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Electrical and photoelectrical properties of *n*-InSe/*p*-$CuInSe_2$ optical contact

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Abstract. Photosensitive heterojunctions were created by the method of optical contact of layered semiconductor InSe to $CuInSe_2$ plates. Due to high quality of contacting surfaces, a strong and enough perfect electrical junction is formed. To understand processes occurring in such heterojunctions, the measurements of current-voltage characteristics in forward and reverse directions, photoelectric modification of the direct branch of the current-voltage characteristic, capacitance-voltage characteristic, spectrum of the relative quantum efficiency have been carried out at the room temperature. The structures had a well-pronounced photovoltaic effect – the open-circuit voltage was 0.5 V and the short-circuit current density – 0.7 mA/cm^2. The conclusion about possibility of application of the obtained heterojunctions as photodetectors is made.

Keywords: $CuInSe_2$, InSe, heterojunction, optical contact, current-voltage characteristics, photovoltaic effect.

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1. Introduction

One of the basic technical problems of electronics is making low-cost and simple photoconverters with exactly predicted properties. For this reason, ternary semiconductor $CuInSe_2$ finds more wide application in high-performance and stable solar cells and competes with devices based on silicon and gallium arsenide [1-3]. All methods available in the modern semiconductor materials technology can be practically applied to production of these structures. Simultaneously, searching new components for heterojunctions based on $CuInSe_2$ is going on. The range of such investigations includes the wide class of layered III-VI semiconductors, InSe in particular. For these compounds, it is typical to form high-quality mirror-like cleaved surfaces, which is possible due to weak van der Waals forces acting between the layers [4]. Therefore, for InSe crystals it is possible to easily have thin plates with perfect and atomically smooth surfaces [5]. The latter allows creating device structures by the method of a direct optical contact [4, 6]. It can be created between two cleaved or cleaved and polished mechanically and chemically surfaces of single crystals. Earlier it was reported about the investigations of *p*-GaSe/*n*-$CuInSe_2$ and *n*-InSe/*n*-$CuInSe_2$ heterojunctions created by the method of the optical contact [7-9]. In this paper, we present investigations of electrical and photoelectrical properties of *n*-InSe/*p*-$CuInSe_2$ heterojunction.

2. Experimental results and discussion

$CuInSe_2$ single crystals of *p*-type conductivity with a hole concentration $p = (1\dots\ 5)\ 10^{17}$ cm^{-3} and resistivity $\rho = 0.5\dots1$ Ohm·cm at $T = 300$ K were grown by the vertical gradient cooling method. The measurements of the conductivity and Hall coefficient showed that the crystals were electrically homogeneous.

InSe single crystals were grown by the Bridgman method from previously synthesized ingots of a non-stoichiometric composition $In_{1.03}Se_{0.97}$. Their electron concentration was $n = 10^{14}\dots10^{15}$ cm^{-3} and resistivity was $\rho = 50...100$ Ohm·cm at $T = 300$ K.

To create heterostructures, single crystal plates of $CuInSe_2$ oriented in the (112) plane with the average in-plane sizes of 5×5 mm and a thickness of 0.3 to 0.6 mm were used. Their surfaces were mechanically polished and chemically etched. Cleaved InSe 50 to 100 μm thick plates were not subjected any treatment. The ohmic contact to $CuInSe_2$ was created by a thermal evaporation of nickel, and to InSe – by soldering indium.

For creation of the optical contact to a freshly etched $CuInSe_2$ sample, the layer semiconductor uniform all over its area was mechanically pressed to it. Then, even in the absence of an external effort, the InSe plate remained in a close contact with $CuInSe_2$, and their spliting needed approximately the same effort as used when cleaving indium monoselenide. It indicates that the obtained optical contacts *n*-InSe/*p*-$CuInSe_2$ are enough stable and long-lived.

To determine the current transfer mechanism in the investigated heterojunctions, the measurement of current-voltage (*I-V*) characteristics in the forward and reverse directions were carried out. The stationary *I-V* characteristics demonstrate clearly pronounced diodic properties. Say, at the applied bias of 1 V the forward current exceeds the reverse one more than a factor of 500.

Fig. 1 shows a dark room temperature *I-V* characteristic of heterojunction *n*-InSe/*p*-$CuInSe_2$ (curve 1). In view of the resistance of both $CuInSe_2$ and more high-resistive component, InSe, the initial section of the *I-V* characteristic in the forward direction at relatively low voltages is described by the expression

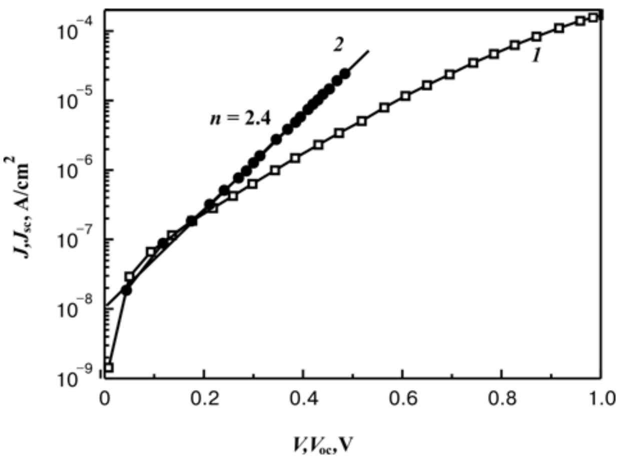

Fig. 1. Forward branch of the current-voltage characteristic of *n*-InSe/*p*-$CuInSe_2$ structure (1) and photovoltaic modification of this branch (2) at $T = 293$ K.

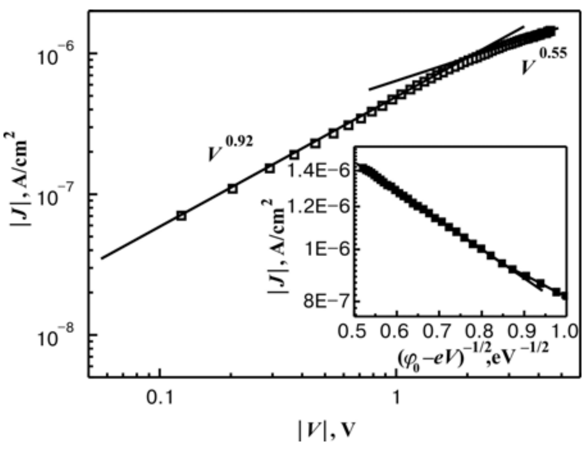

Fig. 2. Reverse branch of the current-voltage characteristic of *n*-InSe/*p*-$CuInSe_2$ structure. Insert – the reverse current density *vs* voltage according to the expression (3). $T = 293$ K.

$$J = J_s\left[\exp\left(A(V - Ir)\right) - 1\right] \quad (1)$$

where *r* is a series resistance of the structure, and the parameter *A* is a slope of the curve.

Investigations of the electrical properties of the structures were also carried out by means of the photoelectric modification of *I-V* characteristics, i.e., dependences of short-circuit currents I_{sc} versus open-circuit voltage V_{oc} and in the range of high density of the forward current where leakage currents are not essential (Fig. 1, curve 2). As one can see from Fig. 1, at higher biases the divergence of the characteristics is observed, and the curve 1 mainly represents a charge transfer through the series resistance *r* instead of the real current transfer mechanism through the rectifying barrier. The *I-V* characteristic forward branch measured by the photoelectric technique (Fig. 1, curve 2) increases according to the exponential law:

$$J_{sc} = J_s\left[\exp\left(\frac{qV_{oc}}{nkT}\right) - 1\right]. \quad (2)$$

Here *n* is the diodic factor equal to 2.4, i.e., the current transfer mechanism in the space-charge region has a tunnel-recombination character.

In our experiments, the dark saturation current determined from the linear part of the forward-biased *I-V* characteristic in the range of a zero bias does not exceed 10^{-8} A/cm^2, which is indicative of a small equilibrium concentration of holes participating in the conductance at the contact.

The reverse branch of the *I-V* characteristic is characterized by two clear regions (Fig. 2). Over the voltage range $0 < |V| < 2$ V the $\lg |J| = f(\lg |V|)$ dependence is linear with an insignificant deviation ($J \sim V^{0.92}$). It is the ohmic conductance which is described by the Ohm law:

$$J = qn_0\mu\frac{V}{d}, \quad (3)$$

where n_0 is the concentration of thermally-equilibrated free carriers in the conduction band, μ is the mobility of carriers, and *d* is the thickness of the structure.

At the increasing reverse-biased voltage, the current density is described by the expression characterizing the tunnel current [10] (insert to Fig. 2):

$$J = a_1 \exp\left[-b_1/(\varphi_0 - eV)^{1/2}\right] \quad (4)$$

where a_1 is the parameter that takes into account the occupancy of energy levels from which tunneling occurs, b_1 is the parameter independent of *V*, φ_0 is the built-in-potential determined from the capacitance-voltage characteristics and equal to 0.8 eV in our case.

The spectral dependences of the relative quantum photoconversion efficiency η for the obtained heterostructures are shown in Fig. 3. In the longwave range, the η(*h*ν) spectrum is exponential with the slope of 40 eV^{-1}. It is caused by photoactive absorption in InSe and does not depend on illumination geometry. The fact

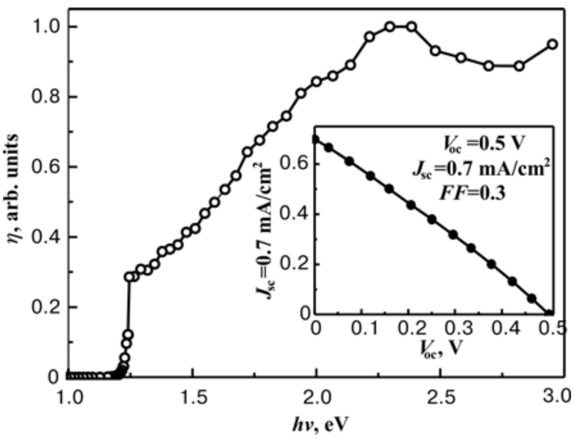

Fig. 3. Spectral dependence of the relative quantum efficiency of photoconversion for *n*-InSe/*p*-$CuInSe_2$ structure. Insert – the loading current-voltage characteristic. T = 293 K.

that photosensitivity of the heterojunction is determined by the interband absorption in the layer semiconductor can be explained by comparative values of the electrical parameters of the contacting materials – the hole concentration in $CuInSe_2$ ($p = 10^{17}$ cm^{-3}) considerably exceeds the electron concentration in InSe ($n = 10^{14}…10^{15}$ cm^{-3}). As a consequence, the active region of these heterostructures is practically completely localized within InSe. The wide-band character of the spectral characteristics takes place because of the usage of thin InSe plates, which results in the fact that the space-charge region of the heterostructure is located at a distance close to the surface and sufficient for a diffusive movement of photocarriers to the *p*-*n*-junction.

Photovoltaic effect dominates at illumination of the heterojunction from the side of the semiconductor with the higher energy gap. When illuminating the structure, the $CuInSe_2$ plate is always charged positively in all the range of photosensitivity. The open-circuit voltage at illumination from a tungsten lamp with a density of the radiation flux of P = 100 mW/cm^2 achieves V_{oc} = 500 mV, and the density of the short-circuit current – J_{sc} = 0.7 mA/cm^2. In insert to Fig. 3, presented is the loading curve characterized by the filling factor FF = 0.3. It is necessary to note that the photoelectric parameters of the created heterostructures do not reveal degradation changes.

3. Conclusion

InSe thin plates are very elastic that enables to produce good-quality heterojunctions on their basis even when another component to them is material of other crystalline structure with less perfect surface. The obtained results allow to conclude that the heterostructures *n*-InSe/*p*-$CuInSe_2$ have well pronounced diodic properties with the recombination character of current transfer. Their open-circuit voltage is 0.5 V and the short-circuit current density – 0.7 mA/cm^2.

Thus, formation of the direct optical contact of InSe plates with semiconductor plates of $CuInSe_2$ allows to receive heterojunctions simple at their manufacturing which can be applied as photodetectors of natural radiation.

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