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Optical Losses of Thin Solar Cells on the Basis of *n*-ZnS / *p*-CdTe and *n*-CdS / *p*-CdTe Heterojunctions

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The optical reflection and absorption losses in the accessory layers of solar cells based on *n*-ZnS / *p*-CdTe and *n*-CdS / *p*-CdTe heterojunctions are defined in this work. Aluminum doped zinc oxide is used as the front conductive layer material. It is shown that the replacement of traditional window material (CdS) for a wide-one (ZnS) leads to an increase in accessory solar cells layers transmittance. When the thickness of the window layers is 50 nm, the transmittance using ZnS windows with the wavelength of 380-500 nm is higher in 7-40 % than the corresponding value for CdS. At 300 nm for the same spectral field the difference increases to 8-89 %.

Keywords: CdS / CdTe heterojunction, ZnS / CdTe heterojunction, Optical losses, Reflection coefficient, Transmittance, Absorption coefficient.

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1. INTRODUCTION

Nowadays thin solar cells (SC) based on *n*-CdS / *p*-CdTe heterojunction (HJ) in the mass production are considered as the alternative photovoltaic devices based on silicium technologies. In fact it is the first technology which allows to obtain solar energy at the price lower than $ 1 / Вт ($ 0,85) [1] The efficiency of SC films with CdTe absorbing layer is 28-30% according to the theoretical evaluations [2]. The real efficiency of such photovoltaic devices is much lower. Though today the efficiency of 17.3 % [3] is obtained for SC based on the *n*-CdS / *p*-CdTe HJ, solar modules efficiency of big area not exceeding 11.6 % [3-4]. The difference between the theoretical provisions and real efficiency values of devices is explained by optical electric and recombination losses while transforming the solar energy into the electric one. The further efficiency increasing of such SC is possible as by means of their design optimization so by means of improvement of separate layers properties.

There are a lot of works devoted to the CE *n*-CdS / *p*-CdTe design optimization and reduction of energy losses in their photoactive layers, but the most of them deal with the losses connected with recombination generated by electron-hole light pairs [5-7]. However, recently a number of authors have paid attention to the necessity of consideration and minimization of light optical losses in photovoltaic devices related to its absorption and reflection in the glass, window and conductive (accessory) layers. The loss of light in SC glass / ITO (TCO) / CdS / CdTe / rear metal contact are studied by the authors [8-9].

The ITO ($SnO_2 + In_2Te_3$) and TCO (SnO_2: F) transparent conductive layers are a traditional collector contact in the photoelements' structures such as «superstrate» [10-11]. In addition, in recent years one began to use aluminum-doped zinc oxide (ZnO: Al) films as a front conductive layers of photovoltaic devices [3, 4]. This material is cheaper than ITO, TCO and does not contain rare metals; it has a specific conductivity and transparency. The corresponding SCs have demonstrated increased stabilization over the time and properties reproducibility, and their efficiency reached 14 % [3, 12].

The selection of window layer plays an important role in thin film SC technology. At present CdS (E_g = 2.42 eV) is widely used. ZnS thin layers can be an alternative to CdS films. Zinc sulfide has a substantially greater than the cadmium sulphide band gap (E_g = 3.68 eV), thus extending the range of relevant SC photosensitivity and increasing their short-circuit currents [13]. It is non-toxic due to its absence in the heavy metals. At last, ZnS layer may play a role of antireflective SC coating, which increases the number of absorbed photons and thus the efficiency of the device [14]. But the impact of the window materials and collector layers' replacement on the SC optical properties with CdTe absorbing layer is not currently investigated.

The main purpose of this work is to determine and compare the optical losses in the reflection and absorption in SC-based on *n*-ZnS / *p*-CdTe and *n*-CdS / *p*-CdTe HJ with front-conductive contact with ZnO.

2. CONSIDERATION OF LIGHT REFLECTION LOSSES

Thin photovoltaic devices based on HJ such as «superstrate» have a multilayer structure and contain a substrate (glass), window (ZnS, CdS), saturation (CdTe), front collector (ZnO) and rear contacts (metal). The construction of a typical SC glass/ ZnO / ZnS(CdS) / CdTe/metal is presented in Fig. 1.

Modeling was carried out in a range of a ZnS (CdS) window layer thickness change d = 50-300 nm and ZnO

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collector front layer thickness was taken equal to $d = 200$ nm. These values are typical for real SC [3, 12].

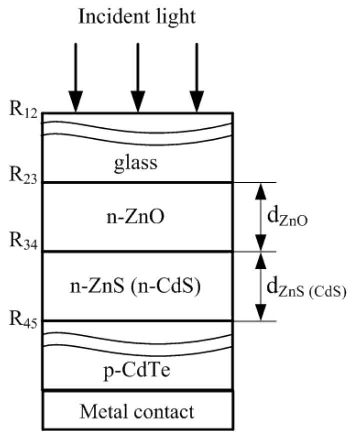

Fig. 1 – SC construction based on *n*-ZnS / *p*-CdTe and *n*-CdS/*p*-CdTe HJ

The flow of sunlight before it reaches the CdTe layer, where the photogeneration of electron-hole pairs, passes through the layers of glass, ZnO and ZnS (CdS). Thus there are optical light losses due to the reflection from the interface: air-glass, glass-ZnO, ZnO-ZnS (CdS) and ZnS (CdS)-CdTe and absorption of luminous flux in the corresponding layers.

Reflection coefficients from the interfaces of contacting layers can be defined by the Fresnel's formula [9]:

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

where n_1, n_2 – refractive coefficients of the first and second contacting materials corresponding.

In the case of electrically conductive materials usage the reflection coefficient was determined with the help of more complex proportion [9]:

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

where, – complex refractive coefficients, k_1, k_2 – attenuation (extinction) coefficients of materials.

Spectral dependence of refractive coefficients and attenuation ones for each layer, which is part of the SC needed for the calculation of light optical losses of are presented in Fig. 2. Value of glass attenuation was taken to be zero ($k = 0$), due to the fact that photovoltaic devices use a special glass which has a very low absorption coefficient.

To determine the refractive coefficient of the glass, Zelmeyer's formula was used [15]:

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

where the constants are $a_1 = 0{,}6962$, $a_2 = 0{,}4079$, $a_3 = 0{,}8974$, $\lambda_1 = 68$ nm, $\lambda_2 = 116$ nm, $\lambda_3 = 9896$ nm.

Guide refractive and attenuation coefficients for ZnO, CdS [16], ZnS, CdTe [17] were used to construct the spectral dependence of n and k values.

The calculated spectral dependence of coefficient of reflection from SC layers in their contact with air are presented in Fig. 3a. It was assumed that $n_1 = 1$, $k_1 = 0$ in the modeling of air.

Spectral dependence of the reflection coefficient from the interface of two contacting materials are calculated in Fig. 3b. The low values of these coefficients (less 0,08-0,05) claim attention. This is explained by a small difference between the optical constants of the contacting materials. For comparison, the results of calculations for the reflection at the interface of the same materials with air give significantly higher values of R: 0,24-0,38 for the interface of air-CdTe, 0,16-0,23 for the interface of air-CdS. However, materials such as ZnO and ZnS, due to the low refractive coefficient, have small reflection coefficients from the air interface.

Coefficient of light transmittance through accessory layers in case of absorption processes neglecting are determined by the expression $T = 1 - R$. By the light flow passing through the CdTe absorbing layer transmittance coefficient can be found by the formula [7]:

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

where R_{12}, R_{23}, R_{34}, R_{45} – reflection coefficients at the interfaces: the air-glass, glass-ZnO, ZnO-ZnS (ZnO-CdS), ZnS-CdTe (CdS-CdTe).

It should be noted that the given ratio does not take into account the multiple reflections in the layers of glass, ZnO, CdS (ZnS), which is quite acceptable for small reflection coefficients at the interfaces of materials (Fig. 3b). Small reflection coefficients allow ignoring the interference effects.

The calculation results of transmittance coefficient dependence on the wavelength of SC-based on *n*-ZnS / *p*-CdTe and *n*-CdS / *p*-CdTe HJ are presented in Fig. 4. As can be seen from the figure, the losses due to reflection at all interfaces of materials do not exceed 18 %, largely accounting for 8,9 %.

3. ABSORPTION LOSSES CONSIDERATION

In general, except the reflection losses one must take into account losses of light absorption in accessory layers of photovoltaic devices. Transmission coefficient with the consideration of reflection losses and absorption in window and conductive layers can be calculated using the expression [7]:

$$T(\lambda) = (1 - R_{12})(1 - R_{23})(1 - R_{34})(1 - R_{45})(e^{-\alpha_1 d_1})(e^{-\alpha_2 d_2}) , \quad (5)$$

where α_1, α_2 – absorption coefficients of materials of the conductive and window layers, d_1, d_2 – their thickness.

The absorption coefficient $\alpha(\lambda)$ can be calculated by the following equation:

$$\alpha(\lambda) = \frac{4\pi}{\lambda} k . \quad (6)$$

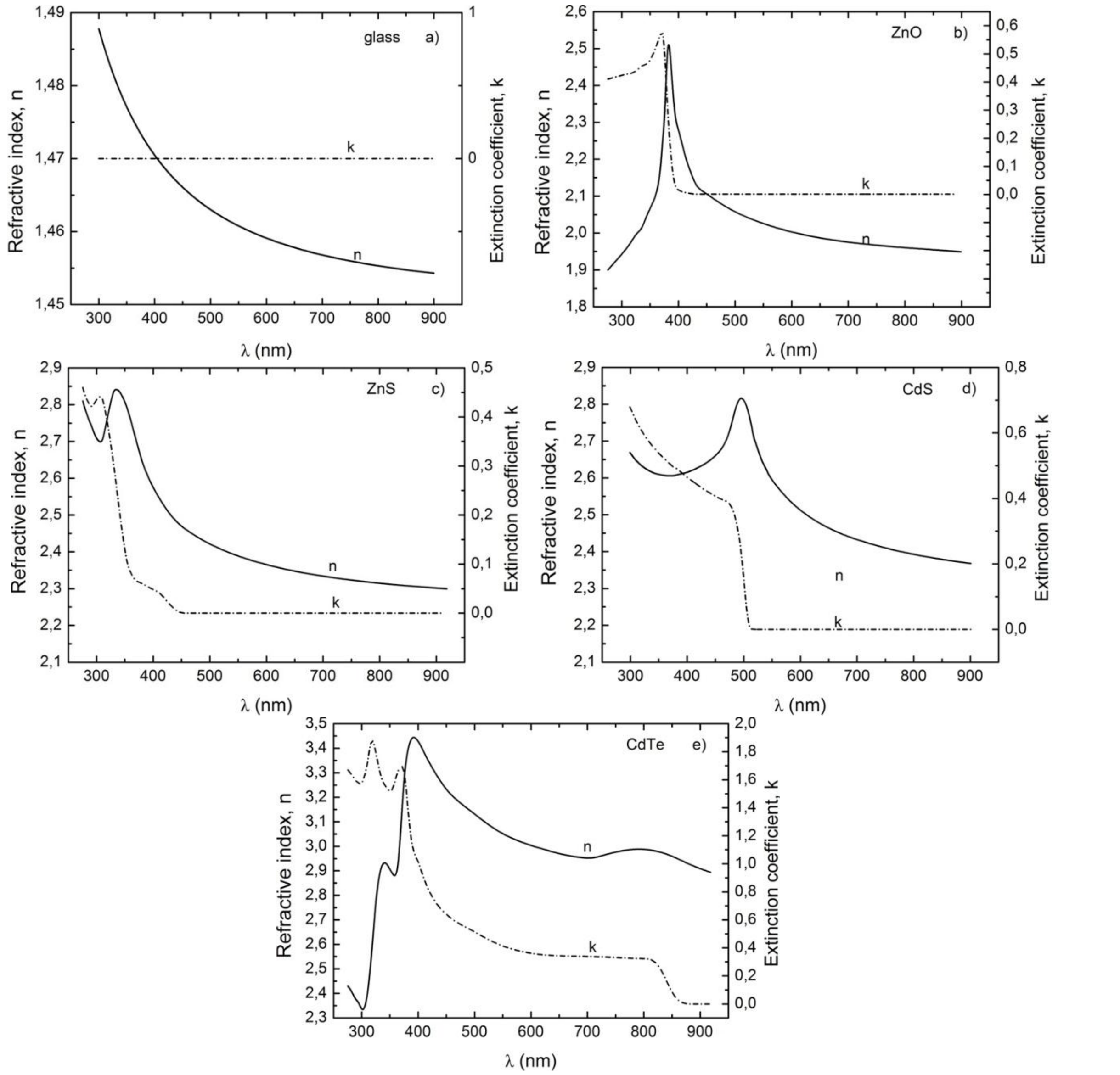

Fig. 2 – Spectral dependences of refractive coefficients and attenuation coefficients of glass (a), ZnO (b), ZnS (c), CdS (d), CdTe (e)

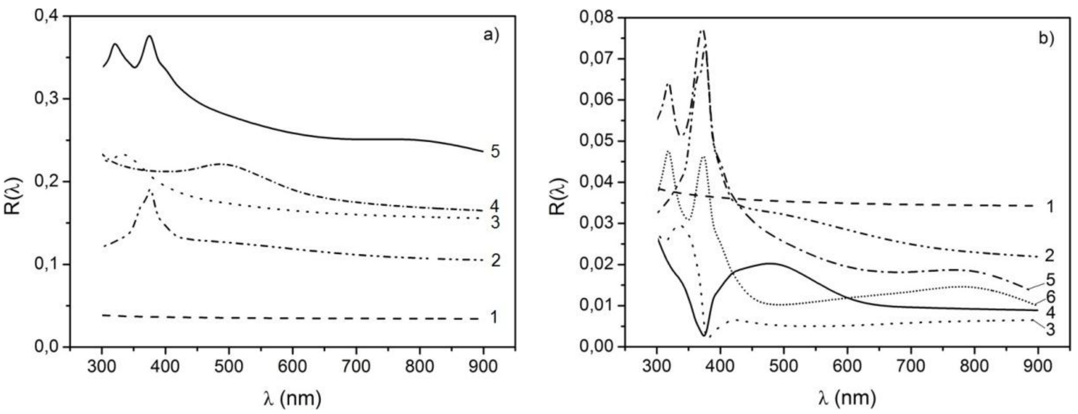

Fig. 3 – Spectral dependences of reflection coefficients (*R*) for the interfaces of air-glass (1), air-ZnO (2), air-ZnS (3), air-CdS (4), air-CdTe (5) (a) and air-glass (1), glass-ZnO (2), ZnO-ZnS (3), ZnO-CdS (4), ZnS-CdTe (5), CdS-CdTe (6), (b)

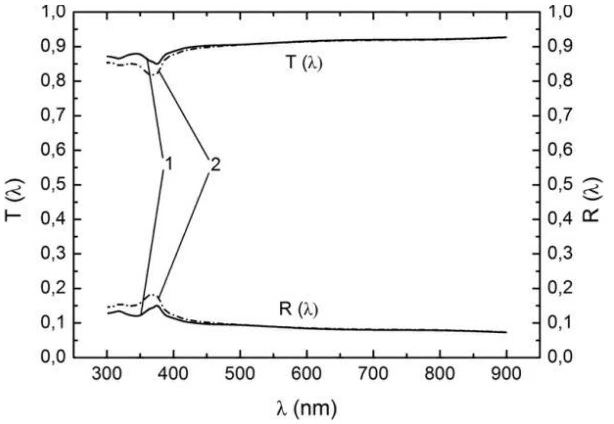

Fig. 4 – Spectral dependences of SC transmittance and reflectance coefficients based on *n*-CdS / *p*-CdTe (1) and *n*-ZnS / *p*-CdTe HJ (2) with the consideration of light reflection from interfaces

Dependence of transmittance coefficient on the wavelength of radiation for SC with ZnS and CdS window layers with different values of their thickness are shown in Fig. 5.

As expected, the use of a wide-band material as a window of photovoltaic device, led to an increase of light transmittance coefficient by auxiliary layers primarily in shortwave region of spectrum. Analysis of the given in Fig. 5 dependences shows that when the thickness of the window layer is 50 nm, the transmittance value in the case of using the ZnS windows with the wavelength of 380-500 nm is higher in 7-40 % than the corresponding value for CdS. At 300 nm, the difference increases to 8-89 % in the interval of the same wavelength.

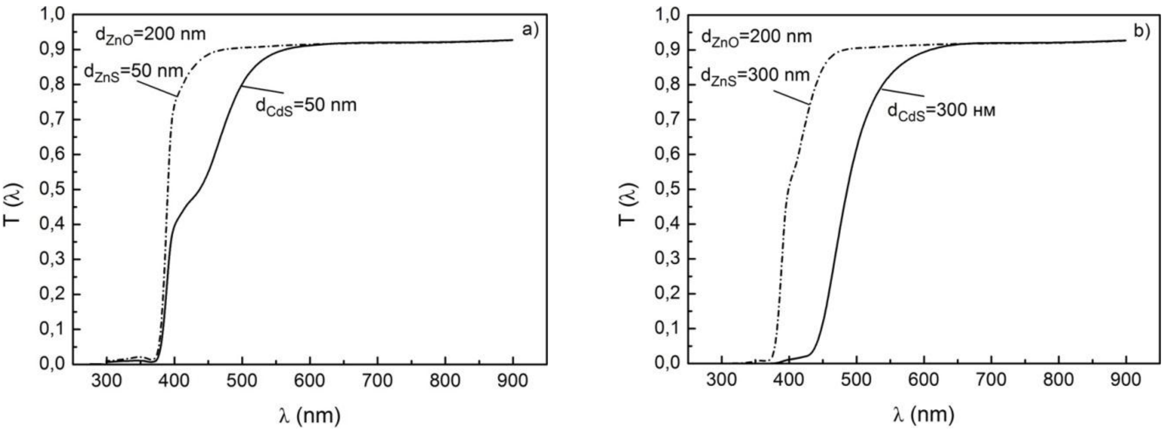

Fig. 5 – Spectral dependences of transmittance coefficients of layers - glass / ZnO / ZnS (CdS) at a thickness of ZnS (CdS): 50 nm (a), 300 nm (b), ZnO 200 nm

4. CONCLUSIONS

The optical losses of reflectance and light absorption in the SC-based on *n*-CdS / *p*-CdTe and *n*-ZnS / *p*-CdT HJ using ZnO as the front collector layer are defined in this work. It is illustrated that the reflection coefficients from the boundaries of two contacting materials take rather low values (0.08-0.05) in comparison with the reflection coefficients at the interfaces of these materials with air.

The calculation results of dependence of transmittance coefficient on the wavelength in SC based on *n*-ZnS / *p*-CdTe and *n*-CdS / *p*-CdTe HJ showed that losses, caused by reflection from all interfaces of materials do not exceed 18%, mainly making up 8 -9 %.

It is shown that the replacement of window material for more wide one-leads to an increase of SC accessory layers transmittance coefficient. When the thickness of the window layer is 50 nm the transmittance coefficient value in the case of using ZnS window with 380-500 nm wavelengths is higher in 7-40 % than the corresponding value for CdS. At 300 nm for the same spectrum difference increases to 8-89 %.

These calculations make it possible to determine the actual maximum of SC efficiency with the consideration of irresistible reflection and absorption losses in the layers of photovoltaic devices.

5. AKNOWLEDGEMENTS

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