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Efficiency Improvement Above 21% of CIGS Thin-Film Solar Cell under the Influence of Optical Losses

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Abstract: This work focuses on determining theoreticaly quite accurately the optimal parameters of the CIGS cell with structure ZnO:Al/CdS/CIGS/Mo/Glass such as: thickness of CdS and the thickness of antireflection layer. The calculations of optical losses are carried out due to reflections from all interfaces and absorption in the transparent conducting oxide (TCO) and n-type layers. The effect of thickness of antireflection coating above TCO surface has been taken into account. It is shown that, the amount of the optical losses is about 23%. The 100 nm thickness of the antireflection layer is sufficient to reduce these losses up to 16 %. At certain parameters of the used materials and with taking into account the reflectivity from back contact, the efficiency of CIGS has been improved and records a value of 21.27%.

Keywords: CIGS solar cell - optical losses; antireflection layer- efficiency.

1 Introduction

Solar cells based on wafer crystalline silicon solar cells are currently constitute the major share of photovoltaics installed and used worldwide. Recently, thin-film solar-cells with $Cu(In,Ga)Se_2$ (CIGS) absorber layers provide a good alternative to silicon solar cells[1-4]. CIGS is a direct semiconductor material of appropriate optical band gap (1.04: 1.67 eV) and possess high absorption coefficient [5, 6]. That means a layer thickness of some micro-meters of CIGS is sufficient for absorption most of the incoming sunlight without the necessity of light trapping structures, which have to be used in silicon devices.
The conversion efficiency of the typical structure of substrate CIGS solar cell consists of ZnO:Al/CdS/CIGS/Mo/Glass can reach 22% [7] and in modules is in the range12-15 % [8]. On the other hand, the theoretical limit of these solar cells is high and can reach 28-30% [8].
Heriche et al [9] studied theoretically the effect of thickness and doping of a window, buffer and absorbent layers on the photovoltaic cell parameters in CIGS based solar cells. They obtained cell efficiency of about 26. Although Heriche et al [6] used CIGS of 1 μm thickness, they obtained theoretically a high efficiency of more than 21.3%. The effect of the absorber layer band-gap was studied by Belghachi and Limam [10]. In their simulation, they found that maximum efficiency of about 23% can be achieved with a band gap of around 1.48 eV and this efficiency can be increased up to 24.34 % corresponding to an optimised back graded absorber of 1.41 eV gap at the front and 1.54 eV gap at the rear contact.
We noted that the high efficiency that observed from these theoretical studies are resulting from that these studies ignored one or more of the losses that can be taken place within the cell. One of these losses is the optical loss, which means that not all the incident photons will reach the absorber layer but there are losses due reflection at interfaces air/ZnO:Al, ZnO:Al/CdS and CdS/CIGS as well as losses due to the absorption in ZnO:Al and CdS.
The present work aims to study the effect of the optical losses on the performance of CIGS solar cell with structure ZnO:Al/CdS/CIGS/Mo/Glass. The quantitative assessment of the optical losses is based on the optical constants (refractive index and extinction coefficient) of the used materials and of course on its thickness.

2 Optical losses

It is certain that not all the incident photons on thin-film solar cell will reach the absorber layer and hence generate photocurrent. There is a part of these photons can be lost due to the reflection losses which take place at interfaces air/ZnO:Al, ZnO:Al/CdS, CdS/CIGS. Besides, there is

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great deal of the incident photons can be lost due to the absorption process which take place in ZnO:Al and CdS layers. These two losses are called the optical losses [11].

The reflectivity (R) at the interface between two contacting layers 1 and 2 can be determined based on the well-known Fresnel equation [12]:

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

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

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

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

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

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

The values of n and k of ZnO:Al and CdS, were taken from the literature data [13, 14, 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:

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

where R_{12}, R_{23} and R_{34} are the reflectivity at the interfaces between 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 $(n_2)^{1/2}$, where n_2 is the refractive index of ZnO:Al material [8].

The reflection coefficient from the material with an antireflection coating has the form [15]:

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

where,

$$\theta = \frac{2\pi}{\lambda} n_{arc} d_{arc} \quad (6)$$

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:

$$r_a = \frac{n_{arc} - n_1}{n_{arc} + n_1} \quad (7)$$

$$r_b = \frac{n_2 - n_{arc}}{n_2 + n_{arc}} \quad (8)$$

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

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

Now we will consider the absorption process that takes place in ZnO:Al and CdS. The losses due to reflection and absorption are called the optical losses. In this case, Eq.9 takes the form:

$$T(\lambda) = (1 - R_{12})(1 - R_{23})(1 - R_{34}) e^{-\alpha_1 d_1} e^{-\alpha_2 d_2} \quad (10)$$

where, α_1 and α_2 are the absorption coefficients of ZnO:Al and CdS and d_1 and d_2 their thickness, respectively.

Figure 1-a represents the optical transmission due to the reflection at interfaces air/ZnO:Al, ZnO:Al/CdS and CdS/CIGS without antireflection, curve 1, (calculated by Eq4) and with various thicknesses of antireflection layer, curve 2, (calculated by Eq.9). It can be seen that the transmission coefficient depends on the thickness of the antireflection coating layer, d_{arc}. As seen, for d_{arc} =100 nm, the transmission coefficient attains its maximum value at wavelength 500 nm:600 nm corresponding approximately to the maximum of the solar radiation under the AM1.5 conditions. More decrease in transmission coefficient can be seen at low wavelength caused by the absorption process takes place in ZnO:Al and CdS layer, as shown in Fig.1-b.

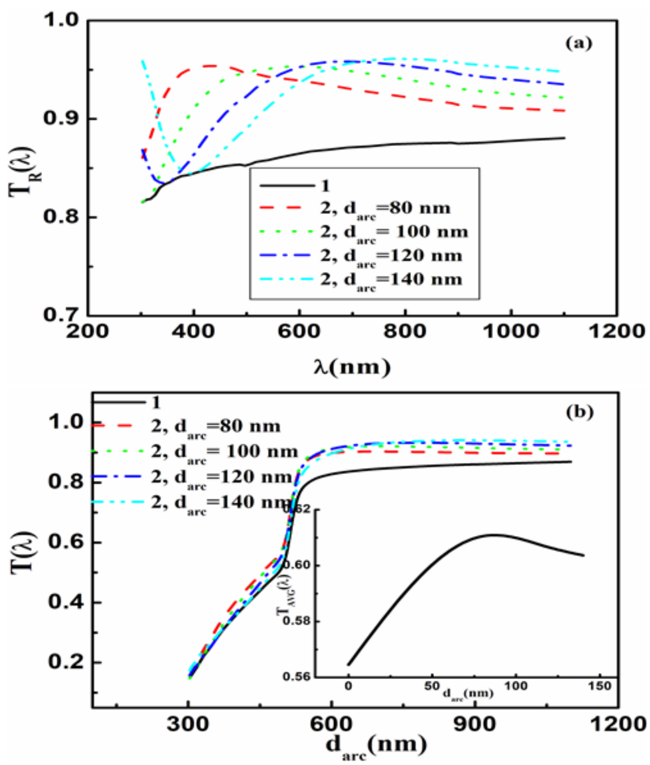

Fig.1: The calculated transmission spectrum considering reflection at all interfaces (a) and the reflection at all interfaces and absorption in ZnO:Al and CdS (b) without (curve 1) and with (curve 2) antireflection coating layer. In the inset Fig.1-b, the average of transmission in whole wavelength as a function of the thickness of the

antireflection coating layer.

As seen from the inset figure (Fig.1-b), the maximum average of transmission (T_{avg}) in whole wavelength range is about 61 % at d_{arc} 100 nm. This result indicates that a great part of the incident light will be lost in the top-layers due to the optical losses.

Quantitative analysis of the optical losses and its effect on the solar cell performance can be obtained by calculating the short-circuit current density J_{sc} given by:

$$J_{SC} = q \sum_i \frac{\Phi_i(\lambda_i)}{h\nu_i} T(\lambda_i)\Delta\lambda_i \quad (11)$$

Where, $T(\lambda)$ is given by Eq. (10).

The optical losses can be determined using the following equation:

$$Losses\ (\%) = \left(1 - \frac{J_{SC}}{J_{sc}^{max}}\right) \times 100 \quad (12)$$

where J_{sc}^{max} is the maximum value of short-circuit current density, which T(λ)=1.

The results of Eq.(11) and the corresponding optical losses are shown in Fig.2. This figure shows the effect of the thickness of antireflection coating layer on J_{SC} values. It can be see, without using the antireflection layer, J_{SC} is about 31.5 mA/cm^2 and the corresponding optical losses are 23%. When the antireflection coating layer is taken into account, the value of J_{SC} increases and records a maximum value of 34 mA/cm^2 and the corresponding minimum optical losses of 16% is observed at d_{arc}=100:120 nm.

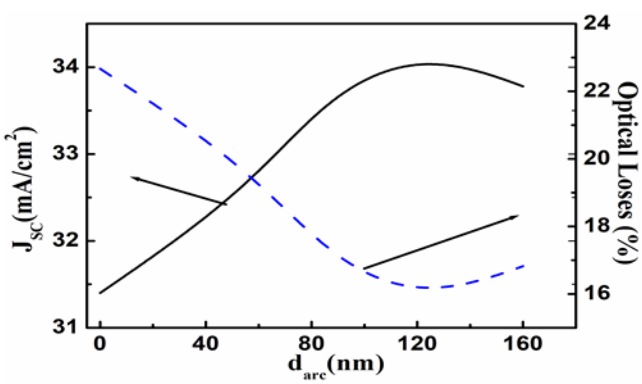

Fig.2: Dependence of short circuit-current density and the corresponding optical losses on the thickness of the antireflection coating layer.

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:

$$J = J_0\left[exp\left(\frac{qv}{AkT}\right) - 1\right] - J_L \quad (13)$$

where J_L is the photogenerated current, J_0 is the reverse saturation current, q is the elementary charge, k the Boltzmann constant, T the absolute temperature and A the ideality factor. The values of J_o and A are taken from [16]. Besides, the cell efficiency which can be expressed by:

$$\eta = \frac{FF \times J_{SC} \times V_0}{P_{in}} \quad (14)$$

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

Equation 9 is employed to plot the I-V curve and determine the cell parameter under the condition of optical losses. The carried out results using Eqs. (13, 14) are plotted in Fig.3.

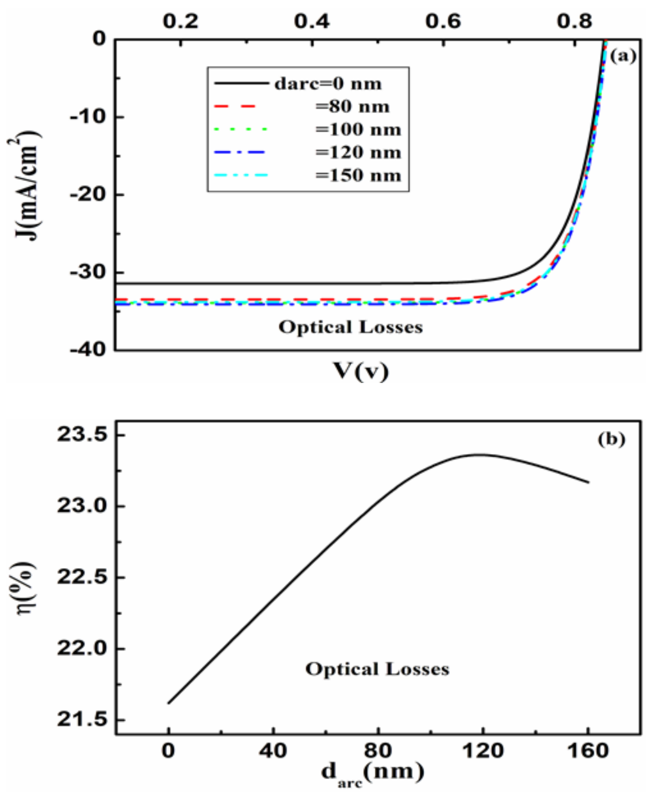

Fig.3: Current-voltage curve under illumination (a) and the efficiency (b) of CIGS solar cell as a function of the thickness of the antireflection coating layer considering the optical losses.

As can be seen, more downward shifts in I-V curves can be observed with increasing the thickness of the antireflection layer up to d_{arc}=100:120 nm. Besides, the maximum efficiency of 23.42 % is observed at d_{arc}=100:120 nm. That means the thickness of antireflection coating layer of 100:120 nm improves the CIGS collar cell efficiency by a ratio of 8% comparing with the value of efficiency at d_{arc}=0.

3 Reflectivity from back Contact

If the absorbent thickness is small, as in our case, a portion of the light is expected to pass to the back contact without absorption. Thus the metallic back contact may be reflecting 100% of the unabsorbed photons. 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 [12, 17] can be used to measure the effect of reflectivity from the back contact on the internal quantum efficiency:

$$\eta_{int}(R) = \eta_{int}[1 + R \times \exp(-\alpha d)] \quad (15)$$

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

Figure 4 represents the dependence of spectral internal quantum efficiency on the ratio of reflectivity from metallic back contact. The obtained results are carried out using Eq.15 at d_{arc}=100 nm and under the influence of optical and recombination losses. The recombination losses have been discussed in our previous studies [17-22]. As shown in this figure, the internal quantum efficiency is increased by increasing the ratio of reflectivity from the metallic back contact particularly at long wavelength. The calculated J_{SC} and the corresponding cell efficiency can be seen in this figure. It can be seen that J_{SC} =30.39 mA/cm^2 at R=0% and this values increase up to 31.1 mA/cm^2 at R=100%. This results indicate the 100% reflectivity from back contact leads to enhancement J_{SC} and the cell efficiency by about 2.3%. Besides, at 100 nm thickness of the antireflection layer, 100% reflectivity from back contact, 1 µm thickness of the absorber layer, 0.3 µm the width of space-charge, 10^6 cm/s of front velocity of recombination at front surface, and 10^7 cm/s of velocity of recombination at back surface, the CIGS efficiency record high efficiency of 21.26%.

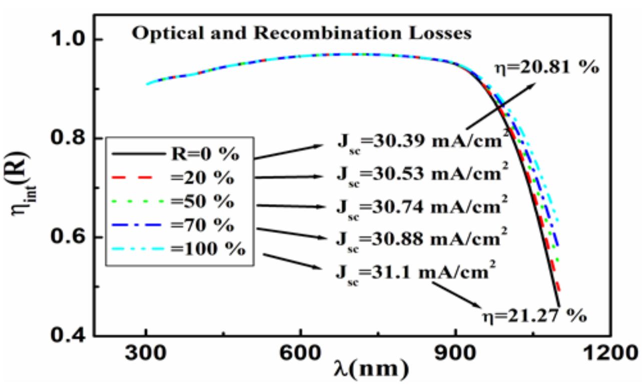

Fig.4: Dependence of spectral internal quantum efficiency on the ratio of reflectivity from metallic back contact and the corresponding values of calculated short circuit-current density considering the optical and recombination losses.

Conclusion

In the present work, the effect of optical losses on the performance of CIGS solar cell with structure ZnO:Al/CdS/CIGS/Mo/Glass have been studied. The quantitative assessment of the optical losses is based on the optical constants of the used materials and of course on its thickness. The thickness of 100 nm of the antireflection coating layer is capable of reduce the optical losses from 23% to 16%. The main part of these loses are due to the absorption losses taking place in ZnO:Al and CdS layers. The 100% reflectivity of back contact can enhance the efficiency of CIGS solar cell by a ratio of 2.3%. The thin-film CIGS solar cell efficiency records high efficiency of 21.27% at the conditions: 100 nm thickness of the antireflection layer, 100% reflectivity from back contact, 1 µm thickness of the absorber layer, 0.3 µm width of the space-charge, 10^6 cm/s of velocity of recombination at front surface, and 10^7 cm/s of velocity of recombination at back surface.

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