Spectral Distribution of Photoelectric Efficiency of Thin-Film CdS/CdTe Heterostructure

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The spectral distribution of the quantum efficiency in thin-film CdS/CdTe solar cells is being investigated by taking into account the drift and diffusion components of photocurrent, recombination at the CdS–CdTe interface, the back surface of the CdTe absorber layer and in the space-charge region. The effect of uncompensated acceptor concentration, lifetime of minority carriers and surface recombination velocity on the charge collection efficiency are discussed. The losses caused by reflections and absorption in the CdS and indium tin oxide layers are also considered.

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1. Introduction

Over the last two decades, thin-film CdS/CdTe heterostructure on conducting glass substrates has been considered prospective for applications in large-area solar modules [1, 2]. The possibility of realizing inexpensive CdS/CdTe thin-film solar cells with the efficiency of $\approx 10\%$ was demonstrated as early as 1982 [3], and in 1993 the efficiency reached about 16% [4]. However, no significant improvement has been achieved afterwards. Further studies are required to reveal the processes determining the photoelectric characteristics and the factors limiting the efficiency.

One of the important factors determining the efficiency of a solar cell is the spectral distribution of the quantum efficiency which accounts for the formation of the drift and diffusion components of the photocurrent and ultimately the short-circuit current density. In this paper we demonstrate the possibility to describe *quantitatively* the quantum efficiency spectra of the thin-film CdS/CdTe solar cells.

2. Experimental

The substrates used for the development of thin film layers were glass plates coated with a semitransparent indium tin oxide (ITO) ($SnO_2+In_2O_3$) layer. The window layer CdS ($\approx 0.1~\mu$m) was developed by chemical bath deposition and the absorber layer CdTe (1–3 μm) was deposited on top of CdS by close-spaced sublimation.

Non-rectifying ohmic contact to the CdTe layer was fabricated by vacuum evaporation of Ni after bombarding the CdTe surface by Ar.

In order to calculate the spectral distribution of the quantum efficiency, a knowledge of the absorption curve $\alpha(\lambda)$ for CdTe is required in a wide spectral range of interband electron transitions. It should be borne in mind that the absorption curves of the same material for single crystal and thin film can be considerably different. The absorption curve $\alpha(\lambda)$ for thin-film CdS was found by using the optical constants obtained by spectroscopic ellipsometry [5].

Figure 1 shows the quantum efficiency spectra of the CdS/CdTe solar cell taken at different temperatures. Compared with the literature data (taken at room temperature), the curves seem to reflect the most common features of the corresponding spectral curves for these devices [6, 7].

As can be seen from Fig. 1, in the long-wavelength region, the spectra are restricted to the value $\lambda_{\rm g}$ corresponding to the bandgap of CdTe which is equal to 1.46 eV at 300 K ($\lambda_{\rm g} = hc/E_{\rm g} = 845$ nm). In the short-wavelength side, the quantum efficiency decays due to the lower transmission through the thin layers: CdS in the range $\lambda < 500$–520 nm and ITO at $\lambda < 350$ nm (Fig. 2).

The *external* quantum efficiency $\eta_{\rm ext}$ is related to the quantum efficiency of photoelectric conversion in the CdTe absorber layer $\eta_{\rm CdTe}$ through the transmission of the glass plate coated by ITO ($T_{\rm ITO}$) and the transmission of the CdS layer ($T_{\rm CdS}$) by the expression:
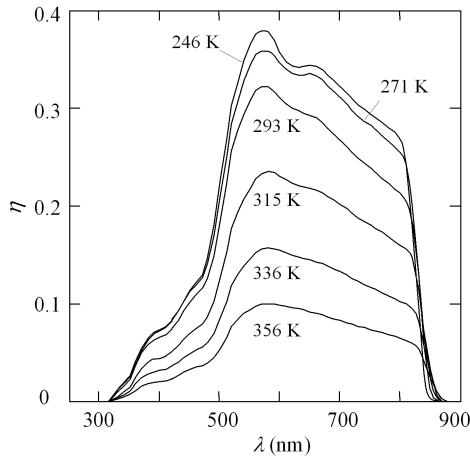
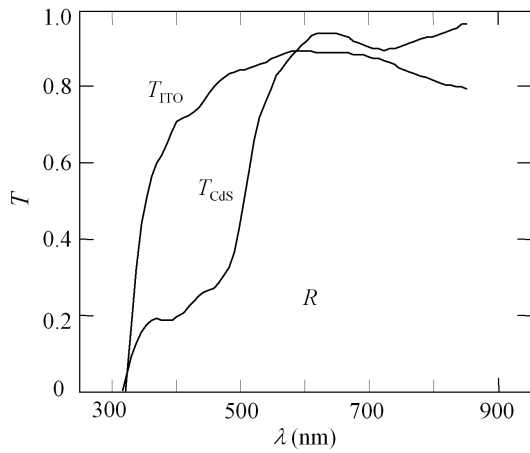Fig. 1. Spectral distribution of the quantum efficiency of CdS/CdTe device at different temperatures.

Fig. 2. The transmission curves of the ITO coated glass (T_{ITO}) and the CdS layer (T_{CdS}) as functions of the wavelength λ.

$\eta_{\mathrm{ext}} = T_{\mathrm{ITO}} T_{\mathrm{CdS}} \eta_{\mathrm{CdTe}}$. In order to describe $\eta_{\mathrm{ext}}(\lambda)$ we used the measured curves $T_{\mathrm{ITO}}(\lambda)$ and $T_{\mathrm{CdS}}(\lambda)$ shown in Fig. 2. The quantum efficiency η_{CdTe} will be calculated below by considering the processes in the diode structure.

3. The expressions for spectral distribution of the quantum efficiency

It is known that in CdS/CdTe solar cells only the CdTe is contributing to the light-to-electric energy conversion and the "window" layer CdS absorbs light in the range $\lambda < 500$–520 nm thereby reducing the photocurrent. Therefore in numerous papers where the energy band diagram of a CdS/CdTe junction is discussed a band bending (and hence a depletion layer) in the CdS layer is not depicted (see, for example [1, 8]). Thus, the depletion layer of the CdS/CdTe diode structure is virtually located in the p-CdTe layer. This is identical to the case of an asymmetric abrupt p–n junction or a Schottky diode, i.e. the width of the space-charge region in the CdS/CdTe heterojunction can be expressed as $W = [2\varepsilon\varepsilon_0(\varphi_0 - qV)/q^2(N_{\mathrm{a}} - N_{\mathrm{d}})]^{1/2}$, where q is the electronic charge, ε_0 is the electric constant, ε is the dielectric constant of the semiconductor, φ_0 is the barrier height at the semiconductor side, V is the applied voltage, and $N_{\mathrm{a}} - N_{\mathrm{d}}$ is the uncompensated acceptor concentration in the CdTe layer [9].

The quantum efficiency η_{CdTe} can be found from the continuity equations for the space-charge region and neutral part of the Schottky diode which are solved using the proper boundary conditions. The exact solution of these equations leads to rather cumbersome expression for the quantum efficiency [10]. However, the expression may be essentially simplified [11] and one can come to the expression for the *drift* component of the photoelectric quantum yield taking into account surface recombination at the CdS–CdTe interface [12]:

$$\eta_{\mathrm{drift}} = \frac{1 + \frac{S}{D_n}\left(\alpha + \frac{2}{W}\frac{\varphi_0 - qV}{kT}\right)^{-1}}{1 + \frac{S}{D_n}\left(\frac{2}{W}\frac{\varphi_0 - qV}{kT}\right)^{-1}} - \exp(-\alpha W), \quad (1)$$

where S is the velocity of surface recombination, D_n is the diffusion coefficient of electrons, and $L_n = (\tau_n D_n)^{1/2}$ is the electron diffusion length.

For the *diffusion* component of the photoelectric quantum yield, which takes into account surface recombination at the back surface of the CdTe layer, one can use the exact expression obtained for the p-layer in a p–n junction solar cell [9]

$$\eta_{\mathrm{dif}} = \frac{\alpha L_n}{\alpha^2 L_n^2 - 1} \exp(-\alpha W)$$
$$\times \left\{ \alpha L_n - \frac{\frac{SL_n}{D_n}\left[\cosh\left(\frac{d-W}{L_n}\right) - \exp\left(-\alpha(d-W)\right)\right] + \sinh\left(\frac{d-W}{L_n}\right) + \alpha L_n \exp(-\alpha(d-W))}{\frac{SL_n}{D_n}\sinh\left(\frac{d-W}{L_n}\right) + \cosh\left(\frac{d-W}{L_n}\right)} \right\}, \quad (2)$$

where d is the thickness of the CdTe absorber layer. The *total* quantum yield of photoelectric conversion in the CdTe absorber layer is the sum of the two components:

$\eta_{\mathrm{CdTe}} = \eta_{\mathrm{drift}} + \eta_{\mathrm{dif}}$.

Our calculations using Eqs. (1) and (2) show that, varying the values of $N_{\mathrm{a}} - N_{\mathrm{d}}$ and τ_n, we can obtain the
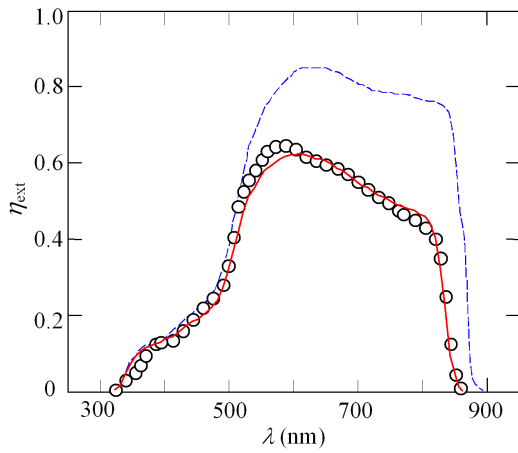
Fig. 3. Comparison of the measured quantum efficiency spectra η_{ext} (circles) and calculated one (solid line) at $N_a - N_d = 7 \times 10^{16}$ cm^{-3}, $\tau_n = 8 \times 10^{-11}$ s. The dashed line shows the spectrum of 100% internal efficiency of the device at $N_a - N_d = 10^{16}$ cm^{-3}, $\tau_n = 10^{-6}$ s, $d = 100$ μm.

photosensitivity spectra of various shapes including those similar to the experimental curves shown in Fig. 1. Figure 3 illustrates the comparison of the calculated curves $\eta_{ext}(\lambda)$ with the measured spectrum taken at 300 K. The figure shows a quite good fit of the calculated values with the experimental data. Let us note that only the two adjustable parameters, the uncompensated acceptor concentration $N_a - N_d$ and electron lifetime τ_n have been used to fit the calculation results with the experimental data and which were found to be 7×10^{16} cm^{-3} and 8×10^{-11} s, respectively.

4. Conclusions

The quantum efficiency spectra of the thin-film CdS/CdTe solar cells on ITO/glass substrate have been investigated experimentally and theoretically. The model taking into account the drift and diffusion photocurrent components with regard to recombination losses in the space-charge region, at the CdS/CdTe interface and the back surface of the CdTe layer allows us to obtain a good agreement with the measured quantum efficiency spectra of CdS/CdTe solar cell.

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