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Optimized conditions for the improvement of thin film CdS/CdTe solar cells

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ABSTRACT

Efficient thin film CdS/CdTe solar cell performance requires optimum parameters of each layer of this cell and of the barrier structure. Moreover, the effect of optical losses, recombination losses at front and back surface of CdTe and recombination losses in the space-charge region (SCR) must be considered in order to really analyze the role of these parameters on the performance of these cells. This work is focused on studying theoretically the effect of the thickness of the front contact (ITO), thickness of the window layer (CdS), thickness of the absorber layer (CdTe), width of the space-charge region and electron lifetime on the efficiency of CdS/CdTe solar cells. The reflection losses from interfaces and absorption losses in ITO and CdS, front and rear surface recombination losses of CdTe as well as recombination losses in SCR have been studied. It has been observed that the short-circuit current strongly depends on the thickness of ITO, thickness of CdS, thickness CdTe and electron lifetime. The concentration of uncompensated impurities ($N_a - N_d$) in CdTe, which determines the width of SCR, plays a key role in the generation of photocurrent. The recombination losses in the SCR decrease rapidly with increasing the carrier lifetime in this region and can be ignored at lifetime of 10^{-7} s. The reflectivity from the back contact introduces a small influence in increasing the short-current density particularly at thick absorber layer (5–8 μm). Under the conditions of $N_a - N_d \sim 10^{16}$ cm^{-3}, $\tau_n = 10^{-6}$ s, $d_{CdTe} = 8$ μm, $d_{ITO} = 100$ nm, and $d_{CdS} = 100$ nm, the recombination and optical losses record their minimum ratio of 27%. Most of these losses (24%) are due to the optical losses. The efficiency of CdS/CdTe under these parameters is about 18.2% which is exactly matching with the recent experimental studies. Moreover, an ultrathin CdTe (=1 μm) is sufficient to introduce high efficiency of 16.4%.

1. Introduction

Thin film photovoltaic solar cell has been considered one of the promising solar cells due to its high energy conversion efficiency, low cost and convenience for large scale production. Typically, the efficiencies of thin-film solar cells are lower compared with silicon (wafer-based) solar cells, but manufacturing costs are also lower. The most successful thin film solar cells have been cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si) with efficiencies of 18.3%, 20% and 12.3, respectively[1]. It was reported that [2], CdTe technology costs about 30% less than CIGS technology and 40% less than A-Si technology. The theoretical efficiency of CdS/CdTe solar cells is predicted to be up to 28–30% [3,4].The major impact factors for this difference are due to the optical losses, surface recombination, recombination in the space-charge region and rear contact effect.

There are number of papers theoretically focused on detailed investigation of the dependence of the efficiency of CdS/CdTe thin film solar cells on some properties such as [5–9]: the thickness of front contact layer, thickness of window layer, thickness of absorber layer, the width of the space-charge region and other parameters. Most of the previous work take into account neither all these parameters nor all the above losses.

This work is focused on studying theoretically the effect of the thickness of indium tin oxide (ITO) layer, thickness of CdS layer, thickness of CdTe layer, width of the space-charge region and electron lifetime on the efficiency of CdS/CdTe solar cells. The calculations are carried out on the basis of the optical losses, front surface recombination losses, back surface recombination losses, recombination losses on the space-charge region as well as effect of reflectivity from back contact. The main purpose is to determine the optimum conditions that lead to enhance the performance of CdS/CdTe solar cells.

2. Effect of the thickness of the ITO and CdS layers

The solar cell with structure of glass/ITO/CdS/CdTe/metal has been used in this study. This structure means a part of the incident radiation will be lost due to reflection at the interfaces of glass substrate–ITO, ITO–CdS, and CdS–CdTe. In addition to reflections, absorption in glass

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substrate, ITO and CdS layers takes place before reaching the incident radiation the absorber layer (CdTe). The transmission coefficient, $T(\lambda)$, due to multi-reflections for L number of layers can be calculated from:

$$T_R = 4\frac{n_1 n_2}{(n_1+n_2)^2}\prod_{j=2}^{L-1}\frac{4\dfrac{n_j n_{j+1}}{(n_j+n_{j+1})^2}}{\left(1-\dfrac{(n_j-n_{j-1})^2(n_j-n_{j+1})^2}{(n_j+n_{j-1})^2(n_j+n_{j+1})^2}\right)} \qquad (1)$$

where n_1 and n_2 are the refractive indices of the air and glass, respectively. When the absorption process has taken place in glass, ITO and CdS, Eq. (1) can be written in the form:

$$T(\lambda) = T_R\left(e^{-\alpha_1 d_1}\right)\left(e^{-\alpha_2 d_2}\right) \qquad (2)$$

where α_1, α_2, d_1, and d_2 are the absorption coefficients and thicknesses of ITO and CdS layers, respectively.

The absorption coefficient is calculated from [10]:

$$\alpha(\lambda) = \frac{4\pi}{\lambda}k(\lambda) \qquad (3)$$

where k is the extinction coefficient of used material.

In these calculations, the extinction coefficient of glass substrate is assumed to be equal zero, while its refractive index is calculated using Sellmeier dispersion equation [11]. The extinction coefficient and refractive index data of ITO, CdS and CdTe were taken from Refs. [9, 12] and [13], respectively.

The dependence of transmission spectra on the thickness of the ITO layers is shown in Fig. 1(a). The upper curve in this figure represents the transmission that is calculated by Eq. (1) (i.e. due to reflection only). It can be seen that the transmission is approximately constant over the wavelength range from 300 nm to 850 nm with average value of 92%. The lower curves in this figure represent the transmission that is calculated by Eq. (2) (i.e. after reflection and absorption effects). The calculations have been done for constant thickness 100 nm of the window layer (CdS). It is clear that the absorption process in the ITO and CdS leads to decrease the value of transmission particularly at short wavelength. At wavelength 550 nm–850 nm, a transmission of about 0.86 is observed for $d_{ITO} = 100$ nm and $d_{CdS} = 100$ nm. With increasing the thickness of ITO, further decrease in the transmission can be observed. Where at $d_{ITO} = 300$ nm, the average value of the transmission is 0.80 in the wavelength range of 550 nm–850 nm. Much more decreasing in the transmission is seen in the wavelength < 500 nm due to the absorption of significant part of the incident light in both ITO and CdS layers. The effect of the thickness of CdS on the transmission spectra is shown in Fig. 1(b). The results from this figure are carried out at fixed thickness of 100 nm of ITO layer. It can be seen that the thickness of CdS is more significant than the thickness of ITO. At wavelength range of 550 nm–850 nm, the average value of transmission is about 0.84 and 0.78 at, $d_{CdS} = 100$ nm and 300 nm, respectively.

The quantitative description of optical losses caused by reflection and absorption can be obtained by calculating the short-circuit current density. The short-circuit current density, J_{sc}, will be calculated for AM1.5 total solar radiation using the Table ISO9845-1:1992 [14]. In general, the J_{sc} is described by the following expression:

$$J_{SC} = q\sum_i T(\lambda)\frac{\phi_i(\lambda_i)}{h\nu_i}\eta_{int}(\lambda_i)\Delta\lambda_i \qquad (4)$$

where $T(\lambda)$ is the optical transmission, Φ_i is the spectral power density ($\mathrm{mWcm^{-2}\,\mu m^{-1}}$), η_{int} is the internal quantum efficiency ($\eta_{int} = 1$ in this case) and $\Delta\lambda_i$ is the interval between the two neighboring values λ_i. Fig. 2 shows the calculated short-circuit current density (J_{SC}) for different thicknesses of ITO and CdS. The straight line at value 31.24 mA/cm^2 of J_{SC} indicates the maximum short circuit current density that occurs when all the incident photons will reach the absorber layer ($T = 1$) and all the generated electron–hole pairs will be collected ($\eta_{int} = 1$). The zero thickness in this figure represents the contribution of reflection loss on the value of the short-circuit current. At this point ($d_{ITO} = d_{CdS} = 0$ nm), the recorded value of J_{SC} is 28.86 mA/cm^2. This indicates that the reflection losses from all interfaces are about 7–8%. As the absorption effect in the ITO and CdS layers is taken into account, a significant decrease in the J_{SC} is observed. At $d_{ITO} = d_{CdS} = 100$ nm, the value of J_{SC} is 23.66 mA/cm^2. At $d_{ITO} = 300$ nm and $d_{CdS} = 100$, the value of J_{SC} is 21.77 mA/cm^2. This refers to the optical losses are about 24% and 30% at $d_{ITO} = 100$ nm and $= 300$ nm, respectively. Indicating that the main portion of the optical losses is caused by absorption process that takes place in the ITO and CdS layers. Besides, it is clear that the increasing in the thickness of CdS layer leads to more decrease in the short-circuit current density than the increasing in thickness of the ITO layer. Where at $d_{ITO} = 100$ nm and $d_{CdS} = 300$ nm, the value of J_{SC} is 19.09 mA/cm^2 (optical losses = 39%). These results pay the attention of the researchers to reduce the absorption coefficient of ITO and CdS (particularly CdS) without changing their electrical properties.

3. Effect of the width of the space-charge region and carriers lifetime

In this section, the dependence of spectral quantum efficiency, η, on the width of the space-charge region (SCR) and on the lifetime of minority carrier (electrons) in CdTe layer will be studied. Quantum efficiency of a solar cell always includes the drift and diffusion components, which are obliged to photogeneration of electron–hole pairs in the SCR and in the neutral part of CdTe absorber, respectively. The expression of

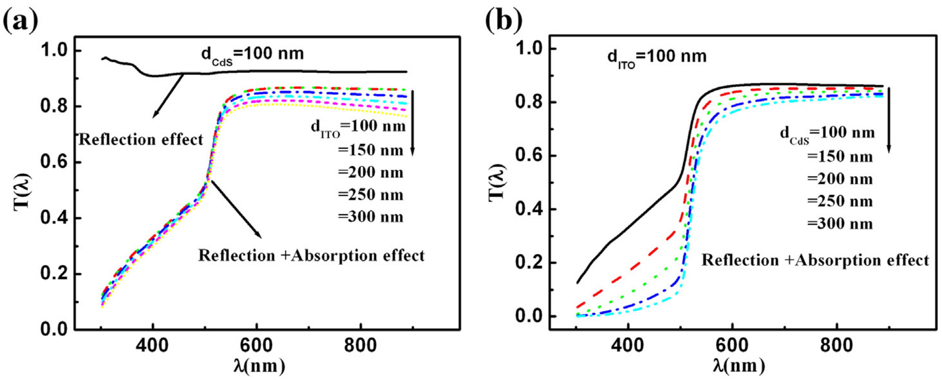

Fig. 1. Transmission (T) of the glass/ITO/CdS structure calculated (a) at 100 nm thickness of CdS and different thicknesses of ITO and (b) at 100 nm thickness of ITO and different thickness of CdS.

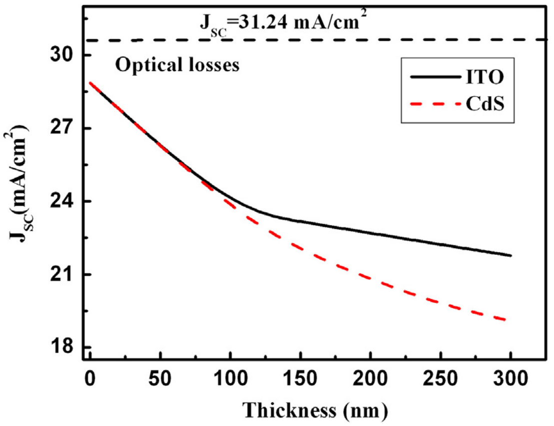

Fig. 2. Effect of the optical losses on the short-circuit current density (J_{SC}) depending on the thickness of ITO and CdS layers.

drift component of the quantum efficiency takes into account the losses due to recombination at the front surface of CdTe. This expression was simplified by Kosyachenko et al. [5] and expressed in the following form:

$$\eta_{drift} = \frac{1+\frac{S}{D_p}\left(\alpha+\frac{2}{W}\frac{\varphi_0-qv}{kT}\right)^{-1}}{1+\frac{S}{D_p}\left(\frac{2}{W}\frac{\varphi_0-qv}{kT}\right)^{-1}} - \exp(-\alpha W) \tag{5}$$

where S is the front surface recombination velocity; ν is the applied voltage; φ_0 is the barrier height; D_p is the diffusion coefficient of holes related to their mobility μ_p by the Einstein relation $qD_p/kT = \mu_p$; W is the width of the space charge region; α is the absorption coefficient of CdTe at a given wavelength, q is the electron charge, k is the Boltzmann constant and T is room temperate.

The width, W, of the space-charge region (depletion layer) as a function of the concentration of uncompensated acceptors ($N_a - N_d$) is given by:

$$W = \sqrt{\frac{2\varepsilon\varepsilon_0(\varphi_0-qv)}{q^2(N_a-N_d)}} \tag{6}$$

where ε is the relative permittivity of the semiconductor and ε_0 is the permittivity of free space.

For the diffusion component of the photoelectric quantum yield that takes into account the surface recombination at the rear surface of the CdTe layer, we can use the exact expression obtained for the p-layer in a solar cell with a p–n junction [15]:

$$\eta_{dif} = \frac{\alpha L_n}{\alpha^2 L_n^2-1}\exp(-\alpha W) \times \left\{ \alpha L_n - \frac{\frac{S_b L_n}{D_n}\left[\cosh\left(\frac{d-W}{L_n}\right) - \exp(-\alpha(d-W))\right] + \sinh\left(\frac{d-W}{L_n}\right) + \alpha L_n \exp(-\alpha(d-W))}{\frac{S_b L_n}{D_n}\sinh\left(\frac{d-W}{L_n}\right) + \cosh\left(\frac{d-W}{Ln}\right)} \right\} \tag{7}$$

where $L_n = (\tau_n D_n)^{1/2}$ is the electron diffusion length; D_n is the electron diffusion coefficient; τ_n is the electron lifetime; S_b is the velocity of recombination at the rear surface of the CdTe layer and d is the thickness of the CdTe layer.

The quantum efficiency η_{int}, appearing in Eq. (4) is the sum of the two components (drift and diffusion) of quantum efficiency. The appearance of W in both drift quantum efficiency and diffusion quantum efficiency reflects the role of the space-charge region width on the generation photocurrent. Using Eqs. (4)–(7) and by varying the lifetime of carriers and the concentration of uncompensated impurities, a description of the quantum efficiency and hence the drift and diffusion components of the short-circuit current density of CdS/CdTe solar cell can be done.

Fig. 3 shows the computed internal quantum efficiency illustrating the effect of concentration of uncompensated impurities (width of SCR). In these calculations ε is taken as 10.6, $D_n = 25$ cm^2/s, $D_p = 2$ cm^2/s and $\varphi_0 - qv = 1$ eV [16]. Besides, it is assumed that the values of the front and back velocity of recombination are equal to 10^7 cm/s and the thickness of CdTe layer (which is included in calculation of η_{dif}) equals 5 μm. It can be seen from Fig. 3(a) that, as the $N_a - N_d$ varies, the shape and behavior of η_{int} undergo significant changes. It is clear that with decreasing the concentration of $N_a - N_d$ from 10^{17} cm^{-3} to 10^{13} cm^{-3}, η_{int} increases first and then decreases. The increase of the internal quantum efficiency is due to increasing the width of the space-charge region up to the width that becomes sufficient to collect the photgenerated carriers ($N_a - N_d = 10^{15}$–10^{16} cm^{-3} or $W < 1$ μm). As the width of SCR increases more than this limit, the electric field becomes weaker than the surface recombination takes place particularly at short lifetime. As the lifetime increases from 10^{-9} s to 10^{-6} s as shown in Fig. 3(b), the carrier lifetime has not practically any influence on the spectral curves of quantum efficiency in the wavelength range $\lambda < 500$ nm. This is because in this spectral range, the penetration depth of photons, α^{-1}, ($\alpha > 10^5$ cm^{-1}) is equal to or even smaller than the width of the space-charge region, W. Besides, the values of η_{int} at $\lambda > 500$ nm increase due to the recombination losses that become less effective.

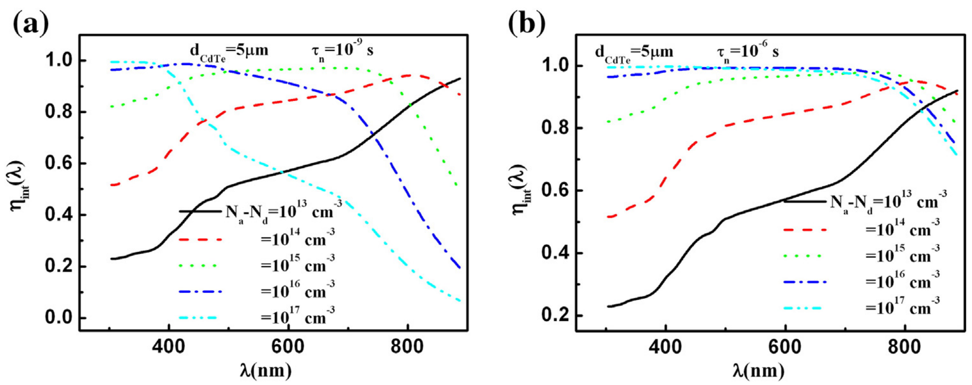

Fig. 3. Internal quantum efficiency spectra (η_{int}) at thickness 5 μm of CdTe for different concentrations of uncompensated impurities $N_a - N_d$ (a) at electron life time of 10^{-9} s and (b) 10^{-6} s.

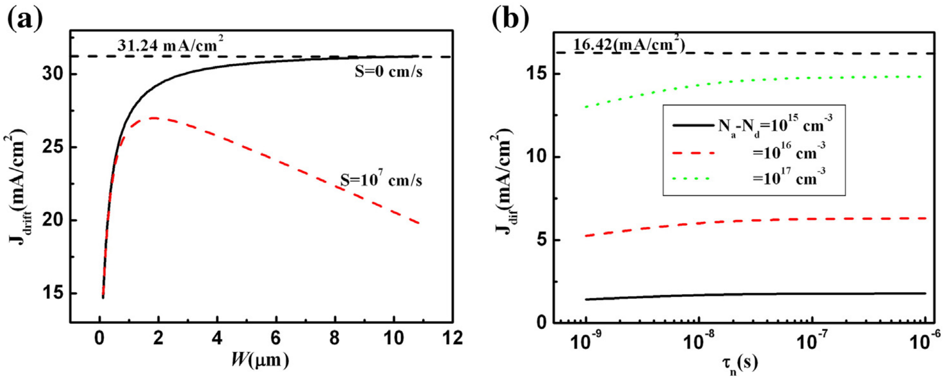

Fig. 4. (a) Drift component of the short-circuit current density (J_{drift}) for the surface recombination velocities $S = 10^7$ cm/s and $S = 0$ and (b) diffusion component of the short-circuit current density (J_{dif}) as a function of the electron lifetime (τ_{n}) for different concentrations of uncompensated impurities $N_{\mathrm{a}} - N_{\mathrm{d}}$.

In order to estimate the contribution of the front recombination losses and back recombination losses, the short-circuit current density is calculated from Eq. (4) using the drift (Eq. (5)) and diffusion (Eq. (7)) components of the quantum efficiency. The results are plotted in Fig. 4. The variation of J_{drift} with the width of the space-charge region, W, at $S = 0$ cm/s and $S = 10^7$ cm/s is shown in Fig. 4(a). At $S = 0$ cm/s, J_{drift} gradually increases with increasing the width, W, and attains its maximum value of 31.24 mA/cm^2 at 10 μm thickness of the space-charge region. The maximum value of the drift current is obtained from Eq. (4) using $T = 1$ and $\eta_{\mathrm{int}}=\eta_{\mathrm{drift}}$. It is assumed that all the incident photons will reach the absorber layer without any optical losses. Such result is expected because the surface recombination is absent in this case and all the photogenerated carriers contribute in increasing the current. At $S = 10^7$ cm/s, J_{drift} increases with increasing W and reaches a maximum value of 27.7 mA/cm^2 at width of about 1 μm. This indicates that the front surface recombination is about 11%. With further increase in the width of SCR up to 10 μm, the electric field becomes weaker and the front surface recombination losses become stronger where the contribution of these losses is about 34%.

According to Eqs. (4), (6) and (7), it is clear that J_{dif} is dependent on the width of the space-charge region, thickness of absorber layer and carrier lifetime. Fig. 4(b) shows the variation of J_{dif} with lifetimes at different concentrations of $N_{\mathrm{a}} - N_{\mathrm{d}}$ at absorber thickness of 5 μm. The maximum J_{dif} of 16.42 mA/cm^2 is obtained at $S_{\mathrm{b}} = 0$ and $d_{\mathrm{CdTe}} =$ 5 μm. It is clear that the variation of $N_{\mathrm{a}} - N_{\mathrm{d}}$ is more significant on the values of J_{dif} than the variation of carriers lifetime. At $\tau_{\mathrm{n}} = 10^{-9}$ s, J_{dif} values are 1.42 mA/cm^2 and 13.02 mA/cm^2 at $N_{\mathrm{a}} - N_{\mathrm{d}} = 10^{15}$ cm^{-3} and 10^{17} cm^{-3}, respectively. As the electron lifetime increases to 10^{-6} s, a small increase in J_{dif} is observed where its values are 1.78 mA/cm^2 and 14.82 mA/cm^2 at $N_{\mathrm{a}} - N_{\mathrm{d}} = 10^{15}$ cm^{-3} and 10^{17} cm^{-3}, respectively. It is known that the diffusion component of the quantum efficiency is obliged to photogeneration of electron–hole pairs in the neutral part of CdTe. And the width of this part is $d - W$, where d is the thickness of CdTe layer. With increasing the width of neutral part of CdTe width, the diffusion component of quantum efficiency and hence the diffusion component of the current increase. This width can be increased with decreasing the width of SCR (W) as implied in this case and/or increasing the thickness of the absorber layer as will be discussed in the next section. This explains the increasing of J_{dif} with increasing the $N_{\mathrm{a}} - N_{\mathrm{d}}$ (decreasing W) and explains the low value of J_{dif} at small concentration of $N_{\mathrm{a}} - N_{\mathrm{d}}$. On the other hand, increasing the electron lifetime leads to increase the electron diffusion length then the diffusion component of the current will be increased. The minimum back surface recombination losses of about 9% are observed at $d_{\mathrm{CdTe}} = 5$ μm, $\tau_{\mathrm{n}} = 10^{-6}$ s and $N_{\mathrm{a}} - N_{\mathrm{d}} = 10^{17}$ cm^{-3}, while the maximum losses are ~20% at $d_{\mathrm{CdTe}} = 5$ μm, $\tau_{\mathrm{n}} = 10^{-9}$ s and $N_{\mathrm{a}} - N_{\mathrm{d}} = 10^{17}$ cm^{-3}. It is clear that the values of $N_{\mathrm{a}} - N_{\mathrm{d}} =$ 10^{17} cm^{-3} and $\tau_{\mathrm{n}} = 10^{-6}$ s give the maximum value of the diffusion component of the current. It is expected that these losses will decrease with increasing the thickness of absorber layer.

4. Effect of the thickness of CdTe

In addition to the effect of thickness of ITO and CdS on the short-circuit current density, thickness of the absorber layer, CdTe, will be investigated in this section. As seen from the above section the thickness of the absorber layer may have a significant role on the values of the internal quantum efficiency (particularly its diffusion component) and hence on the short-circuit current density (particularly its diffusion component). The dependence of J_{dif} on the thickness of the CdTe layer (d_{CdTe}) is shown in Fig. 5. The calculations are carried out at different values of electron lifetime and at the narrowest width of the space-charge region ($N_{\mathrm{a}} - N_{\mathrm{d}} = 10^{17}$ cm^{-3}). It can be seen that J_{dif} increases with increasing the d_{CdTe}. At $\tau_{\mathrm{n}} = 10^{-6}$ s, the value of J_{dif} is 14.82 mA/cm^2 for $d_{\mathrm{CdTe}} = 5$ μm and reaches its maximum value of 16.31 mA/cm^2 at $d_{\mathrm{CdTe}} = 20$ μm and $\tau_{\mathrm{n}} = 10^{-6}$ s. This indicates that the value of the back surface recombination losses is less than 1% at thick absorber layer. It can be concluded that the thickness of absorber layer of 5 μm is sufficient to absorb more than 90% of the incident photons, while in the range from 15 μm to 20 μm, the absorber layer has an ability to absorb most of the incident photons (>99%).

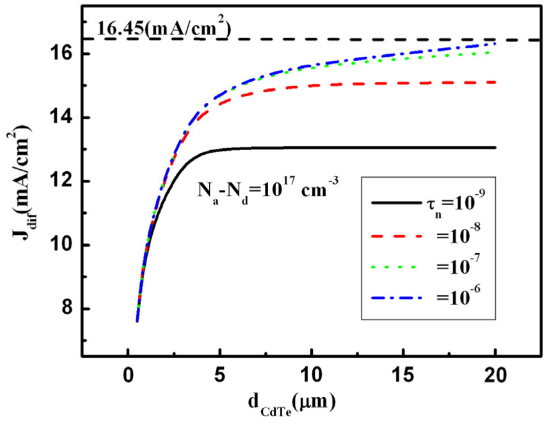

Fig. 5. Dependence of diffusion component of the short-circuit current density (J_{dif}) on the thickness of CdTe layer (d_{CdTe}) at different values of electron lifetime and at $N_{\mathrm{a}} - N_{\mathrm{d}} =$ 10^{17} cm^{-3}.

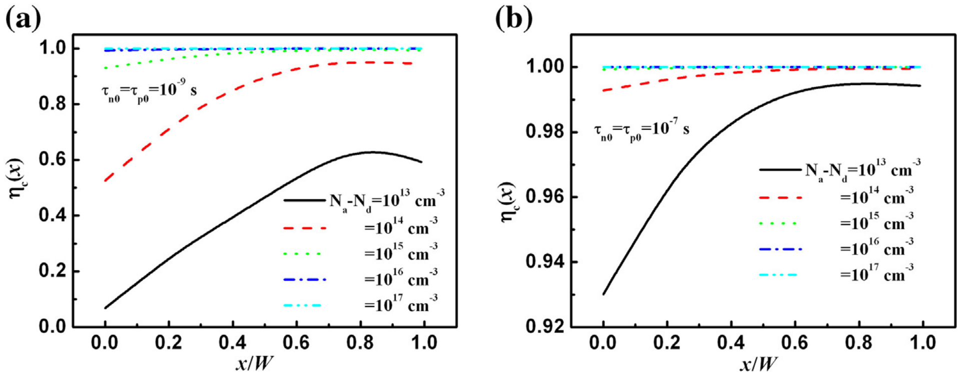

Fig. 6. The coordinate dependences of the charge-collection efficiency (η_c) calculated for different concentrations of uncompensated acceptors ($N_a - N_d$) (a) at electron (τ_{n0}) and hole (τ_{p0}) lifetime = 10^{-9} s and (b) 10^{-7} s.

5. Effect of the back contact and recombination losses in SCR

The recombination losses in the space-charge region (SCR) can be studied, using the Hecht equation [17]:

$$\eta_H = \frac{\mu_p F(x,W)\tau_{p0}}{W}\left[1-\exp\left(-\frac{W-x}{\mu_p F(x,W)\tau_{p0}}\right)\right] + \frac{\mu_n F(0,x)\tau_{n0}}{W}\left[1-\exp\left(-\frac{x}{\mu_n F(0,x)\tau_{n0}}\right)\right] \quad (8)$$

where x is the coordinate s (x is measured from the CdS/CdTe interface), and τ_{n0} and τ_{p0} are the lifetimes of electrons and holes in the SCR, respectively. τ_{n0} and τ_{p0} are related to the electron mobility μ_n and hole mobility μ_p according to the following equation:

$$\lambda_n = \mu_n F\tau_{n0} \quad (9)$$

$$\lambda_p = \mu_p F\tau_{p0} \quad (10)$$

where F is the strength of electric field.

In a Schottky diode, the electric field is not uniform in the space-charge region, but consideration of the uniformity is simplified since the field strength decreases linearly with the x coordinate. In this case, the field strength F in the expressions (9) and (10) for λ_n and λ_p can be replaced by the average values of F in the sections $(0, x)$ and (x, W) for electrons and holes, respectively [7]:

$$F(0,x) = \frac{\Phi_0 - ev}{eW}\left(2-\frac{x}{W}\right) \quad (11)$$

$$F(x,W) = \frac{\Phi_0 - ev}{eW}\left(1-\frac{x}{W}\right). \quad (12)$$

Then the charge collection efficiency in the SCR is determined by:

$$\eta_c = \int_0^W \eta_H(x)\alpha\exp(-\alpha x)dx. \quad (13)$$

In this regard, the short-circuit current density can be calculated from:

$$J_{SC} = q\sum_i T(\lambda)\frac{\phi_i(\lambda_i)}{h\nu_i}\eta_c(\lambda_i)\Delta\lambda_i. \quad (14)$$

Fig. 6 shows the charge collection efficiency (η_c) for different values of $N_a - N_d$ and for electron lifetimes of 10^{-9} s and 10^{-7} s. It is clear that η_c increases with increasing the coordinate x. The value of η_c approaches the unit at $x = W$ and at high concentrations of $N_a - N_d$ (narrow W) as shown in Fig. 6(a). This is because the recombination in such narrow SCR does not occur. With increasing the lifetime from 10^{-9} s to 10^{-7} s as shown in Fig. 6(b), all curves are increased. Thus, the recombination losses in the SCR decrease rapidly with increasing the lifetime of charge carriers. Using Eq. (14), the short-circuit current density due to recombination losses in SCR has been calculated. At $\tau_{n0} = \tau_{p0} = 10^{-9}$ s and $N_a - N_d = 10^{17}$ cm^{-3}, the value of J_{SC} (31.22 mA/cm^2) is so closed to the maximum value of the current density. In this case the recombination loss in SCR is less than 1%. With decreasing the concentration $N_a - N_d$, a considerable decrease in J_{SC} can be observed. At

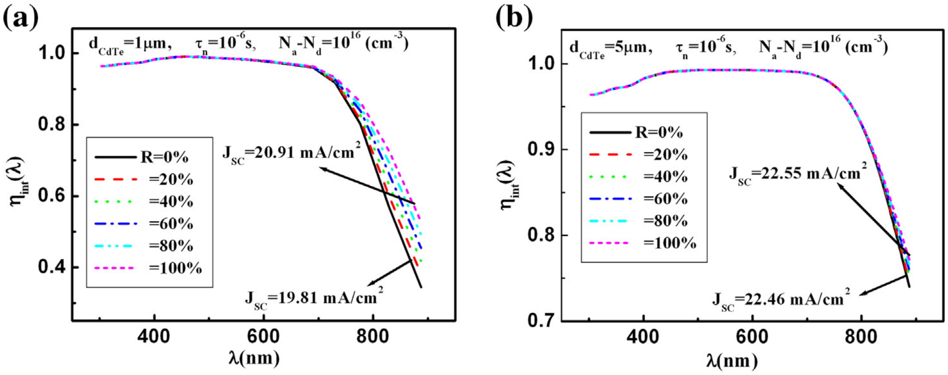

Fig. 7. Internal quantum efficiency spectra (η_{int}) at different ratios of the reflectivity (R%) from the metallic back contact at electron lifetime (τ_{n0}) = 10^{-6} s, concentration of uncompensated acceptors ($N_a - N_d$) = 10^{16} cm^{-3} and at absorber layer thickness (d_{CdTe}) of (a) 1 μm and (b) 5 μm.

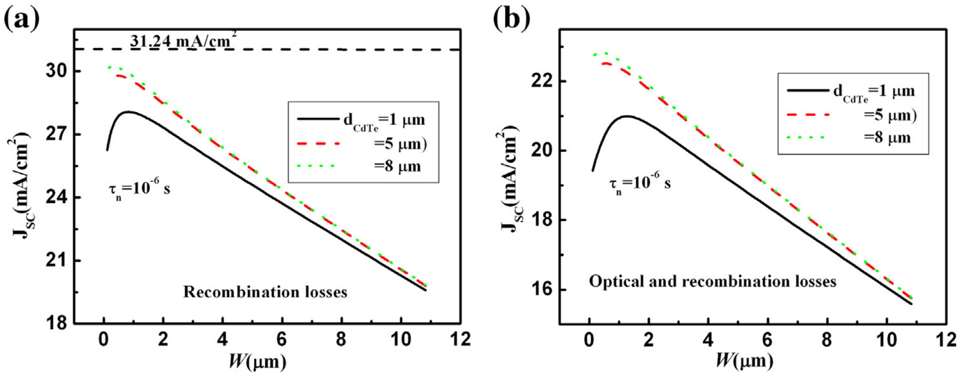

Fig. 8. Short-circuit current density (J_{SC}) as a function of the width of the space-charge region (W) at electron lifetime of 10^{-6} s and at different thicknesses of the absorber layer depending on (a) the recombination losses and (b) optical and recombination losses.

$\tau_{n0} = \tau_{p0} = 10^{-9}$ s and $N_a - N_d = 10^{15}$ cm^{-3}, the value of J_{SC} is 30.27 mA/cm^2, referring that the recombination losses in SCR are about 3%. With increasing the values of carrier lifetime up to 10^{-6} s, the recombination losses in SCR can be ignored.

The effect of the reflectivity from the metallic back contact may reflect a significant impact to enhance the absorptivity in the absorber layer and then increase the photogenerated carriers particularly in a solar cell with a mirror back surface of the CdTe layer. The following formula [18] can be used to measure theoretically the effect of reflectivity from the back contact on the internal quantum efficiency:

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

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

The calculated spectral internal quantum efficiency, η_{int}, as a function of the ratio of reflectivity from back contact of CdS/CdTe solar cell is shown in Fig. 7. The obtained results are carried out at $N_a - N_d = 10^{16}$ cm^{-3} and $\tau_n = 10^{-6}$ s. At thin thickness of the absorber layer of 1 μm, it is observed a small variation on the shape of η_{int} at long wavelength as shown in Fig. 7(a). When the reflectivity from the back contact increases from 0% to 100%, the recorded J_{SC} is 19.81 mA/cm^2 and 20.91 mA/cm^2, respectively. This indicates that the 100% reflectivity of back contact leads to increase the short-circuit current density by 5–6% at $d_{CdTe} = 1$ μm. Note that these values of J_{SC} are carried out on the basis of reflection losses from all interfaces, absorption losses in ITO and CdS as well as recombination losses (front and back). As the thickness of absorber layer is increased to 5 μm as shown in Fig. 7(b), the reflectivity from back contact has too small effect on the shape and values of η_{int}. In this case, J_{SC} increases only by a ratio 0.4%.

6. Optimum parameters for high efficiency CdS/CdTe

In order to estimate the optimum parameters of each layer in CdS/CdTe solar cell to enhance the performance of these cells, the dependence of short-circuit current on the thickness of ITO, thickness of CdS, thickness of CdTe, width of SCR and electron lifetime must be studied. Fig. 8 shows the dependence of J_{SC} on the width of the space-charge region at electron lifetime of 10^{-6} s for different values of CdTe thickness. The results are carried out based on the optical and recombination losses. It is assumed that the carrier lifetime in SCR is about 10^{-7} s, in this regard, the recombination in SCR is neglected. Besides, the back contact is totally reflected (100%) (i.e. the Eq. (15) is used in calculating J_{SC}). It can be seen in Fig. 8(a), J_{SC} decreases with increasing the width of SCR. However, J_{SC} increases with increasing the thickness of absorber layer. The maximum value of J_{SC} is about 30.29 mA/cm^2, which is achieved at $N_a - N_d = 10^{16}$–10^{17} cm^{-3}, $\tau_n = 10^{-6}$ s and $d_{CdTe} = 8$ μm. This refers that the recombination losses under these considerations are very small and its value is about 3%. As the optical losses are taken into account as shown in Fig. 8(b), the short-circuit current density represents the same shape that is obtained in Fig. 8(a) with relatively low values. Where, the maximum J_{SC} is about 22.89 mA/cm^2 is recorded under the above conditions (note the thickness of both ITO and CdS are 100 nm). In this case the optical and recombination losses are about 27%, which confirm the results in Fig. 2.

Solar cells were characterized by current–voltage (J–V) relations in dark and under illumination. In most papers, the analytical description of J–V characteristics has been done using a semi-empirical formula for the dark current density in the so-called “ideal” solar cell which is described by the Shockley equation:

$$J_d(V) = J_S\left[\exp\left(\frac{qV}{kT}\right) - 1\right] \tag{16}$$

where J_s is the saturation current density equals the reverse current independent on the voltage V as qV is higher than a few kT. In this work, the dark current $J_d(V)$ of efficient thin-film CdS/CdTe cells is quantitatively described in terms of the Sah–Noyce–Shockley theory of generation–recombination in the space-charge region of the heterostructure. More details of calculation $J_d(V)$ can be found elsewhere [19–21].

The J–V characteristic under illumination of CdS/CdTe solar cells can be presented as:

$$J(V) = J_d - J_{ph} \tag{17}$$

where J_{ph} is the photocurrent density. The typical J–V characteristic curves for CdS/CdTe solar cell at $N_a - N_d = 10^{16}$ cm^{-3}, $\tau_n = 10^{-6}$ s for different thicknesses of CdTe are shown in Fig. 9. The results are

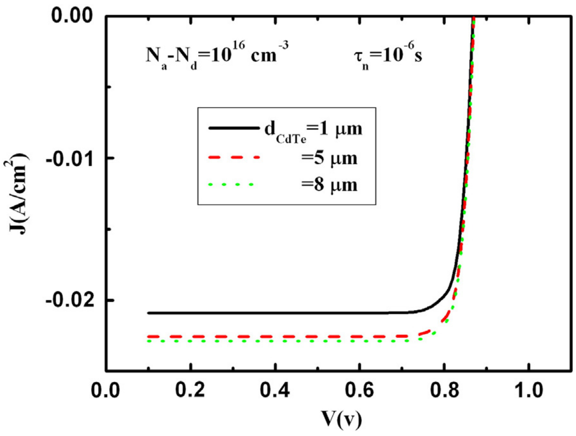

Fig. 9. J–V characteristics of CdS/CdTe heterojunction under AM1.5 solar irradiation, calculated for $N_a - N_d = 10^{16}$ cm^{-3}, electron lifetime (τ_n) = 10^{-6} s and at different thicknesses of CdTe.

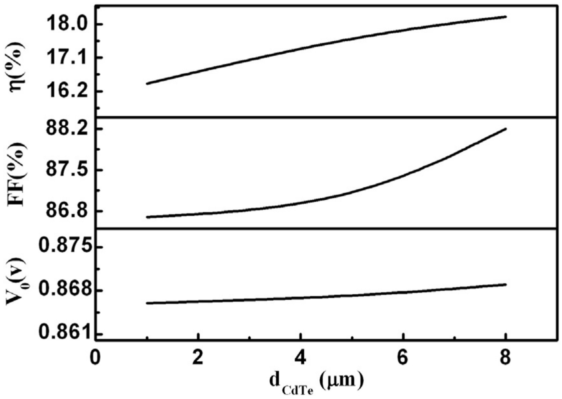

Fig. 10. Dependence the open-circuit voltage (V_0), fill factor (*FF*) and efficiency (η) of CdS/CdTe solar cell on the thickness of CdTe (d_{CdTe}).

carried out under the illumination condition of AM1.5 solar irradiation. It is clear that the curves are shifted down with increasing the thickness of CdTe layer.

The open-circuit voltage (V_0), fill factor (*FF*) and the efficiency (η) are estimated from Fig. 9 and plotted in Fig. 10 as a function of CdTe thickness. It can be seen that the thickness of CdTe has no significant effect on the value of open-circuit voltage (V_0) where its values are 0.866 V, 0.867 V and 0.869 V for d_{CdTe} of 1 μm, 5 μm and 8 μm, respectively. The fill factor (*FF*) is calculated from $FF = V_m J_m / J_{SC} V_0$, where V_m and J_m are the maximum voltage and maximum current. It is found that *FF* increases from 86.7% for $d_{CdTe} = 1$ μm to 88.2% for $d_{CdTe} = 8$ μm. The efficiency of CdS/CdTe solar cell is calculated using the relation $\eta = V_m J_m / P_{in}$, where P_{in} is the density of the total AM 1.5 solar radiation power (equals 96.3 mW/cm^2 [16]). The efficiency at $d_{CdTe} = 1$ μm represents a value of 16.4% indicating the ultrathin absorber layer under the conditions of $N_a - N_d = 10^{16}$ cm^{-3}, $\tau_n = 10^{-6}$ s, $d_{ITO} = 100$ nm, $d_{CdS} = 100$, and 100% reflectivity from back contact, is sufficient to introduce this high efficiency. With increasing the thickness of CdTe, the efficiency increases and reaches the maximum value of 18.2% at $d_{CdTe} = 8$ μm. These results agree with the recent experimental results [1].

7. Conclusions

The effects of the thickness of front contact layer (ITO), thickness of window layer (CdS), thickness of absorber layer (CdTe), width of the space-charge region (SCR) and carrier lifetime on the performance of CdS/CdTe solar cells are studied in this work. The results are carried out on the basis of the reflection losses from interfaces, absorption losses in ITO and CdS, front surface recombination losses of CdTe, back surface recombination losses of CdTe as well as recombination losses in SCR. Moreover, the reflectivity from the metallic back contact is also considered. The results showed that the thickness of CdS introduces more significant changes than the thickness of ITO in the values of short-circuit current density. The optical losses caused by reflection and absorption affect strongly in decreasing J_{SC} by a ratio of 24%, while the front and back recombination losses do not exceed 3% at $N_a - N_d = 10^{15}$–10^{16} cm^{-3}, $\tau_n = 10^{-6}$ s and $d_{CdTe} = 8$ μm. As the lifetime of carriers in SCR is longer than 10^{-7} s, the recombination losses in SCR are neglected. As a thickness of the absorber layer >5 μm, the contribution of the metallic back contact to reflect the photons is very small. The ultrathin absorber layer of 1 μm thickness gives high efficiency of 16.4%. The maximum efficiency of 18.2%, maximum fill factor of 88.2%, maximum J_{SC} of 22.89 mA/cm^2 and maximum open-circuit voltage of 0.869 V are achieved under the conditions of $N_a - N_d = 10^{16}$ cm^{-3}, $\tau_n = 10^{-6}$ s, $d_{ITO} = 100$ nm, $d_{CdS} = 100$, and the reflectivity from back contact is 100%. Finally, it is recommended that reducing the reflection from interfaces and absorption in ITO and CdS without changing the electrical properties of these materials are considered the essential goal to increase the efficiency of CdS/CdTe solar cells.

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