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Features of tensoresistance depending on the crystallographic orientation of γ-irradiated (^{60}Co) germanium and silicon single crystals

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ABSTRACT

The features of the longitudinal tensoresistance of γ-irradiated (^{60}Co) n-Ge and n-Si crystals, as well as γ-irradiated n-Ge crystals after $\mathrm{n} \rightarrow \mathrm{p}$ conversion, at fixed temperatures depending on the direction ($\vec{X} \parallel \vec{J} \parallel$ [111,110], [100]) of application of the mechanical compressive stress $0 \leq X \leq 1.2$ GPa were investigated. The charge carrier concentrations and the Hall mobility values before and after γ-irradiation were controlled by measurements of the Hall effect. It was established that under conditions of the nonsymmetrical arrangement of deformation axis relative to the isoenergetic ellipsoids, the dependences of tensoresistance in the γ-irradiated n-Ge and n-Si crystals pass through a maximum. With a symmetrical placement of the deformation axis such maximum is not observed. In the converted n-Ge crystals under applying of mechanical stress the presence of the region of the increasing resistivity in the initial area of deformation was found, which is explained by increase of the energy gap between the deep level and the top of the valence band with increasing pressure.

1. Introduction

The study of the energy spectrum of typical semiconductors with using the effective mass method allowed to solve the problem about shallow impurity levels, i.e., about levels, generated in the band gap (~10^{-2} eV), when the number of valence electrons of the impurity atoms is different per unit from the number of valence electrons in the atom of the basic substance [1–3]. These states are completely determined by the effective charge of center and the structure of the bottom of energy band, near which they are formed, since them distance from the other bands is about 1 eV. The long-range Coulomb potential, in which an electron belonging to the shallow center is situated, is the main feature of the shallow impurities [4–7].

The localized states in the band gap occupy a special place in the physics of semiconductors. Such states are located at the significant distances (about several tenths of electron-volt) from the edges of allowed bands. They are called by deep levels, and the respective impurities are called by deep centers [8,9]. These include almost all the impurities, except hydrogen-like impurities from the III and V groups in silicon and germanium, as well as the majority of radiation defects and thermodonors [10–12]. The energy position of deep levels can differ greatly depending on the type of impurity atoms [13].

The measurements, carried out under pressure, can be very useful for the study of these impurity states [14–17]. The application of the comprehensive and the uniaxial pressures allows immediately receiving the information about changing the anisotropy of scattering of the charge carriers, about the deformation degree of the internal connections in the lattice, about the bond nature of the localized center with the allowed bands, about the symmetry type for this defect [18–22]. For example, in Ref. [23] it is shown that with increase in the occurrence depth of levels their bond with the corresponding allowed band is strongly attenuated. The pressure coefficient describes the dependence of the energy position of deep levels on the pressure. The pressure coefficient value is about in hundred times greater than the pressure coefficient of shallow states. This fact can be used as some quantitative criterion at the conditional division of states on deep and shallow [24].

If the asymmetrically located defects are present in lattice, then the lowering of the semiconductor lattice symmetry due to the uniaxial elastic deformation can lead to the anisotropic alteration of their parameters, which will be different from the anisotropy of semiconductor [25]. Moreover, the uniaxial elastic deformation commonly leads to splitting of the many-fold degenerate energy levels [26]. On the basis of the measurement results of the shift of deep-level energy position and its splitting with application of the mechanical stresses along the main crystallographic directions of the silicon and germanium single crystals, the atomic state of impurity or radiation defect can be identified, i.e., the physical model of center can be supposed

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[27].

In the applied aspect the role of deep levels is important when using electrical, recombinational, optical, resonant and other physical properties of semiconductors [28–31]. The deep centers of radiation and technological origin are fundamentally changing the sensitivity of silicon and germanium to the mechanical pressure in a wide temperature range, that can be used in tensosensors [18,32,33]. It should be noted that from the practical side the presence of the different kinds of defects, which form the deep energy levels in the forbidden band of semiconductor [34], can lead to both useful effects (the high thermo- [35] and tensosensitivity [36], the impurity photoconductivity [37], fast recombination centers [38] et al.), and undesirable effects (the negative resistance [39], the oscillations [40], the appearance of heterogeneities [41], the capture effects [4], etc.). Therefore, the further comprehensive study of the properties of semiconductors with deep centers, including the application of the measurement technique of tensoresistance when applied the uniaxial mechanical stress to the crystal is very perspective and extremely urgent in the scientific and practical aspects.

The aim of this study was to investigate the features of changes in resistivity of the silicon and germanium single crystals with deep centers, induced by irradiation, depending on the direction of the mechanical compressive stress application (along the main crystallographic axes).

2. Results and discussion

The radiation defects caused by irradiation of germanium have deep energy states in the forbidden band, but the nature and microstructure of many of them is still conclusively unknown. And the main reason lies in the fact that the method of electron paramagnetic resonance can not be applied for germanium crystals. Therefore, it was of interest to apply the tensoresistance measurement method for the study of Ge crystals with radiation defects in a wide range of the uniaxial elastic deformations.

Samples n-Ge ⟨Sb⟩ were cut out for measurements along the main crystallographic directions [111,110] [100], along which the mechanical stress $\vec{X}$ was applied and the current $\vec{J}$ flowed. Hall effect measurements were carried out in the temperature range from 77 to 300 K, and the longitudinal tensoresistance was measured at T=165, 190 and 225 K. The mechanical stress was changed in the range of $0 \le X \le 1.2$ GPa. The γ-quanta irradiation of crystals was carried out from ^{60}Co sources at room temperature, and the irradiation dose was $6{\times}10^7$ R. The irradiation dose was chosen such that the energy level $E_c - 0.2$ eV is clearly manifested on the temperature dependence of the charge carrier concentration (Fig. 1, curve 2).

Figs. 2 and 3 represent the measurement results of the longitudinal tensoresistance for the γ-irradiated n-Ge samples at a fixed temperature and for different directions of the mechanical compression stress application ($\vec{X} \parallel \vec{J} \parallel$ [111,110], [100]).

The resistivity in the crystallographic direction [111] at first increases with the rise of the applied mechanical stress, and then reaches the saturation (Fig. 4, curve 1) in the non-irradiated germanium crystals without deep levels, as well as in the silicon crystals under applying of pressure in the direction [100] (Fig. 4, curve 2). The curves, shown in Fig. 4, are typical for n-Ge and n-Si at T=77 K.

For the γ-irradiated n-Ge crystals in the temperature range where the level of radiation-induced defects $E_c - 0.2$ eV [42,43] is manifested, the character of tensoresistance dependence changes qualitatively: the decrease in resistivity appears with increasing of the mechanical stress after the passage of curves through the maxima (curves 1, 2 in Figs. 2 and 3. It is noted that the values of maxima are significantly larger at a higher temperature (in this case at T=190 K, Fig. 3).This is true both for the direction [111], and for [110].

The maximum is absent in the dependences (Figs. 2 and 3, curves 3), obtained by applying of pressure in the direction [100], but with

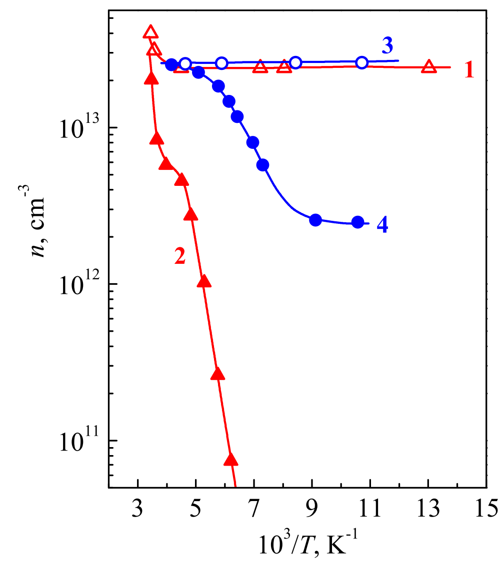

Fig. 1. Temperature dependences of the concentration of conduction electrons before (1, 3) and after (2, 4) γ-irradiation of the germanium and silicon crystals. For n-Ge ⟨Sb⟩ with the charge carrier concentration of $n_{e77\mathrm{K}} = 2.4 \times 10^{13}$ cm^{-3}: 1 – D=0; 2 – $D = 6 \times 10^7$ R; for n-Si ⟨As⟩ with $n_{e77\mathrm{K}} = 2.6 \times 10^{13}$ cm^{-3}: 3 – $D_1 = 0$; 4 – $D_1 = 3.3 \times 10^7$ R.

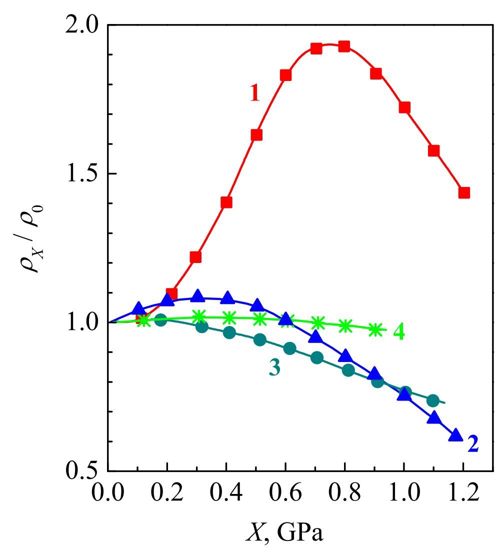

Fig. 2. Dependences $\rho_X/\rho_0 = f(X)$, measured on n-Ge ⟨Sb⟩ after irradiation by dose $D = 6 \times 10^7$ R at T=165 K in conditions: 1–$\vec{X} \parallel \vec{J} \parallel$ [111]; 2 – $\vec{X} \parallel \vec{J} \parallel$ [110]; 3 – $\vec{X} \parallel \vec{J} \parallel$ [100]; 4– at T=225 K, $\vec{X} \parallel \vec{J} \parallel$ [100].

temperature decreasing the sections of the resistivity decrease appear with pressure increase. In n-Ge for the case of $\vec{X} \parallel \vec{J} \parallel$ [100] the relative displacement of the valleys in the conduction band is absent (Fig. 5a), therefore in the ordinary n-Ge crystals the resistivity at such temperatures is not changed up to pressures 1–1.5 GPa (Fig. 6) [44]. In this case, the beginning of curve 4 (Fig. 2) at T=225 K corresponds to such situation, when the centers with level $E_c - 0.2$ eV is almost completely ionized, as shown in Fig. 1.

The main interest was to study the features of the tensoresistance effect in n-Si at presence of deep levels in its forbidden band, which belong to the radiation defects. In the irradiated n-Si crystals the A- or E-centers can be considered as such centers. In silicon crystals grown from the melt, there is usually high oxygen content, so the A-centers, which are by complexes of vacancy with oxygen atom, must be taken into consideration in the first place.

Dislocation-free n-Si crystals with relatively low level of doping by the arsenic impurity (the charge carrier concentration is equal

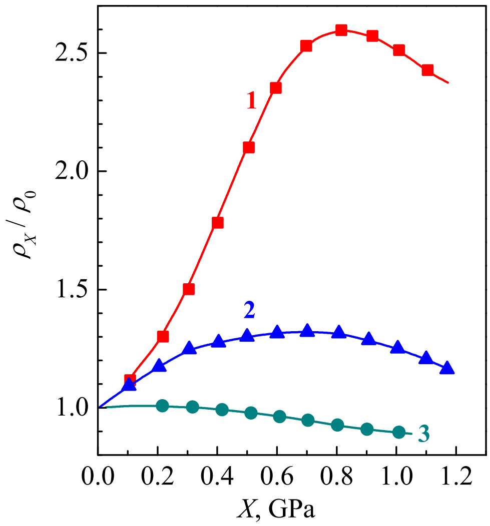

Fig. 3. Dependences $\rho_X/\rho_0 = f(X)$, measured on n-Ge ⟨Sb⟩ after irradiation by dose $D = 6 \times 10^7$ R at T=190 K in conditions: 1– $\vec{X} \parallel \vec{J} \parallel [111]$; 2– $\vec{X} \parallel \vec{J} \parallel [110]$; 3– $\vec{X} \parallel \vec{J} \parallel [100]$.

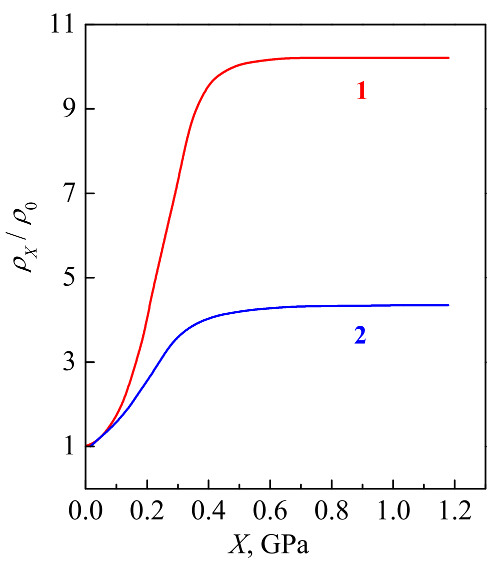

Fig. 4. Dependences $\rho_X/\rho_0 = f(X)$, measured before irradiation at T=77 K on single crystals: 1–n-Ge ⟨Sb⟩, $n_e = 5 \times 10^{13}$ cm^{-3}, $\vec{X} \parallel \vec{J} \parallel [111]$; 2–n-Si ⟨P⟩, $n_e = 7.1 \times 10^{13}$ cm^{-3}, $\vec{X} \parallel \vec{J} \parallel [100]$.

$n_{e77\,K} \equiv N_{As} = 7.2 \times 10^{13}$ cm^{-3}) were used for measuring of the Hall effect and tensoresistance, and the concentration of background oxygen impurity was up to 1.9×10^{18} cm^{-3}. With the purpose of the conduction of comparative experiments the samples were cut out along the main crystallographic directions [100,110], [111], along which the mechanical stresses X were applied. When measured of tensoresistance in conditions $\vec{X} \parallel \vec{J} \parallel [111]$ on the samples, the longitudinal orientation of which corresponds to the crystallographic direction [111], the usual tensoresistance, associated with intervalley scattering of electrons, has been completely excluded (Fig. 5b shows the arrangement of the isoenergetic ellipsoids in the conduction band of n-Si).

The γ-irradiation dose (from ^{60}Co source at room temperature) was chosen such that the energy level E_c – 0.17 *mev* [45], which belongs to A-center, is clearly manifested on the temperature dependence of charge carrier concentration (the curve is similar to curve 4 in Fig. 1).

Fig. 7 shows the measurement results of the longitudinal tensoresistance of the γ-irradiated n-Si samples at fixed temperature and different directions of the mechanical compression stress application ($\vec{X} \parallel \vec{J} \parallel$ [100,110], [111]).

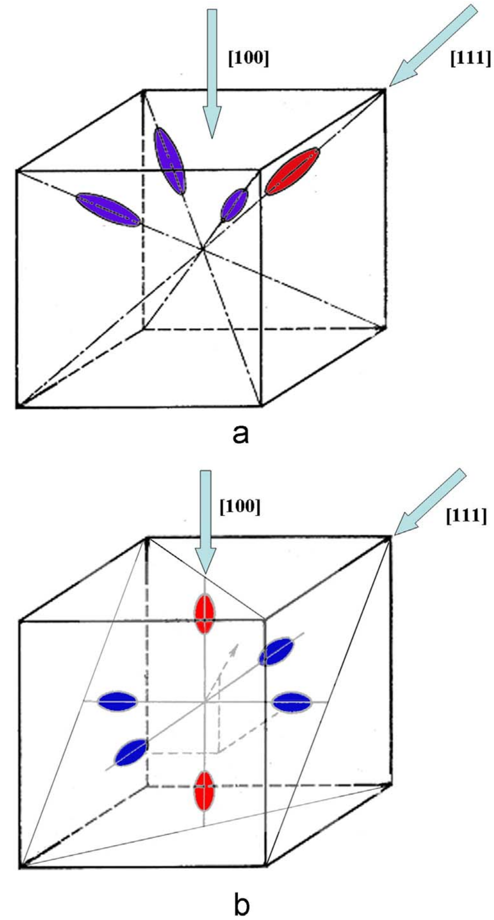

Fig. 5. The shape and arrangement of the isoenergetic ellipsoids: (a)–for the four valleys of the conduction band in n-Ge, oriented along the physically equivalent crystallographic directions ⟨111⟩; (b)–for the six valleys of the conduction band in n-Si, oriented along the physically equivalent crystallographic directions ⟨100⟩.

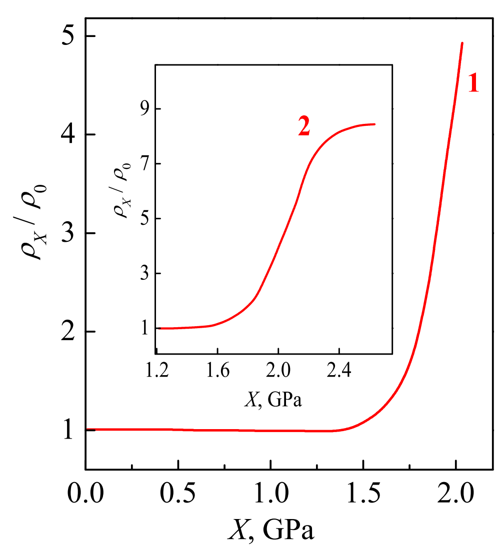

Fig. 6. Dependences $\rho_X/\rho_0 = f(X)$ in n-Ge for the case of $\vec{X} \parallel \vec{J} \parallel [100]$ at T=77 K in the pressure range: 1–0 $\le X \le$ 2 GPa; 2–1.2 $\le X \le$ 2.7 GPa.

As it is known from Ref. [46], in the non-irradiated n-Si crystals (without deep levels) the presence of tensoresistance at $\vec{X} \parallel \vec{J} \parallel [100]$ was due to the migration of the charge carriers from the four ascending valleys with greater mobility $\mu_\perp$ in two descending (on the energy scale) valleys with $\mu_\parallel \ll \mu_\perp$ that leads at first to the increase in dependence

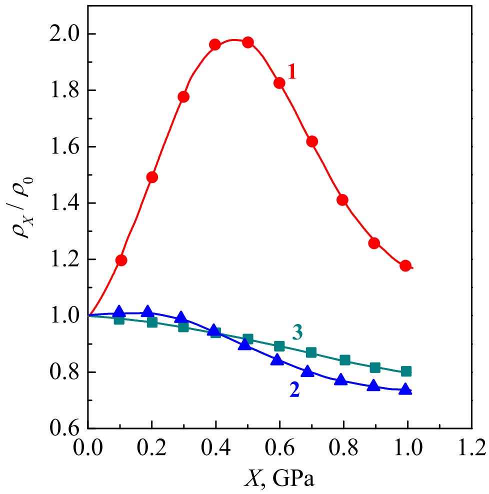

Fig. 7. Dependences $\rho_X/\rho_0 = f(X)$, measured at T=125 K on n-Si ⟨As⟩ crystals, grown by Czochralski method, after γ-irradiation by dose $D = 3.3 \times 10^7$ R in conditions: 1–$\overrightarrow{X} \parallel \overrightarrow{J} \parallel [100]$; 2–$\overrightarrow{X} \parallel \overrightarrow{J} \parallel [110]$; 3–$\overrightarrow{X} \parallel \overrightarrow{J} \parallel [111]$.

$\rho = f(X)$ with subsequent attainment of saturation (Fig. 4, curve 2). However, such dependence can be observed also at room temperature, when the deep center with the level E_c – 0.17 *mev* is almost completely ionized. With temperature decreasing, when the level of radiation defects begins to appear, the character of dependence $\rho_X/\rho_0 = f(X)$ becomes qualitatively different (Fig. 7, curve 1). The feature of dependence, obtained under condition $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [100]$ (Fig. 7, curve 1), is the passing of tensoresistance through the pronounced maximum with a subsequent decrease in resistivity at increasing of the mechanical stresses.

Comparison of curves 1 and 2 in Fig. 7 shows that the dependences $\rho = f(X)$ for the conditions $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [100]$ and $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [110]$ are qualitatively similar, although in the latter case the maximum is not so clearly defined and the section, which is characterized by a decrease in resistivity with deformation, begins to appear at smaller mechanical stresses.

Thus, the experimental results, obtained in the study of tensoresistance for the γ-irradiated n-Ge and n-Si samples in the application conditions of the mechanical stresses along the directions $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [111]$ and $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [110]$ for n-Ge (Figs. 2 and Figs. 3), as well as $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [100]$ and $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [110]$ for n-Si (Fig. 7), were qualitatively similar. The variation of dependences $\rho = f(X)$ for both crystallographic directions, obtained in these experiments, can be explained by two main mechanisms for changing in resistivity with pressure: 1) the redistribution of charge carriers between the ascending and descending valleys (in the energy scale) under the influence of X, that leads to the increase in resistivity with subsequent attainment of saturation at the absence of deep levels [at the constant total concentration of charge carriers $n_e = const$ in the conduction band (c-band)]; 2) an increase in the total concentration of charge carriers in the conduction band due to the deformative reducing of the energy gap between the deep level and the conduction band bottom, that leads to a decrease in the dependences $\rho = f(X)$.

Since at the asymmetric arrangement of the deformation axis relative to the isoenergetic ellipsoids in n-Ge ($\overrightarrow{X} \parallel \overrightarrow{J} \parallel [111,110]$) and n-Si ($\overrightarrow{X} \parallel \overrightarrow{J} \parallel [100,110]$) the redistribution of charge carriers between the valleys is practically finished at the mechanical stresses about $X \approx 0.7$ GPa (in the temperature range 77–300 K) (Fig. 4), at higher values of X only the second from named mechanisms of tensoresistance remains operative.

The maximum of dependence $\rho = f(X)$ is not observed under symmetrical arrangement of the deformation axis relative to all isoenergetic ellipsoids in the γ-irradiated germanium and silicon samples: in n-Ge ($\overrightarrow{X} \parallel \overrightarrow{J} \parallel [100]$) on curves 3 (Figs. 2 and Fig. 3) and in n-Si ($\overrightarrow{X} \parallel \overrightarrow{J} \parallel [111]$) on curve 3 (Fig. 7). In such conditions there is no reason to increase tensoresistance ρ_X/ρ_0 with pressure increasing, since there is no interminimum redistribution of the charge carriers. Consequently, the increase of the mechanical stress X is accompanied by the decrease of tensoresistance, in contrast to the non-irradiated samples (see Fig. 4). Let us consider the n-Si crystals as an example. The falling of the dependence ρ_X/ρ_0 with increase X in the γ-irradiated silicon samples indicates that in n-Si due to the irradiation the deep centers are appeared, which at the measurement temperature (125 K) without the mechanical load on the crystal were not fully ionized. Thus, the curve 3 (Fig. 7) represents the dependence $\rho_X/\rho_0 = f(X)$ obtained at T=125 K, when the level E_c – 0.17 eV is actively manifested. It is evident that (unlike the impurity states) for the level, belonging to A-center, the decrease in the energy gap between the deep level and the conduction band bottom with increasing of the mechanical stress $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [111]$ is observed. This provides (at T=125 K =*const*) the additional ionization of A-centers and the rise of the charge carrier concentration in c-band, thus causing the fall in tensoresistance ρ_X/ρ_0 with pressure increasing.

In p-Ge γ-irradiated at 300 K the creation of complexes with deep levels (of the radiation origin) is very problematic, since such material has high radiation hardness. However under the intense γ-irradiation of n-type Ge the n → p conversion occurs and the states with deep acceptor level E_V + 0.27 ev [47] appear. Therefore there is a need to investigate the features of tensoresistance at the presence of deep levels in the irradiated germanium crystals before and after n → p conversion.

The samples for investigations were cut out along the main crystallographic directions: [111,110], [100]. The charge carrier concentration and Hall mobility value before and after γ-irradiation were controlled by measuring the Hall effect.

Fig. 8 shows the measurement results of the longitudinal tensoresistance for the γ-irradiated n-Ge samples with dose 4×10^8 R at fixed temperature and under application of the mechanical compression stress along $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [111]$. In this case the material remains of n-type, but in the forbidden band the deep levels of E_c – 0.2 eV are appeared, which actively influence on the value $\rho = f(X)$ (curves 1 and 2) with temperature decreasing. Dependences $\rho = f(X)$ were obtained for the cases of $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [110]$ and $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [100]$. These dependences are qualitatively similar to the dependences, shown in Fig. 2 (curves 2 and

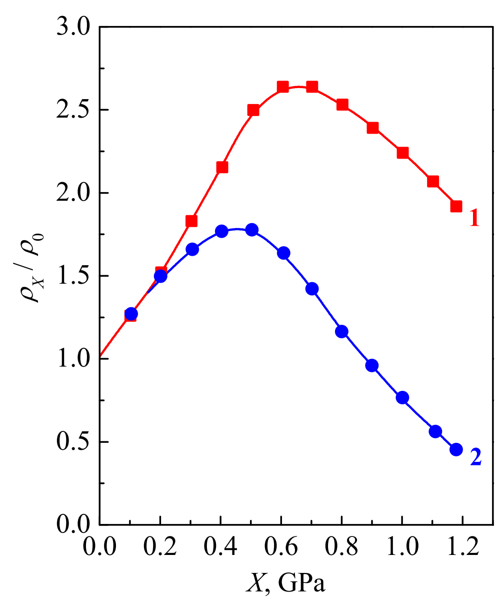

Fig. 8. Dependences $\rho_X/\rho_0 = f(X)$, measured on n-Ge crystals after irradiation by dose $D = 4 \times 10^8$ R in conditions $\overrightarrow{X} \parallel \overrightarrow{J} \parallel [111]$ at fixed temperature T, K: 1 – 190; 2 – 165.

3), and here they are omitted.

After irradiation by dose $D = 6.5 \times 10^8$ R the germanium is converted in the p-type Ge, and the acceptor level of $E_V + 0.27$ eV appears on the temperature dependence of the charge carrier concentration. The measurement results of the longitudinal tensoresistance of such crystals for all directions of the application of mechanical stresses at fixed temperatures are shown in Figs. 9 and 10.

As it is known from Ref. [25], in the intrinsic germanium crystals (i.e., in the undoped p-Ge with residual acceptor impurity and, in addition, without defects that cause the appearance of deep levels in the forbidden band) the availability of tensoresistance under uniaxial elastic deformation in the region of impurity conduction is caused by the simultaneous manifestation of several factors: a) the transition of the holes from upper (in the energy scale) splitted band into the bottom band; b) the substantial restructuring of the band spectrum of the holes under application the strong uniaxial deformation; c) the change with deformation of the relative contribution of the different scattering mechanisms.

The value of resistivity in samples for all investigated crystallographic directions in the temperature range of 77–300 K is always decreased with increasing the mechanical stresses in the result of the effect of mentioned factors. The typical (for the undoped p-Ge) view of these experimental dependences $\rho_X/\rho_0 = f(X)$ is shown in Fig. 9 by curves 1–3, obtained at T=165 K.

The dependences 4–6 (Fig. 9) have also qualitatively similar view. These dependences were obtained on the n → p converted germanium crystals at the relatively high temperatures (T=245 K). At such temperatures the deep centers are practically fully ionized and we observed the very good coincidence of the measured dependences for the n → p converted Ge (curves 4–6) with the experimental values for undoped p-Ge crystals, marked by symbols ■, ▲, ◊ on the corresponding curves 4–6 (Fig. 9) and measured at the same temperature T=245 K. A further lowering of the temperature leads to the quantitative and qualitative difference of the dependences 7–9 in Fig. 9 and Fig. 1– Fig. 3 in Fig. 10 from the dependences 1–3 and 4–6 in Fig. 9 [according to the influence of above mentioned factors, they should be located in the interval between the curves 1–3 and 4–6 (Fig. 9) for the intrinsic germanium crystals at the same temperatures]. Additionally, on the all curves 7–9 (Fig. 9) and 1–3 (Fig. 10) there are the sections of the resistivity increase in the initial deformation area with subsequent

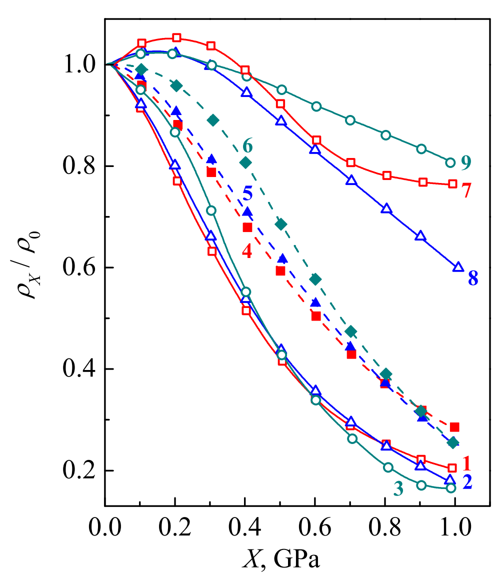

Fig. 9. Dependences $\rho_X/\rho_0 = f(X)$, measured on n-Ge crystals, irradiated by dose $D = 6.5 \times 10^8$ R, after n → p conversion at T=245 K (4, 5, 6) and 165 K (7, 8, 9), as well as for the undoped p-Ge at 165 K (1, 2, 3). Measurements were carried out in conditions: 1, 4, 7 – $\vec{X} \parallel \vec{J} \parallel [111]$; 2, 5, 8 – $\vec{X} \parallel \vec{J} \parallel [110]$; 3, 6, 9 – $\vec{X} \parallel \vec{J} \parallel [100]$.

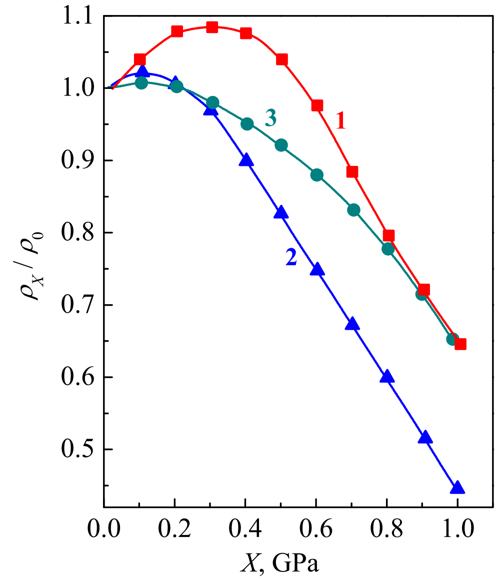

Fig. 10. Dependences $\rho_X/\rho_0 = f(X)$, measured at T=190 K on n-Ge crystals, irradiated by dose $D = 6.5 \times 10^8$ R, after n → p conversion in conditions: 1 – $\vec{X} \parallel \vec{J} \parallel [111]$; 2 – $\vec{X} \parallel \vec{J} \parallel [110]$; 3 – $\vec{X} \parallel \vec{J} \parallel [100]$.

passage of the dependences $\rho_X/\rho_0 = f(X)$ through the maximum, that is impossible for the pure unconverted p-Ge crystals [25].

In order to explain such view of tensoresistance dependences it is necessary (apart from the above mentioned factors a, b and c) to consider the possible change (at presence of deep level) of the hole concentration in the valence band due to the change in the value of the energy gap between the valence band top and the deep level $E_V + 0.27$ eV . Indeed, the increase in resistivity with deformation on the initial sections of dependences $\rho_X/\rho_0 = f(X)$ for all (main) crystallographic directions indicates that the concentration of holes in the valence band is reduced, i.e., the energy gap increases with pressure increase.

The decrease in resistivity of crystals with a further increase X was caused, seemingly, by the subsequent restructuring of the energy spectrum of charge carriers of the valence band and it represents the subject of the independent researches.

3. Conclusion

The following conclusions could be made as a result of performed experiments.

1. It was found that the dependences of tensoresistance pass through a maximum in the γ-irradiated n-Ge and n-Si crystals under conditions of the asymmetrical arrangement of the deformation axis relative to all isoenergetic ellipsoids. The presence of the maximum was explained by two main mechanisms (by the redistribution of charge carriers between the valleys, which deformation-displace in the opposite directions (in the energy scale), and by the increase in total concentration of charge carriers in the conduction band due to the deformation decrease of the energy gap between the deep level and the c-band bottom).
2. The maximum of dependence $\rho_X/\rho_0 = f(X)$ is absent under the symmetrical arrangement of the deformation axis relative to all isoenergetic ellipsoids in the γ-irradiated n-Ge and n-Si crystals. The observed decrease in tensoresistance with increasing the mechanical stress was explained by the appearance (due to the irradiation) of deep centers, which at the temperature of measurements without the mechanical load on crystals were not completely ionized.
3. It is shown that under the measurement of the longitudinal tensoresistance on the irradiated n-Ge crystals after n → p conver-

sion, when applying the mechanical stress at temperatures 190 and 165 K, the regions of resistivity rise appear on all curves in the initial area of deformation with subsequent passage of dependences through a maximum. This fact is explained by the increase of the energy gap between the deep level (located in the band gap) and the top of the valence band with increasing pressure. At higher temperatures (T=245 K), when the deep centers are almost completely ionized, the dependences of tensoresistance are almost identical for n-Ge crystals after n → p conversion and p-Ge crystals without deep levels.

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