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# Fabrication and Properties of the Photosensitive Anisotype $n\text{-Cd}_x\text{Zn}_{1-x}\text{O}/p\text{-CdTe}$ Heterojunctions

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We have fabricated photosensitive anisotype  $n\text{-Cd}_x\text{Zn}_{1-x}\text{O}/p\text{-CdTe}$  heterojunctions by a deposition of  $\text{Cd}_{0.5}\text{Zn}_{0.5}\text{O}$  film onto freshly-cleaved CdTe monocrystalline wafers using a radiofrequency magnetron reactive sputtering of a zinc-cadmium alloy target. Fundamental electrical properties of the heterojunctions were studied. Dominant mechanisms of a current transport were found.  $n\text{-Cd}_x\text{Zn}_{1-x}\text{O}/p\text{-CdTe}$  heterojunctions were photosensitive and were able to operate both in photovoltaic and photodiode modes.

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## 1. Introduction

Properties of the cadmium telluride (CdTe) create pre-conditions for its using in a fabrication of the high-performance solar cells [1–5]. The practical use of the wide-band gap semiconducting components (windows), namely ZnO and CdO, in the fabrication of the CdTe-based heterojunctions is one of peculiar interest.

Zinc oxide is a semiconductor with sufficiently wide band gap ( $E_g = 3.3$  eV) at the room temperature. ZnO is transparent for most of the solar spectrum [6, 7]. Up to present time, the low resistive ZnO films have been obtained and have been used as a wide-band gap window in heterojunctions with low power loss [8]. For these reasons, a study of the  $n\text{-ZnO}/p\text{-CdTe}$  heterojunctions is of great interest [9–11].

Cadmium oxide (CdO) is also a prospective material for utilizing in a photoelectric industry. It could be used as a substitution of the highly-toxic CdS in CdS/CdTe heterojunctions due to its suitable properties [12].

In this regard, the  $\text{Cd}_x\text{Zn}_{1-x}\text{O}$  alloy films have attracted considerable attentions [13–19]. It is well known that the increase of the zinc content ( $0.5 \leq x \leq 1.0$ ) in  $\text{Cd}_x\text{Zn}_{1-x}\text{O}$  solid solutions leads to the increase in band-gap energy. This feature allows expanding the spectral region of the photosensitivity of the CdTe-based solar cells towards short wavelengths.

A main aim of this work is to design the anisotype  $n\text{-Cd}_{0.5}\text{Zn}_{0.5}\text{O}/p\text{-CdTe}$  heterojunctions. We mainly focused on the study of their electrical properties. The dominant current transport mechanisms at direct and reverse bias were established.

## 2. Experimental details

Wafers of  $p$ -type CdTe single crystal (the electrical conductivity  $\sigma = 8.9 \times 10^{-2} \Omega\text{cm}^{-1}$  and the carrier

concentration  $p = 7.2 \times 10^{15} \text{ cm}^{-3}$  at room temperature) were used as substrates for fabrication of  $n\text{-Cd}_x\text{Zn}_{1-x}\text{O}/p\text{-CdTe}$  heterostructures.

$\text{Cd}_x\text{Zn}_{1-x}\text{O}$  films were deposited onto the freshly-cleaved wafers of the bulk CdTe (with size of  $5 \times 5 \times 1$  mm) by the rf reactive magnetron sputtering technique. The sputtering was performed with rf excitation at 13.56 MHz from an alloy target ( $\text{Cd}_{0.5}\text{Zn}_{0.5}$ ) with diameter of 40 mm. Argon and oxygen were used as the sputtering and chemically active gases, respectively. Ar/O<sub>2</sub> gas ratio was maintained at 4:1. The substrate temperature was equal to 373 K. The structures differ from previously investigated similar structures [18], by the method of forming  $\text{Cd}_{0.5}\text{Zn}_{0.5}\text{O}$  film on CdTe substrate.

$\text{Cd}_x\text{Zn}_{1-x}\text{O}$  thin layers were  $n$ -type and characterized by the high values of the conductivity ( $\sigma = 10 \Omega\text{cm}^{-1}$ ) and free carrier concentration ( $n = 10^{19} \text{ cm}^{-3}$ ). The study of the optical transmission spectra reveals the high transparency of the films in the visible ( $T \approx 65\text{--}90\%$ ). A band-gap energy of  $\text{Cd}_x\text{Zn}_{1-x}\text{O}$  film ( $E_g = 2.7$  eV) was determined from the spectral dependence of the absorption coefficient near the fundamental absorption edge. This value corresponds to Cd content as high as  $x = 0.5$  [13].

A front electrical contact to  $\text{Cd}_x\text{Zn}_{1-x}\text{O}$  film was formed by thermal deposition of aluminum at 100°C. The formation of the back electrical contact to  $p\text{-CdTe}$  single crystal was accompanied with irradiation of surface by pulsed laser radiation (with further deposition of the gold and cooper layers). Current–voltage ( $I\text{--}V$ ) and capacity–voltage ( $C\text{--}V$ ) characteristics of  $n\text{-Cd}_{0.5}\text{Zn}_{0.5}\text{O}/p\text{-CdTe}$  heterostructures were measured using the complex of SOLARTRON SI 1286, SI 1255. Light  $I\text{--}V$  characteristics were measured under visible light in the standard illumination conditions closed to AM 1.5 (100 mW/cm<sup>2</sup>).

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### 3. Results and discussion

The surface-barrier  $n\text{-Cd}_x\text{Zn}_{1-x}\text{O}/p\text{-CdTe}$  heterostructures were characterized by the well-described rectification behavior. A potential barrier height  $e\phi_\kappa$  at the  $T = 295$  K was equal to 0.63 eV. A rectification factor at the voltage  $V = 2.0$  V was  $5 \times 10^3$ . Since the free carrier concentration in films ( $n = 10^{19} \text{ cm}^{-3}$ ) is larger than that of substrate ( $p = 7.2 \times 10^{15} \text{ cm}^{-3}$ ),  $n\text{-Cd}_x\text{Zn}_{1-x}\text{O}/p\text{-CdTe}$  heterostructures may be classified as asymmetrical heterojunctions with space-charge region forming in CdTe.

$I$ - $V$  characteristics of  $n\text{-Cd}_x\text{Zn}_{1-x}\text{O}/p\text{-CdTe}$  heterojunctions, which were measured at the forward bias and at different temperatures, are depicted in Fig. 1.

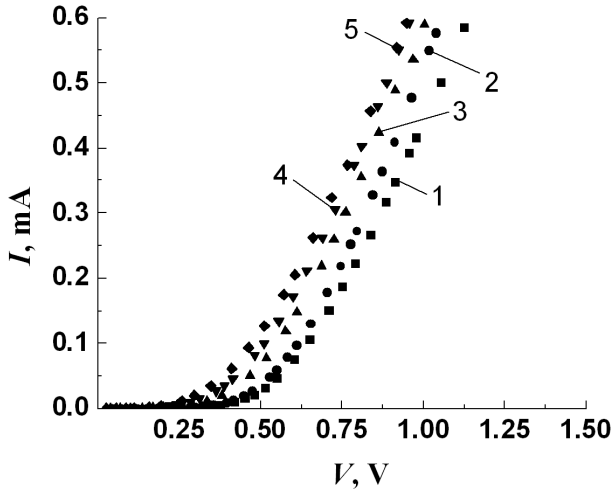


Fig. 1. Direct branches of the  $I$ - $V$  characteristics of  $n\text{-Cd}_x\text{Zn}_{1-x}\text{O}/p\text{-CdTe}$  heterostructures at the different temperatures: 1 — 295 K, 2 — 305 K, 3 — 321 K, 4 — 334 K, 5 — 348 K.

A series resistance  $R_S$  of the heterostructure, which was determined by the straight sections of the  $I$ - $V$  characteristics with consideration of geometrical dimensions of substrate, was about  $8.3 \times 10^2 \Omega$  at the  $T = 295$  K. This value is in good agreement with the value of the resistance of the base material.

The study of the  $C$ - $V$  characteristics showed its linearity in the coordinates  $C^{-2}$ - $V$ , which indicates the homogeneous distribution of the concentration of uncompensated acceptor impurities within the space charge region [20]. In addition, the heterojunction capacitance dependence on the frequency of the excitation signal was observed, which is typical for rectifying structures with a rather large series resistance  $R_S$  [21]. The potential barrier height was determined using the approach proposed in Ref. [21] for structures with high  $R_S$  and was as high as 1.58 eV. Discrepancy between the potential barrier height values determined from  $I$ - $V$  and  $C$ - $V$  characteristics is caused by electrically charged heterointerface [20].

An analysis of the carrier flow mechanisms at the forward bias was carried out with consideration of the series

resistance  $R_S$  because of its great value. In this case  $I$ - $V$  characteristic can be described by the expression [20]:

$$I(V) = I_S \exp\left(\frac{e(V - IR_S)}{kT}\right), \quad (1)$$

where  $I_S$  is the saturation current,  $V$  is the applied voltage,  $IR_S$  is the voltage drop across a series resistance of the structure.

Linear  $I$ - $V$  characteristics in semilog scale suggest exponential dependence of  $\ln I = f(V)$  in the specified voltage range, indicating the presence of two dominant current flow mechanisms (Fig. 2).

Both straight regions of the  $I$ - $V$  characteristics ( $V < 0.5$  V and  $0.5 < V < 1.5$  V) can be quite well described by the formula [22]:

$$I(V) = I_S[\exp(eV/AkT) - 1], \quad (2)$$

where  $I_S$  is the value of saturation current,  $e$  is the elementary charge,  $V$  is the applied voltage,  $k$  is the Boltzmann constant,  $A$  is the nonideality coefficient,  $T$  is the absolute temperature.

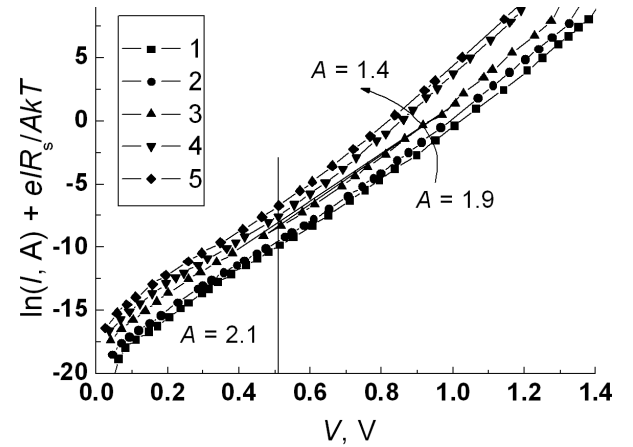


Fig. 2. The forward  $I$ - $V$  characteristics (in semi-logarithmic scale) of  $n\text{-Cd}_x\text{Zn}_{1-x}\text{O}/p\text{-CdTe}$  heterojunctions at the different temperatures: 1 — 295 K; 2 — 305 K, 3 — 321 K, 4 — 334 K, 5 — 348 K.

The nonideality coefficient was about 2.1 for the small voltages ( $V < 0.5$  V) and did not depend on the temperature. It suggests that the main current flow mechanism in this voltage range is the recombination in the space charge region through deep energy states with a small contribution of surface states.

In the voltage range of  $0.5 < V < 1.5$  V,  $A$  value was smaller than 2 and was decreasing from 1.9 to 1.35 when the temperature was changing from  $T = 295$  K to  $T = 348$  K. It indicates that the emission-recombination mechanism of the current flow is dominant. The value of parameter  $A$  (in the voltage range of  $0.5 < V < 1.5$  V) is smaller than 2 and changes from 1.9 to 1.35 with increasing the temperature from  $T = 295$  K to  $T = 348$  K. It indicates that the emission-recombination mechanism of the current flow is dominant. A decrease of  $A$  with increasing the temperature in the given voltage range

indicates an increase in the contribution of emission (over-barrier) component of the electric current, which is caused by reducing the height of the potential barrier.

Measurement of the  $I$ - $V$  characteristics at the reverse bias showed a rapid increase in the value of the reverse current with voltage  $I_{\text{rev}}(V)$ . This behavior can be described by the linear dependence in the coordinates  $I_{\text{rev}}(V) = f(\sqrt{\phi_k - eV})$ , thereby indicating the dominance of the generation processes.

It should be noted that the tunnel-recombination mechanism of carrier transport proper to majority of heterojunctions [22], especially for  $n$ - $\text{Cd}_x\text{Zn}_{1-x}\text{O}/p$ - $\text{CdTe}$  heterostructure [18], was observed neither at forward nor at reverse bias. It can be explained by a decrease in the density of the electrically-active states at the heterointerface due to an improvement of  $n$ - $\text{Cd}_x\text{Zn}_{1-x}\text{O}$  thin films' crystal structure [22].

It is noteworthy that  $n$ - $\text{Cd}_{0.5}\text{Zn}_{0.5}\text{O}/p$ - $\text{CdTe}$  structures were photosensitive (Fig. 3).

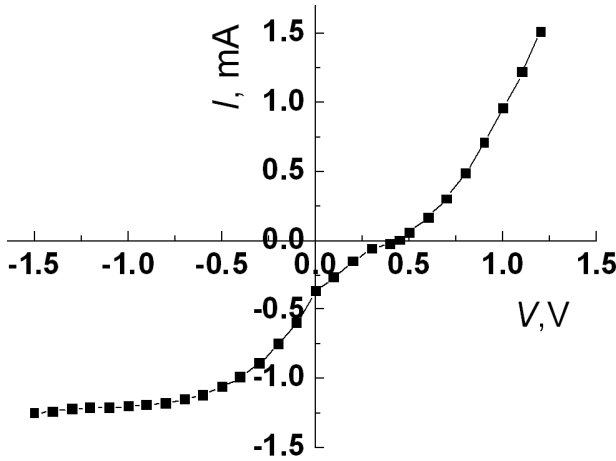


Fig. 3. Light  $I$ - $V$  characteristic of  $n$ - $\text{Cd}_{0.5}\text{Zn}_{0.5}\text{O}/p$ - $\text{CdTe}$  heterostructure under illumination by white light ( $100 \text{ mW}/\text{cm}^2$ ).

The structures were characterized by the presence of the saturation photocurrent region in the voltage range of  $0.5 \text{ V} \leq V \leq 1.5 \text{ V}$ . This fact together with the ratio of photocurrent to dark current (at least  $4 \times 10^3$ ) allow effective use of these heterostructures in the photodiode mode. A circuit voltage  $V_{oc}$  and a short-circuit  $J_{sc}$  current, which were determined from the light  $I$ - $V$  characteristics of  $n$ - $\text{Cd}_{0.5}\text{Zn}_{0.5}\text{O}/p$ - $\text{CdTe}$  heterojunction, were equal to  $0.5 \text{ V}$  and  $2.0 \text{ mA}/\text{cm}^2$ , respectively. However, the dependence of the efficiency of the photogenerated carriers' separation on the applied bias ( $S$ -shaped light  $I$ - $V$ ) significantly reduces the fill factor ( $\text{FF} = 0.23$ ). This dependence can be explained by the presence of the electrical dipole or recombination processes via the surface states at the heterointerface. Such dependence can be caused by both a presence of an electric dipole, which influences on the energetic parameters of the heterojunction, and recombination processes via surface states at

the heterointerface that play the role of traps for photo-generated electrons at the forward bias (Fig. 4).

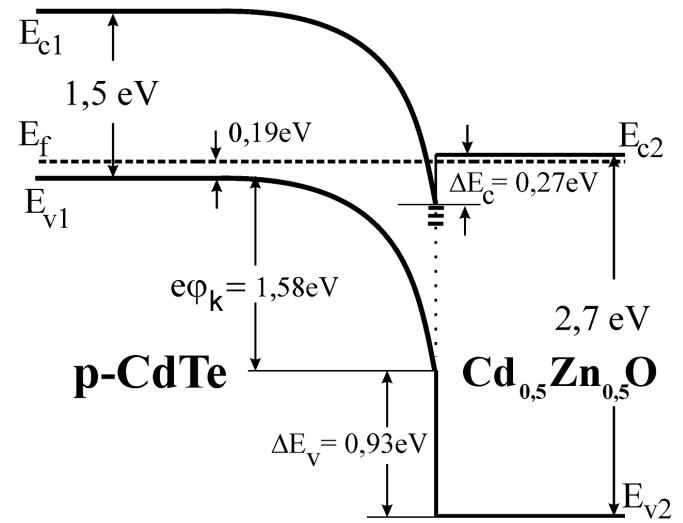


Fig. 4. Energetic diagram of  $n$ - $\text{Cd}_{0.5}\text{Zn}_{0.5}\text{O}/p$ - $\text{CdTe}$  heterostructure.

Further investigation of the dominant mechanisms of recombination losses of photogenerated carriers in  $n$ - $\text{Cd}_{0.5}\text{Zn}_{0.5}\text{O}/p$ - $\text{CdTe}$  heterojunctions is required to improve the photovoltaic parameters of heterostructures.

#### 4. Conclusions

We have fabricated the anisotype photosensitive surface-barrier  $n$ - $\text{Cd}_x\text{Zn}_{1-x}\text{O}/p$ - $\text{CdTe}$  heterostructures grown by rf magnetron reactive sputtering of  $\text{Cd}$ - $\text{Zn}$  alloy target onto freshly-cleaved bulk  $\text{CdTe}$  substrate. It was shown that these heterojunctions were referred to the abrupt asymmetrical surface-barrier structures. It was found that the forward and reverse  $I$ - $V$  characteristics were defined by the generation-recombination processes via surface energy states at the heterointerface.  $n$ - $\text{Cd}_x\text{Zn}_{1-x}\text{O}/p$ - $\text{CdTe}$  heterostructures were photosensitive and could be operated both in photovoltaic and photodiode modes in the voltage range of  $0.5 \text{ V} \leq V \leq 1.5 \text{ V}$ .

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