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# Dependence of efficiency of thin-film CdS/CdTe solar cell on optical and recombination losses

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Thin-film CdS/CdTe solar cells fabricated on glass substrates have been considered as one of the most promising candidates for large-scale applications in the field of photovoltaic energy conversion. The recorded experimental efficiency of these cells is about 16%–17% and the corresponding theoretical values are more than 28%. The main causes of efficiency loss are due to optical and recombination losses. Most of the theoretical literatures either study the effect of recombination or optical losses on the CdS/CdTe solar cell efficiency. The present work studies the effect of both the optical and recombination losses on the current density and hence the solar cell efficiency. Calculations of optical losses have been carried out based on the optical constants (refractive index and extinction coefficient) of materials used and the thickness of ITO and CdS layers. Calculation of recombination losses has been based on the values of width of space-charge region and the absorption coefficient for CdTe. It has been found that the reflection losses of the interfaces air-glass, glass-ITO, ITO-CdS, and CdS-CdTe decrease the short-circuit current ($J_{SC}$) from 31.24 to 28.2 mA/cm$^2$ (9%). The absorption losses in ITO and CdS layers decrease $J_{SC}$ to 22.2 (20%). The recombination losses decrease $J_{SC}$ to 19.7 mA/cm$^2$ (8%). The optical and recombination losses yield efficiency of CdS/CdTe solar cells in the range of 12%–16% at thickness 100 nm of each layer of ITO and CdS. According to these results, there is a good agreement between experimental and theoretical studies and this is the real start to develop the solar cells efficiency in the future studies. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4794201]

## I. INTRODUCTION

CdTe has a direct band gap of 1.5 eV (Ref. 1) at room temperature, which is an ideal match to the solar spectrum for photovoltaic absorber. The function of cadmium sulphide (CdS) is to allow energetic short-wavelength photons to pass to the absorber with minimum absorption loss. The high optical band gap of CdS (2.4 eV (Ref. 1)) assists in this function. The other use of CdS is to provide a junction field for separation of photogenerated minority carriers before recombination.[1] CdS/CdTe based solar cells have been considered as one of the most promising candidates for large-scale applications in the field of photovoltaic energy conversion.[2–4]

The recorded CdS/CdTe cell efficiency remained 16.5% (Ref. 5) for a decade, which was recently reported to be improved to 17.3%.[6] The theoretical studies recorded efficiency of 28%–30% of such type of solar cells.[7,8] It is evident that there is a big difference between the experimental and theoretical values of the efficiency of CdS/CdTe. The main causes of efficiency loss are due to optical, electrical, and recombination losses. Most of these theoretical works are mainly focused on the recombination and electrical losses.[8–10] Recently, Kosyachenko *et al.*[11] studied the effect of optical losses on the efficiency of CdS/CdTe solar cells.

The effect of both optical and recombination losses in CdS/CdTe solar cells is absent in the literature and this is maybe the reason for the big difference between the theoretical and experimental results.

The goal of this paper is to study the effect of both optical (reflection and absorption) and recombination losses in the current density and hence the solar cell efficiency. Calculations of optical losses have been carried out based on the optical constants (refractive index and extinction coefficient) of materials used and the thickness of ITO and CdS layers. Calculations of recombination losses have been based on the values of width of space-charge region and the absorption coefficient for CdTe.

## II. SOLAR CELL STRUCTURE

The typical structure of CdS/CdTe solar cell is shown in Fig. 1. This solar cell is composed of four layers as follows:

1. Transparent conducting oxides layer (ITO), which is called front contact and has some required properties such as: highly transparent (more than 85% in visible region), highly conducting at room temperature (sheet resistance less than 10 Ω/sq), and good adhesion to glass substrate.[12]
2. CdS layer which is the so called window layer. This layer is used as n-type semiconductor. CdS has some required properties such as: relatively high transparency, not too thick to favor the absorption in the CdTe absorber layer, not too thin to avoid the short circuiting, relatively large conductivity to reduce the electrical solar cells losses, and higher photoconductivity to not alter the solar cell spectral response.[13]

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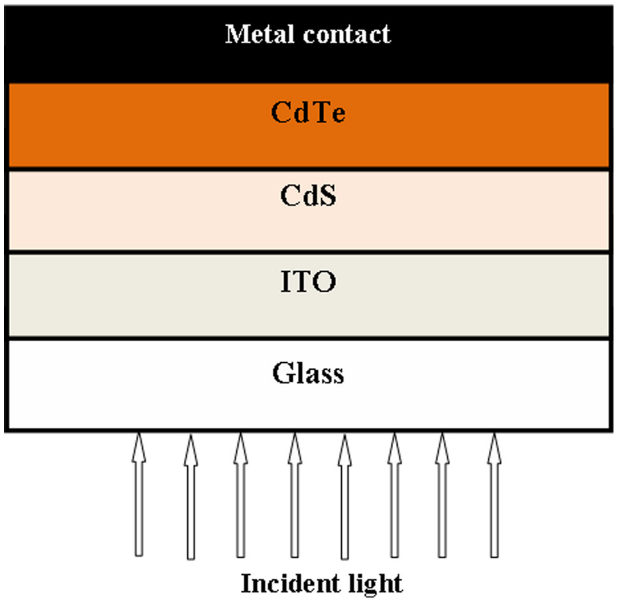


FIG. 1. Schematics of a typical CdS/CdTe solar cell structure.

3. CdTe layer is called the absorber which is made on top of CdS layer and is used as p-type semiconductor. Since CdTe has an ideal band gap energy of ∼1.5 eV and high absorption coefficient ($10^4\,cm^{-1}$),[14] a thin layer of CdTe is sufficient to absorb most of the incoming sunlight.
4. Metal contact layer which is called the back contact and is deposited on top of the CdTe layer. This layer must have high work function (>4.5 eV) to form ohmic contact with CdTe layer and AU has been used in most cases. Besides, Ni-based contacts have also shown promising results.[12]

## III. OPTICAL LOSSES

As shown in Fig. 1, the normal incident light will penetrate glass, ITO, and CdS layers before reaching the active CdTe absorber layer. Through this path, a part of the incident light will be lost in these layers due to reflection from air-glass, glass-ITO, ITO-CdS, and CdS-CdTe interfaces and absorption in glass, ITO, and CdS layers.

As shown in Sec. IV, the reflectivity from the interface between two layers depends on the values of refractive index (n) and extinction coefficient (K) of the contacting materials.

Fig. 2 shows the spectral dependence of refractive index and extinction coefficient of glass, ITO, CdS, and CdTe layers on wavelength. The extinction coefficient ($k$) value of glass substrate was taken as $k = 0$, because the photovoltaic applications often use specialized glass with very low absorption coefficient such as iron glass. The Sellmeier dispersion equation has been applied for calculating the refractive index of glass substrate[15]

$$n^2 = 1 + \frac{a_1\lambda^2}{\lambda^2 - \lambda_1^2} + \frac{a_2\lambda^2}{\lambda^2 - \lambda_2^2} + \frac{a_3\lambda^2}{\lambda^2 - \lambda_3^2}, \tag{1}$$

where $a_1 = 0.6962$, $a_2 = 0.4079$, $a_3 = 0.8974$, $\lambda_1 = 68$ nm, $\lambda_2 = 116$ nm, and $\lambda_3 = 9896$.

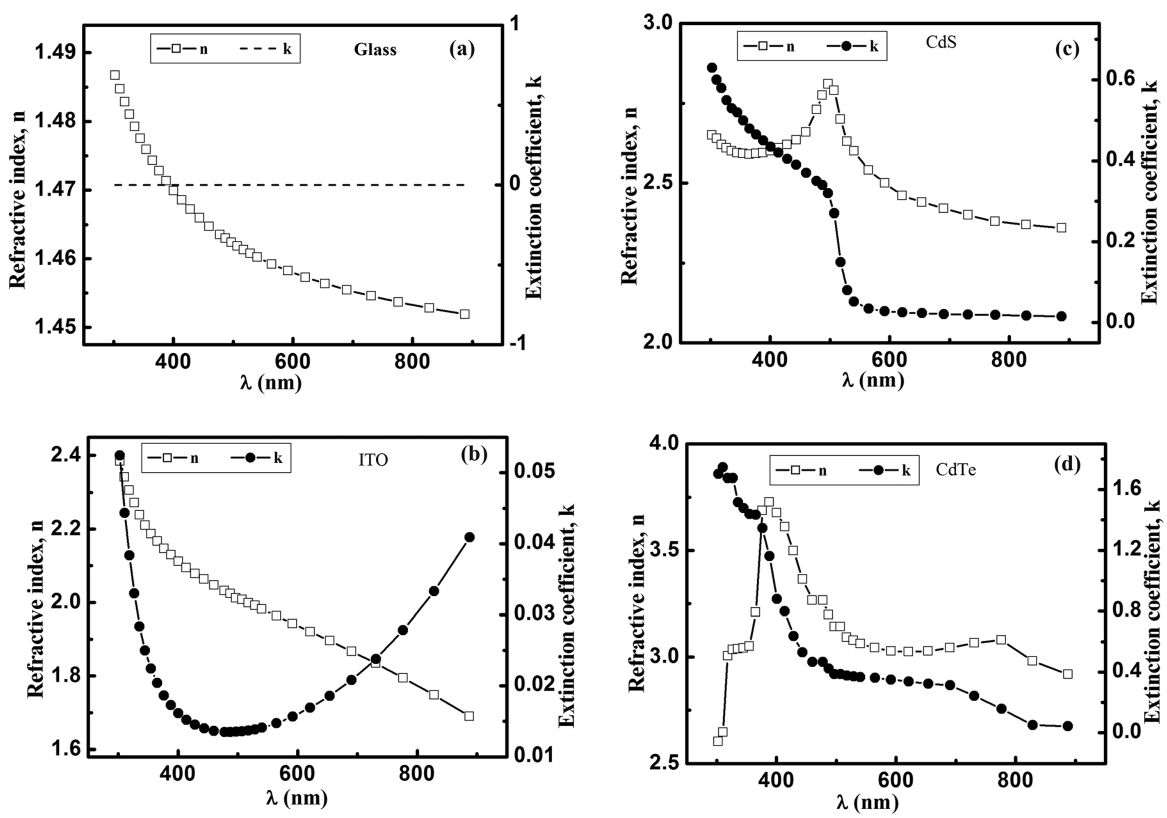


FIG. 2. Spectral dependence of refractive index and extinction coefficient of glass (a), ITO (b), CdS (c), and CdTe (d) layers on wavelength.

The extinction coefficient and refractive index data of ITO, CdS, and CdTe were taken from Refs. 16–18, respectively.

### A. Reflection losses

When one of the ITO, CdS, and CdTe layers is used as a single layer (i.e., the interfaces are between air-ITO, air-CdS, and air-CdTe), the calculated reflection dependence on wavelength has the typical shape as shown in Fig. 3(a). Beside, Fig. 3(b) shows the calculated reflection coefficient from the interfaces between air-glass, glass-ITO, ITO-CdS, and CdS-CdTe as a function of wavelength. In this figure, the reflection from the interface between two contacting materials is determined by Fresnel equation

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2, \tag{2}$$

where $n_1$ and $n_2$ are the refractive index of material one and two, respectively. In the case of electrically conductive materials, the reflection coefficient has the form

$$R = \frac{|n_1^* - n_2^*|^2}{|n_1^* + n_2^{*2}|^2} = \frac{(n_1 - n_2)^2 + (k_1 - k_2)^2}{(n_1 + n_2)^2 + (k_1 + k_2)^2}, \tag{3}$$

where $n_1^*$, $n_2^*$ are the complex refractive index of the two materials, respectively. Comparing Figs. 3(a) and 3(b), it can be noted that the reflection in case of the interface from any layer and air is (25%–35% in case of CdTe-air) greater than the corresponding reflection between any two layers (0.7%–4.5% in case of CdS-CdTe). This low reflection is due to a relatively small difference between the optical constants ($n$, $k$) of contacting materials.

Neglecting the absorption process, the transmission of the normal incident light in each layer is given by $T = 1 - R$. Therefore, the transmission that reaches the absorber CdTe layer due to reflection at all interfaces can be calculated using the formula

$$T(\lambda) = (1 - R_{12})(1 - R_{23})(1 - R_{34})(1 - R_{45}), \tag{4}$$

where $R_{12}$, $R_{23}$, $R_{34}$, and $R_{45}$ are the reflectivity of the interfaces air-glass, glass-ITO, ITO-CdS, and CdS-CdTe, respectively. The top curve in Fig. 4 represents the calculated transmission according to the above equation. It can be noted that the reflection of all interfaces decreases the reached solar radiation to CdTe layer by about 9% in the average wavelength range of 500–850 nm.

### B. Absorption losses

The absorption coefficient $\alpha(\lambda)$ can be calculated using the data of extinction coefficient $k(\lambda)$ according to the following equation:[19]

$$\alpha(\lambda) = \frac{4\pi}{\lambda} k. \tag{5}$$

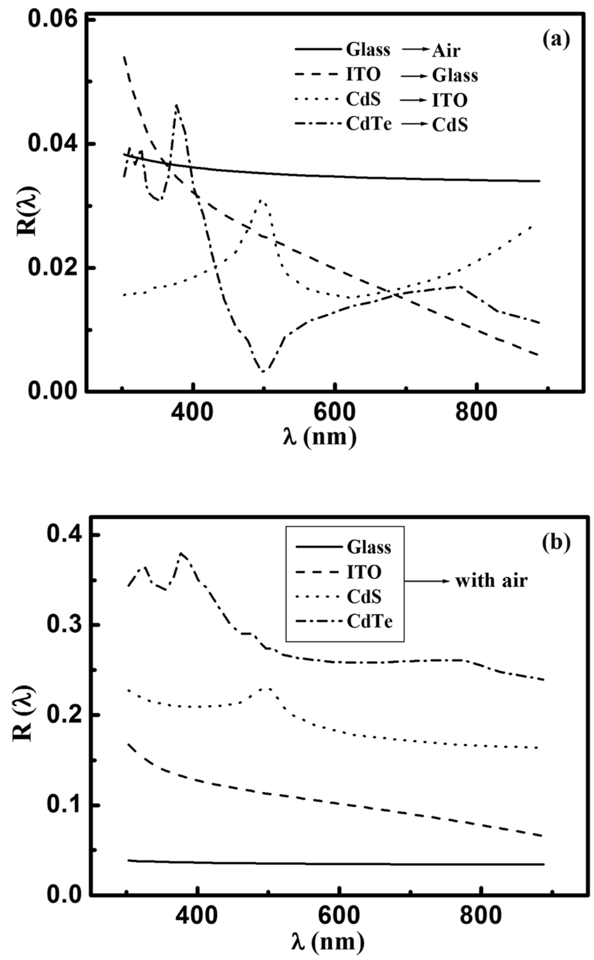


FIG. 3. Reflection coefficient ($R$) as a function of wavelength ($\lambda$) for glass-air, ITO-glass, ITO-CdS, CdS-CdTe (a); and glass-air, ITO-air, CdS-air, CdTe-air (b).

According to the absorption losses in ITO and CdS layers as well as the reflection losses of different interfaces, Eq. (4) can be modified to be written in the form

$$T(\lambda) = (1 - R_{12})(1 - R_{23})(1 - R_{34})(1 - R_{45}) \times (e^{-\alpha_1 d_1})(e^{-\alpha_2 d_2}), \tag{6}$$

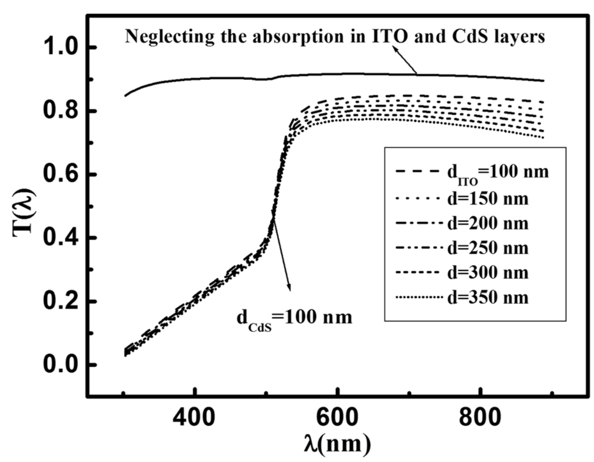


FIG. 4. Calculated transmission (T) as a function of wavelength due to reflection losses (first curve) and reflection and absorption losses at different values of ITO thickness.

where $\alpha_1$, $\alpha_2$, $d_1$, and $d_2$ are the absorption coefficient and thickness of ITO and CdS layers, respectively. Fig. 4 shows the dependence of calculated transmission (from Eq. (6)) on the wavelength at different values of ITO thickness and at 100 nm CdS layer thickness. It can be seen from this figure that the absorption in ITO and CdS layers leads to increase the losses by 18% in the average wavelength range of 500–800 nm at 100 nm thickness of each CdS and ITO layer. With further increase in ITO thickness (150–350 nm) more losses can be observed. Since the maximum losses (26%) are recorded at 350 nm thickness of ITO layer due to absorption. Then, the average of total optical losses is about 35% before the solar radiation reaches the absorber layer, particularly, at higher ITO thickness. It is expected that this loss ratio will increase with increasing the value of CdS thickness because the thick layer leads to more absorption.

## IV. RECOMBINATION LOSSES

One of the main properties of the CdTe layer, which determines the efficiency of photoelectric conversion and used to analyze the losses caused by recombination, is the width $W$ of space-charge region (depletion layer), which mainly depends on the concentration of uncompensated acceptors $N_a - N_d$ (the total concentration of acceptors minus the total concentration of donors). Due to high conduction of CdS, the depletion layer (the space–charge region) of the CdS/CdTe structure is virtually placed in CdTe and band bending also falls onto CdTe.[20,21] Therefore, it can be suggested that electronic processes occur in the CdTe depletion layer similar to those taking place in the depletion layer of the Schottky diode. Then, the space-charge width can be given by[7]

$$W = \sqrt{\frac{2\varepsilon\varepsilon_0(\varphi_0 - qv)}{q^2(N_a - N_d)}}, \quad (7)$$

where $\varepsilon$ is the relative permittivity of the semiconductor, $\varepsilon_0$ is the permittivity of free space, $\varphi_0$ is the barrier height at the semiconductor side, $v$ is the applied voltage, $q$ is the electron charge, and $(N_a - N_d)$ is the concentration of uncompensated acceptors in the CdTe layer. In the present calculation, $(N_a - N_d)$ is taken in the range of $10^{11}$–$10^{17}$ cm$^{-3}$, $\varepsilon$ is taken as 10.6, and $(\varphi_0 - qv)$ is taken as 1 eV.

Once the space-charge width is calculated, the photoelectric quantum yield ($\eta$) of the CdS/CdTe diode structure can be calculated using the following formula:[22]

$$\eta = \frac{1 + \frac{s}{D_P}\left(\alpha + \frac{2}{W}\frac{\varphi_0 - qv}{kT}\right)^{-1}}{1 + \frac{S}{D_P}\left(\frac{2}{W}\frac{\varphi_o - qv}{kT}\right)^{-1}} - \frac{\exp(-\alpha W)}{1 + \alpha L_n}, \quad (8)$$

where $S$ is the recombination velocity at the heterojunction interface, $D_p$ is the diffusion coefficient of holes, $\alpha$ is the absorption coefficient of CdTe at a given wavelength, $k$ is the Boltzmann constant, $L_n = (\tau_n D_n)^{1/2}$ is the electron diffusion length, $\tau_n$ and $D_n$ are the electron lifetime and diffusion coefficient, respectively. It should be noted that Eq. (8) does not take into consideration the recombination at the back surface of the CdTe layer, which can result in significant losses in the case of a thin CdTe layer. Moreover, the second term in Eq. (8) can be ignored at higher absorption region (at low wavelength), and if $S = 0$ (no recombination), thus $\eta = 1$. Therefore, the deviation of $\eta$ from Eq. (1) is caused by surface recombination.

The photoelectric quantum yield spectra ($\eta$) computed by Eq. (8) at different values of concentration of uncompensated acceptors $(N_a - N_d)$ are shown in Fig. 5.

The present calculations of $\eta$ are carried out under the following conditions: $S = 10^7$ cm/s, $\tau_n = 10^9$ s, $D_n = 25$ cm$^2$/s, $D_p = 2$ cm$^2$/s, and $\varphi_0 - qv = 1$ eV. The used absorption coefficient for CdTe in this figure is taken from Ref. 23. It can be observed from the figure that with increasing the wavelength, the photoelectric quantum yield increases and attains its maximum value at the photon energy close to the CdTe bandgap ($\lambda \sim 850$ nm). The value of $\eta$ increases in the case of narrow ablation region $1.083 \times 10^{-4}$ to $1.083 \times 10^{-5}$ cm, which corresponds to $N_a - N_d = 10^{15}$ to $10^{17}$ cm$^{-3}$. It can be concluded from Fig. 5 that the effect of surface recombination becomes strong at lower density of concentration of uncompensated acceptors (wide space-charge region).

## V. SHORT-CIRCUIT CURRENT IN CdS/CdTe

The short-circuit current density $J_{sc}$ is calculated from the following formula:

$$J_{SC} = q\sum_i T(\lambda)\,\frac{\phi_i(\lambda_i)}{h\nu_i}\eta(\lambda_i)\Delta\lambda_i, \quad (9)$$

where $T(\lambda)$ is the optical transmission, $\Phi_i$ is the spectral power density (mW cm$^{-2}$ $\mu$m$^{-1}$), and $\Delta\lambda_i$ is the interval between the two neighboring values $\lambda_i$. The calculation of $J_{SC}$ is carried out for the conditions of AM 1.5 solar radiation using the Standard Tables ISO 9845-1 (1992).[24] In these calculations, the reflection, absorption, and recombination losses are taken into account for barrier height 1 eV.

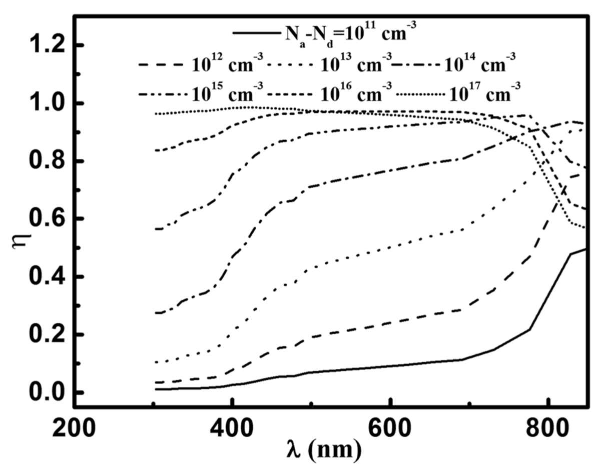


FIG. 5. The computed photoelectric quantum yield spectra ($\eta$) at different values of concentration of uncompensated acceptors $(N_a - N_d)$.

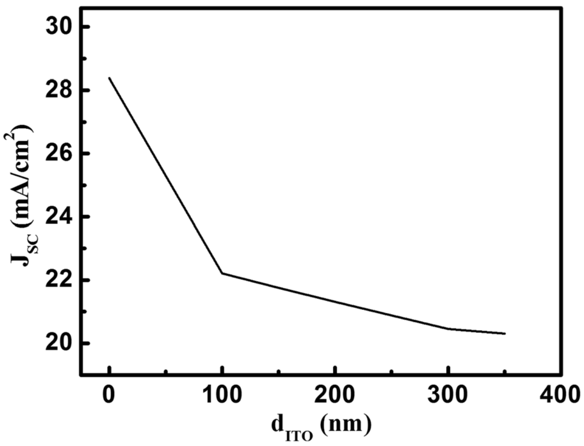


FIG. 6. Short-circuit current density $J_{sc}$ of a CdTe-based solar cell as a function of ITO thickness under the recombination losses.

Fig. 6 shows the short-circuit current density $J_{sc}$ of a CdTe-based solar cell as a function of ITO thickness under the reflection and absorption losses (optical losses). In this case, the photoelectric quantum yield $\eta = 1$ and $d_{CdS} = 100$ nm. The first point (at zero x-axis) represents the effect of reflection losses only ($d_{ITO}$, $d_{CdS} = 0$). At this point, $J_{SC}$ is about 28.38 mA/cm$^2$. Comparing this value with the maximum value $J_{SC}^0 = 31.24$ mA/cm$^2$ ($J_{SC}^0$ is calculated from Eq. (9) at $T(\lambda) = 1$ and $\eta(\lambda) = 1$), it is concluded that the reflection losses of the interfaces air-glass, glass-ITO, ITO-CdS, and CdS-CdTe lead to decrease in the maximum short-current density by 9%. When the absorption losses are taken into account, the calculated $J_{SC}$ decreases with further increase in ITO thickness and records 22.2 and 20.88 mA/cm$^2$ at $d_{ITO} = 100$ and 350 nm, respectively. This indicates that the losses result from absorption ranged from 20% to 24%. Then, the total optical losses are about 29%–33%.

Fig. 7 shows the effect of optical and recombination losses on the short-circuit current density $J_{sc}$ of a CdTe-based solar cell at various values of $N_a - N_d$. It is observed that the current density decreases with increasing the thickness of ITO layer as well as with increasing the width of space-charge region ($W$). At the smallest $W$, the $J_{sc}$ records its maximum value about 19.6 mA/cm$^2$ at $d_{ITO} = 100$ nm. This decrease in current density (22.2 to 19.6 as shown in Fig. 6) is due to the recombination losses, which contribute to decrease in the $J_{sc}$ by about 8%. Then, the total losses that result from optical and recombination reach to about 37% at $d_{ITO} = 100$ nm. And this ratio increases to 43% at $d_{ITO} = 350$ nm as shown from Fig. 7(b). Besides, the recombination losses become stronger at higher values of space-charge region width and record 85%.

## VI. EFFICIENCY

The solar cell efficiency $\eta(\%)$ is calculated using the following equation:[25]

$$\eta(\%) = \frac{V_{OC} J_{SC} FF}{P_{in}}, \tag{10}$$

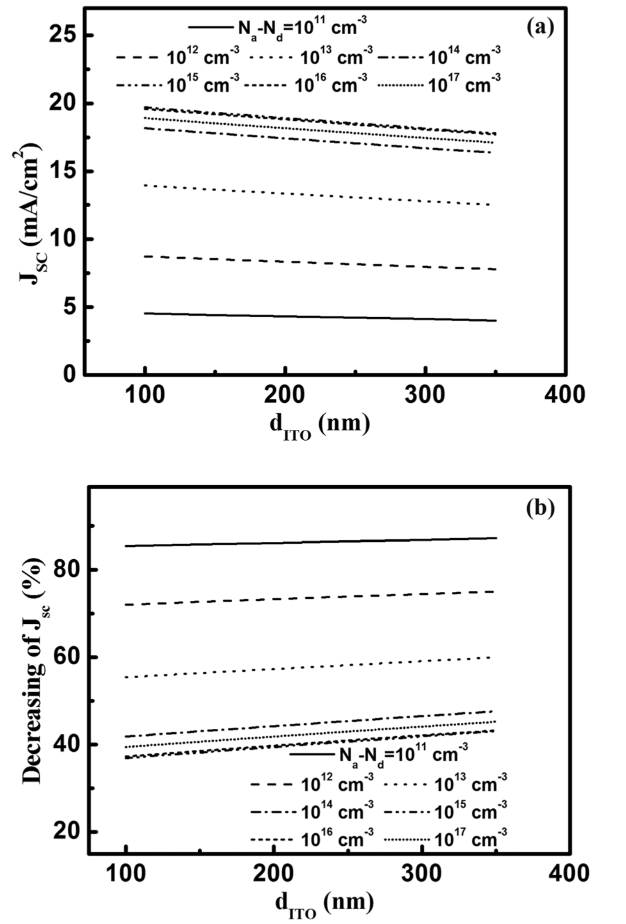


FIG. 7. Short-circuit current density $J_{sc}$ of a CdTe-based solar cell as a function of ITO thickness at various values of $N_a - N_d$ (a); the percentage decreasing of $J_{sc}$ (b).

where $V_{oc}$ is the solar cell open-circuit voltage, $FF$ is the fill factor, and $P_{in}$ is the input power. In these calculations, $V_{oc}$ is assumed to be 845 mV, $FF$ is 75.5%,[12] and $P_{in}$ is 100 mW/cm$^2$ for AM 1.5 global solar radiation. Fig. 8 shows the effect of optical and recombination losses on the efficiency of CdS/CdTe cell as a function of ITO thickness and different values of space-charge width. It is observed that the efficiency is in the range of 12%–16% for lowest width of space-charge

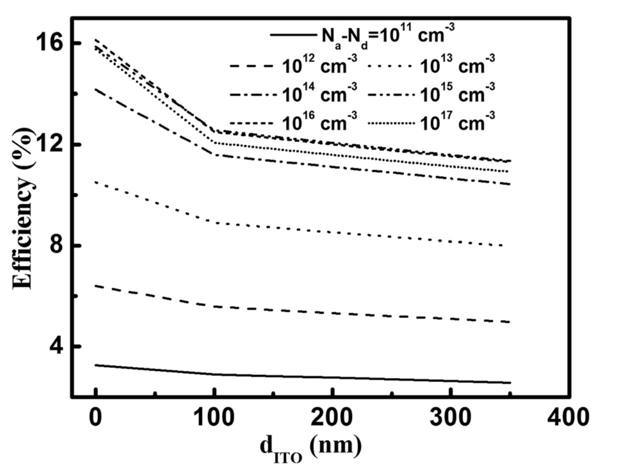


FIG. 8. Effect of the optical and recombination losses on the efficiency of a CdS/CdTe solar cell at various values of $N_a - N_d$.

region, which corresponds to $N_a - N_d = 10^{16}$–$10^{17}\,cm^{-3}$. This result is considered to be in good agreement with other experimental studies.[5,6,26,27] With decreasing the $N_a - N_d$ values, the efficiency decreases dramatically and becomes less than 4% at $N_a - N_d = 10^{11}\,cm^{-3}$.

## VII. CONCLUSIONS

The present work studies the effect of both optical and recombination losses in the calculated short-circuit current density and the efficiency of CdS/CdTe solar cell. It is found that the efficiency of solar cell strongly depends on these losses. It can be concluded that the reflection of all interfaces decreases the reached solar radiation to CdTe layer by about 9%. The absorption process in ITO and CdS layers contributes in increasing the losses by 20%–24%. The recombination losses contribute to decrease $J_{sc}$ by about 8% at the smallest width of space-charge region and $d_{ITO} = 100\,nm$. The effect of surface recombination becomes strong at lower density of concentration of uncompensated acceptors (wide space-charge region) and decreases the short-circuit current density by 85%. Optical and recombination losses yield CdS/CdTe solar cell efficiency in the range of 12%–16% at lowest width of space-charge region, which corresponds to $N_a - N_d = 10^{16}$–$10^{17}\,cm^{-3}$. This ratio of efficiency is in good agreement with other experimental studies. Finally, more studies should be required in the future to decrease the reflection at all interferences and the absorption losses in CdS and transparent conducting oxides (TCO) layers. This maybe based on studying the effect of CdS thickness, roughness of TCO layer, and adding puffer layer between TCO and CdS layers.

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