Optical and recombination losses in CIGS thin-film solar cell and efficiency enhancement methods

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A theoretical analysis of the optical and recombination losses effect on the performance of the solar cell with the structure ZnO:Al/CdS/CIGS/Mo/Glass has been accomplished in this work. All the results are carried out on the basis of the variation of Ga- ratio and the low thickness of the absorber layer ranged from 250 nm to 1 µm. The optical parameters (refractive index, extinction coefficient and energy gap) resulting from the experimental investigation of the used materials are the base to calculate the optical losses caused by the reflection at different interfaces and absorption in ZnO:Al and CdS layers. The calculations of the recombination losses at the front and back surface of CIGS are carried out on the basis of some physical parameters of CIGS layer. The effect of antireflection coating layer and the reflectivity from back contact have been studied to improve the performance of CIGS solar cell. The results show that Ga- ratio of 0.3 has the maximum short-circuit current density of 16.46 mA/cm^2 and at the same time this ratio represents optical losses of about 35 %, these losses have been increased up to 59.5 due to non-absorption losses. It is found that the thickness of CIGS layer has a significant effect on the performance of this solar cell. Under the consideration of antireflection layer, reflectivity from back contact and at certain parameters of the absorber layer, the recorded efficiency of thin- film CIGS solar cell reached a value of 18.12%.

1. Introduction

First generation solar cells based on single-crystalline and multi-crystalline wafer Si represent more than 85% of the current photovoltaic (PV) industry [1, 2]. These cells having indirect optical band gap absorbing materials recorded high efficiencies of 25.6% and 20.8%, respectively [3]. Nevertheless, due to the demanded large thickness of more than 100 µm. The technology cost of solar cells based on Si is very expensive. The second generation solar cells based on thin- film absorbing materials is therefore, the ideal alternative choice. These materials such as Copper indium gallium diselenide $Cu(In_{1-x}Ga_x)Se_2$ (CIGS) [4, 5, 6], Cadmium-Telluride CdTe [7, 8], Copper zinc tin selenide $Cu_2ZnSnSe_4$ (CZTSe) [9, 10], and copper zinc tin sulphide Cu_2ZnSnS_4 (CZTS) [11, 12] have direct energy gap and high absorption coefficient, so few micrometres of them are sufficient to absorb most of the incident light.

Thin- film based on CIGS is being seen as one of the most promising thin-film solar cell technologies with highest confirmed efficiencies. CIGS material has direct energy gap and high absorption coefficient greater than 10^4 cm^{-1} [13]. The most attractive property of CIGS compound is the ability to tune its energy band gap from 1.01 eV up to 1.68 eV by variation of Ga fraction leading to the best match to the solar spectrum [14]. Moreover, CIGS solar cells are suitable for space applications due to their good stability over time and good resistance to ionized radiation [15].

CIGS solar cells achieved a high conversion efficiency more than 21.7% [3], which is still far from the theoretical limit of 28-30% [16] due to some losses which limit the efficiency or cause the power reduction. These losses such as optical, recombination and resistance. Quantitative estimating of these losses and determining the reasons will certainly lead to appropriate solutions to reduce them and thus increase the efficiency and performance of CIGS solar cell.

In this work, a theoretical analysis of the effect of optical and recombination losses on the performance of solar cell of structure ZnO:Al/CdS/CIGS/Mo/Glass has been done. The calculations of optical losses are carried out in the basis of optical parameters (refractive index, extinction coefficient and optical band gap) resulting from the experimental investigation of the used materials. The recombination losses at the front and back surface of CIGS have been calculated using the experimental data of CIGS layer such as absorption coefficient and energy gap. Besides, this work aims to improve the efficiency of CIGS solar cell through studying the effect of antireflection coating layer and the reflectivity from back contact. All these studies have been carried out for low thickness absorber layer to achieve the economic feasibility of this cell.

2. Theoretical model

In this model, a p- type CIGS is used as the absorber layer with different values of energy gap (according to the experimental results taken from [17]). A thin layer of n-type CdS of energy gap (E_g) 2.45 eV is used as buffer layer to make a hetero junction with CIGS. A transparent conducting oxide (TCO) such as ZnO:Al of $E_g = 3.3$ eV is used as window layer. In addition, the spectrum was set to the global AM1.5 standard and the operation temperature

was maintained at 300 K. The other parameters that used in this model are listed in Table 1.

Table 1. The values of open circuit voltage (V_{oc}), maximum voltage (V_m), maximum current density (J_m), fill factor (FF) and efficiency (η) of CIGS solar cell resulting from Fig. 5

x	V_{oc} (V)	V_m (V)	J_m (mA/cm^2)	FF	η (%)
0.1	0.76	0.71	13.87	0.88	9.83
0.2	0.83	0.78	12.13	0.87	9.48
0.3	0.70	0.64	15.76	0.879	10.14
0.4	0.86	0.82	10.14	0.87	8.27
0.6	0.95	0.91	8.49	0.87	7.68

Through this model, the optical losses result from the reflection at air/ZnO:Al, ZnO:Al/CdS, CdS/CIGS interfaces and the light absorption in ZnO:Al and CdS layers as well as the recombination losses at the front and back surface of CIGS can be quantitatively assessment. The quantitative estimation of the optical losses carried out passed on the refractive index, extinction coefficient and energy gap of the used materials. The continuity equation that taking into account the drift and diffusion components of the photocurrent is employed to determine the recombination losses. The quantitative determination of the recombination losses carried out considering the physical properties of the absorber layer (CIGS) such as; the absorption coefficient (α), energy gap (E_g), thickness (d), carrier lifetime (τ), mobility (μ), etc. In addition, the effect of using the antireflection coating and the effect of reflectivity from back contact have been taken into account to enhance the performance of CIGS solar cell.

2.1. CIGS solar cell structure

The schematic structure of substrate thin-film solar cell based on CIGS is shown in Fig. 1.
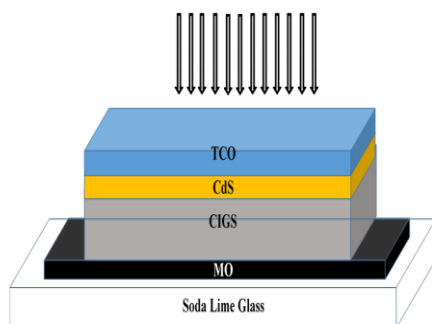

Fig. 1. Schematic cross-section of thin-film CIGS solar cell (color online)

Substrate thin-film solar cells based on CIGS are basically consisted of a substrate, back contact, absorber, buffer layer and front contact.

Soda lime glass is a common substrate that used in this case. It acts as a source of sodium that later is incorporated in the CIGS layer and increasing the conversion efficiency, allegedly by passivation defects in the CIGS layer or at the CIGS/CdS junction [17, 18]. A first layer from molybdenum is deposited onto the soda lime glass to form a back contact. Molybdenum is a good conductor that can allow sodium diffusion. A second layer from CIGS with few micrometres thickness is deposited on the molybdenum layer to act as the absorber. A third layer is a buffer layer from thin CdS (~ 0.1 μm), which is usually deposited on the absorber layer to create a hetero junction with CIGS. CdS must have some required properties such as: relatively high transparency, not too thick in order not to reduce the high absorption in the CIGS absorber layer, not too thin to avoid the short circuiting effect, relatively low resistive to minimize the electrical losses, and higher photoconductive in order not to alter the solar cell spectral response [19]. The last layer is formed from transparent conducting oxide (TCO) such as ZnO:Al that acts as a window layer. The transmission of this layer must be as high as possible (more than 85% in visible region), at the same time has low resistivity at room temperature (sheet resistance less than 10 Ω/sq), and has good adhesion to glass substrate [20].

2.2. Reflection and absorption losses

The reflectivity (R) at two contacting layers 1 and 2 of the interfaces air/ ZnO:Al, ZnO:Al/CdS, CdS/CIGS is determined based on the well-known Fresnel equations [20]:

$$R_{12} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \qquad (1)$$

where n_1 and n_2 are the refractive index of the two materials, respectively.

If the materials are electrically conductive, the refractive index will contain an imaginary part and is written as:

$$n^* = n - ik \qquad (2)$$

where n is the refractive index and k is the extinction coefficient. In this case, the reflection coefficient, R, is written as:

$$R_{12}(\lambda) = \frac{|n_1^* - n_2^*|^2}{|n_1^* + n_2^*|^2} = \frac{(n_1 - n_2)^2 + (k_1 - k_2)^2}{(n_1 + n_2)^2 + (k_1 + k_2)^2} \qquad (3)$$

The values of n and k of ZnO:Al and CdS, were taken from the literature data [21, 22], respectively.

The transmission in this case is given by:

$$T(\lambda) = (1 - R_{12})(1 - R_{23})(1 - R_{34}) \qquad (4)$$

where R_{12}, R_{23} and R_{34} are the reflectivity at the interface between air/ZnO:Al, ZnO:Al/CdS and CdS/CIGS, respectively.

Now we will consider the absorption process that takes place in ZnO:Al and CdS layers. The losses due to reflection and absorption are called the optical losses. In this case, Eq.4 takes the form:

$$T(\lambda) = (1 - R_{12})(1 - R_{23})(1 - R_{34})e^{-\alpha_2 d_2}e^{-\alpha_3 d_3} \quad (5)$$

where, α_2 and α_3 are the absorption coefficient of ZnO:Al and CdS, respectively and d_2 and d_3 their thicknesses. Note that this equation does not take into consideration the effect of antireflection process.

When an antireflection coating layer is deposited on the TCO layer, the reflectance between the air and this layer is significantly reduced. The optimal refractive index value of the antireflection coating (n_{arc}) is suggested to be $(n_2)^{1/2}$, where n_2 is the refractive index of ZnO:Al material [16]. Then, the reflection coefficient (R_{arc}) from the material with an antireflection coating can be written as [23]:

$$R_{arc} = \frac{r_a^2 + r_b^2 + 2r_a r_b \cos(2\theta)}{1 + r_a^2 r_b^2 + 2r_a r_b \cos(2\theta)} \quad (6)$$

where,

$$\theta = \frac{2\pi}{\lambda} n_{arc} d_{arc} \quad (7)$$

d_{arc} in Eq.7 represents the thickness of the antireflection material. In Eq.6, r_a and r_b are the amplitude values of reflectivity (Fresnel coefficients) from the front and back surfaces of the antireflection material, respectively and are given by:

$$r_a = \frac{n_{arc} - n_1}{n_{arc} + n_1} \quad (8)$$

$$r_b = \frac{n_2 - n_{arc}}{n_2 + n_{arc}} \quad (9)$$

Then the optical transmission that given by Eq.4 can be expressed in the following form when the antireflection effect is taken into account:

$$T(\lambda) = (1 - R_{arc})(1 - R_{23})(1 - R_{34}) \quad (10)$$

The second process that contribute in the optical losses is the absorption process that takes place in ZnO:Al and CdS layers. In this case, Eq.10 takes the form:

$$T(\lambda) = (1 - R_{arc})(1 - R_{23})(1 - R_{34})e^{-\alpha_2 d_2}e^{-\alpha_3 d_3} \quad (11)$$

where, α_2 and α_3 are the absorption coefficient of ZnO:Al and CdS, respectively and d_2 and d_3 their thicknesses.

2.3. Recombination Losses

The internal quantum efficiency (η_{int}) of the solar cell is the summation of the drift and diffusion components.

$$\eta_{int} = \eta_{drift} + \eta_{dif} \quad (12)$$

The drift component is obliged to photogenerate of electron- hole pairs in the space- charge region while the diffusion component is obliged to photogenerate of electron- hole pairs in the neutral part of the diode structure.

The drift component of the internal quantum yield (η_{drift}) is given from the solution of the continuity equation in the form [24, 25]:

$$\eta_{drift} = \frac{1 + \left(\frac{S_f}{D_p}\right)\left[\alpha + \frac{\left(\frac{2}{W}\right)(\varphi_o - qV)}{kT}\right]^{-1}}{1 + \left(\frac{S_f}{D_p}\right)\left[\frac{\left(\frac{2}{W}\right)(\varphi_o - qV)}{kT}\right]^{-1}} - \exp(-\alpha W) \quad (13)$$

where, S_f is the recombination velocity at the front surface of CIGS, D_p is the diffusion coefficient of the holes related to the mobility (μ_p) by the Einstein relation $qD_p/kT = \mu_p$, α is the absorption coefficient of CIGS, W is the width of space-charge region, V is the voltage, and φ_o is the barrier height. Note that this equation takes into account the losses due to the recombination at the CdS/CIGS interface, i.e., at the front surface of the absorber layer.

The diffusion component of the internal quantum efficiency (η_{dif}) is also given from the solution of the continuity equation [26]. The solution of the continuity equation was simplified with sufficient accuracy and can be written in the form [16],

$$\eta_{dif} = \frac{\alpha L_n}{\alpha^2 L_n^2 - 1}\exp(-\alpha W) \times \left\{\alpha L_n - \frac{\left(\frac{S_b L_n}{D_n}\right)[\cosh((d-W)/L_n) - \exp(-\alpha(d-W))] + \sinh((d-W)/L_n) + \alpha L_n \exp(-\alpha(d-W))}{\left(\frac{S_b L_n}{D_n}\right)\sinh[(d-W)/L_n] + \cosh[(d-W)/L_n]}\right\}$$

$$(14)$$

where, α is the absorption coefficient of the absorber layer, D_n is the diffusion coefficient of the electrons related to the mobility μ_n by Einstein relation $qD_n/kT = \mu_n$, L_n ($=\tau_n D_n$) is the diffusion length of minority carriers, τ_n is the lifetime of electron, d is the absorber layer thickness and

S_b is the recombination velocity at the back surface of CIGS. Equation (14) takes into consideration the recombination losses at the back surface of the absorber layer, i.e. at the CIGS/MO interface.

The external quantum efficiency η_{ext} of the solar cell can be determined in terms of the optical losses owing to the reflection at different interfaces and absorption in ZnO:Al and CdS in the form:

$$\eta_{ext} = T(\lambda)\,\eta_{int} \qquad (15)$$

where $T(\lambda)$ is given by Eq.11, which takes into account the optical losses.

2.4. Short-circuit current density and the cell parameters

The short-circuit current density (J_{SC}) can be calculated according to this formula [27]:

$$J_{SC} = q \sum_i T(\lambda)\frac{\Phi_i(\lambda_i)}{h\nu_i}\eta_{int}(\lambda_i)\Delta\lambda_i \qquad (16)$$

where, Φ_i is the spectral power density, $\Phi_i/\,h\nu$ is the spectral distribution of the photons, $h\nu$ is the photon energy, $\Delta\lambda$ is the interval between neighbouring values of the wavelength, $T(\lambda)$ is given by Eq. (11) and $\eta_{int}(\lambda)$ is given by Eq. (12).

According to the standard diode equation, the $J(V)$ characteristic of a single- junction solar cell under illumination can be written as the linear superposition of the dark characteristics of the cell and the photogenerated current:

$$J = J_0\left[exp\left(\frac{qv}{AkT}\right) - 1\right] - J_L \qquad (17)$$

where J_0 is the reverse saturation current, J_L is the photogenerated current, q is the elementary charge, k is the Boltzmann constant, T is the absolute temperature and A is the ideality factor. The values of J_0 and A are taken from [28].

The CIGS solar cell efficiency can be expressed by:

$$\eta = \frac{FF \times J_{SC} \times V_0}{P_{in}} \qquad (18)$$

where FF is the fill factor, V_{oc} is the open circuit voltage, P_{in} is the density of the total AM 1.5 solar radiation power.

The fill factor can be written as:

$$FF = \frac{J_m \times V_m}{J_{sc} \times V_0} \qquad (19)$$

where J_m and V_m are the maximum current density and voltage, respectively.

2.5. Reflectivity from back contact

If some light passes to the back contact, which is a metal electrode, thus its reflectivity can be reaching 100 %. This situation can be occurring in the case of low thickness of the absorber layer, which cannot absorb all the incident light. Accordingly, the effect of the reflectivity from the metallic back contact may enhance the absorptivity in the absorber layer and then increase the

photogenerated carriers. The following formula [29, 30] can be used to measure the effect of reflectivity from the back contact on the internal quantum efficiency:

$$\eta_{int}(R) = \eta_{int}[1 + R \times \exp(-\alpha d)] \qquad (20)$$

where R is the reflectivity from the back contact, α is the absorption coefficient of the absorber layer and d its thickness.

3. Results and discussion

The relationship between $(\alpha h\nu)^2$ and $h\nu$ for as – deposited $CuIn_{1-x}Ga_xSe_2$ (CIGS) thin films of various Ga-ratios at low thickness of 250 nm is shown in Fig.2-a. From this figure, the energy gap of 1.72, 1.82, 1.63, 1.87 and 2 eV are estimated of the compositions of x= 0.1, 0.2, 0.3, 0.4 and 0.6, respectively. Besides, the energy gap 1.13 eV and 1.24 eV are detected for the composition of x= 0.3 at higher thickness of 800 nm and 1000 nm, respectively as shown in Fig. 2-b. The results of this figure are carried out on the basis of experiment measurements taken from ref. [17].
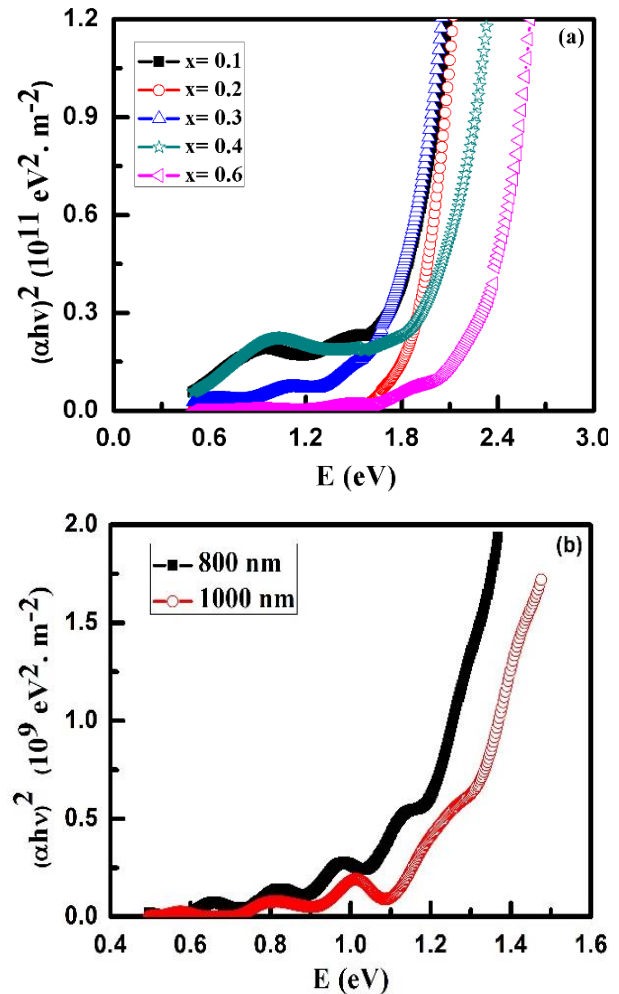

Fig. 2. Plot of $(\alpha h\nu)^2$ vs. h\nu of CIGS thin-film for 250 nm thickness at different Ga-ratios (a) and for Ga-ratio= 0.3 at high thicknesses of thin film CIGS layer (800 and 1000 nm) (b) (color online)

Fig. 3 represents the calculated transmission considering the reflection at interfaces air/ZnO:Al, ZnO:Al/CdS, CdS/CIGS (T_R) as well as the reflection and absorption in window layer (ZnO:Al) and buffer layer (CdS) ($T_{R, A}$). The results of this figure are carried out on the basis of Eqs. (4, 5) for different Ga- ratios of CIGS with thickness of 250 nm. It follows from Fig. 3-a that the transmission due to reflection (T_R) from the interfaces of the contact layers is high and the average value over the spectral range λ= 300 nm to λ= 1100 nm = λ_{Eg} (= 1.13 ev, the optimal energy gap of CIGS [12]) is about 88% for most Ga- ratios. This indicates a small part of the incident light can be lost due to reflection at different interfaces. The effect of both reflection at all interfaces and absorption in ZnO:Al and CdS on the value and behaviour of transmission is shown in Fig. 3- b. It can be seen that there is a significant decrease in the transmission due to reflection *and* absorption $(T_{R,A})$ particularly in low wavelength due to the absorption process which takes place in ZnO:Al and CdS. It is clear that the average of transmission in whole wavelength range is so small (44 %) indicating a loss of great part of the photons due to optical losses (reflection and absorption). Besides, it is observed that the Ga- ratio of x= 0.3 shows the lowest transmitted light that can reach the absorber layer.
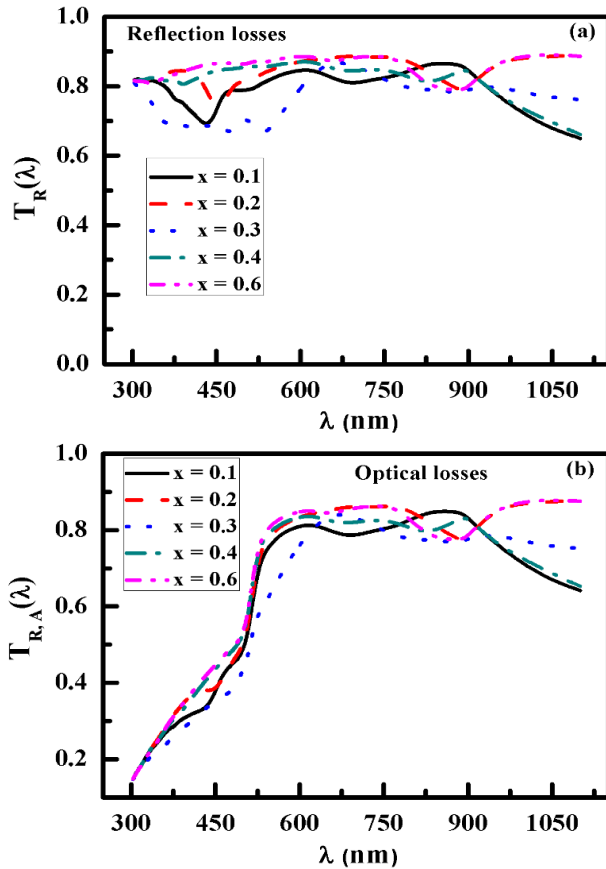
The optical losses can be estimated through calculating the short- circuit current density (J_{SC}) from Eq. 16. The value J_{sc}^{max} has been calculated at $\eta_{int}(\lambda)=1$ for each composition. This means that the summation in Eq. (16) should be separately made for each composition due to the different values of optical band gap corresponding to different Ga- ratios. Fig. 4 represents the calculated J_{SC} and the corresponding optical losses. As unexpected, x=0.3 of Ga- ratio shows the maximum value of 16.46 mA/cm^2 and at the same time this ratio represents optical losses of about 35%. The more important notification that the optical losses of x= 0.3 are considered higher than most of the compositions (x= 0.1, 0.2, 0.4). In order to understand this conflict, it should be born in mind that there is another so important factor that significantly affects on the short- circuit current density namely the optical band gap which can be seen from the limitation of the summation in Eq.(16) (the smaller energy optical band gap, the greater numbers of terms in the summation). As shown in Fig. 2, the composition of x= 0.3 of Ga- ratio represents the lowest energy gap of 1.63 eV which indicates more photons must be absorbed in the absorber layer and consequently more photogenerated current can be achieved. In this aspect, another optical loss can be added to the reflection and absorption, this loss is called non- absorption loss [23, 24]. Therefore, the photons with energy lower than the band gap energy of the absorbing material are transmitted. Thus, the energy of the photons having energy lower than the band gap energy is lost due to the non-absorption by the absorbing material. Accordingly, the total optical losses in this case have been calculated for the optimal CIGS energy gap of 1.13 eV which will be the limit of summation in Eq.16 in calculating J_{sc}^{max}. Under these considerations, the total optical losses have been calculated and plotted in Fig.4 (the dotted line). As can be seen, the total optical losses are higher than those of reflection and absorption (dashed line). Besides, the ratio x= 0.3 shows the minimum total optical losses of about 59.5% and then higher J_{SC} as mentioned above. Moreover, at higher values of Ga- ratio, the total losses are very high and can reach 77% indicting that CIGS absorber layer with these ratios of Ga is not suitable to use in solar cell devices.
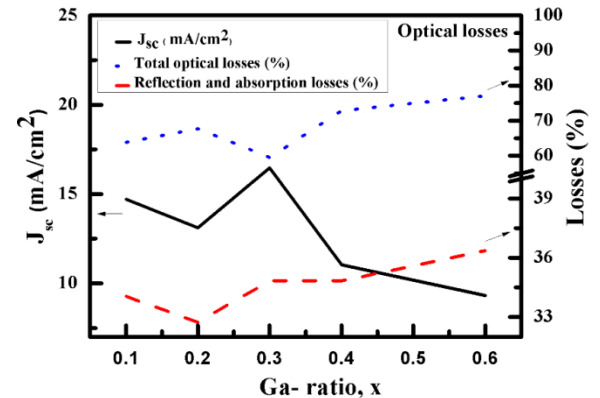

Fig. 3. The transmission due to reflection (T$_R$) of CIGS solar cell with different Ga- ratios considering reflection at all interfaces (a) as well as the transmission due to reflection at all interfaces and absorption (T$_{R,A}$) in (ZnO:Al) and (CdS) layers (b). (color online)

Fig. 4. Short-circuit current density (J$_{SC}$) of CIGS solar cell at different Ga- ratios considering the optical losses (reflection and absorption) and the losses (dashed line) and total optical losses (reflection, absorption and non-absorption losses) (dotted line) (color online)

The current voltage characteristics curve (*J- V*) of CIGS solar heterojunction under illumination at different ratios of Ga is shown in Fig. 5- a. The results of this figure are carried out on the basis of Eq.17. The values of J_{SC} that used in these calculations have been computed based on the optical losses as shown in Fig. 4. The values of saturation current J_{Sc} and quality factor *A* are taken from ref. [28]. As can be seen from this figure, the open-circuit voltage V_{OC} of each Ga- ratio depends on the energy gap of this composition. At x= 0.3, V_{OC} is about 0.7 eV where its energy gap is 1.63 eV and the maximum V_{OC} of 0.940 volts can be observed for x= 0.6 having the greatest optical band gap (2 eV). Fig. 5- b shows the power- voltage curve of CIGS solar cell at different ratios of Ga. From this figure we can determine the maximum power and consequently determine the maximum voltage V_m. Using the results of Fig. 5, the CIGS solar cell efficiency and the value of fill factor can be calculated using Eqs. (18 and 19) respectively. The obtained data of maximum voltage (V_m), maximum current density (J_m), open circuit voltage (V_{OC}), fill factor *(FF)* and efficiency (*η*) are listed in Table 1. It is obvious from Table 1 that the values of fill factor of most compositions are so close each other. The composition of x= 0.3 represents the maximum efficiency of 10.14 % resulting from the highest J_{SC} comparing with the other compositions.

The other important parameter that affects J_{SC} value is the internal quantum efficiency ($\eta_{int}(\lambda)$) which is the summation of drift quantum efficiency and diffusion quantum efficiency (see Eqs.13, 14). As can be seen from these equations, $\eta_{int}(\lambda)$ depends on some physical parameters of the absorber layer (CIGS) such as the absorption coefficient (*α*), minority (electron) lifetime (τ_n), mobility of holes and electrons (μ_p, μ_n) and the thickness of the absorber layer. Besides, $\eta_{int}(\lambda)$ depends on the properties of the space-charge region namely; the width (*W*) and the barrier height (φ_o). Since, the recombination losses at the front surface (CdS/CIGS) and at rear surface (CIGS/Mo) were taken into account in calculating $\eta_{int}(\lambda)$, therefore the velocity of recombination at front and back surface (S_f, S_b) of CIGS must be taken into calculations. The values of these parameters are taken from the previous studies of CIGS solar cells and are listed in Table 2.

Table 2. The used parameters in this paper model

Parameter	Value	Ref.
$d_{Zno:Al}$	100 (nm)	[31]
d_{CdS}	60 (nm)	This work
μ_p	25 (cm^2/Vs)	[32, 33]
μ_n	50 (cm^2/Vs)	[32, 33]
Φ_0-qv	0.7 (eV)	This work
S_b	10^7(cm/sec)	[16]
S_f	10^7(cm/sec)	[16]
τ_n	10 (ns)	[16]
W	0.15(μ m)	This work

Fig. 6 shows the quantum efficiency spectra for absorber CIGS at various values of Ga- ratio. The variation of Ga- ratio will affect on the calculation of $\eta_{int}(\lambda)$ through the absorption coefficient (*α*), energy gap (E_g) and the thickness(d) of CIGS material. The rest parameters which were mentioned in Table 2 are fixed for all compositions. The results of this figure are carried out at *W*= 0.15 µm. It is used this small width of space-charge region because of the small thickness (250 nm) of CIGS films.
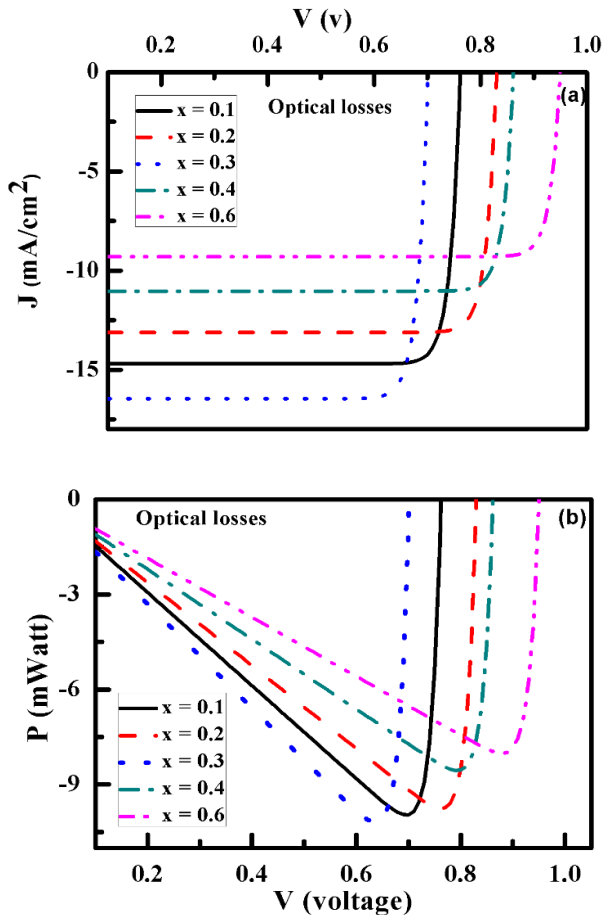

Fig. 5. Current-voltage curve (a) and power voltage curve (b) of CIGS solar cell at different Ga- ratios considering the optical losses (color online)
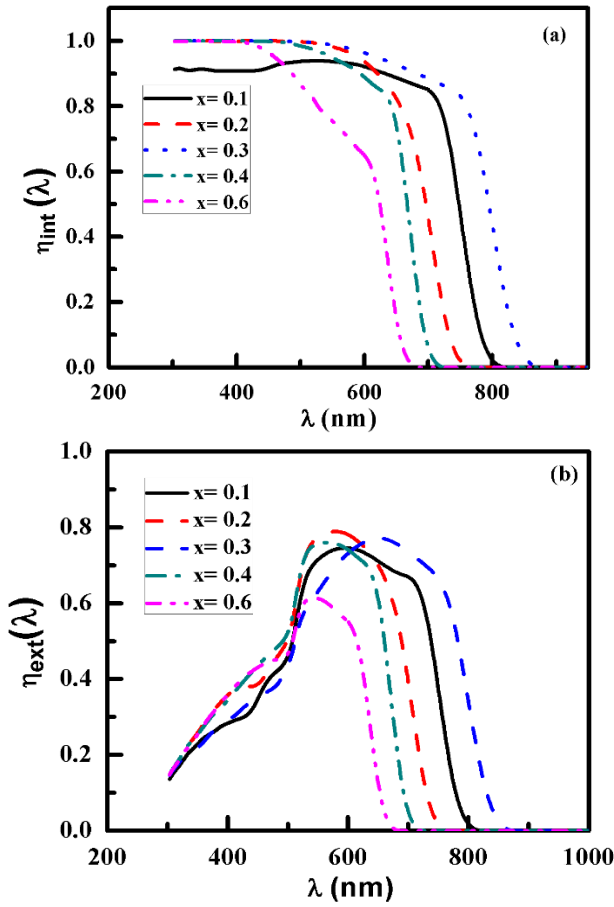
Fig. 6. Spectral internal quantum efficiency (a) external quantum efficiency (b) of CIGS solar cell at different Ga- ratios considering the recombination losses (color online)

As seen from Fig. 6-a, the value and shape of $\eta_{int}(\lambda)$ are significantly affected by Ga- ratio. At low wavelength up to 600 nm, the values of $\eta_{int}(\lambda)$ are close to unity for x > 0.1 which indicating small recombination losses. Besides, $\eta_{int}(\lambda)$ for different compositions attains zero at different values of λ depending on the energy gap of each composition. The maximum value of $\eta_{int}(\lambda)$ can be observed for thin film of x= 0.3 having the lowest energy gap. That means CIGS at Ga-ratio equals 0.3 can absorb more photons comparing with the others. Fig. 6-b shows the spectral external quantum efficiency (η_{ext}) given by Eq. (15) which takes into consideration the optical losses. The value and behaviour of η_{ext} differs from those obtained for η_{int} due to the reflection at interfaces as well as the absorption in window layer (ZnO:Al) and buffer layer (CdS).

Fig. 7 shows the dependence of J_{SC} on Ga- ratio considering the recombination losses which take place at front and back surface of CIGS. The results of this figure are carried out on the basis of Eq. (16) under the condition of $T(\lambda)= 1$. It is seen that the values of J_{SC} are greater than those obtained under the consideration of optical losses. Moreover, the composition of x= 0.3 has the maximum J_{SC} of about 23.66 mA/cm^2 while the minimum current of 12 mA/cm^2 is observed for the composition of x= 0.6. It can be seen that although the composition of Ga- ratio of 0.6

shows the highest losses of about 18%, all other compositions have low values of recombination losses smaller than 10%. The minimum losses of about 6.33% are detected for x = 0.3. This implies that the recombination losses have small significance compared with the optical losses. These results open the way for practical research interested in improving the optical properties of materials contributing to the formation of CIGS solar cell particularly the absorber layer.
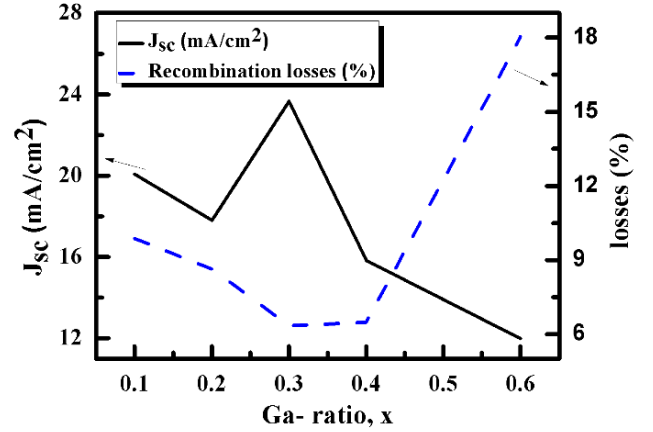

Fig. 7. Short-circuit current density (J_{SC}) of CIGS solar cell at different Ga- ratios and the corresponding recombination losses (dashed line) (color online)

As expected, when the two losses (optical and recombination) are taken into consideration, the short-circuit current density takes small values compared with the results obtained regarding each loss separately. In this aspect, Eq. (16) is employed with the real values of both $T(\lambda)$ and $\eta(\lambda)$ and the results are plotted in Fig. 8. The composition of x= 0.3 still has the maximum J_{SC} of 15.2 mA/cm^2. The behaviour of J_{SC} with considering the optical and recombination losses is similar to J_{SC} that obtained in Figs. 4 or 7 for either optical or recombination losses, respectively.
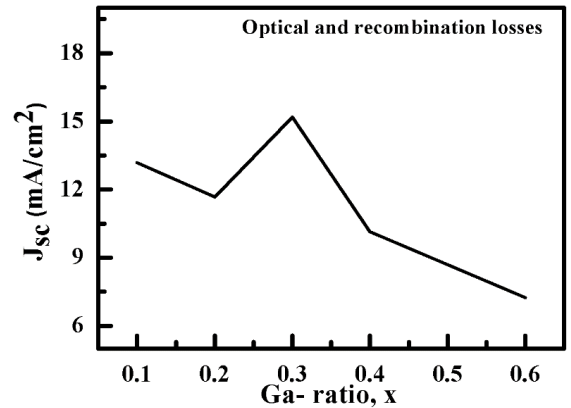

Fig. 8. Short-circuit current density (J_{SC}) of CIGS solar cell at different Ga- ratios considering the optical and recombination losses

Once again, J- V curve for the illuminated CIGS films with different values of Ga- ratio under the influence of

the optical and recombination losses is plotted in Fig. 9. The efficiency of CIGS in this case has estimated. It is found that the composition with Ga- ratio of 0.3 possesses the highest efficiency of 9.3%. This small value of efficiency can be attributed directly to the small values of J_{SC} and V_{OC} because of incomplete absorption as well as due to the small thickness of the absorbing material (250 nm).
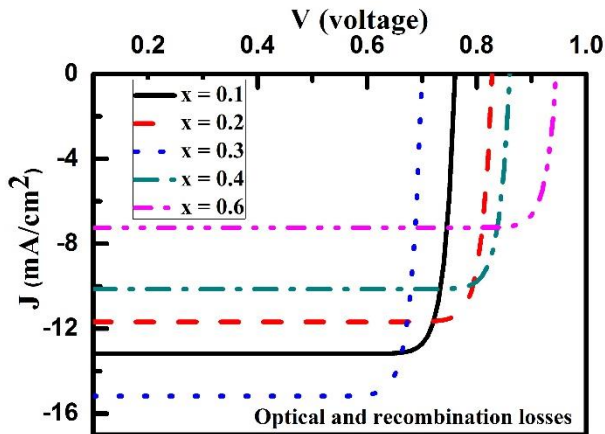

Fig. 9. Current-voltage curve of CIGS solar cell at different Ga - ratios considering the optical and recombination losses (color online)

As referred in the above section, the thickness, 250 nm, of the absorber layer is too small to absorb all the incident photons and the energy gap is so high that can lead to small J_{SC}, V_{OC} and consequently lead to small efficiency. In this section we will study the effect of increasing the thickness of CIGS layer on the performance of CIGS solar cells. Current- voltage curve of CIGS solar cell at Ga- ratio = 0.3 at different thicknesses of CIGS considering the optical losses is shown in Fig. 10. As seen, CIGS film of 800 nm thick achieves the value of J_{SC} of 31.84 mA/cm^2 while the film of 1000 nm thickness has lower value of 29 mA/cm^2. This due to the film of 800 nm has energy gap (1.13 eV) smaller than that of the film of 1000 nm (1.24 eV) (see Fig. 2-b). This indicates that in the case of 800 nm film thickness, more photons will be absorbed and thereby a high value of J_{SC} can be achieved. On the other hand, the calculated values of V_{OC} are 0.669 and 0.808 for the thickness of 800 nm and 1000 nm, respectively. This yields efficiency values of about 14.74% and 16.2% for CIGS films of 800 nm and 1000 nm respectively. Such result shows that the effect of open-circuit voltage is more significant than the short-circuit current density.
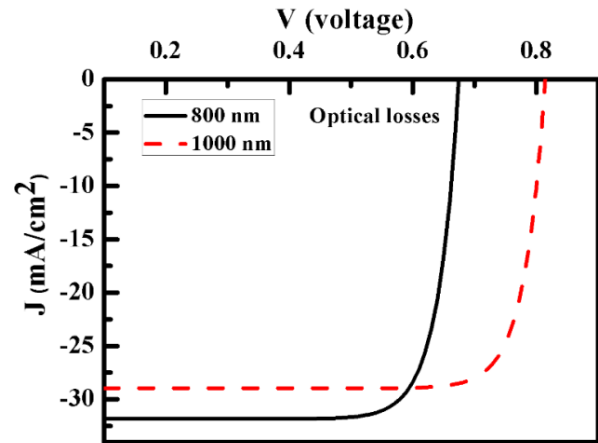

Fig. 10. Current-voltage curve of CIGS solar cell at Ga-ratio = 0.3 at different thicknesses of CIGS considering the optical losses (color online)

Considering the recombination losses, the spectral internal quantum efficiency (η_{int}) and external quantum efficiency (η_{ext}) of CIGS thin films with Ga- ratio of 0.3 and different values of thickness are calculated and plotted in Fig. 11 under the same condition of Table 2. It can be seen that with increasing the thickness of CIGS from 250 nm to 1000 nm, the values of both η_{int} and η_{ext} increase particularly at longer wavelengths. This indicates that small recombination losses at the interfaces CdS/CIGS and CIGS/Mo can be occurred and consequently high J_{SC} can be obtained. It is obviously that, the film of 800 nm thickness seems to have greater values of quantum efficiency compared with the film of 1000 nm. This can be explained in terms of films optical band gap effect.

In order to obtain realistic cell parameters of CIGS solar cells, the influence of both optical and recombination losses have been taken into account. From J- V curve (not appeared in this case) the cell efficiency is estimated and plotted in Fig. 12. This figure shows the efficiency of CIGS of the composition x= 0.3 for different thicknesses of the absorber under influenced by optical losses and optical and recombination losses. It is clear that, with increasing the thickness of the absorber layer from 250 nm to 800 nm, the efficiency increases and reaching about 14.74% under the influence of optical and reflection losses. This can be explained in the terms of increasing of J_{SC} with thickness. With further increase on the thickness from 800 nm to 1000 nm, more increase in the efficiency can be observed where the efficiency reaches about 16.2% under the influence of both optical and recombination losses. This increase of efficiency can be attributed directly to the increase of V_{OC} with the increase in film thickness from 800 nm to 1000 nm.
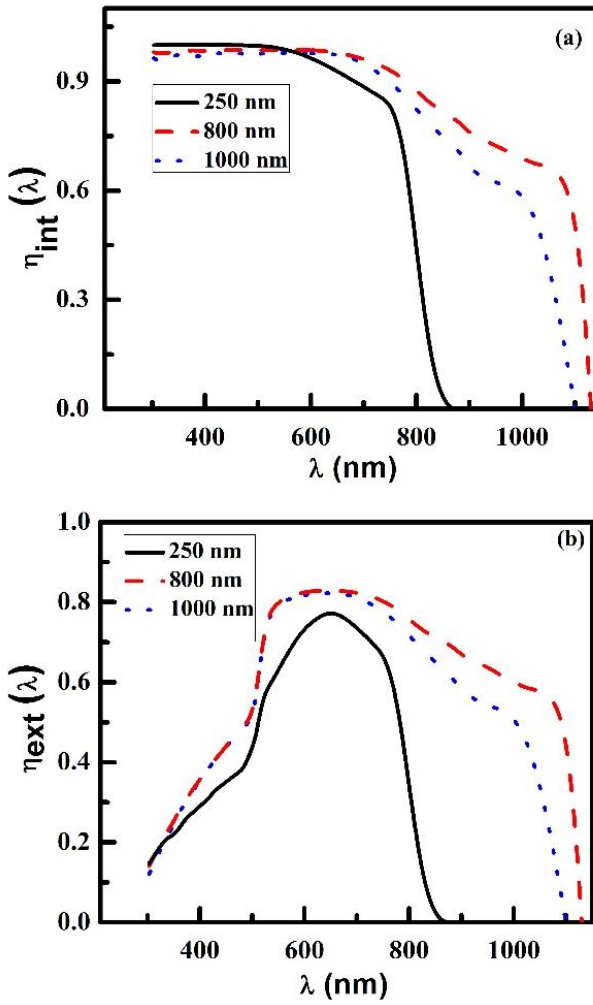
Fig. 11. Spectral internal quantum efficiency (a) external quantum efficiency (b) of CIGS solar cell at Ga- ratio = 0.3 at different thicknesses of CIGS considering the recombination losses (color online)
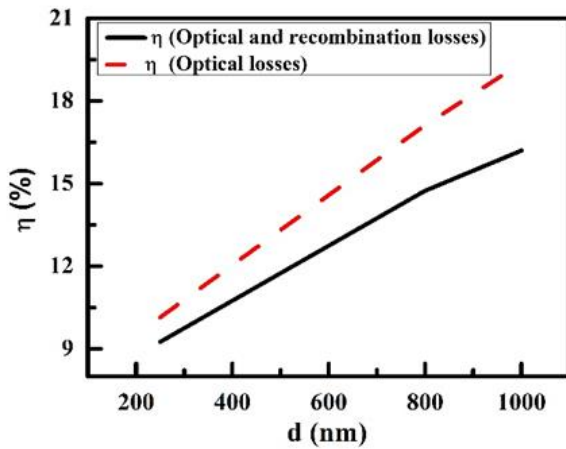

Fig. 12. The efficiency of CIGS solar of the composition x=0.3 for different thickness of the absorber considering the optical and recombination losses (color online)

Further improvements can be achieved by increasing some other parameters such as the electron lifetime, the mobility of electrons and holes, the absorber thickness, the width of space- charge region and by decreasing the velocity of recombination. As can be seen all these parameters are related to the absorbing material or to the junction. Besides, there are other methods can be employed to improve the efficiency of these cells such as coating an antireflection layer between the air and transparent conducting layer (ZnO:Al) and considering the reflection process from the back contact of the cell (Mo).

The effect of thickness of antireflection coating layer, d_{arc}, on J_{SC} values under the influence of optical losses is shown in Fig. 13. The results of this figure are carried out at thickness of 1 µm of CIGS. It can be observed that J_{SC} increases from 29 mA/cm^2 for d_{arc}= 0 and reaches its maximum value of 30.84 mA/cm^2 at d_{arc}=100:120 nm. With further increase in the thickness of the antireflection layer, a slight decrease in J_{SC} can be observed. That indicates the optimum value of thickness of the antireflection layer is in the range 100 nm to 120 nm. The corresponding efficiency of Cu In$_{0.7}$ Ga$_{0.3}$ Se$_2$ with thickness 1 µm is also shown in Fig. 13. The behaviour of η for Cu In$_{0.7}$ Ga$_{0.3}$ Se$_2$ with thickness 1 µm has similar behaviour of J_{SC}. Where, the efficiency attains its maximum value of more than 21 % at d_{arc} 100:120 nm. It can be concluded that the thickness of 100 nm of the antireflection coating layer increases the efficiency of CIGS solar cells by a ratio of about 7 %.
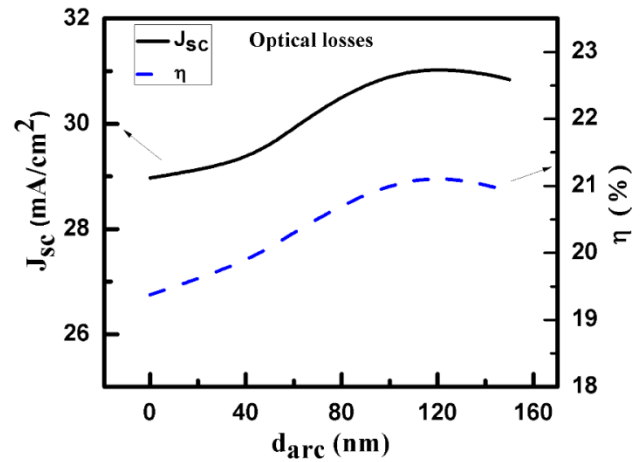

Fig. 13. Plot of short-circuit current density and the efficiency verses the thickness of antireflection coating applied on the ZnO:Al surface for Cu In$_{0.7}$ Ga$_{0.3}$ Se$_2$ with thickness 1 µm (color online)

Fig. 14- a depicts the dependence of spectral internal quantum efficiency on the ratio of reflectivity from metallic back contact. The obtained results are carried out using Eq.20 at x = 0.3, d_{CIGS}= 1 µm and the other parameters as listed in Table 2. As shown in this figure, the internal quantum efficiency is increased by increasing the ratio of reflectivity from the metallic back contact.

The dependence of short-circuit current density and the corresponding efficiency of CIGS solar cells on the reflectivity from back contact is shown in Fig. 14- b. These results are carried out on the basis of the optical and recombination losses as well as the effect of antireflection coating layer (with d_{arc}= 100 nm). It can be seen that the increasing of reflectivity from back contact from 0% to 100% leads to increase in J_{SC} by about 3%. Besides, when the antireflection coating layer with thickness of 100 nm plus 100% reflectivity from back contact are taken into account, J_{SC} increases by a ratio of about 10.5%. Under these considerations, the efficiency of CIGS solar cell is increased from 16.2% to 18.12%.

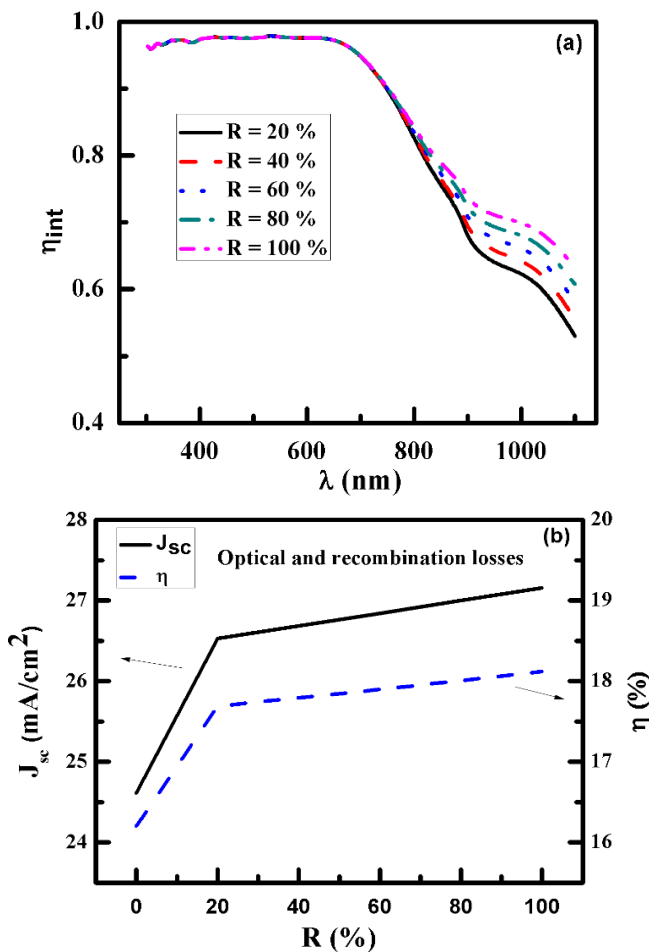*Fig. 14. Internal spectral quantum efficiency at different ratios of reflectivity (R%) from the back contact CIGS/Mo (a) and the short-circuit current density and the corresponding efficiency of CIGS solar cells verses the reflectivity from back contact CIGS/Mo (b) under the influence of optical and recombination losses as well as the antireflection coating layer (color online)*

4. Conclusions

The suggested theoretical model consists of ZnO:Al (100 nm) as conductive transparent layer, CdS (60 nm) as n- type layer, CIGS (250, 800 and 1000 nm) as absorber layer, Mo as metal back contact and the substrate of soda lime glass. Using the measured values of n,k, α for CIGS

films (x = 0.1, 0.2, 0.3, 0.4 and 0.6) for 250 nm and (x = 0.3) for 800 and 1000 nm, The J- V characteristics can be obtained and plotted to determine the values of short circuit current (J_{sc}), open circuit voltage (V_{oc}), fill factor (FF), the maximum current (J_m) and voltage (V_m) on the (J- V) plot, P_{out} and the corresponding efficiency (η%) after considering only the optical losses (reflection and absorption losses due to CdS and ZnO layers) and also the efficiency (η%) after accounting the optical and recombination losses. The analysis reveals that:

i- The highest efficiency (10.14%) was recorded for x = 0.3 having the highest Jsc and Voc compared to other compositions of low thickness (250 nm).

ii- Comparing the thicknesses 250, 800 and 1000 nm for x = 0.3 shows that the highest η ~16.20% is belonging to the film of 1000 nm thick.

iii- Thinner film of 800 nm thick has η ~14.74% comparable with that of the film of 1000 nm thick, which may be considered as a good result.

iv- Enhancement of the solar cell of CIGS absorber of 1000 nm model could be achieved using an antireflection layer (100 nm), taking into consideration the reflectivity from the back contact and increasing the space charge region to 500 nm. This has led to the efficiency enhancing to (17.62%), (18.12%) and finally to (19.82%) respectively. Finally, CIGS film thickness of about 800 nm may be sufficient to absorb the most useful optical radiation and can be employed for CIGS solar cell if other affecting parameters are optimized.

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