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Photosensitive n-$Zn_{0.5}Cd_{0.5}O$/p-InSe Heterostructures Prepared by Magnetron Sputtering

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This paper studied the electrical and photovoltaic properties of n-$Zn_{0.5}Cd_{0.5}O$/p-InSe heterostructures. The n-$Zn_{0.5}Cd_{0.5}O$ film was deposited onto InSe substrate by magnetron sputtering. The advantage of using InSe as the substrate is a simple technology. The atomically smooth surface of the substrate was obtained by simple mechanical exfoliation due to chemical bonding feature of InSe crystals. It did not contain broken bonds and did not require further polishing. The quality of the grown $Zn_{0.5}Cd_{0.5}O$ film was controlled by AFM. The structure of the $Zn_{0.5}Cd_{0.5}O$ film and its growth processes were analyzed on the basis of AFM data. The measurement of current-voltage characteristics at different temperatures was performed for the purpose of determining the mechanism of current flow in the studied heterostructures. The features of forward and reverse branches of current-voltage characteristics were discussed. The value of the diode coefficient was calculated. The capacity-voltage characteristics were measured at room temperature. The height of the potential barrier at the interface was calculated. The photoresponse spectra of heterostructures were studied. New regularities were found that cannot be explained within the framework of the impurity photoconductivity model.

Keywords: Heterostructures, Photosensitivity, *I-V* characteristic, *C-V* characteristic.

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1. INTRODUCTION

Indium monoselenide (InSe) is a layered semiconductor with a weak van der Waals bond between the layers. The InSe band gap (E_g = 1.26 eV) is in the range of optimal values for photoelectric conversion of solar radiation in terrestrial conditions. InSe is an excellent candidate for substrates of different heterostructures. The substrates are obtained by simple mechanical exfoliation, which results in atomically smooth surfaces that do not require further mechanical or chemical treatment. Employment of InSe as a substrate material enables fabrication of photosensitive structures of different types: Schottky diodes [1, 2], homojunctions [3, 4], and heterojunctions [5-7].

This paper presents the results of the characterization of $Zn_{0.5}Cd_{0.5}O$ films deposited onto InSe substrates. The features of growth kinetics are considered. Such studies are of interest because InSe surface does not contain broken chemical bonds thanks to the van der Waals nature of this layered crystal. Therefore, the interface does not contain other intermediate phases. In addition, the van der Waals bond between the layers reduces mechanical stresses that occur at the interface due to the possibility of relative sliding of the layers. As a result, thermal effects have less effect on the quality of the interface compared to substrates made of traditional semiconductors.

In addition, heterostructures formed by deposition of ZnO and CdO films on different semiconducting substrates show promising photosensitive properties [8-10].

2. EXPERIMENTAL

The p-InSe crystals grown by the Bridgman method were used to fabricate n-$Zn_{0.5}Cd_{0.5}O$/p-InSe heterostructures. The p-type conductivity in InSe was achieved by cadmium doping. The concentration of charge carriers was $p \approx 10^{14}$ cm^{-3} and the hole mobility across the c axis was $\mu_{pH} \approx 50$ cm^2/(V·s) at room temperature.

The n-$Zn_{0.5}Cd_{0.5}O$ film was deposited onto InSe substrate by magnetron sputtering. The current-voltage (*I-V*) and capacity-voltage (*C-V*) characteristics were measured with a SOLARTRON SI 1286, SI 1255 complex. The photosensitivity spectra were studied at room temperature using an MDR 3 monochromator.

3. RESULTS AND DISCUSSION

Fig. 1 shows an atomic force microscopy (AFM) image of the $Zn_{0.5}Cd_{0.5}O$ film surface. It can be clearly seen that the film is not continuous. It consists of randomly scattered formations of $Zn_{0.5}Cd_{0.5}O$ with different lateral sizes, their maximum height is about 20 nm.

Fig. 1b shows that the oxide surface is covered with dome-shaped nanoformations. Their growth is due to the migration of oxide molecules to the substrate surface and subsequent merging into larger clusters. The shape of the nanoformations indicates that the oxide molecules do not wet well the substrate surface and tend to form spherical droplets as the most stable formations from the thermodynamic point of view. Due to the large number of nucleation centers on the substrate surface, coalescence processes lead to a uniform distribution of oxide clusters on the substrate.

AFM images show that the film is highly inhomogeneous in structure. It is basically an ensemble of oxide nanoformations separated from each other. The structure of the lower layers of the film is such that

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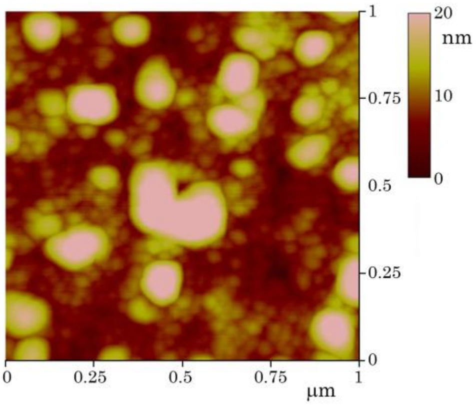
traces of cracking caused by thermal effects and mechanical stresses are visible. All these features of the films must be taken into account when considering the photoelectric characteristics of the oxide/layered crystal film heterojunctions.



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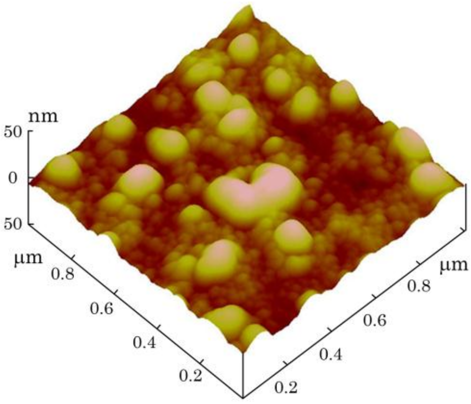
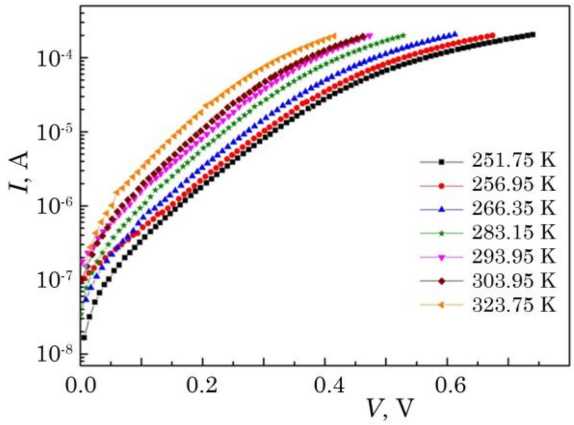


b

Fig. 1 – AFM image of the surface of the $Zn_{0.5}Cd_{0.5}O$ film

The temperature dependences of the *I-V* characteristics in the temperature range $T = 250\text{-}325$ K (Fig. 2) were measured to determine the mechanism of current flow in the heterojunction. The forward branches of the *I-V* characteristic must be linear in semi-logarithmic coordinates. As can be seen from Fig. 2a, only the middle part of forward branches is linear. Deviations from linearity are observed at small and large currents. At low currents, the charge transfer processes are not determined by the barrier. At high currents, they are determined by the effect of the series resistance on the *I-V* characteristics [11]. The curves shift upwards with decreasing temperature. To determine the slope of the *I-V* characteristics, the experimental data were approximated by a straight line. The value of the diode coefficient was greater than 2 (≈ 2.5). Typically, the independence of the slope of the *I-V* characteristic is associated with tunneling processes. But it can also be associated with shunt currents. In case of a significant height of the potential barrier, tunneling is unlikely. So, there are shunt currents. These currents can be caused by the channels created during the formation of the front oxide film, which is confirmed by the AFM image of the film surface.



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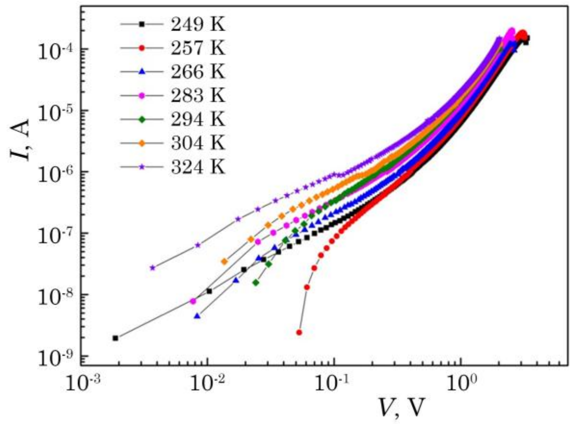

b

Fig. 2 – Temperature dependences of the forward (a) and reverse (b) branches of the *I-V* characteristic of the *n*-$Zn_{0.5}Cd_{0.5}O$/*p*-InSe heterostructure

Fig. 2b shows the temperature dependences of the reverse branches of the *I-V* characteristic. In logarithmic scale, individual parts of the *I-V* characteristics can be approximated by different power dependences, which indicate the mechanism of current flow. We have the following dependences: $I \sim U$ (ohmic law) at low voltage, $I \sim U^2$ (quadratic law) at medium voltage, and $I \sim U^3$ (cubic law) at higher reverse bias [12]. This behavior of the *I-V* characteristics shows that the mechanism of charge carrier generation in a strong electric field of the *p-n* junction is associated with the ionization of different types of impurity levels in the InSe substrate.

The *C-V* characteristics were measured to determine the height of the potential barrier at the interface. They are linear in the coordinates $C^{-2} = f(U)$, because the dependence of the capacitance on the voltage is given by the equation [11]:

$$C/a = [qN_A\varepsilon/2 \cdot 1/(V_D - U)]^{1/2}, \qquad (1)$$

where a is the area of the *p-n* junction, V_D is the contact potential difference, N_A is the concentration of uncompensated acceptors.

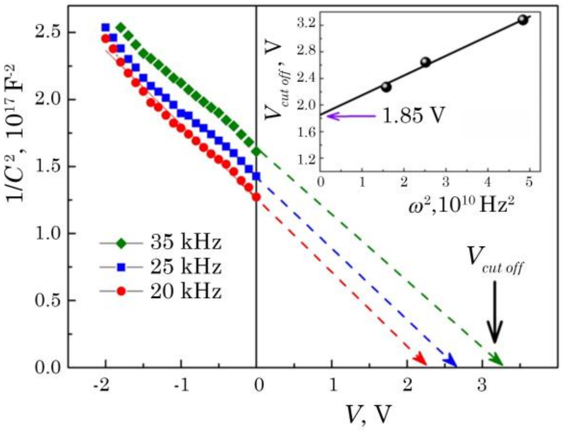

Fig. 3 – *C-V* characteristic of the n-$Zn_{0.5}Cd_{0.5}O$/p-InSe heterostructure

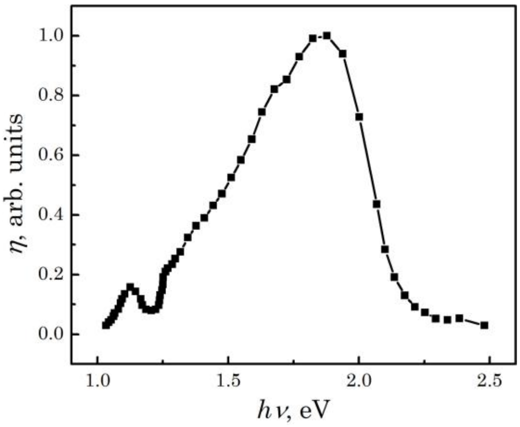

Fig. 4 – Spectral dependence of the relative quantum efficiency of the n-$Zn_{0.5}Cd_{0.5}O$/p-InSe heterostructure

Equation (1) is valid for abrupt heterojunctions. As it can be seen from Fig. 3, Eq. (1) describes well the *C-V* characteristics of our heterostructures. The slope of the curves can be used to determine the concentration of uncompensated acceptors in InSe, because the depleted region is in a more resistive substrate. In addition, a strong frequency dependence of the *C-V* characteristics was detected. If the slope of the *C-V* characteristics at different frequencies does not change, then the cut-off on the bias axis is different. The frequency dependence of the cut-off voltages is shown in the inset in Fig. 3. Approximation of this dependence to zero frequency should give the true value of the height of the potential barrier. As can be seen from the inset in Fig. 3, this value is 1.85 V. However, it is inflated due to shunt currents across the heterojunction, which makes it difficult to measure the capacitance at frequencies lower than 20 kHz.

The important properties of a heterojunction are the photosensitivity and spectral characteristics. The new features were found in the spectrum of the photoresponse, which are shown in Fig. 4. Typically, the absorption spectrum is limited on two sides. On the left, the absorption edges are determined by light absorption in the narrow-band InSe, and on the right – by light absorption in the large band gap oxide. But in the spectra of our heterojunction, a new long-wavelength band with a maximum at 1.1 eV was detected. It is less than the InSe bang gap. The observed changes in the photosensitivity spectrum cannot be explained in terms of impurity photoconductivity, as no additional bands occurred for other heterojunctions with the same InSe substrate. We assume that a new intermediate phase is formed at the interface during deposition of $Zn_{0.5}Cd_{0.5}O$ films. It is responsible for the observed features of the spectrum. The sharp short-wavelength edge of absorption indicates structural perfection of the grown oxide.

4. CONCLUSIONS

The features of growth kinetics of $Zn_{0.5}Cd_{0.5}O$ films deposited onto InSe substrate are discussed. It is found that the film is not continuous but is formed from randomly scattered formations of $Zn_{0.5}Cd_{0.5}O$ with different lateral sizes. It is shown that the value of the diode coefficient is greater than 2 (≈ 2.5). It is also found that the main current transfer mechanism in the heterostructure is shunt currents. These currents can be caused by the channels formed during the film growth, which is confirmed by AFM images. The photoresponse spectra of the heterostructure were also investigated and a new long-wavelength band with a maximum at 1.1 eV was detected. It can be explained by the formation of an intermediate phase at the interface.

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Фоточутливі гетероструктури *n*-$Zn_{0.5}Cd_{0.5}O$/*p*-InSe, виготовлені методом магнетронного розпилення

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В роботі проведено дослідження електричних та фотоелектричних властивостей гетероструктури *n*-$Zn_{0.5}Cd_{0.5}O$/*p*-InSe. Плівка $Zn_{0.5}Cd_{0.5}O$ наносилась на підкладку InSe методом магнетронного розпилення. Перевагою використання InSe є проста технологія виготовлення підкладки. Атомарно-гладка поверхня підкладки отримується простим механічним сколюванням завдяки особливостям хімічного зв'язку кристалів InSe. Вона не містить розірваних зв'язків та не потребує подальшого полірування. Якість вирощеної плівки $Zn_{0.5}Cd_{0.5}O$ перевірялась за допомогою АСМ мікроскопії. На основі АСМ зображень проаналізовано структуру плівки $Zn_{0.5}Cd_{0.5}O$ та процеси її росту. Для визначення механізму протікання струму в досліджуваній гетероструктурі були проведені виміри ВАХ при різних температурах. Обговорено хід прямих та обернених віток. Визначено значення діодного коефіцієнту. Проведені виміри ВФХ при кімнатній температурі. Визначена висота потенційного бар'єру на інтерфейсі. Досліджено спектри фотовідгуку гетероструктури. Встановлено нові закономірності, які не можна пояснити в рамках моделі домішкової фотопровідності.

Ключові слова: Гетероструктури, Фоточутливість, Вольт-амперні характеристики, Вольт-фарадні характеристики.