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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 $n \to p$ conversion, at fixed temperatures depending on the direction ($\vec{X} \parallel \vec{J} \parallel$ [111,110], [100]) of application of the mechanical compressive stress $0 \le X \le 1.2$ 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 6×10^7 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

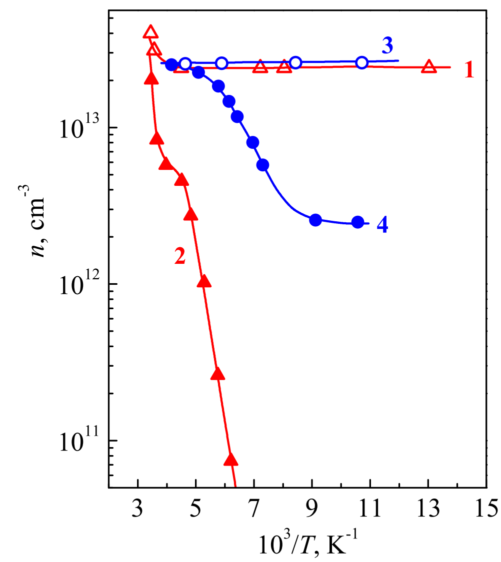

Fig. 1. Temperature dependences of the concentration of conduction electrons before (1, 3) and after (2, 4) γ-irradiation of the germanium and silicon crystals. For n-Ge ⟨Sb⟩ with the charge carrier concentration of $n_{e77K} = 2.4 \times 10^{13}$ cm^{-3}: 1 – D=0; 2 – $D = 6 \times 10^7$ R; for n-Si ⟨As⟩ with $n_{e77K} = 2.6 \times 10^{13}$ cm^{-3}: 3 – $D_1 = 0$; 4 – $D_1 = 3.3 \times 10^7$ R.

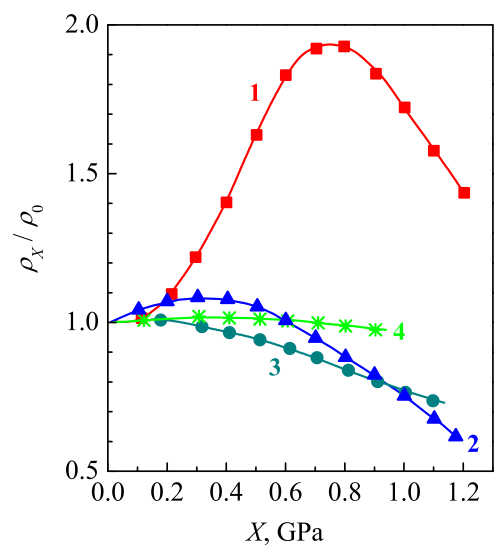

Fig. 2. Dependences $\rho_X/\rho_0 = f(X)$, measured on n-Ge ⟨Sb⟩ after irradiation by dose $D = 6 \times 10^7$ R at T=165 K in conditions: 1–$\vec{X} \parallel \vec{J} \parallel$ [111]; 2 – $\vec{X} \parallel \vec{J} \parallel$ [110]; 3 – $\vec{X} \parallel \vec{J} \parallel$ [100]; 4– at T=225 K, $\vec{X}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