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Effect of HRT ZnO Film on Optical Spectra of Transmission in CdS/CdTe Solar Elements

A.B. Danylov*, H.A. Ilchuk and R.Yu. Petrus
Lviv Polytechnic National University, 12, S. Bandera Str., 79013, Lviv, Ukraine

The comprehensive analysis of transmission spectra for light propagated through ITO/ZnO/CdS multilayers to solar cell active layer of CdTe is performed. Optimal thickness of ZnO high resistive oxide supplying minimal optical losses in CdTe solar cell working range was determined. We get the maximal light transmission to active layer for ZnO film with thickness of 230 nm. The advantages of glass superstrate for multilayer structure with ZnO upper layer is discussed in comparison with the structure with ITO upper layer. Calculation of transmittance for textured surfaces of top face of solar element showed significant minimization of optical losses in the structure with ITO upper layer textured by inverted pyramids while for textured glass superstrate there is no ponderable profit as compared to multilayer structure with planar surface.

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1. Introduction

CdS/CdTe heterojunction is one of the most promising photovoltaic systems for solar energy conversion. Theoretical limit of CdTe solar cell efficiency approaches to 30%, but maximal efficiency of experimental cells up to date reported by First Solar is 22.1% [1]. The main energy losses are caused by solar light reflection at solar element (SE) layer interfaces, propagation of radiation through the element without absorption, recombination losses and high value of series resistance in the element. The thinner is buffer layer of CdS, the higher is irradiance at CdS/CdTe interface and as a result the higher is photogeneration in CdTe active layer. The CdS/CdTe heterojunction annealing is a technological regime of SE formation. The structure annealing even for gentle temperature conditions leads to pinhole formation into CdS thin film. The film becomes discontinuous that leads to shunting junction formation between transparent conductive oxide (TCO) and CdTe active layer and decrease of shunting resistance. The additional high resistive transparent (HRT) layer can be deposited between TCO and buffer layer. This step allows avoiding the effect and preventing the diffusion of undesirable impurities into active layer. ZnO is a transparent n-type wide bandgap metal oxide semiconductor with diverse application as electrodes in optoelectronic devices, window and buffer layers in solar cells. The material can be also used as TCO supplying high shunting resistance of SE. As reported in [2, 3] such HRT layer deposited between TCO and CdS buffer layer significantly increases open-circuit voltage and short-circuit current, in such way improving solar cell efficiency. But still there are no works devoted to studying the optical properties of multilayered ITO/ZnO/CdS/CdTe SE in the whole. Partially the properties were considered in [4] where transmission spectra were calculated for three-layer coating. The aim of the paper is carrying out the comprehensive analysis of transmission spectra for CdTe SE at the interface of buffer and active layers including the influence of light reflection at the SE active layer interface and considering the other ways of SE efficiency enhancement by decrease of optical losses.

*corresponding author; e-mail: andanylov@yahoo.com

2. Calculation background

In the present work we performed comprehensive analysis of optical spectra in the working range of CdTe SE for the structure with ITO as TCO, ZnO inorganic oxide as HRT and CdS/CdTe heterojunction. We explored the tendencies of changes in optical spectra of absorption and transmission caused by different layer thickness variation. As a basic for simulation we chose the structure

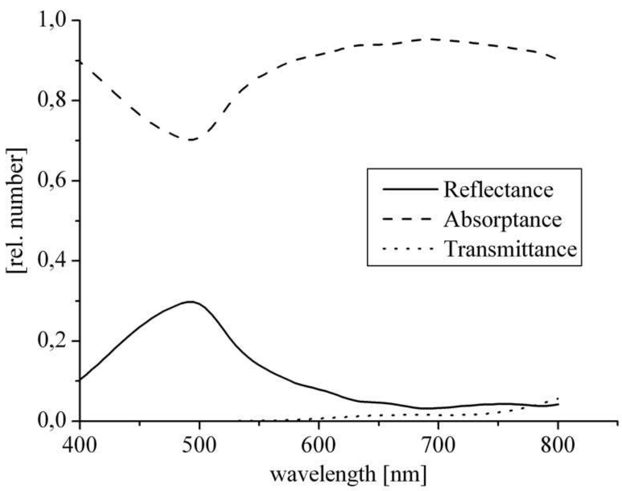

Fig. 1. Optical spectra of ITO/ZnO/CdS/CdTe solar element, basic for simulation.

ITO(25 nm)/ZnO(250 nm)/CdS(50 nm)/CdTe(800 nm). The reason for such choice was the following. Such thickness of CdTe layer is sufficient for practically total light absorption in all working range of the SE (Fig. 1), that supplies minimum of optical losses, caused by light transmission through SE active layer. Therefore in our calculation we can neglect the light transmission and reflection at the rear face of CdTe layer. Thicknesses of ITO and CdS are close to minimal possible ones in true technological regimes of solar cell fabrication. Optical constants for all the above mentioned layers were taken from [5–8]. We restricted our consideration to normal light incidence and spectral range from 400 to 800 nm that corresponds to working range of CdTe SE. The calculations were based on the Fresnel and generalised Fresnel formulae [9] and recurrent formulae of Scandone–Ballerini for multilayer structure [10]. Calculations for textured layer surfaces were performed by Monte Carlo algorithm [11] when the random array of thousand beams is generated and total light intensity includes all reflections from interfaces and light transmission meanwhile beam intensity does not decay in exponential factor. The texture elements were taken in the shape of regular triangle pyramid.

3. Simulation results and discussion

We calculated the transmission spectra for upper layers (TCO/HRT/buffer layer) of SE including light reflection from the interface CdS/CdTe but without consideration of light propagation into CdTe substrate. The spectra showed distinct interference nature. Mean transmittance of the structure increases with buffer layer thickness decrease (Fig. 2a) and from technological aspects the thickness of buffer layer 50 nm can be optimal for SE with HRT layer. Variation of ITO thickness in the range of 25 to 100 nm in our simulations showed the highest transmission for thinnest layer, too (Fig. 2b). The main attention was paid to ZnO film thickness (Fig. 2c).

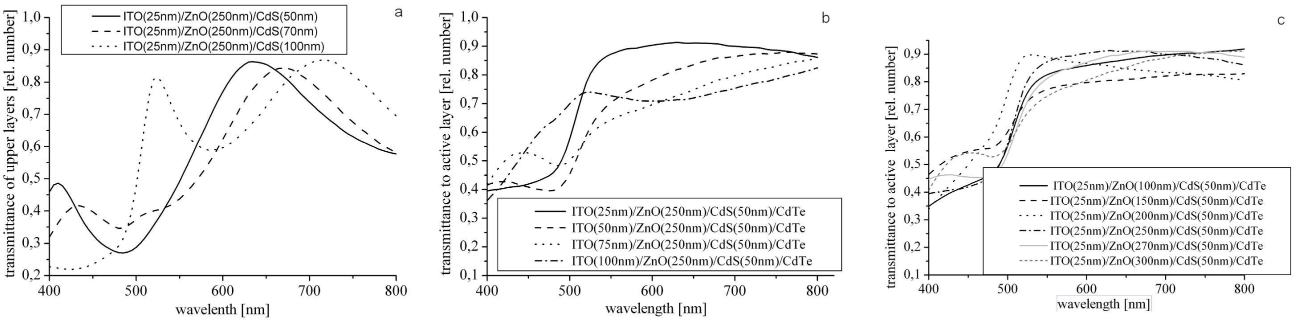

Fig. 2. Transmission spectra for ITO/ZnO/CdS/CdTe solar element calculated at CdS/CdTe interface: (a) CdS thickness variable, (b) ITO thickness variable, (c) ZnO thickness variable.

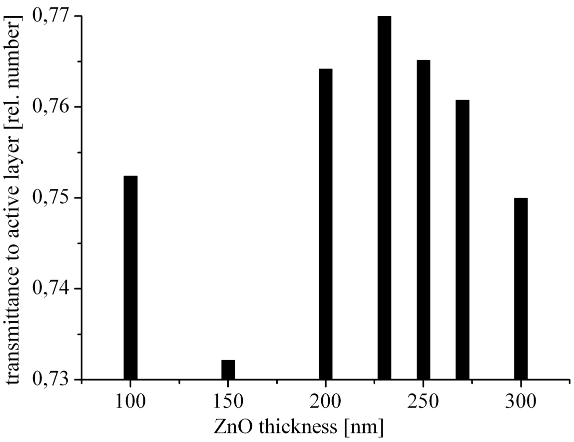

Fig. 3. Mean transmittance (in SE spectral range) to active layer for ITO/ZnO/CdS/CdTe solar element with different HRT oxide thickness.

We determined optimal thickness of ZnO layer which supplies minimum of interference in reflection geometry for the stacked structure. For ZnO layer thickness equal to 230 nm the mean transmittance of light to CdS/CdTe interface in wavelength range of 400-800 nm becomes the highest and approaches to 77% (Fig. 3). The result is in good coincidence with the results based on electrical measurements of other authors [12]. HRT oxide extra layer inclusion into SE structure between buffer layer and TCO layer slightly decreases transmission to CdS/CdTe interface (especially in the range of 400 to 500 nm) but significantly improves the electrical characteristics of SE.

There are two different ways of solar cell fabrication. First method relies on glass superstrate and consequential deposition of all relevant layers on the glass plate. The second one is in substrate configuration where solar cell is formed by layer deposition at the surface of back metal contact. Therefore we studied also the changes in optical spectra caused by glass superstrate. Additional glass superstrate can be fruitful for structure with upper layer of ZnO because of at least threefold decrease of reflection from the structure in the whole (Fig. 4a), but when ITO is the first film in the stack the reflection significantly increases in the long wavelength range of 600–800 nm in comparison with the structure without top glass plate and the total transmission into the active layer decreases (Fig. 4b). It is reasoned by significant difference between refraction indices of ITO and ZnO in the explored wavelength region.

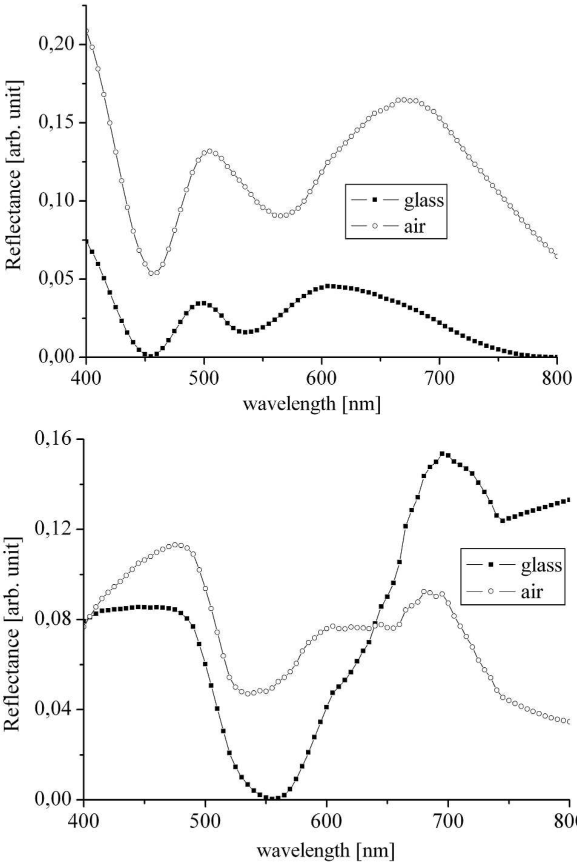

Fig. 4. Total reflection losses in ZnO/CdS/CdTe multilayer structure with glass superstrate and without one (a), total reflection losses in ITO/CdS/CdTe multilayer structure with glass superstrate and without one (b).

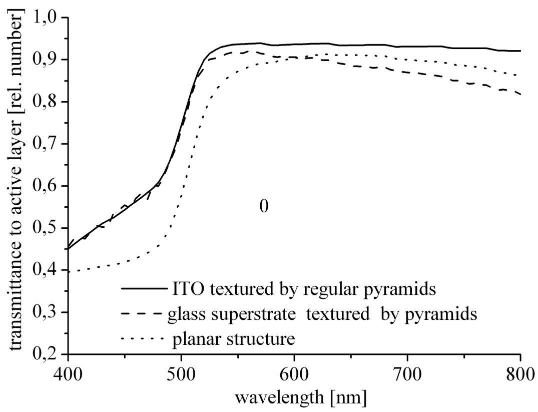

Fig. 5. Transmission spectra for upper layers of solar element with textured superstrate.

Surface texturing increases the effective surface of element and supplies additional light reflection at interface. Calculated spectra for structure with textured top surface in the shape of set of regular triangle pyramids revealed essential rise of transmission in the region of CdS absorption range (from 400 to 500 nm) and 5% gain in the rest region as compared with planar structure (Fig. 5). But the texturing profit becomes negligible for the case of glass superstrate texturing. Therefore, as findings, in superstrate configuration with glass superstrate the additional thin ZnO level deposited at the top of glass with further traditional TCO/HRT/buffer layer/active layer multilayer structure formation could be useful.

4. Conclusions

We determined the optimal thickness of ZnO layer for minimal optical losses into CdTe solar cell as 230 nm. Analysis of reflection spectra for SE with glass superstrate and ZnO upper layer showed a threefold decrease of reflection in comparison with air superstrate. In contrast, the spectra for SE with glass superstrate and ITO highest layer in SE confirm the increase of total reflection in comparison with air superstrate structure. Surface texturing practically in all cases improves optical properties of the structure in the whole. But, surprisingly, the advantage is negligible for glass superstrate texturing and for long wavelengths the total structure transmittance decreases.

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