

Fabrication and Characterization of Photosensitive n -CdO/ p -InSe Heterojunctions

Z.R. KUDRYNSKYI^{a,*}, Z.D. KOVALYUK^a, V.M. KATERYNCHUK^a, V.V. KHOMYAK^b,
I.G. ORLETSKY^b AND V.V. NETYAGA^a

^aInstitute for Problems of Materials Science of National Academy of Sciences of Ukraine
Iryny Vilde 5, Chernivtsi 58001, Ukraine

^bChernivtsi National University, Kotsubynskogo, 2, Chernivtsi 58012, Ukraine

(Received February 16, 2013; in final form April 3, 2013)

Photosensitive n -CdO/ p -InSe heterojunctions were developed and studied for the first time. The heterojunctions were fabricated by dc reactive magnetron sputtering of CdO thin films onto the freshly cleaved p -InSe single-crystal substrates (0 0 1). Surface morphology of the obtained films was studied by means of atomic force microscopy. From the X-ray diffraction result it is shown that the CdO film is polycrystalline with cubic structure. The mechanisms of current transport through the space-charge region under forward and back biases were established by investigation of temperature dependences of the I - V characteristics. The main photoelectric parameters and the photosensitivity spectra were measured at room temperature.

DOI: [10.12693/APhysPolA.124.720](https://doi.org/10.12693/APhysPolA.124.720)

PACS: 73.40.Lq, 73.40.Gk, 68.35.B-, 72.20.Jv

1. Introduction

Indium monoselenide (InSe) belongs to $A^{III}B^{VI}$ layered semiconductor crystals [1]. It presents a layered structure, exhibiting weak “van der Waals” bonding between separate, covalently bonded Se–In–In–Se layers [1, 2]. Such layered crystal structure results in strong anisotropy of its properties [1]. InSe crystals can be easily cleaved along the basal plane. Atomically smooth surface of the cleaved facet features a low density of surface states ($\leq 10^{10} \text{ cm}^{-2}$) and small value of root-mean-square roughness ($\approx 0.05 \text{ nm}$) [3, 4]. The absence of dangling bonds on InSe cleaved surface makes it possible to use this semiconductor as a substrate for growing molecular [5] and metal [6] nanostructures, as well as fabrication of heterostructures on the basis of semiconductor materials with different symmetries and lattice spacings [7–10].

Cadmium oxide (CdO) is a promising transparent conducting oxide [11, 12]. It has attracted much attention because of its high optical transmittance and low resistivity [13–15]. CdO is a wide bandgap semiconductor and exhibits n -type conductivity [16].

Thin films of CdO have been used in wide variety of applications such as photovoltaic cells [17–20], transparent electrodes [21], photodiodes [22] and phototransistors [23].

CdO is of particular interest because of its application as a wide bandgap “window” layer in heterojunctions [14, 15, 24].

In the present study, we developed new photosensitive n -CdO/ p -InSe heterojunctions. We report on surface morphology of CdO thin films deposited onto p -InSe substrates, as well as electrical and photoelectrical properties of the obtained heterojunctions.

2. Experimental methods

We used p -InSe single crystals as substrates of the heterojunctions. The InSe single crystals were grown by the Bridgman method and doped by adding cadmium in order to obtain p -type conductivity. The content of cadmium dopant was 0.01%. At room temperature the concentration of uncompensated acceptors and majority carrier mobility were measured to be $p = 10^{14} \text{ cm}^{-3}$ and $\mu_p = 100 \text{ cm}^2/(\text{V s})$, respectively.

The CdO thin films were deposited onto the freshly cleaved p -InSe single-crystal substrates (0 0 1) with typical dimensions $5 \times 5 \times 0.3 \text{ mm}^3$ by dc reactive magnetron sputtering, as it had been described in [25]. High purity indium (In) was used as a contact material. Figure 1 shows the schematic diagram of the n -CdO/ p -InSe heterojunction.

The crystal structure of the developed heterojunction was investigated using an X-ray diffraction (XRD) system (DRON-2.0 diffractometer) with a Cu K_α source. LATTIK-KARTA software was used to analyze the obtained XRD patterns.

The current–voltage (I - V) characteristics of the heterojunction were measured in the temperature range $254 \div 332 \text{ K}$ using a “Schlumberger SI.1255” setup.

Photosensitivity spectra of the n -CdO/ p -InSe heterojunctions were measured by means of MDR-3 monochromator (reciprocal linear dispersion 2.6 nm/mm) at room temperature.

*corresponding author; e-mail: kudrynskyi@gmail.com

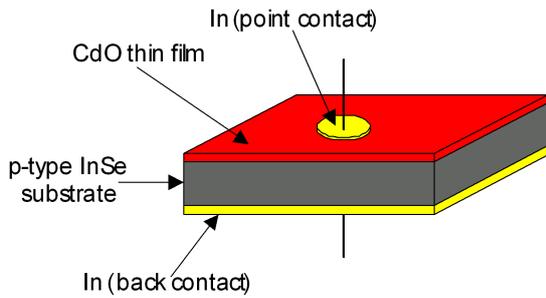


Fig. 1. Schematic diagram of the n -CdO/ p -InSe heterojunction.

Surface morphology of the CdO thin films was studied by atomic force microscopy (AFM) using Nanoscope IIIa Dimension 3000SPM (Digital Instruments).

3. Results and discussion

Figure 2 shows the XRD pattern of the n -CdO/ p -InSe heterojunction. In the XRD pattern, besides the reflections of the InSe substrate, one can see the reflections of CdO: 111, 200, 220, 311, 222 (the peaks are indicated by arrows).

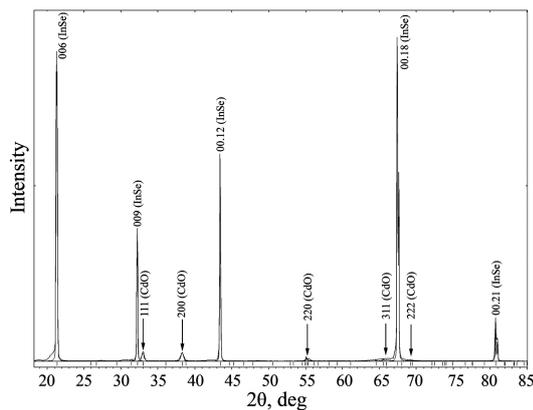


Fig. 2. XRD pattern of the n -CdO/ p -InSe heterojunction. The peaks of CdO are indicated by the arrows.

The XRD analysis revealed that the structure of the InSe substrate had the following lattice constants: $a = 4.002 \text{ \AA}$, $c = 24.9678 \text{ \AA}$. The CdO films were polycrystalline with cubic structure. The lattice constant a was evaluated from the XRD patterns: $a = 4.6954 \text{ \AA}$. The data obtained from the XRD analysis are in good agreement with other studies [11, 14, 26].

It should be noted that the (0 0 1) surface of the InSe layered crystal is a natural cleaved facet. Since the interaction between the adjacent layers is of "Van der Waals" type, there are very few dangling bonds and their role is insignificant. This peculiarity of the bonds determines the inert properties of the surface. Previous studies on

surface morphology of the cleaved facets of InSe crystals showed that the surface is atomically smooth [3, 4]. The 3D atomic force microscopy (AFM) image of the CdO thin film deposited onto p -type InSe is shown in Fig. 3. As seen in Fig. 3, the surface of the CdO film is not smooth. The root-mean-square value of the surface roughness was evaluated to be 0.432 nm.

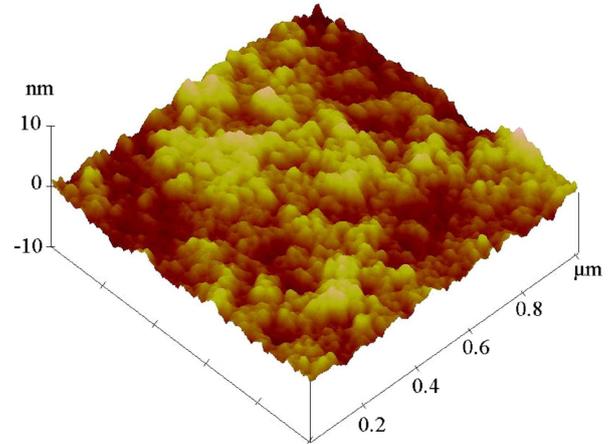


Fig. 3. 3D AFM image of CdO deposited onto p -type InSe.

The experimental results of the investigation of I - V characteristics of the n -CdO/ p -InSe heterojunctions can be described by the following equation:

$$J = J_s \left[\exp \left(\frac{qU}{nkT} \right) - 1 \right], \quad (1)$$

where J_s is the saturation current, q is the electron charge, U is the applied voltage, n is the ideality factor, k is the Boltzmann constant, T is the temperature. The value of n is different for different current mechanisms. In order to define it, as follows from Eq. (1), it is necessary to conduct the measurements of the forward branches of the I - V characteristics at different temperatures.

These dependences of the n -CdO/ p -InSe heterojunction are plotted and shown in Fig. 4. They were investigated in the temperature range from 254 K to 332 K. In the semilogarithmic coordinates all the curves have linear segments in the voltage interval 0 ÷ 0.4 V. By taking into account the slope of the linear segments it is possible to define the ideality coefficient (n) of the forward branches of the I - V characteristics at each studied temperature. The parallel shift of the I - V characteristics, which occurs during the decrease of temperature, indicates that forward current is temperature independent. This is typical for tunneling. But tunneling of carriers through the p - n junction at low forward bias is improbable, because the barrier region is too thick and prevents tunneling. Tunnel-recombination model can be an alternative explanation of the observed dependences of the forward current. In this model the defects of the heterointerface are determinant. The defects can be resulted by crystal lattice mismatch of CdO and InSe. The

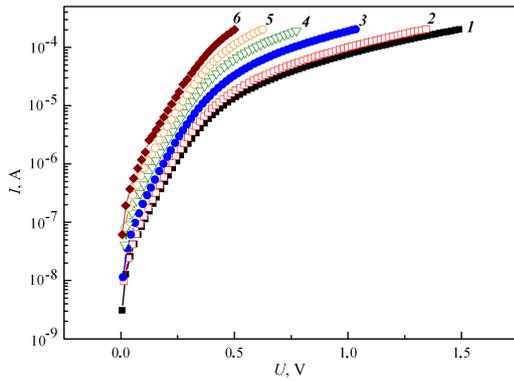


Fig. 4. The I - V characteristics of the n -CdO/ p -InSe heterojunctions under forward bias in the semilogarithmic scale at temperatures T : 1 — 254, 2 — 260, 3 — 277, 4 — 296, 5 — 313, 6 — 332 K.

value of n at low current density exceeds 2 and is equal to 2.45 at room temperature.

It is also seen from Fig. 4 that at high current the curves become almost saturated. In this case, charge carrier transport occurs mostly through series resistance and does not reflect the real current mechanism through the rectifying barrier.

Temperature dependences of the I - V characteristics under back bias, which reflect the current through the space-charge region, are plotted in log-log scale and shown in Fig. 5.

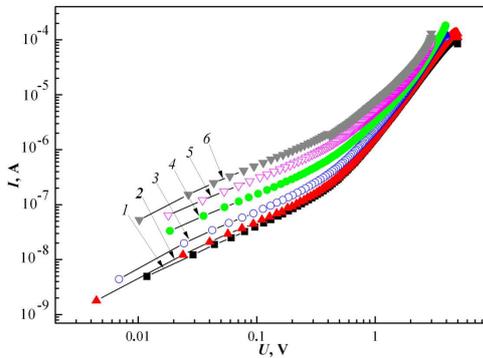


Fig. 5. The I - V characteristics of the n -CdO/ p -InSe heterojunctions under back bias in log-log scale at temperatures T : 1 — 254, 2 — 260, 3 — 277, 4 — 296, 5 — 313, 6 — 332 K.

As seen in Fig. 5, the dependences of current on bias are linear with different slopes. It means that they can be described by a power function $I \sim U^m$. At room temperature the I - V characteristic has 3 different slopes with $m = 1, 2, 3$. Such behaviour of the I - V characteristic of the space-charge region is typical for the currents limited by space charge.

The n -CdO/ p -InSe heterojunctions produced the open-circuit voltage $V_{oc} = 0.53$ V and the short-

-circuit current $I_{sc} = 6 \text{ mA cm}^{-2}$ under illumination of 100 mW cm^{-2} .

Analysis of the photosensitivity spectra of the n -CdO/ p -InSe heterojunctions allowed us to establish their peculiarities and detect a thin structure in the long-wave edge. The photosensitivity spectrum is shaped as a band, which is abruptly limited in terms of energy from both sides (Fig. 6). The maximum is observed at 2.48 eV which corresponds with the band-gap energy of CdO [16, 27–29].

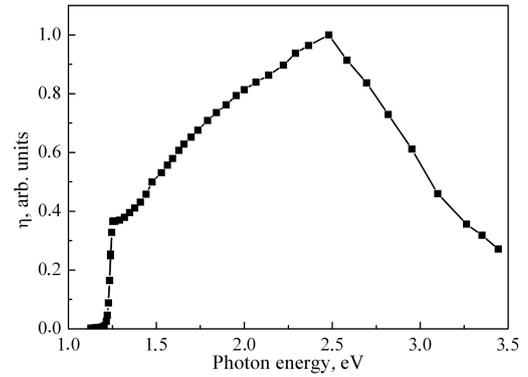


Fig. 6. The photosensitivity spectrum of the n -CdO/ p -InSe heterojunction.

The light with the energy $h\nu < E_{g1}$ (E_{g1} is the band-gap energy of the frontal semiconductor CdO) is absorbed directly in the near-surface region of the base semiconductor E_{g2} (InSe), where the p - n junction region is simultaneously located. In this heterojunction the “window” effect is used. It means that the light of certain energy ($E_{g2} < h\nu < E_{g1}$) passes through the frontal semiconductor without obstruction, and the regions of photogeneration and space-charge coincide. The photogenerated carriers are separated by electric field and form the long-wave edge of the photosensitivity. In the long-wave edge of the spectrum, one can observe a sharp maximum, which is of exciton nature.

4. Conclusion

We developed new photosensitive n -CdO/ p -InSe heterojunctions. The heterojunctions were fabricated by dc reactive magnetron sputtering of CdO onto the freshly cleaved p -InSe single-crystal substrates (001). The analysis of AFM images of the CdO thin film revealed that the surface is nanostructured. The root mean square value of the surface roughness was evaluated to be 0.432 nm.

The mechanisms of current transport through the space-charge region under forward and back biases were established by the investigation of temperature dependences of the I - V characteristics. The main mechanism of current transport through the potential barrier is tunnel recombination. This is resulted by the mismatch of crystal lattice constants of CdO and InSe at the heterointerface. Under back bias the main currents are limited

by the space charge and described by a power function dependence.

The developed heterojunctions are photosensitive. Their spectrum is limited in the scale of photon energies by the light absorption in the oxide and the base semiconductor. The long-wave edge of the spectrum has a sharp peak at room temperature. It can be explained by the influence of not only the fundamental but also excitonic light absorption in InSe crystal. It is worth noting that the *n*-CdO/*p*-InSe heterojunctions were fabricated without the optimization of technological parameters and additional treatments. It is expected that the controllable change of technological parameters of the CdO thin films' deposition and annealing of the heterojunctions in vacuum can enhance the efficiency of the photoelectric conversation.

References

- [1] F.S. Ohuchi, M.A. Olmstead, in: *Wiley Encyclopedia of Electrical and Electronics Engineering*, Ed. J.G. Webster, Wiley, New York 1999, Vol. 19, p. 147.
- [2] I.C.I. Terhell, *Prog. Cryst. Growth Charact.* **7**, 55 (1983).
- [3] V.M. Katerynychuk, Z.D. Kovalyuk, *Semicond. Phys. Quantum Electron. Optoelectron.* **14**, 106 (2011).
- [4] V.M. Katerynychuk, Z.D. Kovalyuk, *Inorg. Mater.* **47**, 749 (2011).
- [5] K. Ueno, K. Sasaki, K. Saiki, A. Koma, *Jpn. J. Appl. Phys.* **38**, 511 (1999).
- [6] W. Jaegermann, C. Pettenkofer, B.A. Parkinson, *Phys. Rev. B* **42**, 7487 (1990).
- [7] N. Wisotzki, A. Klein, W. Jaegermann, *Thin Solid Films* **380**, 263 (2000).
- [8] A.P. Bakhtinov, V.N. Vodop'yanov, E.I. Slyn'ko, Z.D. Kovalyuk, O.S. Lytvyn, *Tech. Phys. Lett.* **33**, 86 (2007).
- [9] V.M. Katerynychuk, Z.R. Kudrynskyi, Z.D. Kovalyuk, *J. Nano-Electron. Phys.* **4**, 02042 (2012).
- [10] Z.D. Kovalyuk, V.M. Katerynychuk, A.I. Savchuk, O.M. Sydor, *Mater. Sci. Eng. B* **109**, 252 (2004).
- [11] B.J. Lokhande, P.S. Patil, M.D. Uplane, *Mater. Chem. Phys.* **84**, 238 (2004).
- [12] B. Roy, *II-VI Compounds*, Pergamon Press, Oxford 1969.
- [13] K.L. Chopra, S.R. Das, *Thin Film Solar Cells*, Plenum, New York 1983.
- [14] M. Caglar, F. Yakuphanoglu, *J. Phys. D, Appl. Phys.* **42**, 045102 (2009).
- [15] S. Karatas, F. Yakuphanoglu, *J. Alloy Comp.* **537**, 6 (2012).
- [16] N. Ueda, H. Maeda, H. Hosono, H. Kawazoe, *J. Appl. Phys.* **84**, 6174 (1998).
- [17] C.H. Champness, K. Ghoneim, J.K. Chen, *Can. J. Phys.* **63**, 767 (1985).
- [18] C. Sravani, K.T.R. Reddy, P. Jayarama Reddy, *J. Alloys Comp.* **215**, 239 (1994).
- [19] R.A. Ismail, O.A. Abdulrazaq, *Sol. En. Mater. Sol. Cell* **91**, 903 (2007).
- [20] M. Ocampo, P.J. Sebastian, J. Campos, *Phys. Status Solidi A* **143**, K29 (1994).
- [21] F.A. Benko, F.P. Koffyberg, *Solid State Commun.* **57**, 901 (1986).
- [22] R. Kondo, H. Okhimura, Y. Sakai, *Jpn. J. Appl. Phys.* **10**, 1547 (1971).
- [23] L.M. Su, N. Grote, F. Schmitt, *Electron. Lett.* **20**, 717 (1984).
- [24] C. Sravani, K.T.R. Reddy, O.Md. Hussain, P. Jayarama Reddy, *Thin Solid Films* **253**, 339 (1994).
- [25] V.V. Brus, M.I. Iashchuk, V.V. Khomyak, Z.D. Kovalyuk, P.D. Maryanchuk, K.S. Ulyanytsky, *Semiconductors* **46**, 1152 (2012).
- [26] O. Vigil, F. Cruz, A. Morales-Acevedo, G. Contreras-Puente, L. Vaillant, G. Santana, *Mater. Chem. Phys.* **68**, 249 (2001).
- [27] H. Khlyap, *Physics and Technology of Semiconductor Thin Film-Based Active Elements and Devices*, Bentham Sci. Publ. Ltd., Kaiserslautern 2009.
- [28] R.A. Ismail, A.-M.E. Al-Samarai, S.J. Mohmed, H.H. Ahmed, *Solid State Electron.* **82**, 115 (2013).
- [29] R.A. Ismail, *J. Mater. Sci., Mater. Electron.* **20**, 1219 (2009).