Barrier structures were produced using optical contact between the indium and gallium selenides. The effect of mechanical pressure ranging from 0 to 100 kPa on the electrical properties of the GaSe/InSe heterocontacts was investigated. The data was analyzed assuming the SIS (semiconductor – insulator – semiconductor) model. Using this model we were able to explain the current – voltage dependence. It was found that the modification of heteroboundary significantly affects the electric transport.

**Keywords:** Semiconductors; heterostructures; electrical properties.

Se formaron estructuras barreras usando contactos ópticos entre dos semiconductores de GaSe y InSe. El efecto de la presión mecánico desde 0 hasta 100 kPa sobre las propiedades eléctricas de los heterocontactos de GaSe/InSe fue investigado. Los resultados son analizados considerando el modelo de semiconductor – aislador – semiconductor. Utilizando este modelo, explicamos las características corriente – voltaje. Se encontró que la modificación de heterofrontera afectan significativamente el transporte eléctrico.

**Descripciones:** Semiconductores; heteroestructuras; propiedades eléctricas.

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1. **Introduction**

Heterojunctions based on anisotropic InSe and GaSe crystals are analogues of silicon structures in their operation under exposure to intense radiation [1]. The energy gap of InSe at room temperature is close to 1.2 eV. The energy gap of GaSe is 2.0 eV at 300 K. InSe based photodiodes are sensitive to visible and infrared rays. GaSe is a wide direct bandgap material that is sensitive in the visible region. So GaSe/InSe heterocontacts are structures with attractive characteristics for solar energy conversion [2,3,4]. Gallium and indium monoselenides belong to a vast class of layered semiconductors. They have a significant anisotropy of chemical bonds, within and between the layers, which enables preparation of natural and clean surface with a high optical quality by cleavage. Moreover, a GaSe/InSe heterostructure, fabricated by bringing the surfaces of two semiconductors into direct optical contact, is a semiconductor – insulator – semiconductor (SIS) structure where a layer of oxygen atoms adsorbed from atmosphere acts as a dielectric layer [5]. This layer is in non-equilibrium state with a very long relaxation time.

This paper presents investigations of the influence of static pressure from 0 to 100 kPa, normal to the barrier plane, on the electrical and photoelectrical parameters of \( n \)-InSe–\( p \)-GaSe heterojunction. The changes of the electrical and photoelectrical parameters of the InSe/GaSe heterojunction are discussed from the point of view of the modification of the interface layer.

2. **Experimental**

Single crystals of GaSe and InSe, prepared in exact stoichiometric proportion of Ga (In) and Se, were grown by the Bridgman method. The samples obtained have had hexagonal crystal lattice consisting of a large single crystal region with good cleavage property parallel to (001) crystal planes. Freshly cleaved InSe platelets with 100 to 200 \( \mu \)m in thickness, exhibiting \( n \)-type conductivity and electrical resistivity of about 2 \( \Omega \cdot \text{m} \) in the direction parallel to the \( c \)-axis [normally to the (001) planes], have been used as substrates for the addition of the thin GaSe layer by bringing the cleavage surface into direct contact. The thicknesses of the thin GaSe layers have been of the order of 20 \( \mu \)m. The thin GaSe layers have shown \( p \)-type conductivity with the electrical resistivity of about 10\(^2\) \( \Omega \cdot \text{m} \) at room temperature. The concentrations of main carriers, from the analysis of Hall effect measurements in \( p \)-GaSe and \( n \)-InSe samples, were \( p=10^{16} \text{ cm}^{-3} \) and \( n=10^{15} \text{ cm}^{-3} \) at 300 K, and carrier mobilities were \( \mu_p=10 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \) and \( \mu_n=800 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \), respectively.

Heterostructures were produced by the original method, namely: the optical contact of a thin \( p \)-GaSe layer with a substrate produced of \( n \)-InSe [4]. The area of the heterocontact has been of the order of 25 mm\(^2\). Soldered indium has been applied as an ohmic contact to InSe. Silver colloidal paste proved to be a good ohmic contact to GaSe. The heterocontacts were subjected to a uniaxial pressure directed perpendicularly to the interface plane (along the \( c \)-symmetry axis of InSe and GaSe crystals).

3. **Results and discussion**

Figure 1 shows the room temperature forward and reverse bias \( I-V \) characteristics before and after pressure \( P=40 \text{ kPa} \) of the \( p \)-GaSe/\( n \)-InSe heterocontact. The value of the parameters from these characteristics are the voltage difference \( \phi_0=0.5 \text{ eV} \), the ideality factor \( n=1.7 \), the forward saturation
current $I_0=1.2 \times 10^{-11}$ A for the initial sample, and $\phi_0=0.97$ eV, $n=2$, and $I_0=1.1 \times 10^{-10}$ A for the pressured sample.

The forward bias characteristics can be divided into two regions, a low-voltage and high-voltage region. In the low-voltage region (i.e. for voltage of less than 0.35 V at room temperature) the measured curves can be fitted to an expression of the form [6]:

$$I = I_r + I_t = I_{0r} \left[ \exp \left( \frac{eV}{2kT} \right) - 1 \right] + I_t \quad (1)$$

where $I$ is the total current; $V$ is the applied voltage; $I_{0r}$ is the current of the cut-off at $V=0$; $I_r$ is the space-charge recombination current; $I_t$ is the tunnel current; $e$ is the electronic charge; $k$ is the Boltzman constant; and $T$ is the absolute temperature. The forward characteristics found for the $p$-GaSe/$n$-InSe heterocontact, which are described by Eq. (1) for the low-voltage region, could be interpreted in terms of the recombination-tunnelling mechanism of the current transport. Under low forward bias conditions after pressure $P=40$ kPa, one source of current prevails in heterocontacts, namely, space-charge recombination in the GaSe/InSe junction.

The downward curvature in the forward $I−V$ plots at sufficiently large applied voltage is due to the series resistance.

Moreover, the reverse bias of the pressured sample has a better saturation compared to that of the initial sample (Fig. 1). This can be explained by the presence of oxygen layer in the semiconductor / semiconductor interface, which arises as a result of the adsorption of extraneous gases from the surrounding atmosphere. The pressure can give rise to a modification of the interface layer that can affect the electrical properties.

The modification of the interface layer may cause a change in the relative quantum efficiency of GaSe/InSe heterojunctions subjected to pressure [7]. The increase of the relative quantum efficiency of the InSe/GaSe heterocontact is caused by a decrease of the layer of oxygen atoms adsorbed at the interface to minimum values of its thickness or area, as well as by an increase of the heterojunction area. The decrease of the quantum efficiency in photon energy ranging above the band gap of GaSe (2 eV) at an increasing pressure of $P > 30$ to 40 kPa (Fig. 2) is caused by the appearance of defects both at the interface and in the bulk of the contacting semiconductors. For the registered $X$-ray diffraction patterns for the samples subjected to static pressure we have found broadening half-width of the diffraction reflexes which indicates of an increase of defect density in the crystalline structure of layered indium and gallium selenides.
diffusion current, which recombines at the interface, flows erocontact is shown in Fig. 4a. The thermal-emission or where $\phi$ is the contact potential difference after the uniaxial compression. The capacitance – voltage characteristic, where the diode factor has the value 1.7 at room tem-

diagram of the p-GaSe/n-InSe heterojunction in thermal equilibrium (b). $E_F$ is the Fermi level; $E_C$ and $E_V$ are the conduction and valence band edges; $\Delta E_C$ and $\Delta E_V$ are the shifts in the conduction and valence band edge, respectively (dimensions electron-volts).

In heterojunctions, the depletion layer capacitance $C$ can be expressed as [6]:

$$C^{-2} = \frac{2(\varepsilon_pN_A + \varepsilon_nN_D)(\phi_0 - V)}{\varepsilon_p\varepsilon_nN_A N_D A^2}$$  \hspace{1cm} (2)

where $A$ is the effective area of the heterojunction; $\phi_0$ is the voltage difference at zero bias and is determined from the extrapolation of the linear $C^{-2} - V$ plot to the $V$ axis; $N_A$ and $N_D$ are the concentrations of the noncompensated ionized donors and acceptors; $\varepsilon_p$ and $\varepsilon_n$ are the dielectric constants of the material on the N and P sides, respectively; and $V$ is the applied bias. Figure 3 shows the reverse bias $C^{-2} - V$ characteristics of the p-GaSe/n-InSe heterocontact before and after pressure. The capacitance – voltage characteristics of GaSe/InSe heterocontacts showed an increase of contact potential difference after the uniaxial compression. Again, the values of $\phi_0$ indicate that the diode does not obey the ideal Anderson’s theory [6].

A model for a transport process of the p-GaSe/n-InSe heterocontact is shown in Fig. 4a. The thermal-emission or diffusion current, which recombines at the interface, flows in narrow-gap material, while the tunneling current flows through the wide-gap material barrier. These two currents flow in series and are related by the interface parameters.

Figure 4b shows the band diagram for an ideal p-GaSe/n-InSe heterojunction in thermal equilibrium. Since the Fermi levels align, the built-in barrier is the difference in the work-


