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# Effect of pressure on the electrical properties of GaSe/InSe heterocontacts

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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 ópticas 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 cararterísticas corriente – voltaje. Se encontró que la modificación de heterofrontera afectan significativamente el transporte eléctrico.

*Descriptores:* 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 $\Omega$·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 $10^2$ $\Omega$·m at room temperature. The concentrations of main carriers, from the analysis of Hall effect measurements in $p$-GaSe and $n$-InSe samples, were $p$=$10^{16}$ cm$^{-3}$ and $n$=$10^{15}$ cm$^{-3}$ at 300 K, and carrier mobilities were $\mu_p$=10 cm$^2$/V·s and $\mu_n$=800 cm$^2$/V·s, 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 kPa of the $p$-GaSe/$n$-InSe heterocontact. The value of the parameters from these characteristics are the voltage difference $\phi_0$=0.5 eV, the ideality factor $n$=1.7, the forward saturation

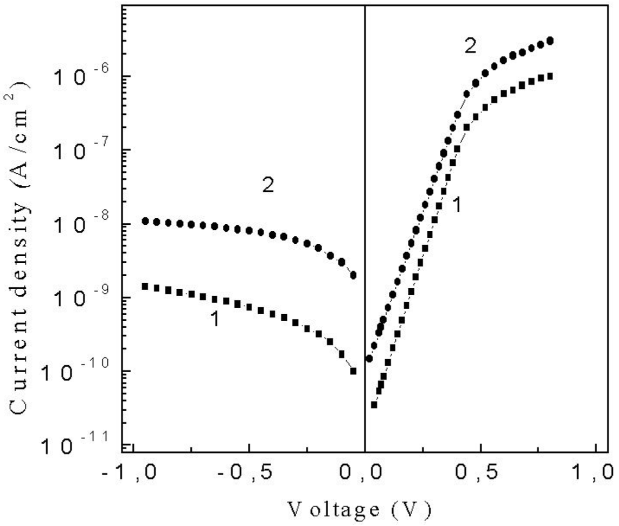

FIGURE 1. Forward and reverse bias current – voltage plots of the $p$-GaSe/$n$-InSe heterocontact before (1) and after pressure $P$=40 kPa (2). $T$=300 K.

current $I_0$=1.2×$10^{-11}$ A for the initial sample, and $\phi_0$=0.97 eV, $n$=2, and $I_0$=1.1×$10^{-10}$ 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 lees than 0.35 V at room temperature) the measured curves can be fitted to an expression of the form [6]:

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

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

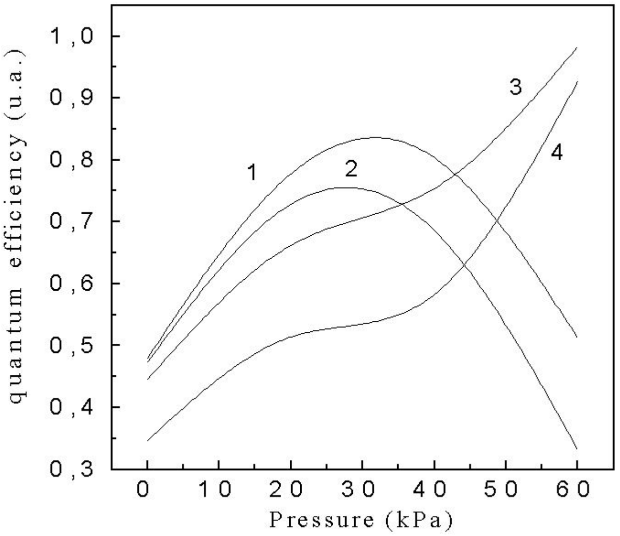

FIGURE 2. Spectral dependences of the relative quantum efficiency in relation to the pressure applied to the $p$-GaSe/$n$-InSe heterocontact for various values of photon energy, eV: 1 – 2.13, 2 – 2.08, 3–1.75, 4 – 1.35. $T$=300 K.

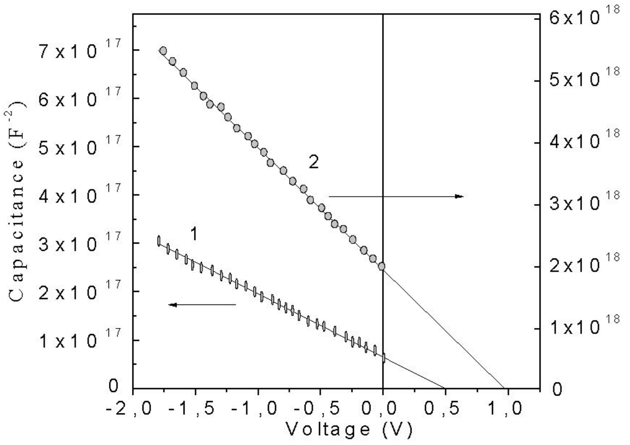

FIGURE 3. The reverse bias capacitance – voltage ($C^{-2}$ – V) characteristic of the $p$-GaSe/$n$-InSe heterocontact before (1) and after pressure $P$=40 kPa (2). $T$=300 K.

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.

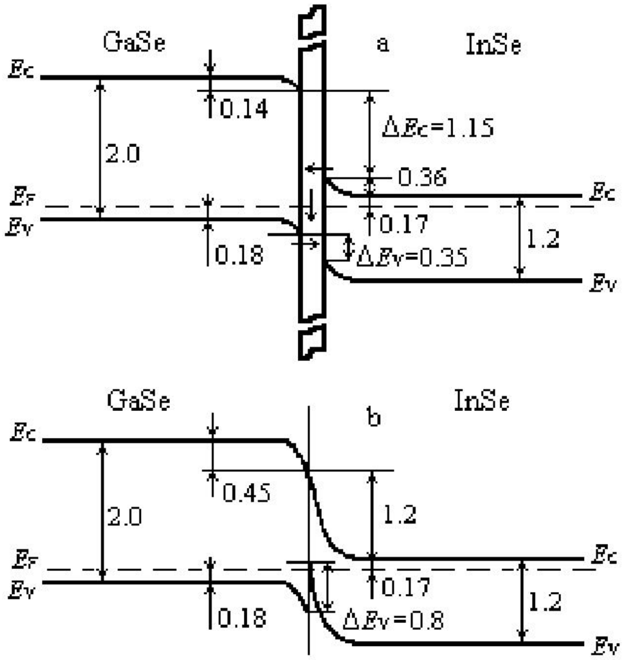

FIGURE 4. Band energy diagram of the $p$-GaSe/$n$-InSe heterocontact and the direct of current transport (a); band energy diagram of the ideal $p$-GaSe/$n$-InSe heterojunction in thermal equilibrium (b). $E_F$ is the Fermi level; $E_C$ and $E_V$ are the conduction and valence band edges; $\Delta E_C$ 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]:

$$C^{-2} = \frac{2(\varepsilon_p N_A + \varepsilon_n N_D)(\varphi_0 - V)}{e\varepsilon_p \varepsilon_n N_A N_D A^2} \qquad (2)$$

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-function levels. A discontinuity in the form of a spike and a notch are formed in the valence band edge. As can be seen from Fig. 3, the value of $\phi_0$ of the$p$-GaSe/$n$-InSe heterocontact after pressure tends to the value of the contact potential difference calculated in the context of the Anderson model for ideal heterojunctions. At the same time, measurements of the capacitance-voltage characteristics for the structures exposed to pressure indicate that the contact potential difference still falls short of the value determined from the relation obtained for ideal heterojunctions [6]:

$$\varphi_0 = (\chi_p + E_{gp} - E_{Fp}) - (\chi_n + E_{Fn}) \qquad (3)$$

where $\chi_p$ and $\chi_n$ are the electron affinities for $p$- and $n$-type semiconductors, respectively; $E_{gp}$ is the bandgap of a $p$-type semiconductor; $E_{Fp}$ is the energy spacing between the valence band top and the Fermi level in a $p$-type semiconductor; and $E_{Fn}$ is the energy spacing between the conduction band bottom and the Fermi level in a $n$-type semiconductor. This circumstance indicates that it is impossible to completely eliminate the effect of transition layer formed of oxygen atoms adsorbed from the atmosphere on the value of $\phi_0$, even in the presence of pressure.

## 4. Conclusions

As a consequence of an increase in the band-bending magnitude, the shape of the current–voltage characteristics of the heterojunctions to pressure changes: the forward characteristics of the initial samples can be described by the expression, where the diode factor has the value 1.7 at room temperature, whereas for the structures subjected to pressure the diode factor $n$ has the value 2. In the forward bias case, the contact potential difference $\phi_0$ increased from 0.5 to 0.97 eV after the uniaxial pressure. For the $p$-GaSe/$n$-InSe, the parameters of the pressured sample represent an increase in the barrier height, $I_0$ (about one order of magnitude) and ideality factor $n$ compared to those of the initial sample. Thus, it has been demonstrated that pressure can be used in order to improve the electrical characteristics of the $p$-GaSe/$n$-InSe heterocontacts. These results indicate that it is possible to control change of the parameters of heterojunctions and to vary the applications in optoelectronic devices.

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1. S.I. Drapak, M.O. Vorobets, and Z.D. Kovalyuk, *Semiconductors* **39** (2005) 600.
2. S.I. Drapak, M.O. Vorobets, and Z.D. Kovalyuk, *Material Research Society Symposium Proceedings*, Vol. **865** (San Francisco, CA, USA 2005) F1.1.

3. A. Segura, A. Chevy, J.P. Guesdon, and J.M. Besson, *Solar Energy Materials* **2** (1980) 159.
4. S. Shigetomi and T. Ikari, *J. Appl. Phys.* **88** (2000) 1520.
5. S.I. Drapak, V.B. Orletskii, and Z.D. Kovalyuk, *Semiconductors* **38** (2004) 546.
6. L. Sharma and R.K. Purohit, *Semiconductor heterojunctions.* (London: Pergamon Press, 1974).
7. S.I. Drapak, M.O. Vorobets, S.V. Gavrylyuk, and Z.D. Kovalyuk, *Euroconference Photovoltaic Devices: Manufacturing issues – From laboratory to mass production*, (Kranjska Gora, Slovenia, 2004) p. 37.