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Optical and Recombination Losses in Thin Film Solar Cells Based on Heterojunctions *n*-ZnS (*n*-CdS) / *p*-CdTe with Current Collecting Contacts ITO and ZnO

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The optical and recombination losses in auxiliary and absorbing layers of solar cells based on heterojunctions *n*-ZnS / *p*-CdTe and *n*-CdS / *p*-CdTe with current collecting front sublayers ITO and ZnO were determined. As a result, spectral dependence of light transmittance (T) of solar cells, taking into account its reflections from the boundaries of the contacting materials and in case of absorption in the auxiliary layers of solar cells was calculated. The influence of optical and recombination losses in the solar cell structure ITO (ZnO) / CdS (ZnS) / CdTe on the short circuit current (J_{sc}) and efficiency (η) of solar cells with different thickness of the window layer CdS (ZnS) (50-300 nm) and constant current collecting layer (200 nm) was investigated. It has been established that the greatest efficiency values (15.9-16.1%) solar cells have the structure of ZnO / ZnS / CdTe at a concentration of uncompensated acceptors in the absorbent layer $(N_a - N_d) = 10^{15}$-10^{17} cm^{-3} and the window layer thickness of 50 nm.

Keywords: Thin films solar cells, *n*-CdS / *p*-CdTe, *n*-ZnS / *p*-CdTe, Optical losses, Recombination losses, Efficiency.

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1. INTRODUCTION

The mass use of photovoltaic cells (PVC) for the conversion of solar energy into electricity is one of the ways out of the global energy crisis. Currently, the most common solar cells (SC), which are used, are those based on silicon technology. Thin film SC on the basis of heterojunction (HJ) *n*-CdS / *p*-CdTe are an alternative to these converters. We should note, this is the first technique which allowed to decrease the solar energy production cost to 0.57 $/W that is lower than the economically justified price of the solar energy 1 $/W [1].

According to theoretical estimates, efficiency of film SC with absorbing CdTe layer is equal to 28-30 % [2]. However, the real coefficient of performance of SC based on *n*-CdS / *p*-CdTe HJ with "superstrate" structure is today equal to 20.4 % [3], and efficiency of solar modules with an area larger than 1 cm^2 – 16.5 % [4, 5]. The difference between theoretical predictions and real values of the device efficiency is explained by optical, electrical and recombination losses in the conversion of solar energy into electricity.

The main irreversible energy losses in PVC are connected with:

– reflection of solar radiation from the surface and heteroboundaries of the PVC;

– passage of a part of radiation through the PVC without absorption;

– scattering by thermal lattice vibrations of the excess photon energy;

– recombination of the electron-hole pairs formed under the action of light on the surfaces and in the interior of the PVC;

– internal resistance of the converter;

– some other physical processes.

Further increase in the SC efficiency is possible only by minimization of these losses during the optimization of their design and improvement of the properties of separate layers.

ITO ($(In_2O_3)_{0.9}$-$(SnO_2)_{0.1}$) or FTO (SnO_2 : F) is traditionally used as a current collecting sublayer in the design of *n*-CdS / *p*-CdTe SC of the "superstrate" type [6, 7]. Moreover, aluminum-doped zinc oxide films (ZnO : Al) are recently used as frontal current collecting layers of PVC [8, 9]. This material is cheaper than ITO or FTO and does not contain rare and expensive elements, to which, for example, indium belongs.

We should note, the choice of a window layer plays an important role in the production of thin film SC. In this guise, CdS ($E_g = 2.42$ eV) is widely used currently. Thin ZnS layers which have already found application in SC based on CIS, CIGS, CZTSe, and CZTS compounds [10, 11] can be an alternative to CdS films. Zinc sulfide has a significantly larger band gap ($E_g = 3.68$ eV) than cadmium sulfide that allows to extend the range of photosensitivity of the corresponding SC and increase their short circuit currents [12]. This compound is non-toxic due to the absence of heavy metals in the composition. Finally, ZnS layer can act as anti-reflective coating of SC that increases the number of photons absorbed by PVC and, correspondingly, its coefficient of performance [13].

The authors of the works [14, 15] have considered the light reflection losses in SC with the following design: glass / ITO (TCO) / CdS / CdTe / back metal contact. Recombination losses of photogenerated carriers in these PVC are considered in [14, 16]. However, the influence of the optical and recombination losses on the efficiency of SC of the design glass / ZnO / ZnS / CdTe / back metal contact has not been studied up to now. This has conditioned the goal of the investigation.

The main aim of the present work is the determination and comparison of the optical and recombination losses in PVC of two different designs, investigation of their influence on the efficiency of SC on the basis of *n*-ZnS / *p*-CdTe and *n*-CdS / *p*-CdTe HJ with frontal current collecting contacts ITO and ZnO.

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2. OPTICAL LIGHT REFLECTION LOSSES IN SC

Thin film SC based on HJ of the "superstrate" type have a multi-layer structure and contain the substrate (glass), window (CdS, ZnS) and absorbing (CdTe) layers, current collecting frontal (ITO, ZnO) and back metal contacts. Schematic view of the typical PVC with the structure glass / ITO (ZnO) / CdS (ZnS) / CdTe / back contact is illustrated in Fig. 1.

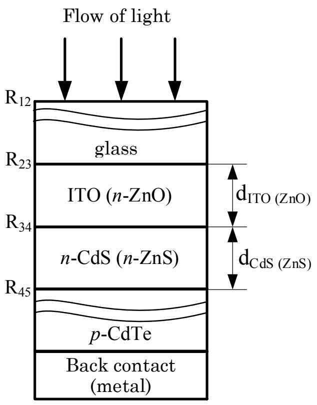

Fig. 1 – Schematic representation of the SC design based on n-ZnS / p-CdTe and n-CdS / p-CdTe HJ (R_{ij} are the boundary light reflection coefficients; d is the layer thickness)

We have performed the modeling of the light reflection processes from a multilayer structure in the thickness range of the CdS (ZnS) window layer $d = 50$-300 nm and constant thickness of the current collecting frontal layer ITO (ZnO) $d = 200$ nm. These values are typical for real SC [9].

The flow of sunlight before reaching the absorbing CdTe material, where photogeneration of electron-hole pairs occurs under the action of light, passes through a number of auxiliary SC layers: glass, ITO (ZnO) and CdS (ZnS). The optical energy losses because of light reflection from the interfaces air-glass, glass-ITO (ZnO), ITO (ZnO)-CdS (ZnS) and CdS (ZnS)-CdTe and absorption of a luminous flux in the auxiliary layers of glass, ITO (ZnO) and CdS (ZnS) occur in this case.

We have determined the reflection coefficient from the interfaces of contacting materials by the Fresnel formula [14]

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

where n_1, n_2 are the refractive indexes of the first and the second contacting materials, respectively.

In the case of the use of current-conducting materials, n_1^*, n_2^* are the complex refractive indexes; k_1, k_2 are the attenuation (extinction) indexes of the materials.

Spectral dependences of the refractive and attenuation indexes for each layer entered into the SC composition, which are necessary for the calculations of the optical light losses, are represented in Fig. 2. The value of the attenuation index for glass was taken to be zero ($k = 0$), in connection with the fact that a special glass, which has a very small absorption coefficient, is usually used in PVC. For the determination of the refractive index of glass, the Zelmeer formula was applied [17]

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

where constants are equal to $a_1 = 0.6962$, $a_2 = 0.4079$, $a_3 = 0.8974$, $\lambda_1 = 68$ nm, $\lambda_2 = 116$ nm, $\lambda_3 = 9896$ nm.

For the construction of the spectral dependences of n and k we have used the reference values of the refractive and attenuation indexes for ITO, ZnO, CdS, ZnS, CdTe [18, 19]. In the modeling, it was taken for air that $n_1 = 1$, $k_1 = 0$.

The calculated spectral dependences of the reflection coefficient from SC layers at their direct contact with air are illustrated in Fig. 3a. As seen from the figure, the maximum reflection coefficient is observed on the air/CdTe interface and the minimum reflection coefficient – on the air/glass interface.

In Fig. 3b we present the calculated spectral dependences of the reflection coefficient from the interface of two contacting materials. Emphasis is placed on the obtained low values of these coefficients which belong to the range 0.002-0.085. For comparison, calculation results for the reflection at the interface of the same materials with air give much higher values $R = 0.034$-0.380. As seen from Fig. 3b, ZnO / ZnS interface has the smallest reflection values (0.002-0.036) that is explained by low light refractive indexes in these materials.

The light transmittance through auxiliary layers of glass, ITO (ZnO), and CdS (ZnS) in the case of neglect of the absorption processes is determined by the formula $T = 1 - R$. Thus, transmittance of multilayer SC structure can be found by the formula [20]

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

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

We should note that the given correlation does not take into account multiple light reflections in layers of glass, ITO (ZnO), CdS (ZnS) that is quite acceptable for small reflection coefficients at the interfaces of materials (Fig. 3b). Small reflection coefficients allow also to ignore the interference effects.

Calculation results of the light transmission and reflection coefficients on the wavelength in SC based on n-ZnS / p-CdTe and n-CdS / p-CdTe HJ are represented in Fig. 4. As seen from the figure, in the short-wave spectral region at the wavelength $\lambda = (300$-$450)$ nm the light transmittance of SC with ZnO and ZnS layers is larger (by 0.6-5.7 %) than the corresponding values for PVC in which ITO and CdS layers are used.

3. OPTICAL LIGHT ABSORPTION LOSSES IN SC

In a general case, except reflection it is necessary to take into consideration light absorption losses in auxiliary layers of PVC. Transmittance of a multilayer structure including reflection and absorption losses in the window and current conducting layers of SC can be calculated using the expression [20]

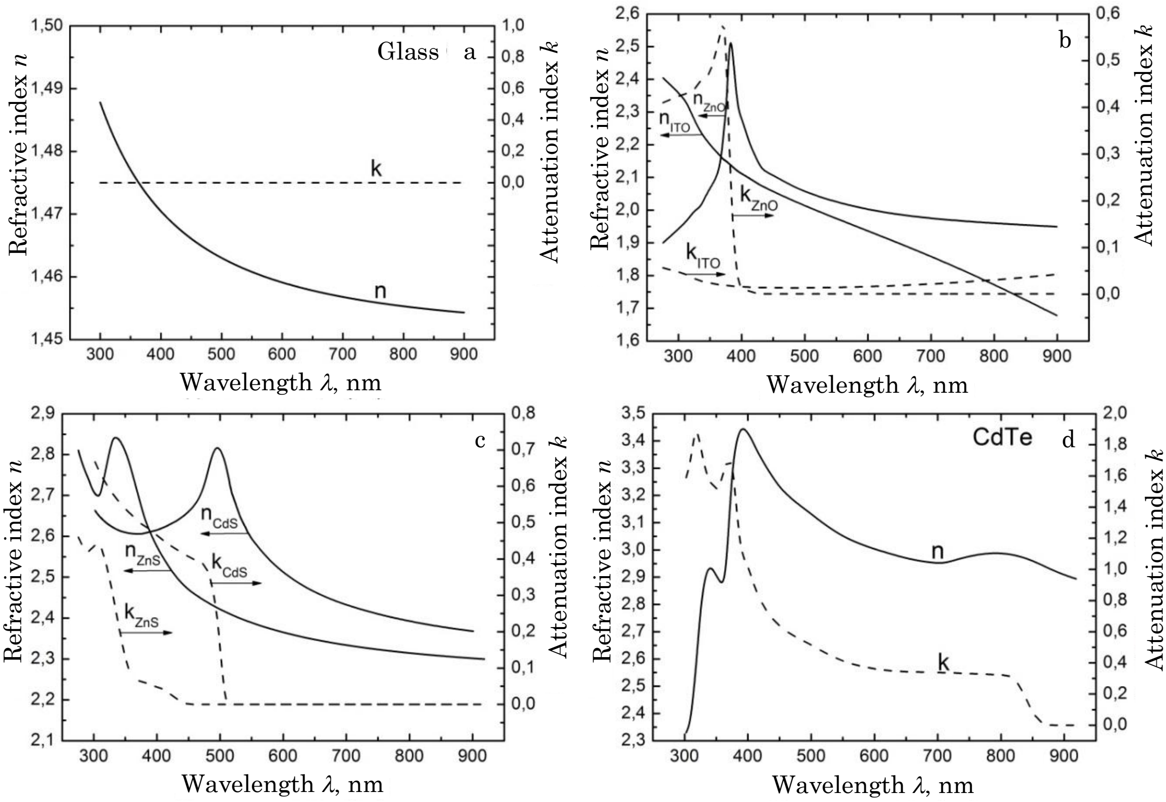

Fig. 2 – Spectral dependences of the refractive and attenuation indexes for glass (a), ITO (ZnO) (b), CdS (ZnS) (c), CdTe (d)

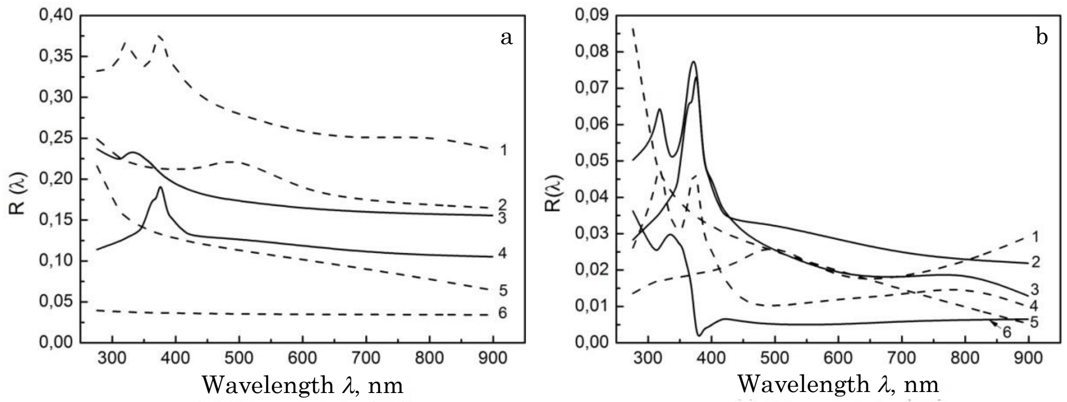

Fig. 3 – Spectral dependences of the reflection coefficients (R) for the interfaces: air-glass (6), air-ITO (5), air-ZnO (4), air-CdS (2), air-ZnS (3), air-CdTe (1) (a) and glass-ITO (5), glass-ZnO (2), ITO-CdS (1), ZnO-ZnS (6), CdS-CdTe (4), ZnS-CdTe (3) (b)

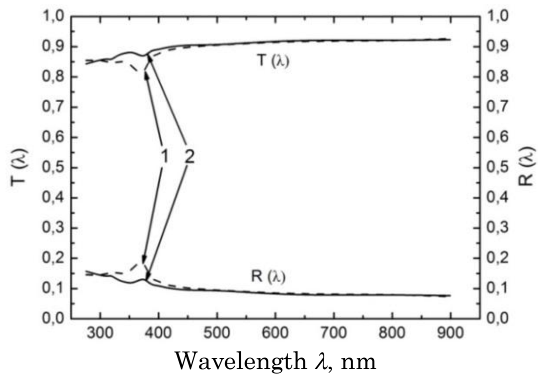

Fig. 4 – Spectral dependences of the transmittance and reflection coefficient for SC with ITO/CdS/CdTe (1) and ZnO/ZnS/CdTe (2) structures with taking into account light reflection from the interfaces

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

where α_1, α_2 are the absorption coefficients of the of the materials of the conducting and window layers; d_1, d_2 are their thicknesses.

Solar radiation absorption coefficient $\alpha(\lambda)$ with regard to the attenuation index as a function of the wavelength $k(\lambda)$ can be calculated by the following correlation:

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

Dependences of the transmittance on the radiation wavelength for SC with ITO, CdS and ZnO, ZnS layers taking into account absorption in auxiliary layers at different values of their thickness are shown in Fig. 5.

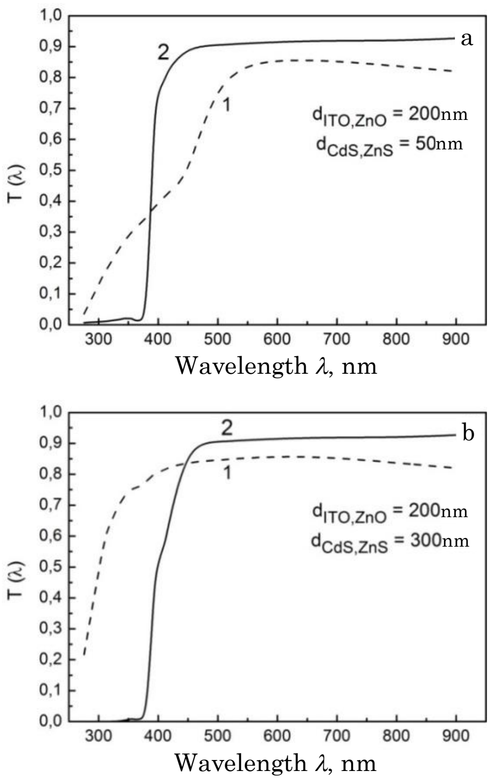

Fig. 5 – Spectral dependences of the transmittance of multilayer glass / ITO / CdS / CdTe (1) and glass / ZnO / ZnS / CdTe (2) structures for CdS (ZnS) thickness: 50 nm (a), 300 nm (b) and ITO (ZnO): 200 nm

As expected, the use of a wider gap material as window of PVC leads to the increase in the transmittance of a multilayer structure, primarily, in the short-wave spectral region. Analysis of the dependences illustrated in Fig. 5 implies that at the thickness of window layers of $d = 50$ nm the value of the transmittance of SC with ZnO / ZnS layers in the wavelength range of $\lambda = (380$-$900)$ nm are larger by (2-42) % than the corresponding value for the ITO / CdS structure, and at $d = 300$ nm – by (1-8) % at the wavelength of $\lambda = (450$-$900)$ nm.

4. SPACE CHARGE REGION WIDTH AND SC QUANTUM YIELD

The space charge region width (d), in other words, the depletion region appearing at the heteropair contact is one of the important parameters which determines the efficiency of photovoltaic light conversion and is used for the analysis of the recombination losses in SC. This width depends mainly on the concentration of uncompensated acceptors $N_a - N_d$ (i.e. the difference between acceptor and donor concentrations) located in the material. Because of the high doping level of window material and correspondingly high conductivity of doped films of cadmium sulfides (10^{17}-10^{18} cm^{-3}) and zinc (10^{17} cm^{-3}), the depletion region of n-CdS (n-ZnS) / p-CdTe HJ is located in the CdTe layer. Thus, the charge transfer processes occurring in the depletion region of HJ from the physical point of view are similar to those, which take place in the Schottky diode depletion regions. In this case, the space charge region width can be found using the expression [2]

$$d = \sqrt{\frac{2\varepsilon\varepsilon_0(\varphi_0 - qU)}{q^2(N_a - N_d)}} , \quad (7)$$

where ε is the relative permittivity of the material; ε_0 is the permittivity of free space; φ_0 is the HJ barrier height; U is the applied external voltage; q is the electron charge; $(N_a - N_d)$ is the concentration of uncompensated acceptors in absorbing layer.

The values presented in Table 1 we used in the work for the calculation of d.

Calculation of the space charge region width gives the possibility to determine the quantum yield Q of SC n-CdS (n-ZnS) / p-CdTe by the following formula:

$$Q = \frac{1 + \dfrac{S}{D_P}\left(\alpha + \dfrac{2\cdot(\varphi_0 - qU)}{d\cdot kT}\right)^{-1}}{1 + \dfrac{S}{D_P}\left(\dfrac{2\cdot(\varphi_0 - qU)}{d\cdot kT}\right)^{-1}} - \frac{e^{-\alpha d}}{1 + \alpha L_n}, \quad (8)$$

where S is the recombination rate of carriers at the HJ boundary; D_n, D_p are the diffusion coefficients of holes; α is the light absorption coefficient in CdTe layer; k is the Boltzmann constant; T is the temperature; L_n is the diffusion length of electrons ($L_n = (\tau_n D_n)^{1/2}$, where τ_n is the lifetime of electrons).

Table 1 – The main parameters which were used for the determination of d and Q

Parameter	Values
ε	10.6
$\varphi_0 - qU$	$(0.70\ \text{eV})_{CdS}$, $(0.82)_{ZnS}$
$(N_a - N_d)$	10^{11}-10^{17} cm^{-3}
S	10^7 cm/s
τ_n	10^{-9} s
D_n	25 cm^2/s
D_p	2 cm^2/s
T	300 K

The values of the light absorption coefficient in CdTe for the wavelength range of 300-850 nm were taken from the work [18]. It was assumed that recombination rate of carriers at the boundaries in both HJ was the same.

We should note that expression (8) does not take into account recombination at the back surface of CdTe layer which can lead to significant losses in the PVC efficiency in the case of a small thickness of absorbing layer. If neglect the second term in expression (8) (due to the strong absorption of a luminous flux at small wavelengths) and also at the absence of charge carrier recombination at the surface ($S = 0$), then the value of the quantum yield can reach 1. Thus, deviations of the obtained values of Q from the maximum ones for the wavelength $\lambda = (300\text{-}850)$ nm can be explained by the surface recombination.

In Fig. 6 we show the dependence of the photoelectric quantum yield on the concentration of uncompensated acceptors ($N_a - N_d$) in absorbing CdTe layer (the calculated values of the parameters are represented in Table 1) for n-CdS / p-CdTe (a) and n-ZnS / p-CdTe (b) HJ. We have to note that calculated values of Q for the given HJ are close that can be explained by a small difference in the heights of potential barriers in these structures (Table 1).

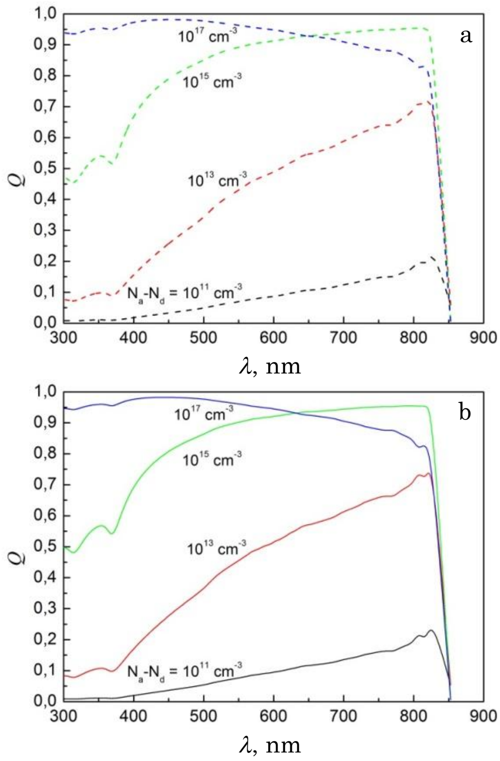

Fig. 6 – Calculated quantum yield Q of SC at different values of the concentration of uncompensated acceptors in CdTE layer ($N_a - N_d$) for n-CdS / p-CdTe (a) and n-ZnS / p-CdTe (b) HJ

As seen from Fig. 6, if $N_a - N_d = 10^{11}\text{-}10^{15}$ cm^{-3} the increase in the SC quantum yield occurs with increasing wavelength of a luminous flux. In this case, the given factor takes the maximum values at the photon energy close to the CdTe band gap ($\lambda \approx 840$ nm). The calculations show that quantum yield takes the maximum values at the concentrations of uncompensated acceptors of $10^{15}\text{-}10^{17}$ cm^{-3}, i.e. at the space charge region width of $d = (0.11\text{-}1.08)$ μm. The last value is close to the region thickness of 98 % of light absorption in CdTe. Thus, the presence of a pulling electric field in the region of basic radiation absorption leads to the considerable increase in the SC quantum yield. The analysis shows that doping of the absorbing material to the values of $N_a - N_d = 10^{15}\text{-}10^{17}$ cm^{-3} are optimal for the obtaining of the maximum efficiency of PVC based on the considered HJ.

It also follows from the dependences shown in Fig. 6 that surface recombination has a larger influence on the values of the quantum yield at a smaller concentration of uncompensated acceptors (wider space charge region).

5. DETERMINATION OF THE SHORT-CIRCUIT CURRENT DENSITY OF SC (J_{SC})

The short-circuit current density of SC (J_{sc}) can be calculated by the formula [14]

$$J_{sc} = q\sum_i T(\lambda)\frac{\varphi_i(\lambda_i)}{h\upsilon_i}Q(\lambda_i)\Delta\lambda_i\ , \qquad (9)$$

where φ_i is the spectral power density of solar radiation; $\Delta\lambda_i$ is the interval between neighboring values of the wavelength λ_i.

Calculation of the short-circuit current was carried out during the irradiation of SC by solar radiation in the conditions of AM 1.5 (Tables ISO 9845-1:1992). We should note that light losses by reflection, absorption and recombination were calculated for the barrier height of 0.7 eV in the case of n-CdS / p-CdTe HJ [22] and 0.82 eV – n-ZnS / p-CdTe HJ [23].

In Fig. 7 we illustrate the dependence of the short-circuit current density of ITO (ZnO) / CdS (ZnS) / CdTe SC on the window layer thickness in view of the light losses by reflection and absorption in the PVC auxiliary layers. Here, thickness of a current conducting ITO (ZnO) layer was equal to 200 nm; this value is typical for SC.

Reflection losses at the SC interfaces were only taken into consideration in the calculation of the first point in Fig. 7 ($d_{CdS(ZnS)} = 0$, $d_{ITO(ZnO)} = 0$). The obtained values of J_{sc} for SC with ITO / CdS / CdTe and ZnO / ZnS / CdTe structures are represented in Table 2.

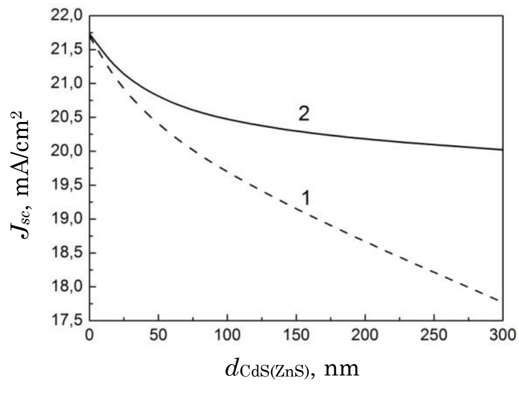

Fig. 7 – Dependence of the short-circuit current density J_{sc} on the window layer thickness for SC based on ITO / CdS / CdTe (1) and ZnO / ZnS / CdTe (2)

Table 2 – The values of the short-circuit current density J_{sc} (mA/cm^2) for ITO / CdS / CdTe and ZnO / ZnS / CdTe SC at different window layer thicknesses

SC structure		Window layer thickness, nm			
		0	50	100	300
ITO/CdS/CdTe	J_{sc} (mA/cm^2)	21.70	19.99	19.66	17.77
ZnO/ZnS/CdTe	J_{sc} (mA/cm^2)	21.73	20.40	20.18	20.02

Thus, when taking into consideration the reflection and absorption losses in the auxiliary layers of SC with ZnO / ZnS / CdTe structure, the values of the short-circuit current density are higher by (0.03-0.52) mA/cm^2 than the corresponding values of ITO / CdS / CdTe SC in the whole variation range of the window layer thickness of (0-300) nm.

In Fig. 8 we present the dependences of the impact of the optical and recombination losses on the short-circuit current density in ITO / CdS / CdTe and ZnO / ZnS / CdTe SC at different values of the concentration of uncompensated acceptors. As seen from the figure, for ZnO / ZnS / CdTe SC the short-circuit current density values slightly decrease with increasing window layer thickness and doping level of CdTe layer (space charge region width). At the same time, the inverse dependence is observed for ITO / CdS / CdTe SC. The maximum difference in the values of J_{sc} between mentioned SC structures appears for the window layer thickness of 50 nm and is equal to (2.1-5.7) mA/cm^2.

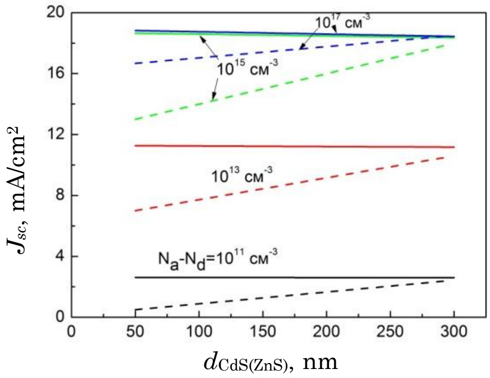

Fig. 8 – Short-circuit current density J_{sc} for ITO / CdS / CdTe (chain line) and ZnO / ZnS / CdTe (solid line) SC depending on the window layer thickness and concentration of uncompensated acceptors ($N_a - N_d$)

General (optical and recombination) losses at values of $d_{(CdS)ZnS} = 50$ nm and $(N_a - N_d) = 10^{17}$ cm^{-3} in different SC designs are equal to: ITO / CdS / CdTe – 21.3 %, ZnO / ZnS / CdTe – 13.4 %. Analyzing Fig. 8, we should note that with increasing concentration of uncompensated acceptors to 10^{17} cm^{-3} in absorbing CdTe layer and at different values of the window layer thickness, the short-circuit current J_{sc} for multilayer ITO / CdS / CdTe and ZnO / ZnS / CdTe SC structures takes the following values: 16.67 mA/cm^2, 18.82 mA/cm^2 ($d_{ITO(ZnS)} = 50$ nm) and 18.35 mA/cm^2, 18.44 mA/cm^2 ($d_{ITO(ZnS)} = 300$ nm), respectively.

6. INFLUENCE OF THE RECOMBINATION AND OPTICAL LOSSES ON THE SC EFFICIENCY

SC efficiency η (%) can be calculated using formula [9]

$$\eta = \frac{U_{xx} \cdot J_{sc} \cdot FF}{P_{in}}, \qquad (10)$$

where U_{xx} is the open-circuit voltage of SC; J_{sc} is the short-circuit current density; FF is the filling factor; P_{in} is the input power.

In Table 3 we specify the parameters of real PVC which were used for further calculations.

We should note that from the physical point of view the open circuit voltage (U_{xx}) cannot exceed the value of the potential barrier height at HJ.

Table 3 – The values of the main parameters of the real ITO/CdS/CdTe and ZnO/ZnS/CdTe SC for the determination of the efficiency of photoconversion

SC structure	U_{xx}, mV	FF, %	P_{in}, mW/cm^2	Reference
ITO/CdS/CdTe	0.572	63	100	[1]
ZnO/ZnS/CdTe	0.817	80		[5]

In Fig. 9 we show the dependence of the SC efficiency on the thickness of window layers (CdS, ZnS) and doping level of absorbing layer.

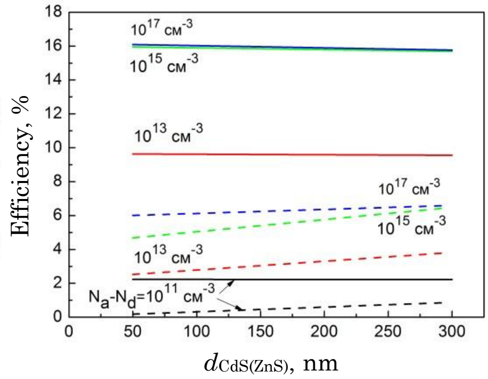

Fig. 9 – Influence of the optical and recombination losses on the efficiency of SC with ITO / CdS / CdTe (chain line) and ZnO / ZnS / CdTe (solid line) structures depending on the window layer thickness and the concentration of uncompensated acceptors ($N_a - N_d$)

It is seen from Fig. 9 that SC with ZnO / ZnS / CdTe structure have the maximum values of the efficiency (15.9-16.1 %) at the concentration of uncompensated acceptors of (10^{15}-10^{17} cm^{-3}). For the given structure, with decreasing concentration of uncompensated acceptors ($N_a - N_d$) to 10^{11} cm^{-3}, efficiency of energy conversion by PVC sharply decreases to ≈ 2.3 %. It is established that the value of η for SC with ITO / CdS / CdTe structure is lower by (2-10) % subject to the window layer thickness and width d than with ZnO / ZnS / CdTe.

7. CONCLUSIONS

In the present work we have determined and compared the optical and recombination losses in SC based on n-ZnS / p-CdTe and n-CdS / p-CdTe HJ with frontal current conducting contacts ITO and ZnO. It is shown that the use of wider gap material (ZnS) as a PVC window leads to the increase in the transmittance of multilayer structures in the ultraviolet spectral region. For the window layer thickness of $d = 50$ nm ($d = 300$ nm), the value of the transmittance of SC with the structure glass / ZnO / ZnS / CdTe is larger by (2-42) and (1-8) % at the wavelength of $\lambda = (380\text{-}900)$ and $\lambda = (450\text{-}900)$ nm, respectively.

It is found that the calculated value of the quantum yield of SC takes the maximum values at the photon energy close to E_g CdTe ($\lambda \approx 840$ nm) and concentration of uncompensated acceptors of 10^{15}-10^{17} cm^{-3}. Decrease in Q connected with surface recombination of light-generated charge carriers occurs with decreasing length of incident radiation. Surface recombination in a greater degree influences the value of the quantum yield at a smaller concentration of uncompensated acceptors.

Calculated general (optical and recombination) losses in SC of different constructions are the following: ITO / CdS / CdTe – 21.3 %, ZnO / ZnS / CdTe – 13.4 % at $d_{(CdS)ZnS}$ = 50 nm and $(N_a - N_d) = 10^{17}$ cm^{-3}. It is established that SC with ZnO / ZnS / CdTe structure has the maximum values of the efficiency (15.9-16.1 %) at the concentration of uncompensated acceptors of (10^{15}-10^{17} cm^{-3}) and window layer thickness of 50 nm. The values of the efficiency for SC with ITO / CdS / CdTe structure are lower by (2-7) % depending on the window layer thickness d.

The carried out calculations give the possibility to determine the real maximum value of the SC efficiency with taking into account the optical and recombination losses in PVC layers.

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