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Modeling of current–voltage characteristics of CdS/CdTe solar cells

M. S. Anjan and M. Z. Kabir*

Department Electrical and Computer Engineering, Concordia University, 1455 de Maisonneuve West, Montreal, Quebec H3G 1M8, Canada

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* Corresponding author: e-mail kabir@encs.concordia.ca, Phone: +1 514 848 2424, ext: 5688, Fax: +1 514 848 2802

An analytical model is developed to study the current–voltage characteristics of CdS/CdTe thin film solar cells by incorporating exponential photon absorption, carrier trapping, and carrier drift in the CdTe layer. An analytical expression for the external voltage dependent photocurrent is derived by solving the continuity equation for both electrons and holes. The overall load current is calculated considering the actual solar spectrum. It is found that the solar cell efficiency critically depends on the hole transport in the CdTe layer and the recombination current dominates over the ideal diode current. The theoretical model is fitted with the published experimental data and shows a very good agreement.

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1 Introduction The second generation thin film solar cells are increasingly promising for their cheaper production and better efficiency [1]. Polycrystalline cadmium telluride (CdTe) is one of the most potential photoconductors for thin film solar cells because of its excellent efficiency [2]. The CdTe based solar cells have a superstrate device structure of glass/SnO_2/CdS/CdTe/metal [3, 4]. The cell has a n–p heterojunction structure where a very thin layer ($\sim$0.1 to 0.3 μm) of CdS acts as a very highly doped n-layer and CdTe acts as a very lightly doped p-type absorber layer [5]. The thickness of the p-layer is few micrometers. The photons are mainly absorbed in the CdTe layer and the photocarriers are collected by the built-in electric field in this layer. The voltage dependent charge collection in the depleted absorber layer (i.e., CdTe layer) is the dominant charge collection mechanisms in thin film solar cells [4, 6].

There has been an active theoretical and experimental research to improve the performance of these devices. Hegedus et al. reviewed a few theoretical models to describe the current–voltage (J–V) characteristics in CdS/CdTe solar cells [7]. They have shown that the most successful model calculates the photocurrent by considering carrier drift and utilizing Hecht collection efficiency formula in the nearly intrinsic CdTe layer [7]. However, the previous model has made an unrealistic assumption that all the carriers are generated near the n–p interface. The previous model has also used a number of fitting parameters such as maximum photocurrent with complete charge collection, reverse saturation diode current, effective attenuation coefficient, series resistance, and carrier ranges. The incident photons are absorbed exponentially across the CdTe layer. In this paper, we solve the continuity equation for both electrons and holes considering exponential photon absorption, exponential electron–hole pair generation across the CdTe-layer, carrier trapping, and carrier drift in the CdTe layer. We obtain an analytical expression for the external voltage V dependent photocurrent. The overall load current is calculated considering the effect of voltage dependent forward dark current and the actual solar spectrum.

The present model only considers carrier ranges and series resistance as fitting parameters and thus eliminates other fitting parameters such as reverse saturation current and effective attenuation coefficient. We analyze the *current–voltage* characteristics and efficiency with varying the transport properties of the CdTe layer and the operating conditions. The model is verified with the published experimental data. The fitting of the model with the published experimental data considering the actual solar spectrum determines the carrier transport properties (mobility-lifetime product), and the amount of reflection and other losses in CdTe solar cells.

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2 Analytical model The photon absorption in the highly doped CdS layer will contribute a negligible current because of its very short diffusion length and very thin width. The photogenerated electrons and holes are drifted in opposite directions by the built-in electric field in the CdTe layer. Electrons drift towards the radiation-receiving contact (top contact) and holes drift towards the bottom contact. The following assumptions are made to allow the problem to be analytically tractable; (i) The thermal equilibrium concentration of charge carriers is negligibly small because of high bandgap materials, (ii) The CdTe layer is fully depleted and the built-in electric field F is nearly uniform across the CdTe layer because of its lightly doping, (iii) the diffusion of carriers is negligible compared with their drift in the fully depleted CdTe layer, (iv) a constant drift mobility μ and a single lifetime τ' are assigned to each type of carriers (holes and electrons). The voltage dependent electric field near the n–p interface is slightly higher than that near the bottom contact. The photogenerated carriers will drift with a slightly higher velocity near n–p interface compared to that near the bottom contact. Therefore, assuming an average drift velocity of the carriers throughout the CdTe-layer will not make any significant difference in the calculation of charge collection.

Considering the assumptions mentioned above, the steady-state continuity equation for holes is

$$\frac{\partial p}{\partial t} = -\mu_{\mathrm{h}} F \frac{\partial p}{\partial x} - \frac{p}{\tau'_{\mathrm{h}}} + G\mathrm{e}^{-\alpha x} = 0, \tag{1}$$

where $\alpha(\lambda)$ is the absorption coefficient of CdTe, λ is the photon wavelength, x is the depth in the CdTe layer from the n–p interface, G is the carrier generation rate at $x=0$, p is the hole concentration. The subscript h refers to holes. Since the carriers start drifting immediately after generation, $p(x=0)=0$. Therefore, the solution of Eq. (1) is,

$$p(x,\lambda) = \frac{G\tau'_{\mathrm{h}}}{1-\alpha\mu_{\mathrm{h}}F\tau'_{\mathrm{h}}}\left(\mathrm{e}^{-\alpha x} - \mathrm{e}^{\frac{-x}{\mu_{\mathrm{h}}F\tau_{\mathrm{h}}}}\right). \tag{2}$$

The photocurrent density for holes drifting towards the bottom contact is [8, 9]

$$\begin{aligned} j_{\mathrm{h}}(\lambda, V) &= \frac{e\mu_{\mathrm{h}}F}{W}\int_0^W p(x,\lambda)\,\mathrm{d}x \\ &= \frac{eGW}{\left(\tau_{\mathrm{h}}^{-1} - \Delta^{-1}\right)}\left[\Delta\left(1-\mathrm{e}^{-\frac{1}{\Delta}}\right) - \tau_{\mathrm{h}}\left(1-\mathrm{e}^{-\frac{1}{\tau_{\mathrm{h}}}}\right)\right], \end{aligned} \tag{3}$$

where e is the elementary charge, W is the width of the CdTe layer, Δ $(=1/\alpha W)$ is the normalized absorption depth, τ_{h} $(=\mu_{\mathrm{h}}\tau'_{\mathrm{h}}F/W)$ is the normalized carrier lifetime (carrier lifetime per unit transit time) for holes. Since F is voltage dependent τ_{h} is voltage dependent and so does j_{h}.

Similarly, the photocurrent density for electrons drifting towards the top contact is

$$j_{\mathrm{e}}(\lambda, V) = \frac{eGW}{\left(\tau_{\mathrm{e}}^{-1} + \Delta^{-1}\right)}\left[\Delta\left(1-\mathrm{e}^{-\frac{1}{\Delta}}\right) - \tau_{\mathrm{e}}\left(\mathrm{e}^{-\frac{1}{\Delta}} - \mathrm{e}^{-\frac{1}{\Delta}-\frac{1}{\tau_{\mathrm{e}}}}\right)\right], \tag{4}$$

where $\tau_{\mathrm{e}} = \mu_{\mathrm{e}}\tau'_{\mathrm{e}}F/W$. The subscript e refers to electrons. The resultant photocurrent density, $j_L(\lambda, V) = j_{\mathrm{h}}(\lambda, V) + j_{\mathrm{e}}(\lambda, V)$. Therefore, the photocurrent density,

$$\begin{aligned} j_L(\lambda, V) = eGW\Big\{&\left(\tau_{\mathrm{h}}^{-1} - \Delta^{-1}\right)^{-1}\left[\Delta\left(1-\mathrm{e}^{-\frac{1}{\Delta}}\right) - \tau_{\mathrm{h}}\left(1-\mathrm{e}^{-\frac{1}{\tau_{\mathrm{h}}}}\right)\right] \\ &+ \left(\tau_{\mathrm{e}}^{-1} + \Delta^{-1}\right)^{-1}\left[\Delta\left(1-\mathrm{e}^{-\frac{1}{\Delta}}\right) - \tau_{\mathrm{e}}\left(\mathrm{e}^{-\frac{1}{\Delta}} - \mathrm{e}^{-\frac{1}{\Delta}-\frac{1}{\tau_{\mathrm{e}}}}\right)\right]\Big\}. \end{aligned} \tag{5}$$

The electron–hole pair (EHP) generation rate can be written as

$$G(\lambda) = \alpha(\lambda)\mathrm{e}^{-\alpha_1 d}[1-R(\lambda)]\lambda I_0(\lambda)/hc, \tag{6}$$

where α_1 is the absorption coefficient of CdS layer, d is the CdS layer thickness, c is the speed of light, h is the Planck constant, I_0 is the intensity of the solar spectra ($\mathrm{W/cm^2\,nm}$), and R is the total reflection and other loss factor. The other losses include shading from the grid, absorption in the top SnO_2 layer, and incomplete EHP generation in the CdTe layer [4].

The total photogenerated current density is obtained by integrating over all incident photon wavelengths of the solar spectra, i.e.,

$$J_L(V) = \int_0^\infty j_L(\lambda, V)\,\mathrm{d}\lambda. \tag{7}$$

The net current density from a solar cell is

$$J(V) = J_{\mathrm{d}}(V) - J_L(V), \tag{8}$$

where $J_{\mathrm{d}}(V)$ is the forward diode current density. The external voltage dependent electric field is given by [4]

$$F(V) = \frac{V_0 - V_{\mathrm{j}}}{W} = \frac{V_0 - (V - JR_{\mathrm{s}})}{W}, \tag{9}$$

where R_{s} is the effective series resistance including all contact resistances, V_{j} $(=V-JR_{\mathrm{s}})$ is the junction voltage, and V_0 is the flat-band voltage so that $J_L(V)=0$ at $(V-JR_{\mathrm{s}})=V_0$. The flat-band voltage V_0 is slightly higher (typically $\sim$0.1 V) than the open circuit voltage V_{OC}. It is expected that the electric field reduces to zero when the applied junction voltage is equal to the built-in potential V_{bi}. However, it is found that the electric field collapses to zero just beyond V_{OC} and little less than V_{bi} [4, 7]. Therefore, V_0 is considered as a fitting parameter.

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The forward diode current density can be written as

$$J_{\mathrm{d}}(V) = J_0 \exp\left[\frac{e(V - JR_{\mathrm{s}})}{AkT}\right], \tag{10}$$

where J_0 is the reverse saturation current density of the p–n junction, A is the diode ideality factor, k is the Boltzman constant, and T is the absolute temperature. Since the depletion region is thick, the recombination current within CdTe-region should be dominant over ideal diffusion current [3]. Assuming a constant electric field in the depletion region, the reverse saturation current density can be written as [3, 10]

$$J_0 \approx \frac{\pi q n_{\mathrm{i}} W V_t}{2\sqrt{\tau'_{\mathrm{e}}\tau'_{\mathrm{h}}}(V_0 - V + JR_{\mathrm{s}})}, \tag{11}$$

where n_{i} is the intrinsic carrier concentration of CdTe and $V_t = kT/e$.

3 Results and discussions The *J–V* characteristics of the CdS/CdTe solar cells are calculated by iteratively solving Eqs. (5)–(11). The incident photon flux $I_0(\lambda)$ is taken as the air mass (AM) 1.5 global spectrum from the ASTM G-173-03 standard [11]. The absorption coefficients for CdTe and CdS are obtained from the absorption curves in Ref. [5]. The CdS layer thickness may vary from 0.1 to 0.3 μm [5]. The effect of CdS layer thickness on the incident sun spectra at CdTe layer is shown in Fig. 1. Even 0.1 μm thick CdS layer significantly absorbs photons up to 500 nm of wavelength, and thus can reduce the photo current and its overall efficiency.

The theoretical model is verified by fitting with the published experimental data. Figure 2 shows the *J–V* curves of CdS/CdTe solar cells at three sun intensities (100%, 32%, and 10% of 1.5 AM global spectrum). The symbols represent experimental data and the solid lines represent the theoretical fit to the experimental data. The experimental data were extracted from Fig. 2 of Ref. [6]. The CdTe thickness is 1.8 μm. The CdS thickness is assumed as 0.2 μm. The theoretical model shows a very good agreement with the experimental data. The best fit $\mu\tau'$ of holes and electrons are $\mu_{\mathrm{h}}\tau'_{\mathrm{h}} = 10^{-6}\,\mathrm{cm^2/V}$ and $\mu_{\mathrm{e}}\tau'_{\mathrm{e}} = 1.8\times10^{-5}\,\mathrm{cm^2/V}$, which are consistent with the $\mu\tau'$ values in electrodeposited CdTe [12, 13]. The other fitted parameters in Fig. 2 are: $V_0 = 0.8$ V, $A = 1.8$, $R_{\mathrm{s}} = 6\,\Omega\,\mathrm{cm}^2$, and $R = 0.25$. Assuming typical values for electrodeposited CdTe layer, $\mu_{\mathrm{h}} = 5\,\mathrm{cm^2/V\,s}$ [12] and $\mu_{\mathrm{e}} = 180\,\mathrm{cm^2/V\,s}$ [7], the carrier lifetimes become, $\tau'_{\mathrm{h}} = 0.2$ μs and $\tau'_{\mathrm{e}} = 0.1$ μs. Note that the previous model failed to distinguish the electron and hole transport properties and thus mentioned an effective mobility-lifetime product of $8.4\times10^{-7}\,\mathrm{cm^2/V}$ by fitting the experimental data with the single carrier Hecht collection efficiency formula [7]. The diode quality factor is 1.8, which implies that the recombination current dominates over the diffusion current.

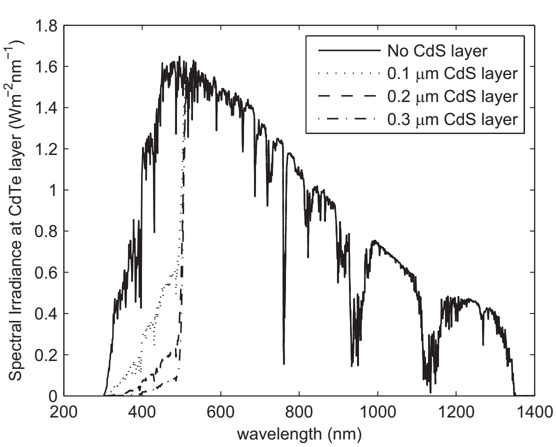

Figure 1 The figure shows the effect of CdS layer thickness on the incident sun spectra at the CdTe layer. The sun spectra up to 1400 nm is shown since the solar cell is transparent to the photons of wavelengths that are higher than 900 nm.

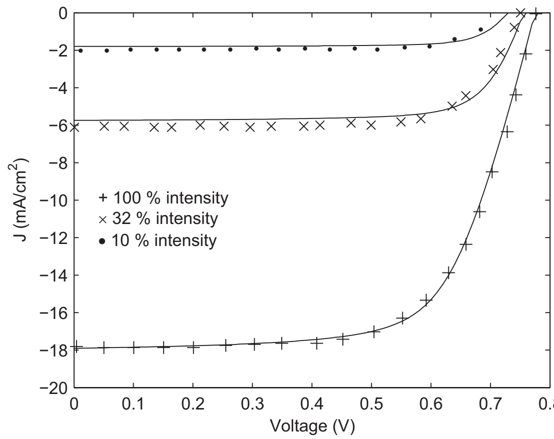

Figure 2 Net current density versus voltage at three sun intensities. The symbols represent experimental data and the solid lines represent the theoretical fit to the experimental data. The experimental data were extracted from Ref. [6].

The EHPs are generated exponentially across the CdTe layer. Since the photon absorption coefficient up to 900 nm of wavelength is very high, the EHPs are mainly generated near the n–p interface in the CdTe layer. Therefore, electrons quickly move towards the top electrode and holes have to move a much longer distance towards the bottom electrode. Thus, the charge collection should mainly be controlled by the hole transport properties [14]. Figure 3a and b shows the *J–V* characteristics of CdS/CdTe solar cells for various levels of $\mu\tau'$ products of holes and electrons. All other parameters in Fig. 3 are the same as in Fig. 2. The theoretical overall efficiency varies from 5.73% to 11.21% by changing the $\mu_{\mathrm{h}}\tau'_{\mathrm{h}}$ values from $10^{-7}\,\mathrm{cm^2/V}$ to $10^{-4}\,\mathrm{cm^2/V}$, whereas it varies from 8.2% to 9.7% by changing the $\mu_{\mathrm{e}}\tau'_{\mathrm{e}}$ values from $10^{-7}\,\mathrm{cm^2/V}$ to $10^{-4}\,\mathrm{cm^2/V}$. As evident from Fig. 3a and b that the *J–V* characteristics is much more sensitive to the hole transport than to the electron transport. The efficiency is reduced drastically if $\mu_{\mathrm{h}}\tau'_{\mathrm{h}}$ is less than $10^{-6}\,\mathrm{cm^2/V}$. It increases slightly with increasing $\mu_{\mathrm{h}}\tau'_{\mathrm{h}}$ above $10^{-5}\,\mathrm{cm^2/V}$. Therefore, the performance of CdS/CdTe solar cells is sensitive to the hole transport.

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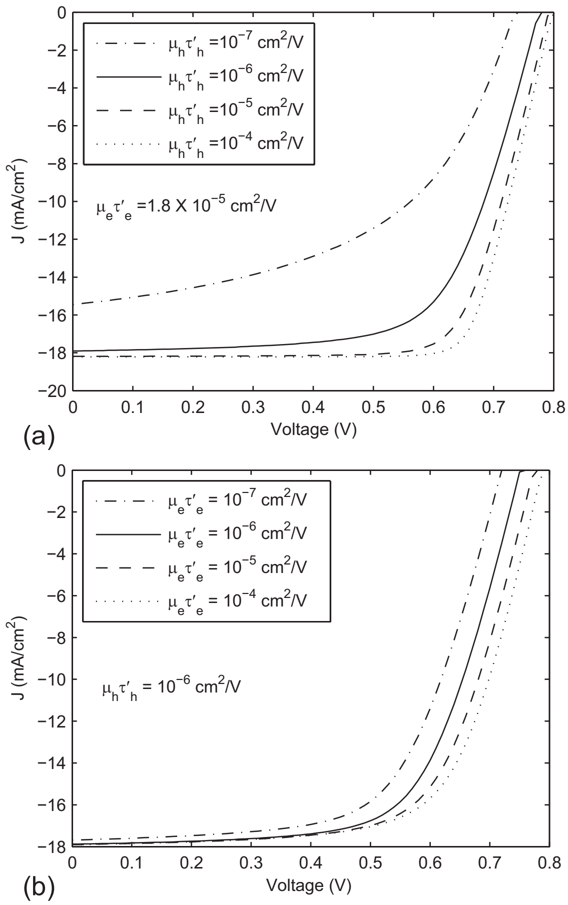

Figure 3 Theoretical net current density versus voltage for various levels of $\mu\tau'$ products of holes (a) and electrons (b) in CdTe solar cells.

4 Conclusions

An analytical model to study the current–voltage characteristics of CdS/CdTe thin film solar cells has been developed. An analytical expression for the external voltage dependent photocurrent is derived by considering exponential electron–hole pair generation, carrier trapping, and carrier drift in the CdTe layer. The overall load current is calculated considering the forward dark current and the actual solar spectrum. The recombination current in the depletion region dominates over the ideal diode current. The solar cell efficiency depends critically on the hole transport in the CdTe layer. The theoretical model shows a very good agreement with the published experimental data.

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