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Quantitative assessment of optical losses in thin-film CdS/CdTe solar cells

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For the first time, based on the known optical constants of the materials (refractive index and extinction coefficient), calculations of optical losses in glass/transparent conducting oxide (TCO)/CdS/CdTe solar cells have been carried out taking into account reflections at the interfaces and absorption in the TCO (it can be indium tin oxide (ITO) or SnO_2:F) and CdS layers. It has been shown that the losses caused by reflections at the interfaces result in lowering the short-circuit current by $\sim$9 % whereas absorption in the TCO and CdS layers with the typical thicknesses lead to losses of 15–16% for glass/SnO_2/CdS/CdTe, and 22–24% for glass/ITO/CdS/CdTe solar cells. At 100% photoelectric conversion in the CdTe absorber layer, this corresponds to a loss in short-circuit current by $\sim$3 mA/cm^2 due to reflection, and 4–7 mA/cm^2 due to absorption at the glass/SnO_2(or ITO)/CdS stack. Losses due to absorption in float glass and low-iron glasses are 3.3–3.5% and 0.6–0.7%, respectively.

1. Introduction

Since the beginning of the last decade mass production of solar modules based on thin-film CdS/CdTe has been started. In 2009–2010, annual production capacity of such devices by one company, First Solar, exceeded 1 GW and in 2011 it is expected to double the production [1]. It is considered that the rapid development of this solar energy technology sector is mainly due to the lower cost of CdTe modules compared to those based on Si wafers. Today the challenge facing the researchers and technologists is how to increase the efficiency of CdS/CdTe modules from the current large area efficiency of 10–11% and decrease the gap between actual efficiency and the theoretical limit of 28–30% [2–4]. The main causes of efficiency loss in CdTe/CdS solar cells are optical, electrical and recombination, a topic of study discussed in a substantial amount of papers. In the literature there are a good amount of experimental data on the optical transmission of the glass/ITO(or SnO_2) and glass/ITO(or SnO_2)/CdS structures that provide information about the losses caused by reflection from the interfaces and absorption in the ITO, SnO_2 and CdS layers (ITO is a solid solution of indium oxide (In_2O_3) and tin oxide (SnO_2)) [5–7]. However, in the first case, the surface of ITO (or SnO_2) layer is in optical contact with air, rather than with CdS, as in the real case. In the second case, the surface of CdS is in contact with air rather with the CdTe layer. As discussed in this paper, measuring the transmission of the glass/ITO (or SnO_2) and glass/ITO (or SnO_2)/CdS structures leads to the results, which differ significantly from those measured on the real structure of the solar cell. Due to the large differences in refractive indices and extinction coefficients between air and other device layers such as ITO, SnO_2 and CdS, the reflection coefficient at the interfaces measured and reported can be higher than that in the case of the real structure. Further, in the literature, pronounced interference oscillations in the transmission curves are always observed, which are relatively stronger than in the real device structure (as follows from the calculation results discussed here). To our knowledge, the studies of optical losses in CdTe/CdS solar cells based on optical constants of materials used, i.e. based on general principles, are absent in the literature. The present study focuses on optical losses due to absorption and reflection at the interfaces in CdTe/CdS solar cells. Calculations have been carried out based on the optical constants of materials used, the refractive index and extinction coefficient. It seems that the results of these calculations are interesting from a scientific and practical point of view, since they suggest possible ways to increase the efficiency of CdTe/CdS solar cells by reducing the optical losses, and vice versa they show the efforts that are not justified if a decrease in the optical losses gives only a small gain.

2. Reflection losses

The sketch of a typical glass/TCO/CdS/CdTe solar cell is shown in Fig. 1 (TCO refers to a transparent conducting oxide). Before reaching the photoelectrically active CdTe absorber layer, solar radiation penetrates the glass plate, a TCO layer and a CdS

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window layer. Obviously, this is accompanied by optical losses upon reflection from the following interfaces: air–glass, glass–TCO, TCO–CdS and CdS–CdTe, and absorption in glass plate, TCO and CdS. According to the Fresnel equations, when the light is at near-normal incidence, the reflection coefficient (reflectivity) from the interface between two contacting materials is determined by their refractive indices n_1 and n_2

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

In the case of electrically conductive materials, the refractive index contains an imaginary part and is written as $n^*=n-i\kappa$, where n is the refractive index, and κ is the extinction coefficient ($i=\sqrt{-1}$). The reflection coefficient from the interface is defined as the square of the modulus $[(n_1^*-n_2^*)/(n_1^*+n_2^*)]$ [8] and has the form:

$$R=\frac{|n_1^*-n_2^*|^2}{|n_1^*+n_2^*|^2}=\frac{(n_1-n_2)^2+(\kappa_1-\kappa_2)^2}{(n_1+n_2)^2+(\kappa_1+\kappa_2)^2} \quad (2)$$

At the air–glass interface (see Fig. 1) we will find the reflection coefficient R_{12} taking $n_1=1$, and $\kappa_1=0$ for the air. For the convenience of presenting the main optical losses, we first assume that for glass $\kappa_2=0$. This is justified by the fact that photovoltaic applications often use specialized glass with low iron oxide content, where the absorption is observed only in the ultraviolet region. As it will be shown later, absorption in the low-iron glass practically does not exhibit itself in short-circuit current, however, in the case of ordinary glass (float glass) absorption losses become noticeable.

For the refractive index of glass n_1 we will use the Sellmeier (Zelmeer) dispersion equation applied for quartz (SiO_2) [9]:

$$n^2=1+\frac{a_1\lambda^2}{\lambda^2-\lambda_1^2}+\frac{a_2\lambda^2}{\lambda^2-\lambda_2^2}+\frac{a_3\lambda^2}{\lambda^2-\lambda_3^2} \quad (3)$$

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

To find the reflection coefficients at the interfaces: glass–TCO, TCO–CdS and CdS–CdTe it is necessary to know the values of the refractive index and extinction coefficient of TCO, CdS and CdTe in the spectral range 300–850 nm. In the discussion below we consider the two most common structures of CdTe/CdS solar cell in which indium tin oxide (ITO) and F-doped tin oxide (SnO_2:F) are used as TCO. Fig. 2 shows the spectral dependences of n and κ for ITO (typically 90% In_2O_3, 10% SnO_2) taken from Refs. [10,11] and for SnO_2:F taken from Ref. [12]. Also shown are data on CdS [13] and CdTe [14].

Note that the data on the optical constants of the materials cited in various sources differ somewhat, depending on the method adopted to grow the crystal or film. However, with a few exceptions, these differences manifest themselves weakly in the results of the calculation of the integral characteristics of a multilayer solar cell, which is short-circuit current J_{sc}. For example, calculations of J_{sc} using data for n and κ, obtained by ellipsometry for CdTe single crystal and films [14], lead to almost identical results.

Fig. 3 shows the spectral dependence of the reflection coefficients $R(\lambda)$ at the interfaces calculated by substituting n and κ

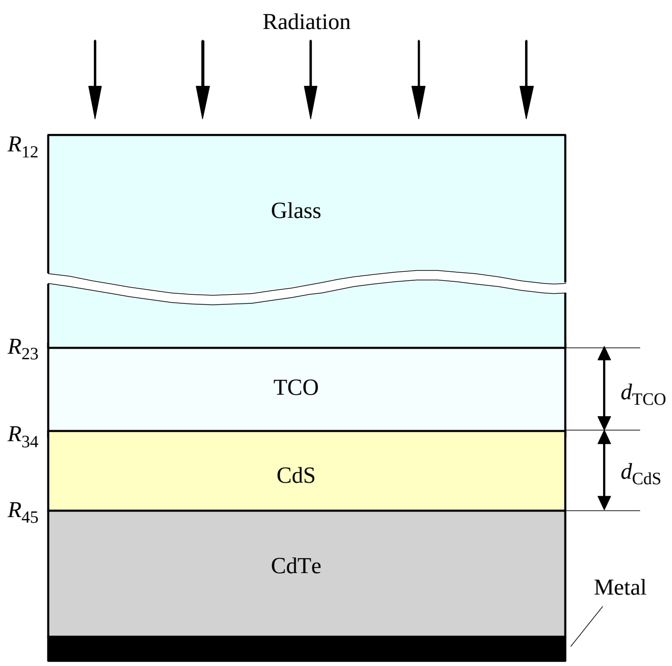

Fig. 1. Schematic cross-section of thin-film CdS/CdTe solar cell.

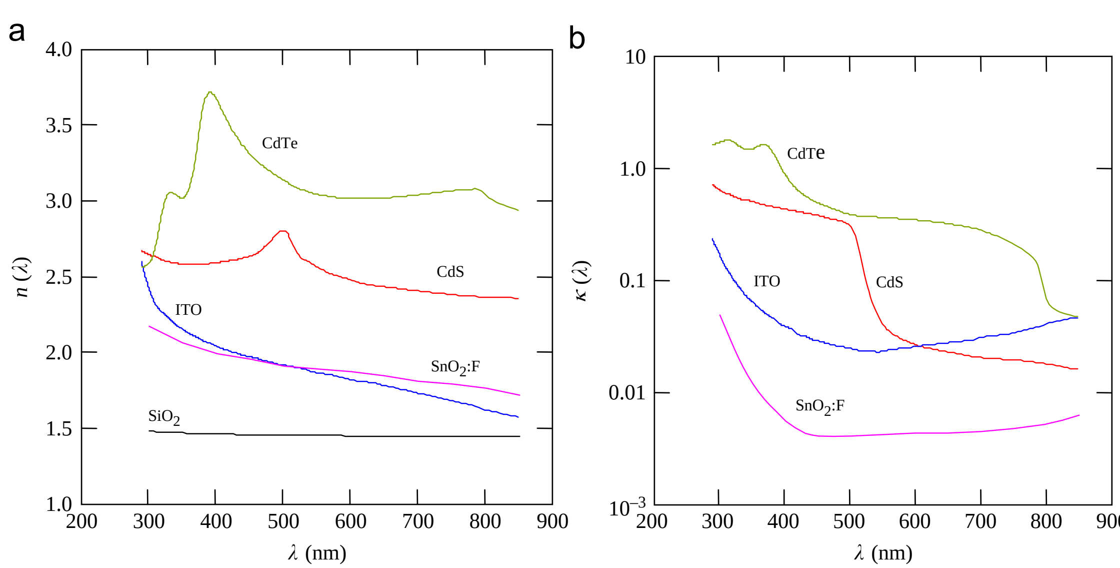

Fig. 2. Refractive index (a), and extinction coefficient (b) of SiO_2, ITO, SnO_2:F, CdS and CdTe as a function of wavelength (the curves $\kappa(\lambda)$ for glasses are shown in Fig. 7(b)).