International Journal of Energy and Power Engineering
2016; 5(5): 171-176
http://www.sciencepublishinggroup.com/j/ijepe
doi: 10.11648/j.ijepe.20160505.12
ISSN: 2326-957X (Print); ISSN: 2326-960X (Online)

Effect of the Pyramidal Texture of the Front Outer Layer on the Macroscopic Electric Parameters of a N-Zno/N-Cds/P-Cu(In, Ga) Se_2 Solar Cell

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To cite this article:
Alain Kassine Ehemba, Mouhamadou Mamour Soce, Demba Diallo, Salif Cisse, Moustapha Dieng. Effect of the Pyramidal Texture of the Front Outer Layer on the Macroscopic Electric Parameters of a N-Zno/N-Cds/P-Cu(In,Ga)Se_2 Solar Cell. *International Journal of Energy and Power Engineering.* Vol. 5, No. 5, 2016, pp. 171-176. doi: 10.11648/j.ijepe.20160505.12

Received: September 20, 2016; **Accepted**: September 28, 2016; **Published**: November 3, 2016

Abstract: In this work a theoretical study on the behavior of the macroscopic physical parameters of the solar cell according to the texture of the front outer surface is conducted. The morphology of the texture of surface can vary according to the angle formed by the edges of the pyramidal structure and according to the depth. The studied macroscopic 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. The study of the influence of the angle of texture indicates an angle optimal of 70° which give a short-circuit current density of 0.3361mA.cm^{-2}, an open circuit voltage of 0.8289V and a maximum power of 0.2375mW. The quantum efficiency in ultraviolet wavelength range is reduced by the increase in the angle of texture, while it increases the EQE in the near infrared range. The maximum absorption area extends on both sides of the visible wavelength range. The study of the variation of the electric parameters according to the combined effects of the angle and the depth of texture gives optimal performances for a texture angle of 70° and a texture depth of 21.875nm.

Keywords: Antireflective Layer, Pyramidal Texture, Electrical Parameters, Cu(In, Ga) Se_2

1. Introduction

The performances of a solar cell depend not only on the internal factors, but also on the external factors such as the temperature of use [1]-[2], the shade and the front reflection due to reflecting surfaces. However compared to the front reflection they generally use an antireflective layer. The antireflective layer has as a role to reduce in a remarkable way the reflection of the incidental light. The specific property of this layer is its morphology. Indeed a smooth surface reflects more than other surface with a different morphology. This is why it is preferentially used a process of texture which gives a surface in zigzag (pyramidal).With this morphology, the incidental light can be partly reflected. This reflected beam can meet another side of the antireflective layer and be transmitted. For a smooth surface the considered beam is not recovered and turns over in the external environment. The antireflective layer improves optical confinement. Its choice must take into account its refractive index and its thickness which must adapt to the external and internal mediums of the cell. The Figure 1 presents the texture of the antireflective layer.

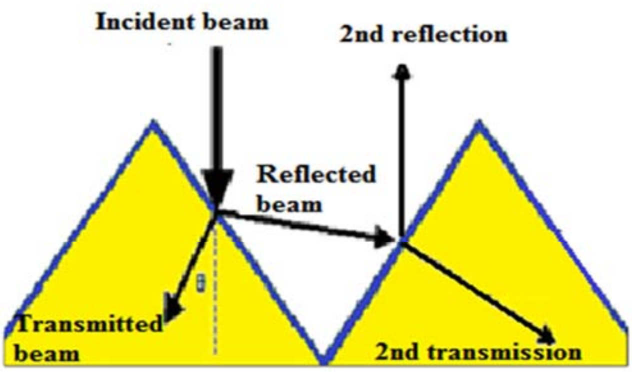

Figure 1. *Texture and principle of operation of the antireflective layer.*

In the bibliography there are studies which relate to the thickness of the antireflective layer [3], the angle-averaged transmission [4], or even the elaboration of the antireflective layer [5].

In this work a theoretical study is undertaken on the behavior of the macroscopic physical parameters of the solar cell according to the texture of the front outer surface. Indeed the morphology of the texture can vary according to the angle formed by the edges of the pyramidal structure and according to the depth. The study of the impact of these variations on the electric parameters would provide whatever the nature of the used antireflective layer, information on the ideal angle of texture and the ideal depth. These parameters would grant us a better front optical confinement. The studied macroscopic 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. Their variation according to the angle is studied first, then according to the combination of the two parameters angle and depth of texture.

2. Materials and Methods

The model of solar cell is a photovoltaic solar cell containing Cu (In, Ga)Se_2 thin film. This cell is presented by the figure 2. The front outer layer is an antireflective layer with pyramidal texture playing the role of Window layer. It's a ZnO layer N-doped. The second layer the CdS buffer layer in CdS N-doped. The third layer is the absorber layer wich is P-doped CIGS thin film.

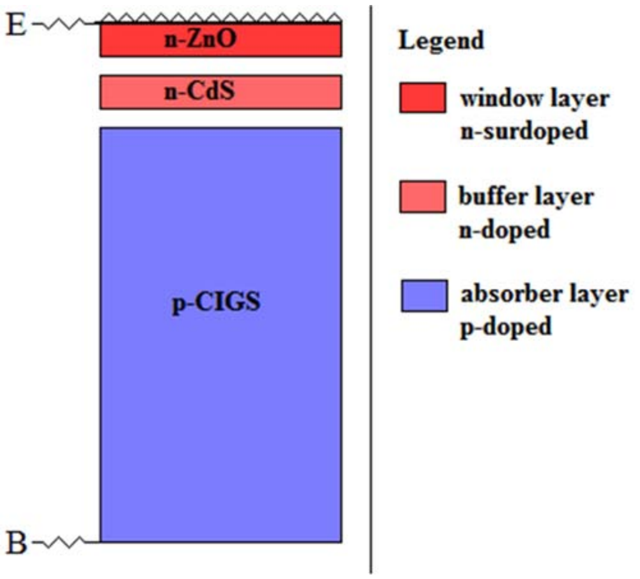

Figure 2. *Device schematic.*

Our study starts with the resolution of the fundamental equations which govern the operation of a solar cell. The principal equations used are:

- Transport equations:

$$\overrightarrow{J_p} = -eD_p\vec{\nabla}p - ep\mu_p\vec{\nabla}V + p\mu_p kT\vec{\nabla}(n_{ie}L_n) \quad (1)$$

$$\overrightarrow{J_n} = eD_n\vec{\nabla}n - en\mu_n\vec{\nabla}V - n\mu_n kT\vec{\nabla}(n_{ie}L_n) \quad (2)$$

The absorption coefficient of the incidental light (IL) relating to the direct gap of the thin layers used:

$$\alpha_{IL} = A_{IL}\sqrt{h\nu - E_{g,IL}} \quad (3)$$

- The absorption coefficient of the charge carriers (CC):

$$\alpha_{cc} = K_1 n\lambda^a + K_2 p\lambda^b \quad (4)$$

In these equations AIL, K1, K2, ***a*** and ***b*** are empirically determined constants and relate to materials used.

To check the convergence of the mathematical results, a simulation using the PC1D is carried out. 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 doping rates, raised injection levels, the no plane structures and the transients [6]-[7].However it is software used especially for the crystalline structures in particular containing Silicon. Software is 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 convergence of the results obtained was corrected and the characteristics were traced with Matlab. It's visualization and computation software, whose basic entities are matrices. The 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 [8]-[9].

3. Results and Discussion

The front surface texture can have several types of morphologies of which most frequent are the pyramidal structure and a reversed pyramidal structure [10]-[11].In this study only the pyramidal structure is taken into account. The measurement of the angle of texture is taken in relation to the crystalline structure (002), which corresponds to the preferential orientation of the window layer ZnO which plays also the role of antireflective layer.[12] The angle measured compared to the polar coordinates corresponds to the azimuthal angle formed by the edges of the pyramidal texture.[13] The variation of the angle of texture goes from 0° (peaks texture) to 80° (pyramid texture).

3.1. Effect of the Front Surface Textured Angle on the

Macroscopic Electric Parameters

3.1.1. Variation of the Short-Circuit Current Density Jsc According to the Front Surface Textured Angle

When the photovoltaic cell does not deliver any voltage, there is a current called short circuit current which is released. The short circuit current density Jsc is obtained while applying:

$$J_{sc} = J_{ph} - J_s\left[e^{\frac{qV}{kT}} - 1\right] \quad (5)$$

The Figure 3 presents the variation of the short circuit current density of the cell according to the front surface textured angle.

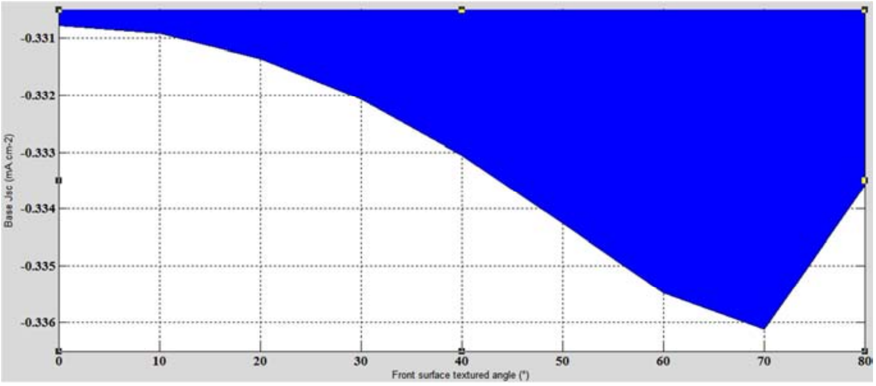

Figure 3. *Variation of the short-circuit current density Jsc according to the front surface textured angle.*

The photovoltaic cell is a device which functions like a rectifier, from where the negative character of the output density of current. For an angle of texture of 0°, $\left|J_{sc}\right|$ is equal to a minimal value of approximately 0.3308mA.cm^{-2}.This value increases with the opening of the angle of texture to reach a maximum value of approximately 0.3361mA.cm^{-2} corresponding to an angle of texture of 70°.When this last exceeds 70° the Jsc decreases. These variations of Jsc are indeed related to the optical confinement of incidental light. When the angle of texture increases, the optical confinement increases absorbed beam. The short circuit current density being proportional to incidental light, a remarkable improvement is noted. However when the angle of texture exceeds 70, its pyramidal morphology tends towards a plane structure which decreases optical confinement. This gives a decrease of Jsc. The Table 2 recapitulates the values of the short-circuit current density according to the front surface textured angle.

Table 2. *Numerical values of the short circuit current density Jsc.*

Front texture angle (°)	**0**	**30**	**60**	***70***	**80**
$\left\|J_{sc}\right\|$ (mA.cm^{-2})	0.3308	0.3321	0.3355	*0.3361*	0.3336

3.1.2. Variation of the Open Circuit Voltage Voc According to the Front Surface Textured Angle

The open circuit voltage Voc is the voltage delivered by the photovoltaic cell when it does not product any current. Its expression is:

$$V_{oc} = \left(\frac{kT}{q}\right)\log\left(1 + \frac{J_{sc}}{J_s}\right) \quad (6)$$

It is obtained by the fundamental equation of the voltage delivered by the photovoltaic cell:

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

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

The figure 4 gives the variation of the open circuit voltage according to the front surface textured angle.

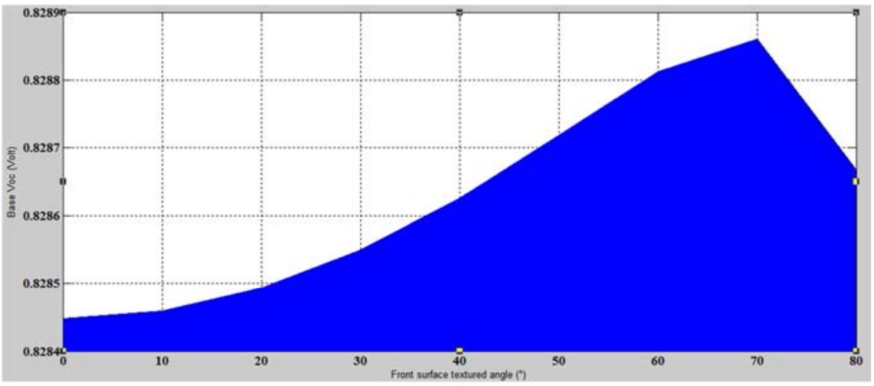

Figure 4. *Variation of the open circuit voltage Voc according to the front surface textured angle.*

The open circuit voltage Voc is equal to a minimal value of 0.82844V for an angle of texture equalizes to 0°.This voltage improves gradually with the increase of the angle of texture up to a maximum value of 0.82886V for an angle of texture of 70°.When this angle is exceeded the open circuit voltage decreases. This behavior of the Voc is explained by the fact that the increase in the angle of texture increases optical confinement. A reflected incidental beam has the possibility of meeting other side of the texture for a second absorption. This double transmission improves the absorption of the incidental beams which is accompanied by an increasing of Voc. The table 3 recapitulates the values of the open circuit according to the angle of texture.

Table 3. *Numerical values of the open circuit voltage Voc.*

Front texture angle (°)	0	30	60	70	80
Voc (V)	0.8284	0.8285	0.8288	0.8289	0.8287

3.1.3. Variation of the Maximum Power Pm of the Cell According to the Front Surface Textured Angle

The maximum power of a solar cell of 1cm^2 is evaluated by making the product of the maximum current density by the maximum voltage:

$$P_m = J_m \times V_m \tag{8}$$

The figure 5 presents the variation of this maximum power according to the front surface textured angle.

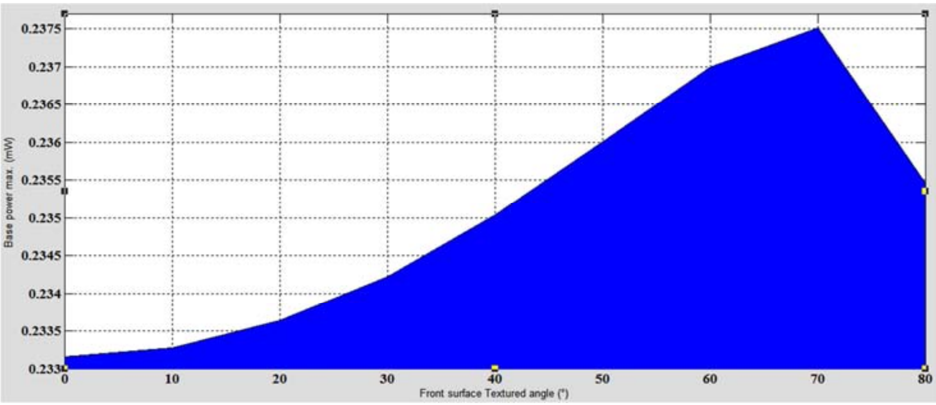

Figure 5. *Variation of the maximum power Pm of the cell according to the front surface textured angle.*

In agreement with the studies of variations of the short circuit current density Jsc and of the open circuit voltage Voc according to the angle of texture, a minimal value of the maximum power of 0.2331mW is noted for the peaks texture. This power evolves gradually with the opening of the angle of texture to reach a maximum value of approximately 0.2375mW for an angle of 70°. As described previously the variations of the maximum power depend on the optical confinement which is optimal for an angle of texture of 70°.When this angle is exceeded optical confinement decreases is the performance of the cell regresses. The table 4 recapitulates the numerical values of the maximum power.

Table 4. *Numerical values of the maximum power Pm of the cell.*

Front texture angle (°)	0	30	60	70	80
Pm (mW)	0.2331	0.2342	0.2370	0.2375	0.2354

3.1.4. Variation of External Quantum Efficiency EQE According to the Front Surface Textured Angle

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. A constant illumination of 0.1W.cm^{-2} is used, and incidental wavelengths going from 300nm to 1200nm thus covering the ultraviolet wavelengths range, the Visible range and the near infrared range. The figure 6 presents to us the variation of external quantum efficiency according to the incidental wavelengths for various front surface textured angles.

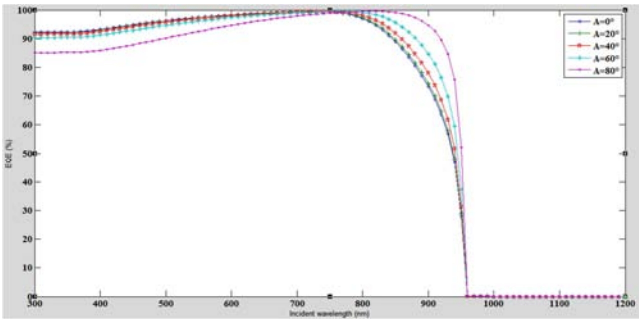

Figure 6. *Variation of external quantum efficiency EQE according to the front surface textured angle.*

In the ultraviolet range, which relates to the wavelengths going from 300nm to 380nm, the increase in the angle of texture decreases the EQE. Indeed optical confinement for the high injections level, the number of collected carriers falls because the incidental energy is largely higher than the optical gaps of materials. In the visible range, which relates to the wavelengths going from 380nm to 780nm, the EQE remains significant whatever the angle of texture.It's the zone of maximum absorption of the absorber in Cu(In, Ga)Se_2 thin film. In the near infrared range, the increase in the angle of texture is accompanied by an increase in the EQE. Indeed it's the zone of weak injections and the number of collected carriers increases with optical confinement.

In table 5 the maximum values of external quantum efficiency are recapitulated by specifying the wavelengths and incidental energies.

Table 5. *Numerical values of the maximum of the EQE with incidental wavelengths and energies.*

	EQE		
Front surface textured angle (°)	**Max value (%)**	**Corresponding incidental wavelength (nm)**	**Corresponding incidental energy (eV)**
0	99.44	730	1.70
20	99.45	730	1.70
40	99.46	740	1.68
60	99.49	770	1.62
80	99.53	820	1.51

The point of maximum absorption moves towards the near infrared range with the opening of the angle of texture.

3.2. Study of the Effects Combined of the Angle and the Depth of the Front Outer Layer Texture on the Electric Parameters

The combined effects of the angle and the depth of front texture on the electric parameters are studied. Indeed whatever the angle of texture, it is necessary to use an adequate depth so that reflected beam can meet another side of texture for a second absorption. The studied parameters this time are the short circuit current density, the open circuit voltage Voc and the maximum power Pm of the cell.

3.2.1. Variation of the Short Circuit Current Density Jsc

The Figure 7 presents to us the short circuit current density according to the angle and the depth of front texture. The cell behaving like a rectifier, a current density profile with the shape of a basin is obtained. The noted peak of this characteristic corresponds to a short circuit current density of $\left|J_{sc}\right|$ = 0.1682 mA. cm^{-2} for an angle of 70° and a depth of texture of 21.875nm.

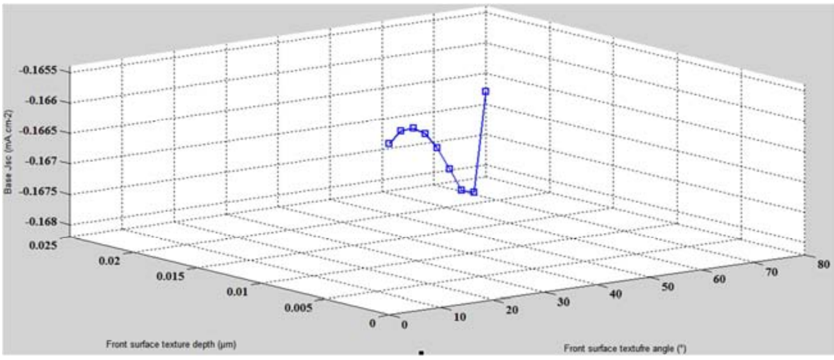

Figure 7. *Variation of short-circuit current density Jsc according to the angle and the depth of front surface textured.*

3.2.2. Variation of the Open Circuit Voltage Voc

The Figure 8 gives the variation of the open circuit voltage Voc according to the angle and depth of font surface textured. The improvement and the fall of the voltage are easily perceived with this characteristic. A noticed peak corresponds to the optimal values of the angle and depth of texture.

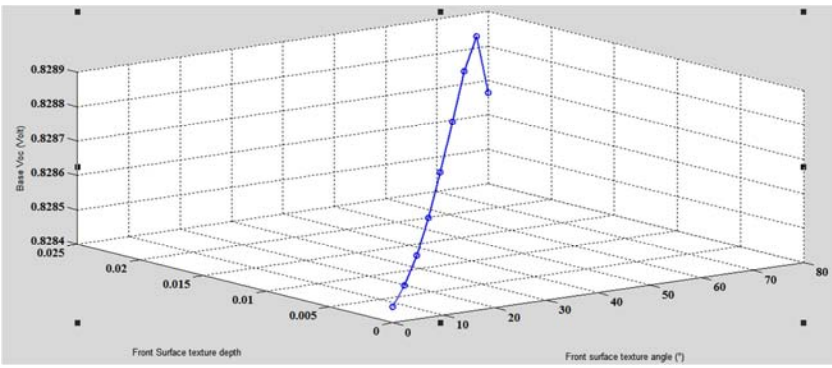

Figure 8. *Variation of the pen circuit voltage Voc according to the angle and the depth of front surface textured.*

A maximum value of Voc=0.8289V for a depth of 21.875nm and an angle of texture of 70° is found.

3.2.3. Variation of the Maximum Power Pm of the Cell

The figure 9 shows the variation of the maximum power of the solar cell according to the depth and the angle of front surface textured. The characteristic makes it possible to locate the optimal parameters of the front texture. They correspond to a depth of 21.875nm and an angle of texture of 70°. These parameters give a maximum power of 0.1195mW. This is in agreement with the variations of the short-circuit current density and the open circuit voltage.

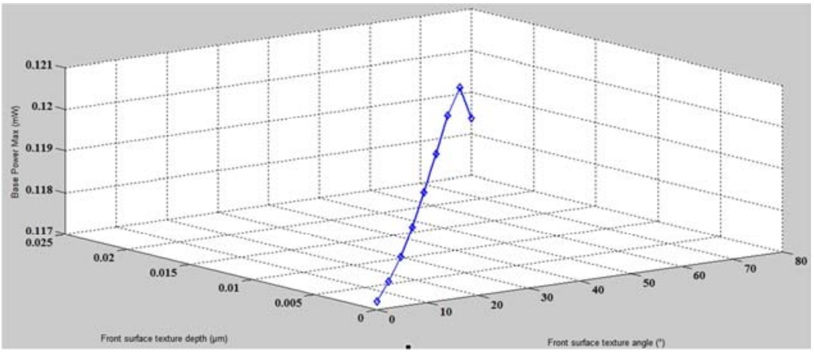

Figure 9. *Variation of the maximum power Pm of the cell according to the angle and the depth of front surface texture.*

The Table 3 recapitulates the results found by calculation related to the variations of the electric parameters of the cell studied according to the combined effects of the depth and the texture of front surface. The column which gives the optimal parameters is that marked of a gray color.

Table 6.*Variation of the electric parameters according to the angle and depth of front surface texture.*

Texture angle (°)	0	30	60	*70*	80
Texture depth (nm)	0	9.375	18.750	*21.875*	25.000
Voc (Volt)	0.8284	0.8285	0.8288	*0.8289*	0.8287
$\left\|J_{sc}\right\|$ (mA.cm^{-2})	0.1654	0.1661	0.1678	*0.1682*	0.1668
Pm (mW)	0.11721	0.11778	0.11926	*0.11953*	0.11838

4. Conclusion

This theoretical study on the behavior of the macroscopic physical parameters of the solar cell according to the texture of the front outer surface gives a remarkable improvement of the performances of the Cu(In, Ga)Se_2 thin film solar cell. The first part of our work indicates to us an optimal angle of texture of 70° which gives a short circuit current density of $\left|J_{sc}\right|$= 0.3361mA.cm-2, an open circuit voltage of 0.8289V and a maximum power of cell of 0.2375mW. The increase in the angle of texture reduces quantum efficiency in the ultraviolet wavelengths range, while it increases the EQE in the near infrared range. The area of maximum absorption extends on both sides of the visible range. The study of the variation of the electric parameters according to the combined effects of the angle and the depth of texture gives optimal performances for an angle of 70° and a texture depth of 21.875nm.

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