Indian J Phys
https://doi.org/10.1007/s12648-019-01626-0

ORIGINAL PAPER

Modelling of high-efficiency substrate CIGS solar cells with ultra-thin absorber layer

A S Mohamed[1,2] and H A Mohamed[3]*

[1]Department of Physics, College of Sciences, King Saud University, Riyadh 11451, Saudi Arabia

[2]Physics Department, Faculty of Science, Al-Azhar University, Nasr City, Cairo, Egypt

[3]Physics Department, Faculty of Science, Sohag University, Sohâg 82524, Egypt

Received: 19 February 2019 / Accepted: 03 September 2019

Abstract: Solar cells based on Cu(In,Ga)Se_2 (CIGS) are very promising thin-film solar cells due to their high absorption coefficient and appropriate optical band gap. In this work, a model of substrate thin-film solar cell of structure ZnO:Al/CdS/CIGS/Mo/glass has been established to estimate the cell parameter of ultra-thin absorber layer. The quantitative assessment of the optical losses due to reflection at interfaces and absorption in window layer (ZnO:Al) and buffer layer (CdS) as well as the recombination losses at front and rear surface of CIGS layer has been studied. The optical losses are carried out based on the optical constants of the used materials, and the recombination losses are carried out in terms of the parameters of the absorber layer. The effect of antireflection coating and reflectivity from metal electrode on the short-circuit current density and hence on the cell efficiency has been studied. It has been shown that the optical losses can prevent 30% of the incident photons from reaching the absorber layer at 150 nm thickness for each of the ZnO:Al and CdS layers. The antireflection coating of 100 nm thickness is capable of increasing J_{SC} by 8%. High efficiency of 19.56% has been obtained at 1 μm thickness of CIGS layer under certain parameters of the used materials, and this efficiency can reach 20.22% at 100% reflectivity from the back contact.

Keywords: CIGS solar cell; Optical loss; Recombination loss; Efficiency

PACS Nos.: 72.40.+w; 78.20.−e; 78.20.Bh; 78.20.Ci; 84.60.Jt

1. Introduction

Thin-film solar cell based on Cu(In, Ga)Se_2 (CIGS) is a very promising thin-film photovoltaics and offers a number of interesting advantages compared to the bulk silicon devices [1]. Because of its high absorption coefficient ($> 10^4$ cm^{-1}) and appropriate optical band gap (1.04:1.67 eV) [2, 3], CIGS thin-film solar cell has achieved the highest conversion efficiency. Cu(In,Ga)Se_2 (CIGS) thin-film solar cells are classified into two types, namely substrate and superstrate device [4, 5]. The efficiency of superstrate device with structure glass/SNO_2:F/CIGS/CdS/Ag can only reach 12.8% due to the low thickness of the absorber layer [6]. For the substrate CIGS device of structure ZnO:Al/CdS/CIGS/Mo/glass, the conversion efficiency can reach 22.6% [7].

Due to the high prices of both indium and gallium, the cost of CIGS solar cells is somewhat expensive despite its small thickness and this of course affects the use of CIGS thin-film solar cells. Many studies have been carried out based on reducing the thickness of the absorber layer to reduce the cost of these cells. Vermang et al. [8] have used CIGS absorber layer with a thickness of 0.385 μm, and they have achieved an efficiency of 13.5%. On the other hand, based on numerical modelling and using 1 μm thickness of CIGS absorber layer, Amin et al. [9] have achieved an efficiency of 17.2%.

The main goal of this work is focused on understanding the optical and recombination losses of CIGS solar cells at low thickness of the absorber layer. In this aspect, a model of substrate thin-film solar cell of structure ZnO:Al/CdS/CIGS/Mo/glass has been established. The losses due to

*Corresponding author, E-mail: hussein_abdelhafez2000@yahoo.com

Published online: 27 November 2019

reflection at interfaces air/ZnO:Al ZnO:Al/CdS and CdS/CIGS as well as the losses due to absorption in CdS and CIGS layers have been studied. The quantitative assessment of the optical losses is carried out based on the refractive index and extinction coefficient of the used materials. In addition, the recombination losses at the front and back surfaces of CIGS layer have been taken into account. The quantitative assessment of the recombination losses is carried out on the basis of the parameters of the absorber layer. The effect of the energy gap and the absorption coefficient of the used materials on both the optical and recombination losses have been studied also. Moreover, the effect of the antireflection coating and the thickness of ZnO:Al and CdS on the performance of CIGS solar cells have been investigated.

2. Model

In recent years, interests in theoretical studies have a great importance for the understanding and design of thin-film solar cells based on CdTe [10–13], PbS [14, 15], CITS [16, 17] and CIGS [3, 8, 18, 19]. However, the major difficulty lies in the large number of parameters influencing the performance of thin-film solar cells. In this model, the absorber (CIGS) is a *p*-type, with a gap of 1.13 eV, and the junction is made between the Cu(In,Ga)Se_2 *p*-type and *n*-type CdS with a gap of 2.45 eV, whereas the window layer is formed from ZnO:Al with a gap equals 3.3 eV. The schematic structure of thin-film ZnO:Al/CdS/CIGS/MO/glass solar cell is shown in Fig. 1. In the present study, the spectrum is set to the global Am 1.5 standard and the operation temperature is maintained at 300 K. The other parameters that used in this study are listed in Table 1.

2.1. Reflection and absorption losses

In the calculations of short-circuit current density (J_{SC}) of solar cells, one needs to know the optical transmission $T(\lambda)$ that will reach the absorber layer, which is limited for CIGS cell by reflections from the interfaces air/ZnO:Al, ZnO:Al/CdS and CdS/CIGS as well as absorption in the ZnO:Al and CdS layers.

The reflectivity (R) at the interface between two contacting layers 1 and 2 can be determined based on the well-known Fresnel equation [10]:

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

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

In the case of electrically conductive materials, the refractive index contains an imaginary part and is written as:

$$n^* = n - ik \tag{2}$$

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

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

The values of n and k of ZnO:Al, CdS, CIGS were taken from the literature data [18, 20, 21, respectively].

The transmittance can be estimated using the optical calculation regarding the materials' refractive indices and extinction coefficients. The transmission in this case is given by:

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

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

The antireflection coating effect significantly reduces the reflectance between the air and transparent conducting layer (ZnO:Al in this work). The theoretical optimal refractive index value of the antireflection coating (n_{arc}) is

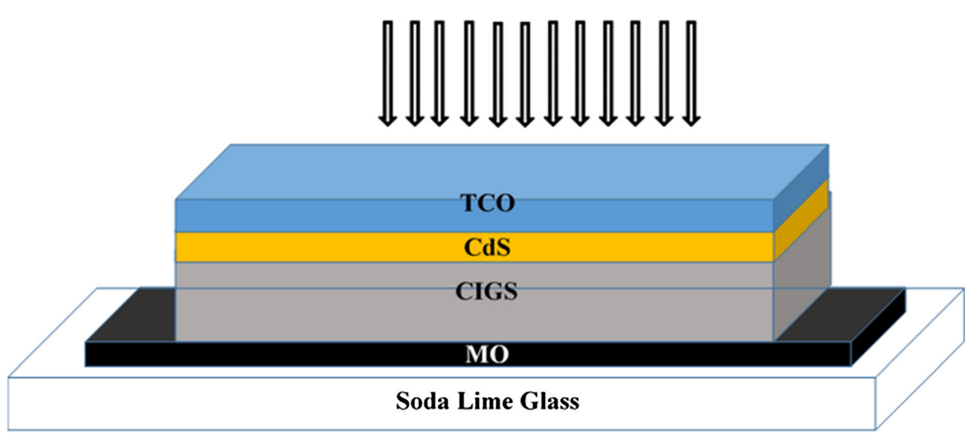

Fig. 1 Schematic structures of thin-film solar cells based on CIGS

Table 1 Parameters' values used in the model

Parameter	$\varphi_o - qV$ (eV)	W (μm)	S_f (cm/s)	S_b (cm/s)	μ_n (cm^2/V s)	μ_p (cm^2/V s)	τ_n (ns)	T (K)
Value	0.7	0.6	10^7	10^7	20	30	10	300

$(n_2)^{1/2}$, where n_2 is the refractive index of ZnO:Al material [18].

The reflection coefficient from the material with an antireflection coating has the form [22]:

$$R_{arc} = \frac{r_a^2 + r_b^2 + 2r_a r_b \cos(2\theta)}{1 + r_a^2 r_b^2 + 2r_a r_b \cos(2\theta)} \tag{5}$$

where

$$\theta = \frac{2\pi}{\lambda} n_{arc} d_{arc} \tag{6}$$

d_{arc} in Eq. 6 represents the thickness of the antireflection material. In Eq. 5, 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:

$$r_a = \frac{n_{arc} - n_1}{n_{arc} + n_1} \tag{7}$$

$$r_b = \frac{n_2 - n_{arc}}{n_2 + n_{arc}} \tag{8}$$

Then, when the antireflection effect is taken into account, the optical transmission that given by Eq. 4 has a form:

$$T(\lambda) = (1 - R_{arc})(1 - R_{23})(1 - R_{34}) \tag{9}$$

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. 9 takes the form:

$$T(\lambda) = (1 - R_{arc})(1 - R_{23})(1 - R_{34})e^{-\alpha_2 d_2} e^{-\alpha_3 d_3} \tag{10}$$

where α_2 and α_3 are the absorption coefficients of ZnO:Al and CdS, respectively, and d_2 and d_3 are their thicknesses. Note that this equation takes into consideration the effect of antireflection process.

2.2. Recombination losses

The other important parameter affects J_{SC} is the internal quantum yield (η_{int}). It is defined as the ratio between the photogenerated electron–hole pairs and the total amount of the photons, which are absorbed in the absorber layer. The optimal value of η_{int} = 1. The variation of unity is due to the recombination losses.

The internal quantum efficiency of the solar cells is the summation of the drift and diffusion components, which are obliged to photogenerate electron–hole pairs in the space-charge region and in the neutral part of the diode structure, respectively. The drift component of the internal quantum yield (η_{drift}) is given from the solution of the continuity equation in the form [23, 24]:

$$\eta_{drift} = \frac{1 + \left(S_f/D_p\right)\left[\alpha + (2/W)(\varphi_o - qV)/kT\right]^{-1}}{1 + \left(S_f/D_p\right)\left[(2/W)(\varphi_o - qV)/kT\right]^{-1}} - \exp(-\alpha W) \tag{11}$$

where S_f is the recombination velocity at the front surface of CIGS, D_p is the diffusion coefficient of the holes related to their 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. This equation takes into account the losses due to 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 by the solution of the continuity equation [25]. The solution of the continuity equation was simplified with sufficient accuracy and can be written in the form [18]:

$$\eta_{dif} = \frac{\alpha L_n}{\alpha^2 L_n^2 - 1}\exp(-\alpha W) \times \left\{ \alpha L_n - \frac{\left(\frac{S_b L_n}{D_n}\right)\left[\cosh((d-W)/L_n) - \exp(-\alpha(d-W))\right] + \sinh((d-W)/L_n) + \alpha L_n \exp(-\alpha(d-W)))}{\left(\frac{S_b L_n}{D_n}\right)\sinh[(d-W)/L_n] + \cosh[(d-W)/L_n]} \right\} \tag{12}$$

where α is the absorption coefficient of the absorber layer, D_n is the diffusion coefficient of the electrons related to their mobility μ_n by the 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 (12) takes into consideration the recombination losses at the back surface of the absorber layer, i.e. at the CIGS/MO interface.

The total internal quantum yield (η_{int}) is easy to determine as the sum of all quantum yields:

$$\eta_{\text{int}} = \eta_{\text{drift}} + \eta_{\text{dif}} \tag{13}$$

The account of the optical losses owing to the reflection at different interfaces and absorption in ZnO:Al and CdS gives the opportunity to determine the external quantum efficiency η_{ext} of the solar cells:

$$\eta_{\text{ext}} = T(\lambda)\eta_{\text{int}} \tag{14}$$

where $T(\lambda)$ is given by Eq. 10, which takes into account the optical losses.

2.3. Absorptive capacity and effect of the back contact

If the thickness of the absorber layer is too thin, there is a part of the incident photons on the absorber layer which is lost due to the incomplete absorption in this layer. Considering this effect, the exact values of integrated absorptive capacity (A_{hv}) of the CIGS layer must be estimated taking into consideration the spectral distribution of solar radiation and the absorption coefficient of the material rather than to determine the absorptive capacity for one wavelength in the range $hv > E_g$ as usually estimated. The value of integrated absorptive capacity of the semiconductor layer depends not only on the spectral distribution of solar radiation but also on the optical transmission of the ZnO:Al and CdS layers that modifies the solar radiation spectrum. Thus, the integrated absorptivity is equal to the ratio of the number of photons absorbed in the CIGS layer to the number of photons penetrated through the ZnO:Al and CdS layers [26]:

$$A_{hv}(d) = \frac{\sum_i T(\lambda)(\emptyset_i/hv_i)[1-\exp(-\alpha_i d)]\Delta\lambda_i}{\sum_i T(\lambda)(\emptyset_i/hv_i)\Delta\lambda_i} \tag{15}$$

where d is the thickness of CIGS layer, ϕ_i (mWcm^{-2} mm^{-1}) is the spectral power density, hv is the photon energy, α is the absorption coefficient of CIGS layer, $\Delta\lambda$ is the interval between neighbouring values of the wavelength and $T(\lambda)$ is the spectral transmission and is given by Eq. (10).

When the thickness of the absorber layer is too thin, then not all the incident photons have been absorbed on it. In this case, the reflectivity from back contact takes place; particularly, the back contact is a metal electrode and its reflectivity can reach 100%. 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 [14] can be used to measure theoretically the effect of reflectivity from the back contact on the internal quantum efficiency:

$$\eta_{\text{int}}(R) = \eta_{\text{int}}[1 + R \times \exp(-\alpha d)] \tag{16}$$

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

2.4. Short-circuit current density and the cell parameters

The spectral distribution of the photons can be found as Φ_i/hv, where Φ_i is the spectral power density, and hv is the photon energy. The short-circuit current density (J_{SC}) can be calculated according to the following formula [12]:

$$J_{SC} = q\sum_i T(\lambda)\frac{\Phi_i(\lambda_i)}{hv_i}\eta_{\text{int}}(\lambda_i)\Delta\lambda_i \tag{17}$$

where $\Delta\lambda$ is the interval between neighbouring values of the wavelength, $T(\lambda)$ is given by Eq. (10) and $\eta_{\text{int}}(\lambda)$ is given by Eq. (13).

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:

$$J = J_L - J_0\left[\exp\left(\frac{qv}{AkT}\right) - 1\right] \tag{18}$$

where J_L is the photogenerated current, J_0 is the reverse saturation 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 Jo and A are taken from Ref. [27].

The CIGS solar cell efficiency can be expressed by:

$$\eta = \frac{\text{FF} \times J_{SC} \times V_0}{P_{\text{in}}} \tag{19}$$

where FF is the fill factor, V_0 is the open-circuit voltage and P_{in} is the density of the total AM 1.5 solar radiation power.

The fill factor can be written as:

$$\text{FF} = \frac{J_m \times V_m}{J_{SC} \times V_0} \tag{20}$$

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

3. Results and discussion

Figure 2-a shows the transmission spectra $T(\lambda)$ as a function of CdS thickness at 100 nm thickness of the ZnO:Al layer. The results are carried out based on Eq. 10 with $R_{\text{arc}} = 0$, i.e. the effect of antireflection coating is

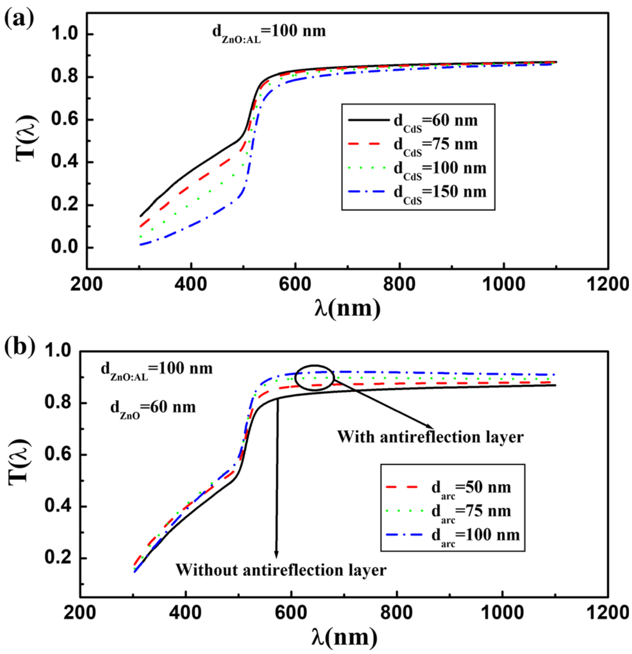

Fig. 2 Optical transmission of the ZnO:Al/CdS at various values of CdS thickness (**a**) and at various thicknesses of the antireflection coating (**b**)

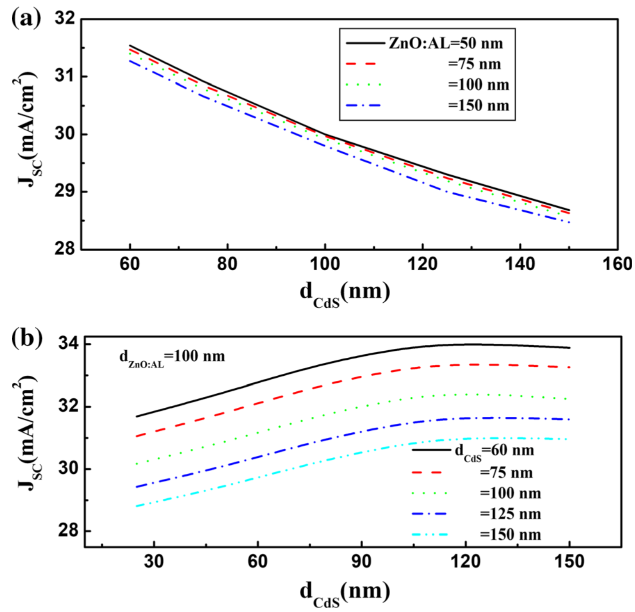

Fig. 3 Short-circuit current density as a function of CdS thickness at various thicknesses of ZnO:Al (**a**) and as a function of antireflection coating thickness at various thicknesses of CdS (**b**)

neglected. The reflection at interfaces air/ZnO:Al, ZnO:Al/CdS and CdS/CIGS as well as the absorption in ZnO:Al and CdS is taken into account. According to this figure, we note that the transmitted light that will reach the absorber layer is less than unity due to these losses. Appreciable losses are observed in the wavelength range $\lambda = 500$–600 nm, and much more losses are observed in the region $\lambda < 500$ nm caused by absorption in CdS together with ZnO:Al. As the thickness of CdS increases, the optical losses due to the absorption in this layer increases and then $T(\lambda)$ decreases. When the antireflection coating is taken into account as shown in Fig. 2-b, the value of $T(\lambda)$ increases comparing with this shown in Fig. 2-a. This figure shows also the increase in the thickness of the antireflection coating leads to the increase in the value of $T(\lambda)$, which reaches more than 90% at d_{arc} = 100 nm corresponding approximately to the maximum of the solar radiation under the AM1.5 conditions.

The dependence of short-circuit current density (J_{SC}) on the thickness of CdS at various thicknesses of ZnO:Al is shown in Fig. 3-a. Equation 17 is used to calculate J_{SC} with $\eta_{int}(\lambda) = 1$(i.e. ignoring the effect of recombination losses). As it was expected, the values of J_{SC} decrease with increasing both the thickness of CdS and ZnO:Al layers. To estimate the quantities of optical losses, firstly we have to calculate the maximum short-circuit current density (J_{SC}(max)) by using Eq. 17 under the conditions of $T(\lambda) = 1$ and $\eta_{int}(\lambda) = 1$ (i.e. all the incident photons will reach the absorber and create pairs of electron–hole without any losses) and then compare the values of J_{SC} represented in Fig. 3 with J_{SC}(max), which equals 40.55 mA/cm^2. It can be seen that at $d_{ZnO:Al}$ = 50 nm and d_{CdS} = 60 nm, the recorded J_{SC} is 31.54 mA/cm^2 and then the optical losses are about 22%. The optical losses can reach their maximum value of 30% at $d_{ZnO:Al}$ = 150 nm and d_{CdS} = 150 where J_{SC} = 28.47 mA/cm^2, which indicates that a great part of the incident photons can be lost before reaching the absorber layer. This result represents the importance of improving the optical properties of the ZnO, CdS and CIGS layers. This can be done through decreasing the difference in refractive indices for two consecutive layers in order to limit the reflection loss and decreasing the absorption coefficient for both ZnO and CdS layers in order to limit the absorption loss.

The calculations show that in the case of using the antireflection coating, the values of J_{SC} as a function of d_{CdS} increase as shown in Fig. 3-b. It can be observed that the maximum value of J_{SC} of about 34 mA/cm^2 is achieved in the range d_{arc} = 100 nm–120 nm and the optical losses record the minimum value of 16%. It indicates that the appropriate thickness (100 nm) of antireflection coating can increase J_{SC} by 7–8%.

I–V curve of the CIGS heterojunction under illumination is calculated using Eq. 18, and the results are shown in Fig. 4. From this figure, we can see that the open-circuit voltage V_o = 0.84 V, and the maximum current J_m and voltage V_m are 32.37 mA/cm^2 and 0.72 V, respectively. From these data and using Eqs. 19 and 20, the fill factor *FF*

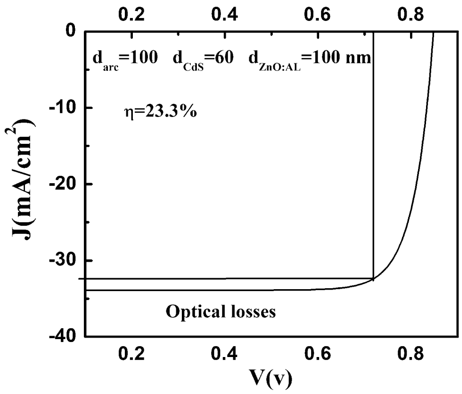

Fig. 4 *J–V* curve of CIGS solar cell under the influence of the optical losses

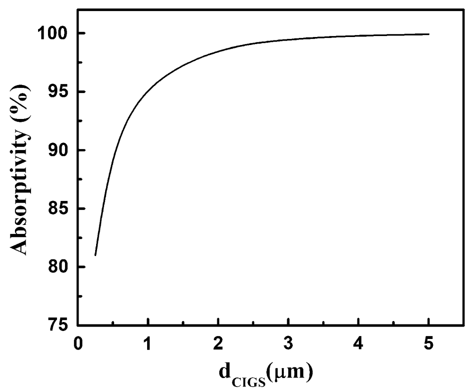

Fig. 5 Absorptivity of CIGS as a function of its thickness under the condition of the total AM 1.5 solar radiation

records 81% and the efficiency of CIGS cells when the optical losses are taken into calculations is 23.3%.

The dependence of the absorptivity on the thickness of CIGS is shown in Fig. 5. It can be seen that a thickness of 0.5 μm of CIGS layer is capable of absorbing about 89% from the incident photons. And this ratio rises up to 95% when the thickness of CIGS becomes 1 μm. The absorptivity of photons in the CIGS layer with a typical thickness of 2–3 μm is about 99%.

Figure 6 shows the photoelectric quantum yield spectra (internal and external quantum efficiency) computed by Eqs. 11–13 for different parameters of the absorber layer that are listed in Table 1. The deviation of internal quantum efficiency from unity is caused by surface recombination. (Note that $\eta = 1$ for S = 0.) In our calculations, the recombination velocity at front surface and at back surface is taken by 10^7 cm/s. This means that the recombination losses take place where the surface recombination reveals itself mostly within the short-wavelength region. The decay of the efficiency at short wavelengths is usually attributed to the surface recombination, which intensifies as the electric field decreases [28]. Figure 6-b represents the

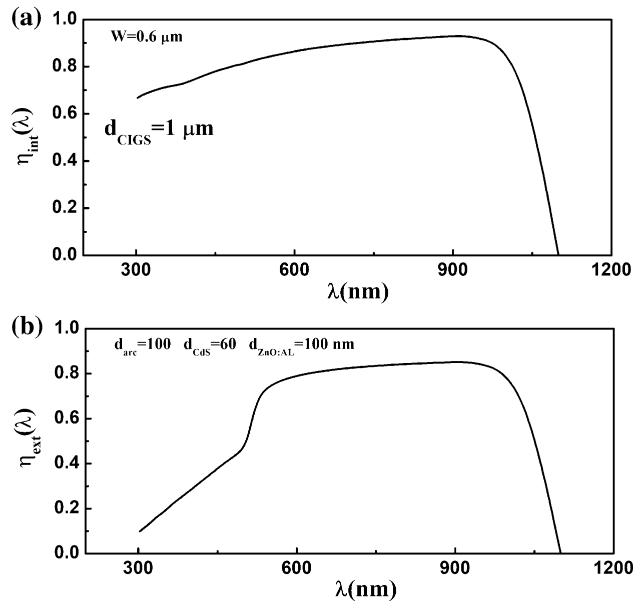

Fig. 6 Spectral of the internal quantum efficiency (η_{int}) (**a**) and external quantum efficiency (η_{ext}) (**b**) of CIGS solar cell

external quantum efficiency when the reflection losses at interfaces air/ZnO:Al, ZnO:Al/CdS and CdS/CIGS as well as the absorption in both ZnO:Al and CdS layers are taken into consideration. It can be seen that there is a steep decay of η_{ext} in the short-wavelength region caused by absorption in the ZnO:Al and CdS layers as shown in Fig. 2; in general, the value of η_{ext} is less than η_{int} due to the value of $T(\lambda)$ as shown in Eq. 14.

In order to estimate the recombination losses at front and back surface of CIGS layer, we have to calculate J_{SC} from Eq. 17, which takes into account the value of η_{int} that is given by Eqs. 11, 12. In this case, we assume that $T(\lambda) = 1$. Under these notes, J_{SC} records 34.15 mA/cm^2 and hence the recombination losses are about 15%.

When the optical and recombination losses are taken into account, the value of J_{SC} is about 28.7 mA/cm^2 and the values of optical and recombination losses are more than 29%. These results are carried out under the conditions of $d_{arc} = 100$ nm, $d_{ZnO:Al} = 100$ nm, $d_{CdS} = 60$ nm, $d_{CIGS} = 1$ μm and other data that are listed in Table 1.

Once again, *J–V* curves for CIGS under illumination are shown in Fig. 7. This figure shows also the effect of reflectivity from back contact. The results from this figure are carried out under the effect of both optical and recombination losses at the conditions that shown in the above paragraph. It can be seen that when the reflectivity from back contact is ignored, the cell parameters represent $V_0 = 0.84$ V, $J_m = 27.12$ mA/cm^2, $V_m = 0.72$ V, $FF =$ 81% and $\eta = 19.56$%. At 100% reflectivity from back contact, the cell parameters represent $V_0 = 0.84$ V, $J_m =$ 28.07 mA/cm^2, $V_m = 0.72$ V, $FF = 81.5$% and

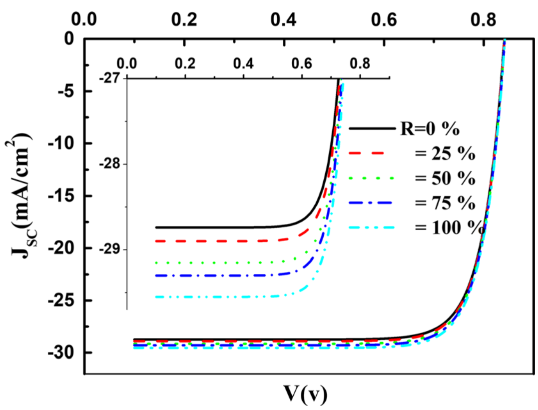

Fig. 7 *J–V* curves of CIGS solar cell under the influence of the optical and recombination losses for various values of reflectivity from back contact (the inset shows the magnifications of the curves)

η = 20.22%. These results indicate that even though the thickness of the absorber layer is small (1 μm) and only absorbs 95% from the incident light (see Fig. 5), the absorbed light and hence J_{SC} are high due to the reflectivity from back contact takes place due to using a metallic electrode. It can be seen that the 100% reflectivity from back contact can increase the efficiency by a ratio of 3.4%.

To know the quality of the results of this work, these results must be compared with recent papers that published on CIGS solar cells with ultra-thin absorber layer. Xiao et al. [29] obtained efficiency of 10.5% for submicron thick of CIGS (800–900 nm). Li et al. [30] obtained efficiency reached to 11.72% for 1.3 μm of the absorber layer without any light trapping and antireflecting coating techniques. Kim et al. [31] obtained efficiency 15.4% of CIGS for 1 μm thickness. Additionally, Vermang et al. [8] have used CIGS absorber layer with ultra-thickness of 0.385 μm and they have achieved an efficiency of 13.5%.

4. Conclusions

In the present study, we have established a model of substrate thin-film solar cell of structure ZnO:Al/CdS/CIGS/Mo/glass. The optical losses resulting from the reflection at interfaces air/ZnO:Al, ZnO:Al/CdS and CdS/CIGS as well as the absorption in ZnO:Al and CdS layers have been studied. The quantitative assessment of the optical losses is carried out based on the refractive index and extinction coefficient of the used materials. The recombination losses at the front and back surfaces of CIGS layer have been taken into account. The quantitative assessment of the recombination losses is carried out on the basis of the parameters of the absorber layer. The results show that the optical losses are in the range of 22–30% depending on the thickness of window layer (ZnO:Al) and buffer layer (CdS). The antireflection coating with thickness 100 nm improves the short-circuit current density by 7–8%. At particular parameters of d_{arc} = 100 nm, $d_{ZnO:Al}$ = 100 nm, d_{CdS} = 60 nm and d_{CIGS} = 1 μm, the short-circuit current density records 28.7 mA/cm^2 and the optical and recombination losses are more than 29%. The solar cells with these parameters give an electric efficiency of 19.56% with a fill factor of 81% and voltage of open circuit of 0.84 V. The 100% reflectivity from back contact increases the cell efficiency by 3.4%, and this efficiency reaches 20.22%. The obtained efficiency in the present study is better than those reported so far in the literature for CIGS-based solar cells. What's new in this work is to get a high efficiency of CIGS solar cell despite the use of a small thickness of the absorber through choosing the optimum conditions for each layer in this cell.

Acknowledgements This project was supported by King Saud University, Deanship of Scientific Research, College of Sciences Research Center.

References

[1] H Movla *Optik* **124** 5871 (2013)
[2] T Wada, Y Hashimoto, S Nishiwaki, T. Satoh, S Hayashi, T Negami and H. Miyake *Sol. Energy Mater. Sol. Cells* **67** 305(2001)
[3] H Heriche, Z Rouabah and N Bouarissa *Int. J. Hydrogen Energ.* **42** 9524 (2017)
[4] T Nakada, Y Hirabayashi, T Tokado, D Ohmori and T Mise *Sol. Energy* **77** 739 (2004)
[5] T Nakada *Thin Solid Films* **480–481** 419 (2005)
[6] 6.M D Heinemann, V Efimova, R Klenk, B Hoepfner, M Wollgarten, T Unold, H-W Schock and C A Kaufmann *Prog. Photovolt. Res. Appl.* **23** 1228 (2015)
[7] http://www.nrel.gov/ncpv/images/efficiency_chart.jpg
[8] B Vermang, JT Wätjen, V Fjällström, F Rostvall, M Edoff, R Kotipalli, F Henry and D Flandre *Prog. Photovolt Res. Appl.* **22** 1023 (2014)
[9] N Amin, P Chelvanathan, H M Istiaque and K Sopian *Energy Procedia* **15** 291 (2012)
[10] H A Mohamed *J. Appl. Phys.* **113** 093105 (2013)
[11] H A Mohamed, *Thin Solid Films* **589** 72 (2015)
[12] H A Mohamed, A S Mohamed and H M Ali *Mater. Res. Express* **5** 056411 (2018)
[13] H A Mohamed *Can. J. Phys.* **92** 1350 (2014)
[14] H A Mohamed *Philos. Maga.* **94** 3467 (2014)
[15] H A Mohamed *Solar Energy* **108** 360 (2014)
[16] S Lee and K Price *J Park Thin Solid Films* **619** 208 (2016)
[17] O A Dobrozhan, P S Danylchenko, A I Novgorodtsev and A S Opanasyuk *J. Nanoelectron. Optoe.* **12** 1 (2017)
[18] L A Kosyachenko, X Mathew, P D. Paulson, V Ya Lytvynenko and O L Maslyanchuk *Sol. Energy Mater. Sol. Cells* **130** 291 (2014)
[19] J Liu, M Zhang and X Feng *Optik* **172** 1172 (2018)
[20] Q Xu, R D Hong, H L Huang, Z F Zhang, M K Zhang, X P Chen and Z Y Wu *Opt. Laser Technol.* **45** 513 (2013)
[21] S Ninomiya and S Adachi *J. Appl. Phys.* **78** 1183 (1995)
[22] M Born and E Wolf *Principles of Optics,* 7th ed. (Cambridge: Cambridge University Press) p 65 (1999)

[23] L Kosyachenko and T Toyama *Sol. Energy Mater. Sol. Cells* **120** 512(2014)
[24] L A Kosyachenko *Semiconductors* **40** 710 (2006)
[25] S M Sze and K K Ng *Physics of Semiconductor Devices* (New Jersey: Wiley-Interscience) p 723 (2006)
[26] L A Kosyachenko, E V Grushko and T I Mykytyuk *Semiconductors* **46** 466 (2012)
[27] W Wang, M T Winkler, O Gunawan, T Gokmen, T K Todorov, Y Zhu and D B Mitzi *Adv. Energy Mater.* **4** 1301465 (2014)
[28] L A Kosyachenko, EV. Grushko and VV Motushchuk *Sol. Energy Mater. Sol. Cells* **90** 2201 (2006)
[29] P Xiao, Z Ming, Z Daming, S Rujun, Z Leng, W Yaowei, L Xunyan, W Yixuan and R Guoan *Appl. Surf. Sci.* **442** 308 (2018)
[30] H Li, F Qu, H Luo, X Niu, J Chen, Y Zhang, H Yao, X Jia, H Gu and W Wang *Results Phys.* **12** 704 (2019)
[31] S T Kim, K Kim, J H Yun and B T Ahn *Curr. Appl. Phys.* **18** 912(2018)