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PECULIARITIES OF THE TENSORESISTANCE OF N-GE SINGLE CRYSTALS AT THE STRONG UNIAXIAL PRESSURES

The tensoresistive effect in n-Ge single crystals was studied at room temperature and liquid nitrogen temperature under the uniaxial pressure along the crystallographic directions [100], [110], and [111]. The increasing tensoresistance of the investigated n-Ge single crystals is explained by the decrease in electron mobility under the uniaxial pressure, which becomes a tensor when deformed along the [110] and [111] crystallographic directions. A significant increasing tensoresistance at the uniaxial pressures P//[100] is associated with (L_1-Δ_1) - inversion of the absolute minimum type in germanium. The obtained dependences tensoresistance of n-Ge can be used in the design of pressure sensors with a wide range of tensosensitivity.

Keywords: *tensoresistance, tensosensitivity coefficient, germanium single crystals, (L_1-Δ_1) – inversion, uniaxial pressure.*

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ОСОБЛИВОСТІ ТЕНЗООПОРУ МОНОКРИСТАЛІВ N-GE ПРИ СИЛЬНИХ ОДНОВІСНИХ ТИСКАХ

Досліджено тензорезистивний ефект в монокристалах n-Ge при кімнатній температурі та температурі рідкого азоту в умовах, коли одновісний тиск прикладався вздовж кристалографічних напрямків [100], [110] та [111]. Зростання тензоопору досліджувальних монокристалів n-Ge пояснюється зменшенням рухливості електронів при одновісному тискові, яка при деформації вздовж кристалографічних напрямків [110] та [111] стає тензором. При одновісних тисках P//[100] значне зростання тензоопору пов'язане з (L_1-Δ_1) – інверсією типу абсолютного мінімуму в германії. Одержані залежності тензоопору n-Ge можуть бути використані при конструюванні тензодатчиків з широким діапазоном тензочутливості.

Ключові слова: *тензоопір, коефіцієнт тензочутливості, монокристали германію, (L_1-Δ_1) – інверсія, одновісний тиск.*

Statement of the problem. Pressure sensors are widely used in experimental studies of the stressed state of structures, as well as strain transducers in various measuring devices. Semiconductor pressure sensors, compared to wire and foil gauges, have much smaller dimensions and 50-60 times higher sensitivity. Germanium is one of the promising materials for semiconductor pressure sensors and is widely used in microelectronics for the production of diodes, triodes, crystalline detectors, and power rectifiers [1-4]. The influence of high uniaxial pressures leads to a radical deformational reconstruction of the conduction and valence bands of germanium, as well as the energy structure of defects. [5-7]. Such changes in the band structure will consequently affect the tensoresistance of germanium, which is not thoroughly studied at the high uniaxial pressures.

Setting tasks. Obtaining the dependences of the tensoresistance and the tensosensitivity coefficient on the uniaxial pressure along different crystallographic directions for n-Ge single crystals at liquid nitrogen and room temperature.

Presentation of the main material. Tensoresistive effect in single-crystal n-type germanium doped with antimony impurities was investigated in this study. The uniaxial pressure was applied along the crystallographic directions [100], [110], and [111] in the experiments. Measurements were performed at room temperature and liquid nitrogen temperature. Investigated samples were fabricated in a dumbbell-shaped form. Such a specific shape of the samples increases their mechanical robustness compared to samples with a parallelepiped shape. For cases of uniaxial pressure along the crystallographic directions [110] and [111], the tensoresistive effect will be absent for pressures above 1.6 GPa, both at liquid nitrogen temperature and room temperature (Fig. 1 and Fig. 2). In these cases, there will be a deformational redistribution of electrons between the L1 minima of the germanium conduction band with different mobility, which becomes a tensor under the deformation [6]. Such a redistribution leads to a decrease in effective mobility and, accordingly, an increase in the n-Ge resistivity at the pressures $P<1.6$ GPa. A significant tensoresistive effect was revealed at the uniaxial pressure $P>1.5$ GPa along the crystallographic direction [100], at the temperature of liquid nitrogen (Fig. 1, curve 2). The resistivity of n-Ge single crystals begins to increase monotonically at uniaxial pressures $P>1$ GPa and does not reach saturation at a room temperature under these conditions (Fig. 2, curve 2). In this case, there will be no deformational redistribution of electrons between L1 minima, and the growth of the tensoresistance is associated with the deformational redistribution of electrons between non-equivalent L1 minima and Δ1, which have different mobilities. [5]. There will be an (L1-Δ1) type inversion of the absolute minimum in germanium for the pressures P>2.1 GPa.

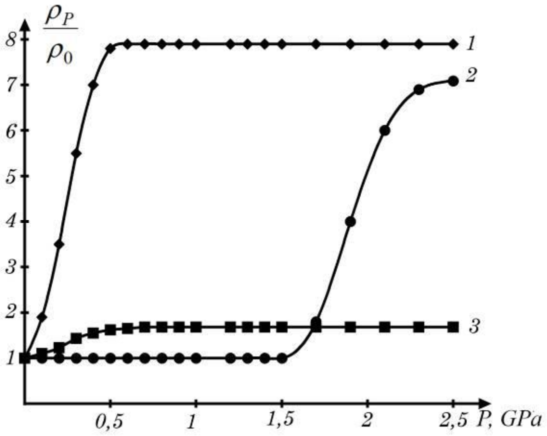

Fig. 1. **Tensoresistive effect in n-Ge at the temperature of liquid nitrogen for different crystallographic directions: 1 – uniaxial pressure along the crystallographic direction [111]; 2 – uniaxial pressure along the crystallographic direction [100]; 3 – uniaxial pressure along the crystallographic direction [110].**

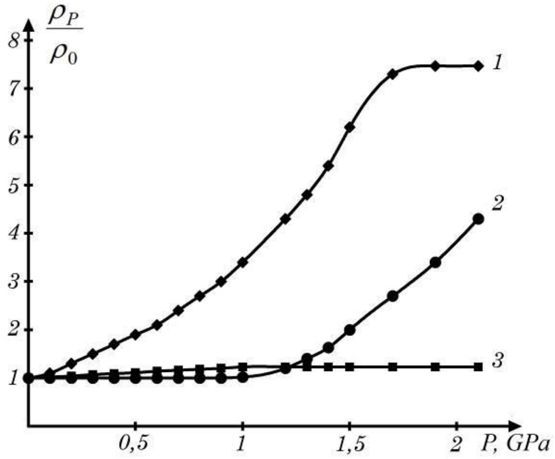

Fig. 2. **Tensoresistive effect in n-Ge at room temperature for different crystallographic directions: 1 – uniaxial pressure along the crystallographic direction [111]; 2 – uniaxial pressure along the crystallographic direction [100]; 3 – uniaxial pressure along the crystallographic direction [110].**

The coefficient of tensosensitivity under conditions of uniaxial deformation will be determined by the expression [8]:

$$S=\frac{E\left(\frac{c_P}{c_0}-1\right)}{P}, \tag{1}$$

where $\frac{c_P}{c_0}$ – the ratio of the resistivity of the deformed n-Ge single crystal to the undeformed one (magnitude of the tensoresistive effect), E – Young's modulus, which is determined from the expression

$$\frac{1}{E}=\frac{C_{11}+C_{12}}{\left(C_{11}+2C_{12}\right)\left(C_{11}-C_{12}\right)}+\left(\frac{1}{C_{44}}-\frac{2}{C_{11}-C_{12}}\right)\left(n_1^2n_2^2+n_1^2n_3^2+n_2^2n_3^2\right). \tag{2}$$

In expression (2) C_{11}, C_{12}, C_{44} – the elastic constants for the crystal lattice of germanium; n_1, n_2, n_3 – components of the unit vector normal to the deformation area of the sample. In the coordinate system associated with the crystallographic axes [100], [110] and [111], the components of this vector depending on the direction of uniaxial pressure are as follows: with uniaxial pressure

P//[100] $n_1 = 1$, $n_2 = 0$, $n_3 = 0$; for uniaxial pressure P//[110] $n_1 = 1$, $n_2 = 1$, $n_3 = 0$ and for uniaxial pressure P//[111] $n_1 = 1$, $n_2 = 1$, $n_3 = 1$. Elastic constants are known parameters: $C_{11} = 1{,}292 \ 10^{11}$ Pa, $C_{12} = 0{,}479 \ 10^{11}$ Pa, $C_{44} = 0{,}67 \ 10^{11}$ Pa.

Then, according to (2), we obtain the following values of Young's modulus: $E = 1{,}55 \ 10^{11}$ Pa, $E = 1{,}37 \ 10^{11}$ Pa, $E = 1{,}03 \ 10^{11}$ Pa for uniaxial deformation along the crystallographic directions [111], [110] and [100], respectively.

Taking into account expressions (1), (2) and experimental results of the tensoresistive effect of n-Ge single crystals, it is possible to obtain the dependences of the tensosensitivity coefficient on uniaxial pressure for different crystallographic directions at the temperature of liquid nitrogen and the room temperature (Fig. 3 and Fig. 4).

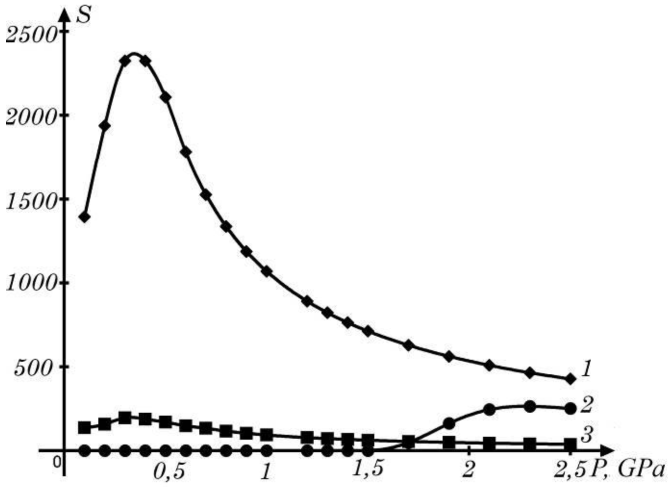

Fig. 3. **Dependence of the tensosensitivity coefficient in n-Ge on uniaxial pressure at the temperature of liquid nitrogen (T=77 K) for different crystallographic directions: 1 – uniaxial pressure along the crystallographic direction [111]; 2 – uniaxial pressure along the crystallographic direction [100]; 3 – uniaxial pressure along the crystallographic direction [110].**

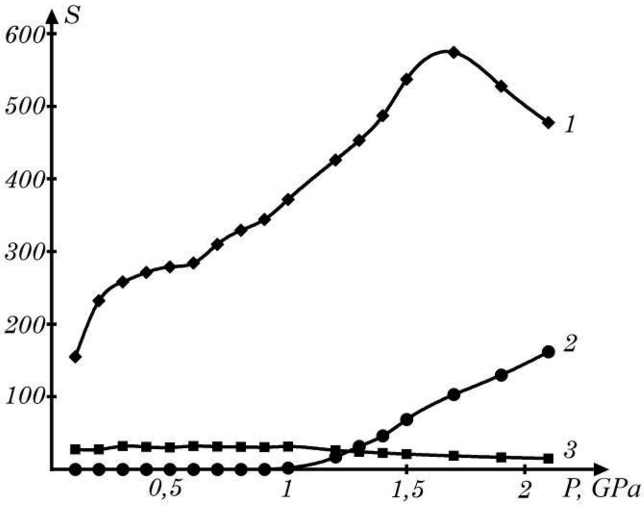

Fig. 4. **Dependence of the tensosensitivity coefficient in n-Ge on uniaxial pressure at room temperature for different crystallographic directions: 1 – uniaxial pressure along the crystallographic direction [111]; 2 – uniaxial pressure along the crystallographic direction [100]; 3 – uniaxial pressure along the crystallographic direction [110].**

Tensosensitivity coefficient for n-Ge at the uniaxial pressure along the crystallographic directions [100], [110] and [111] were calculated based on the obtained experimental results of tensoresistance. It was shown that the maximum value of the tensosensitivity coefficient (S=2325) can be reached under the uniaxial deformation P~0.4 GPa of n-Ge single crystals along the crystallographic direction [111].

Conclusions. The presence of the tensoresistive effect in n-Ge is associated with a decrease in electron mobility under the deformation. Electron mobility becomes anisotropic under the uniaxial pressure along the [110] and [111] crystallographic directions, which is the reason increasing resistivity in n-Ge. For the case of uniaxial pressure along the crystallographic direction [100], a deformational redistribution of electrons will occur between the L1 and Δ1 minima of the conduction band of germanium with different mobilities, as a result of which a significant effect of tensoresistance is observed for n-Ge. From the analysis of the obtained results, it follows that it is advisable to make strain gauges from n-Ge for measuring uniaxial pressures P<1 GPa, when this pressure is directed along the crystallographic directions [111] or [110]. The obtained significant tensoresistive effect at P>1.5 GPa and a sharp increase in the coefficient of strain sensitivity for the crystallographic direction [100] can be used to design pressure sensors based on n-Ge single crystals, which will be able to work in significant deformation fields.

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