 2 and 3 give the equations of continuity.

For electrons $$\frac{\partial n}{\partial t} = \frac{1}{e} div\overrightarrow{J_n} + G_n - R_n \quad (2)$$

For holes $$\frac{\partial p}{\partial t} = -\frac{1}{e} div\overrightarrow{J_p} + G_p - R_p \quad (3)$$

With: $\overrightarrow{j_n}$ and $\overrightarrow{J_p}$ densities of current of the electrons and the holes respectively, G_n *and* G_p rates of generations of the electrons and the holes respectively, R_n *and* R_p rates of recombination of the electrons and the holes respectively, e is the elementary electric charge.

The Relations 4 and 5 present the transport equations.

$$\overrightarrow{J_p} = -eD_p\vec{\nabla}p - ep\mu_p\vec{\nabla}V + p\mu_p kT\vec{\nabla}(n_{ie}L_n) \quad (4)$$

$$\overrightarrow{J_n} = eD_n\vec{\nabla}n - en\mu_n\vec{\nabla}V - n\mu_n kT\vec{\nabla}(n_{ie}L_n) \quad (5)$$

The second stage consists with the simulation of a solar cell of n-ZnO/n-CdS/p-CIGS type using the PC1D5. 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 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, raised levels of injection, the no plane structures and the transients[10,11].

However it is software used especially for the crystal structures in particular containing Silicon. We adapted it to the cells containing Cu (In,Ga) Se_2 thin film. The Table-1 presents the properties of materials used for simulation.

Table-1
Physical properties of materials

	n-ZnO	**n-CdS**	**p-Cu(In,Ga)Se_2**
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

The third part of the work concerns the tracing of the curves using Matlab. 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[12,13].

The Figure-2 presents the energy bands of the window layer, the buffer layer and the absorber layer.

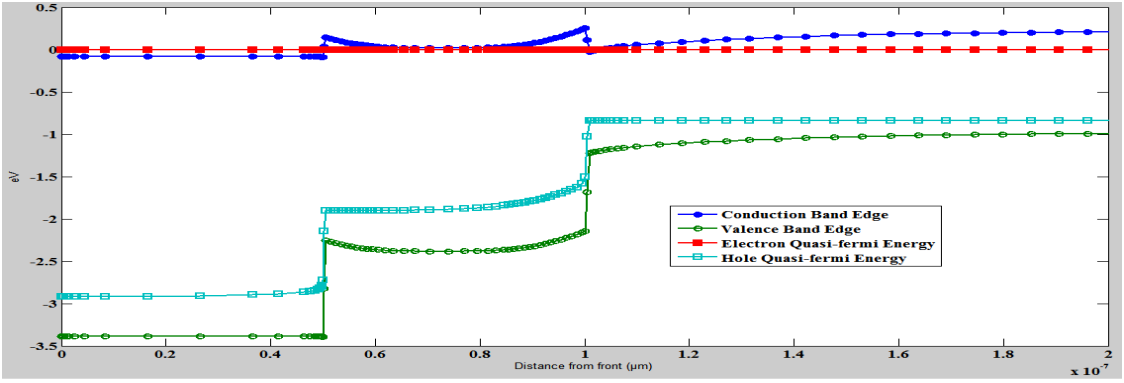

Figure-2
Energy bands

However the cut with at the back field was made at a depth of 0.1µm in the absorber layer for better perceiving the hetero junctions ZnO/CdS and CdS/Cu(In,Ga)Se_2. From 0µm to 0.05µm we are in the ZnO window layer doped N+ with a broad gap of 3.3eV. This high gap explains the distance which separates the conduction and valence bands. From 0.05µm to 0.1µm we approach the CdS buffer layer which is doped N. The noted slope is due on the one hand to the formation of the ZnO/CdS hetero junction because the electrons quasi-Fermi energy of materials must correspond. In addition we note the weaker gap of CdS which is of 2.4eV which explains also the proximity of the conduction and valence bands edge. From 0.1µm to 0.2µm we are in the absorbing layer of the cell which is a Cu (In,Ga)Se_2 thin film doped p. Its gap weaker 1.2eV and the correspondences of the quasi-Fermi energies explain the second slope. The tunnel effects at the hetero junctions, which can be a trap for the minority carriers, are not taken into account.

The three combined stages of our work enable us to advance with logic towards obtaining right and reliable results. Thus we studied the effect of the reflection on the short circuit current density Jsc, the open circuit voltage Voc, the maximum power Pm of the cell and the variation of the external quantum efficiency EQE. We take into account a broad band of the irradiation, which contains wavelengths from 300nm to 1200nm, with a constant incidental illumination of 0.1W.cm $^{-2}$, under standard condition AM1.5.

Results and Discussion

Consequences of the front external reflection on the short circuit current density Jsc: The short circuit current density *Jsc* expressed in $mA.cm^{-2}$ is the current density which circulates in the cell under illumination and without delivered voltage. Indeed for a real cell *Jsc* is translated by the relation:

$$J_{sc} = J_{ph} - J_s\left[e^{\frac{qV}{kT}} - 1\right] \quad (6)$$

The Figure-3 presents the variation of the short circuit current density of the cell according to the front external reflection.

The photovoltaic solar cell functions in rectifying device. It explains the negative sign of the current density. For a front reflection null we note a short circuit current density $\left|J_{sc}\right|$ equal to 0.0325mA.cm^{-2}. This value decreases with the increase in the front external reflection to be equal to 0.0065mA.cm^{-2} with a reflection of 80%. This phenomenon is explained by the proportionality of the short circuit current density with the incidental luminous flux. More the reflection of this incidental flux is significant less the photocurrent density is significant.

Consequences of the front external reflection on the open circuit voltage Voc: The fundamental equation of the voltage V delivered by a photovoltaic cell at the boundaries of its circuit of use is given by:

$$V = \left(\frac{kT}{q}\right)\log\left(1 + \frac{J_{ph} - J}{J_S}\right) - R_s J \quad (7)$$

We note that *Jph* is the photocurrent density, *Js* the saturation current density, *J* the current density at the boundaries of the circuit of use and *Rs* series resistance.

The open circuit voltage *Voc* expressed in Volt is the voltage which reigns in the cell when no current circulates there (J=0).Indeed the Voc is evaluated while applying:

$$V_{oc} = \left(\frac{kT}{q}\right)\log\left(1 + \frac{J_{sc}}{J_s}\right) \quad (8)$$

The Figure-4 gives the variation of the open circuit voltage according to front external reflection.

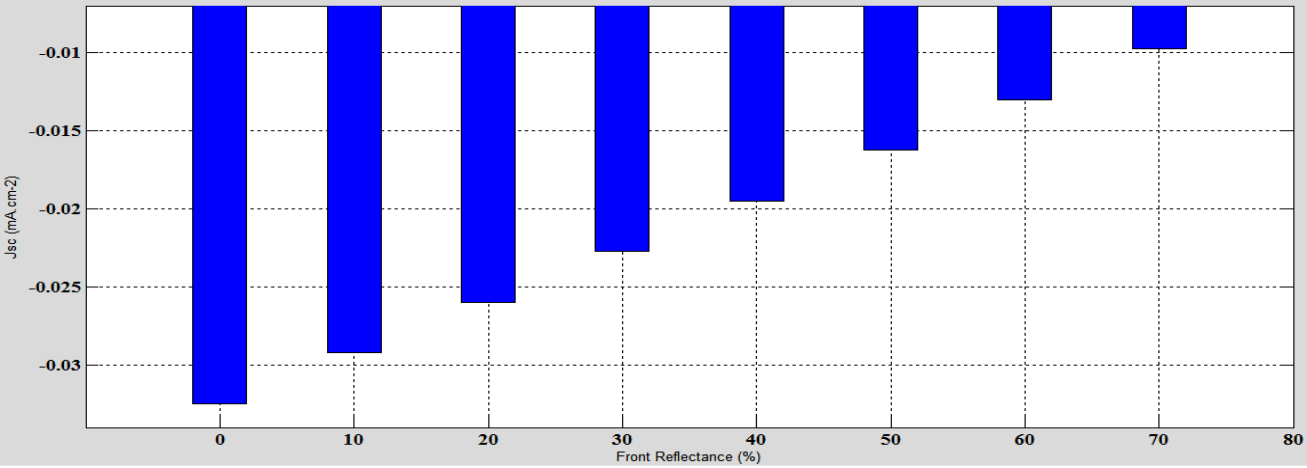

Figure-3
Variation of the short circuit current density Jsc according to the front external reflection front

For an easier reading of the found results, we use the bar diagrams. The front external reflection varies from 0 to 80% of incidental luminous flux. When a reflection does not intervene we note a maximum open circuit voltage of 0.8337V. When this reflection increases the open circuit voltage decreases. We obtain for a reflection of 80%, a minimal voltage of 0.7923V. This behavior of the Voc is due to the fact that the short circuit current density Jsc is proportional to incidental luminous flux. The increase of the reflection contributes to the reduction of the absorbed flux, which causes the drop of the open circuit voltage Voc.

Consequences of the front external reflection on the maximum power Pm of the solar cell: The power of a solar cell of 1cm^2 can be evaluated by applying the relation:

$$P = J \times V \quad (9)$$

We can then evaluate a maximum power which corresponds to the product of maximum voltage Vm and the maximum current density Jm:

$$P_m = J_m \times V_m \quad (10)$$

The Figure-5 presents the variation of this maximum power according to the front external reflection.

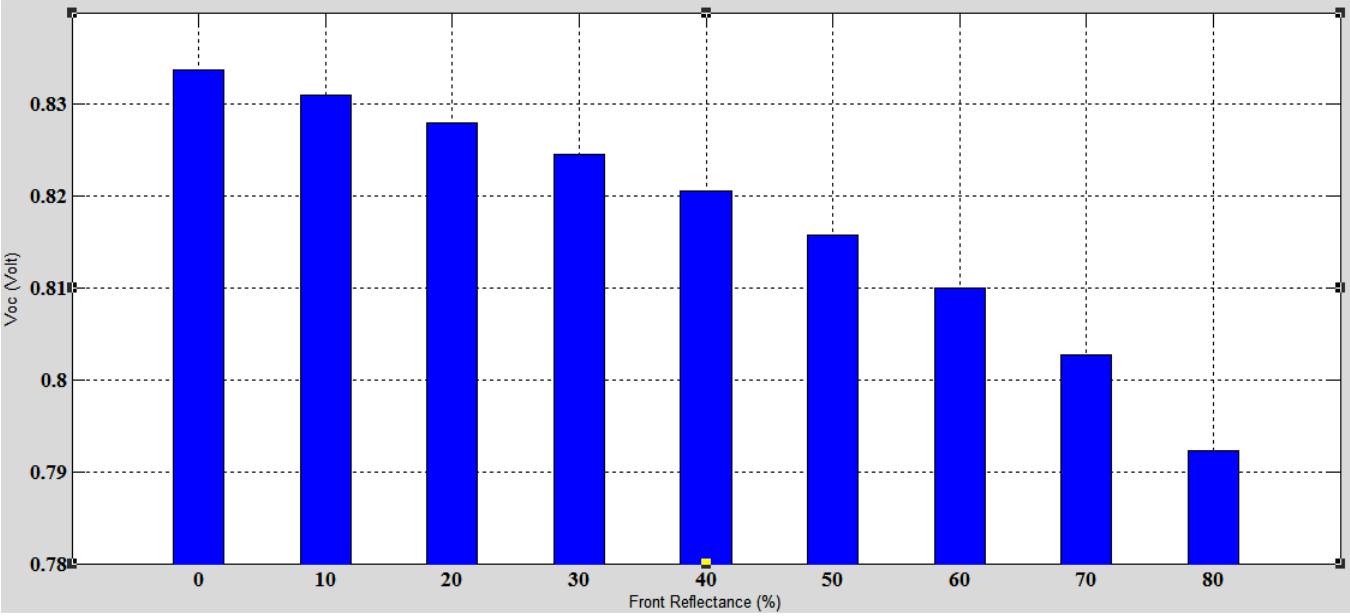

Figure-4
Variation of the open circuit voltage Voc according to the front external reflection

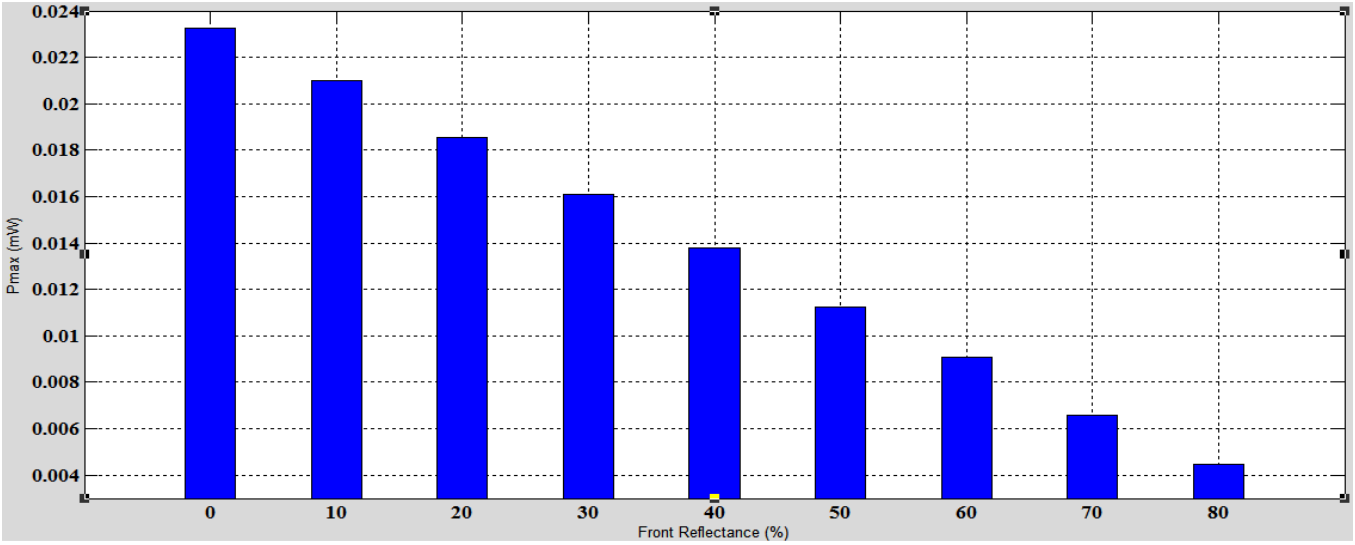

Figure-5
Variation of the maximum power Pm of the cell according to the front external reflection

For a null reflection there is a maximum power of 0.0223mW. This power of the cell decreases with the increase in the reflection coefficient to equalize a minimal value of 0.0045mW for a front external reflection of 80%. The behaviors of the open circuit voltage and the short circuit current density with the increase in the coefficient of reflection make it possible to predict and explain the fall of the maximum power of the device.

Consequences of the front external reflection on the quantum efficiency: The quantum efficiency of the solar cell is the ratio of the number of collected charges and the number of incidental photons. We study in this work the two types of quantum efficiency. The internal quantum efficiency IQE which is the ratio of the number of collected charges and the number of photons really absorbed. It corresponds to the front reflection null (R=0). The characterization of the cell by its quantum efficiency makes it possible to do without the studies of transmittance and reflectance. The external quantum efficiency EQE which is the ratio of the number of collected charges and the number of incidental photons. It corresponds to the other reflection coefficients different from 0.

The Figure-6 presents to us the IQE and the variation of the EQE according to the front external reflection.

For incidental wavelengths going from 300nm to 1200nm we note, however the value of the front external reflection, a broad range of absorption. In the same way however the reflection, the quantum efficiency is the coefficient is cancelled for an incidental wavelength of 960nm. This value corresponds to an incidental energy of approximately 2.4eV. This energy is in agreement with the gap of the CdS buffer layer used which is also 2.4eV. However the impact of the front external reflection consists in the reduction of external quantum efficiency. For better determining this reduction we interpret the indications of Table-2. The maximum value of external quantum efficiency drops considerably with the increase of the front reflection. It passes from 99.29% for a null coefficient of reflection to 19.86% for a coefficient of reflection equal to 80%. This reduction is physically explained by the fact that quantum efficiency is related to the spectral sensitivity. Indeed when the front reflection increases, the spectral response of the cell decreases owing to the fact that the current produced compared to the received power remains weak.

Table-2
Maximum value of external quantum efficiency according to the front external reflection

	EQE		
Front reflectance R (%)	**Max value (%)**	**Incident wavelength (µm)**	**Incident energy (eV)**
0	99.29	0.71	1.75
20	79.43	0.71	1.75
40	59.57	0.70-0.71	1.75-1.77
60	39.71	0.70-0.72	1.72-1.77
80	19.86	0.69-0.72	1.72-1.80

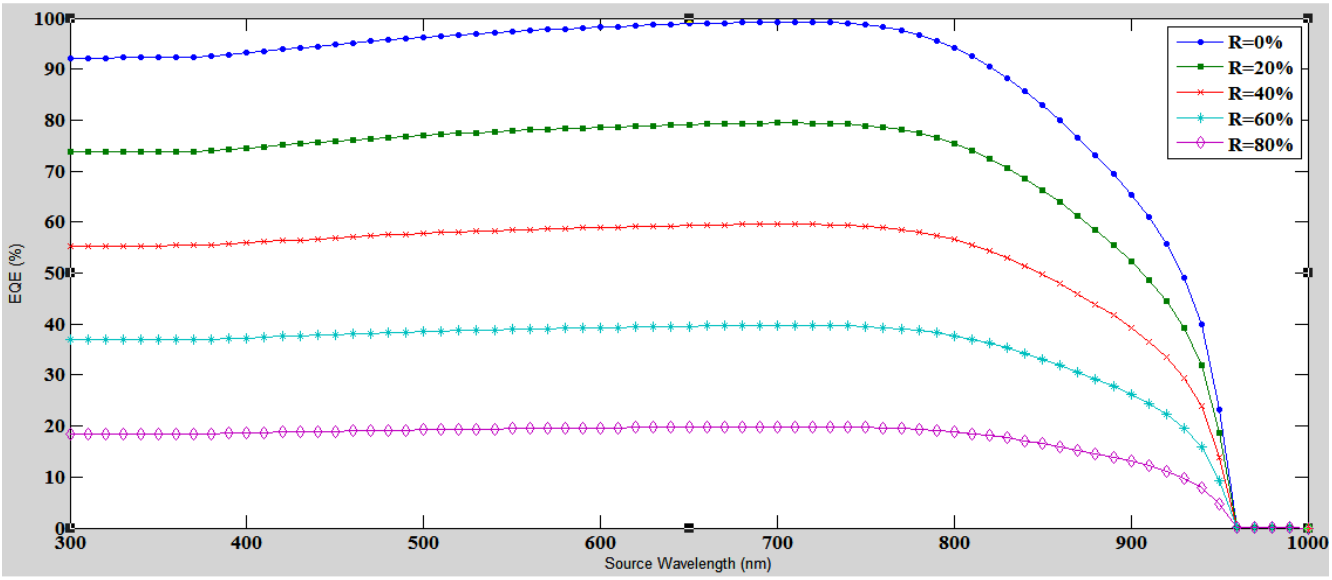

Figure-6
Variation of the quantum efficiency according to the front external reflection

Conclusion

We undertook a study on the consequences of the front external reflection on the electric parameters of the Cu(In, Ga)Se_2 thin film solar cell. We note that with the use of an "ideal" anti-reflecting layer, corresponding to a reflection of 0%, we can obtain an open circuit voltage of 0,8337V, a short circuit current density of 0.0325mA.cm $^{-2}$, a maximum power of cell of 0.0233mW and a maximum value of the external quantum efficiency of 99.29%.However these physical parameters are deeply affected by the front external reflection. Taking into account all the external factors which can slow down the absorption of the incidental light flux we use a maximum reflection coefficient of 80%.All the studied physical parameters decrease considerably. We find an open circuit voltage of 0,7923V, a short circuit current density of 0.0065mA.cm^{-2}, a maximum power of cell of 0.0045mW and a maximum value of the external quantum efficiency of 19.86%.We then note a fall in the open circuit voltage of 0.0414V, a fall in the short circuit density of 0.026mA.cm $^{-2}$, a fall in the maximum power of the cell of 0.0188mW and a fall in the maximum value of the external quantum efficiency of 79.43%.

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