Semiconductor Physics

Dose dependence of tensoresistance for the symmetrical orientation of the deformation axis relatively to all isoenergetic ellipsoids in γ-irradiated (^{60}Co) *n*-Si crystals

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Abstract. The dose dependence of tensoresistance ρ_X/ρ_0, which was measured at the symmetrical orientation of the deformation axis (compression) relatively to all isoenergetic ellipsoids both in the initial and in γ-irradiated samples, was investigated in *n*-Si crystals. It has been shown that changing the irradiation doses is accompanied by not only quantitative but also qualitative changes in the functional dependence $\rho_X/\rho_0 = f(X)$. Features of tensoresistance in *n*-Si irradiated samples were found depending on three crystallographic directions, along which the samples were cut out and the mechanical stress *X* was applied.

Keywords: silicon, γ-irradiation, mechanical stress, deformation axis, tensoresistance.

doi: https://doi.org/10.15407/spqeo21.01.048
PACS 61.80.Ed; 61.82.Fk; 72.20.Fr

Manuscript received 26.12.17; revised version received 18.01.18; accepted for publication 29.03.18; published online 29.03.18.

1. Introduction

Within the framework of concepts [1–3], which relate the resistivity change of the uniaxially deformed many-valley semiconductors ρ_X/ρ_0 (ρ_0 is the resistivity of undeformed crystal) with interminimum redistribution of charge carriers (that appear, as a result of removal of equivalent minima degeneracy on energy) natural under conditions of $\vec{X} \parallel \vec{J}$ and is pronounced as follows (*X* is the mechanical compression stress, $\vec{J}$ – current):

1) the substantial growth of $\rho_X/\rho_0 = f(X)$ with the increase in *X* (under $\vec{X} \parallel [111]$ in *n*-Ge and under $\vec{X} \parallel [100]$ in *n*-Si);

2) the growth of tensoresistance ρ_X/ρ_0 with increasing *X* up to saturation, which is responsible (at a given temperature) for the full transition of the charge carriers into the lowest (in the case of *n*-Ge) or two lowest (in the case of *n*-Si) energy minima;

3) the absence of resistivity change, associated with the interminimum redistribution of charge carriers, with growth of *X* under the complete symmetry in orientation of the axis of mechanical stress *X* with respect to the axes of all isoenergetic ellipsoids in the studied crystals, *i.e.*, at $\vec{X} \parallel [100]$ in *n*-Ge and $\vec{X} \parallel [111]$ in *n*-Si.

The obtained results concerning the tensoresistance within the region 0…1.0 GPa of the mechanical stresses allowed experimental proving the mechanism of tensoresistance, associated with interminimum redistribution of charge carriers in the conditions of asymmetric orientation of the deformation axis with respect to the isoenergetic ellipsoids in many-valley semiconductor.

Absence of tensoresistance in *n*-Ge in the studied area $X \le 1.0$ GPa at the symmetric orientation of the axis $\vec{X} \parallel \vec{J}$ with respect to isoenergetic ellipsoids in the frame of these concepts is the result of a physical picture of the phenomenon, because this situation excludes redistribution of charge carriers between the valleys of the same type (L_1-valleys) due to their "synchronous" shift on the energy scale under the uniaxial deformation [2, 4, 5]. However, within *n*-Ge, except the main L_1-minima of the conduction band (oriented along the equivalent directions ⟨111⟩); in the direction of ⟨100⟩ there are six the so-called "silicon" Δ_1-minima. According to [2], these minima (in the absence of deformation) are located by 0.18 eV above the absolute minima and therefore in the equilibrium conditions do not contribute to the transport phenomena. However, at quite marked decrease in the value of the energy gap between the L_1- and Δ_1-valleys, when applying the large uniaxial stresses, the transition of electrons in the minima type $\langle 100 \rangle$ is possible, and this should lead to the emergence of the new mechanism of tensoresistance effect in *n*-Ge.

As it is well known [6], in the effective mass approximation the equal energies and wave functions of the shallow impurity center depend on the structure of the band in the point of extremum. The presence of the equivalent extremes in *n*-Ge and *n*-Si leads to an additional *N*-fold degeneracy of the impurity states (for *n*-Ge $N = 4$, and for *n*-Si $N = 6$). Under the deformation influence, the energy and wave functions both of the basic and excited states of the shallow impurity centers are changed.

Since at the asymmetric orientation of the pressure axis relative to the isoenergetic ellipsoids the different extremes are shifted differently along the energy scale under deformation, then in these conditions deformation leads to the removal of many-valley degeneracy of the impurity basic state in the same extent, in which it causes the removal of degeneracy of the band bottom under this deformation [6]. For example, under deformation of *n*-Ge in the direction of [111] the extreme located along the axis [111] will shift by the value of ΔE_1, and with it the state of impurity center that responds to this extreme will shift by the same value, meanwhile the other three minima will shift by the value $\Delta E_2 = \Delta E_3 = \Delta E_4$. As a result of this deformation, the split of the four-fold degenerate impurity state into one- and triply degenerate states occurs.

Similarly, deformation of *n*-Si along the axis [001] splits the six-fold degenerate state of shallow donor center by the two- and four-fold degenerate ones, *i.e.*, by the value of energy between them, which is equal to the splitting of the bottom of conduction band under deformation [7]. It should be noted that in the case of a symmetrical arrangement of the axis with respect to all isoenergetic ellipsoids ($\vec{X} \parallel [111]$), there is no splitting in the spectra of shallow donors in *n*-Si.

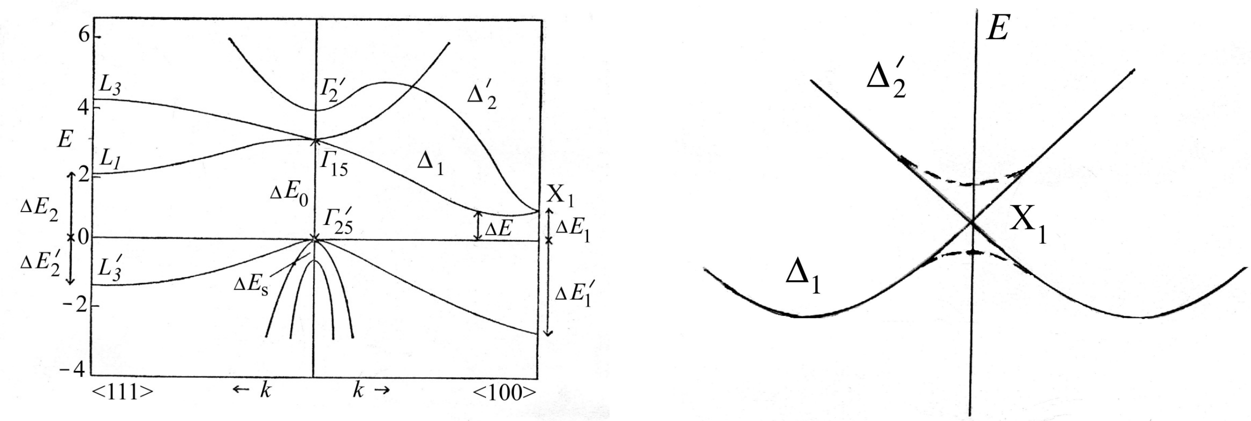
The presence of additional minima of Δ_1-type in *n*-Ge leads to the fact that, besides the basic states associated with the L_1-minima, there are levels that belong to the same impurities, but associated with Δ_1-minima. The energy position of these levels can be located in the band gap and can coincide with some levels in the allowed band. Moreover, since the effective masses of charge carriers and their anisotropy for Δ_1- and L_1-valleys should be significantly different; it is natural to assume that the ionization energy of shallow impurity levels for these valleys also should differ. The experiments on the study of low-temperature impact ionization of neutral donors [8] confirmed the theoretical assumption that each energy minimum has its own energy level of the same impurity.

In *n*-Si, the tensoresistance effect that occurs when $\vec{X} \parallel \vec{J} \parallel [111]$ is qualitatively different not only from the usual Smith–Herring tensoresistance, but also from the observed one at $\vec{X} \parallel \vec{J} \parallel [100]$ in the area of large pressure *X* in *n*-Ge. The discussed effect in *n*-Si differs from Smith–Herring tensoresistance by the dependence behaviour on the temperature (experimentally we obtain the relation $\frac{\rho_X}{\rho_0}(300\,\text{K}) > \frac{\rho_X}{\rho_0}(78\,\text{K})$, which is inverse as compared to the usual sequence in arrangement of tensoresistance curves measured at the room and nitrogen temperatures). From tensoresistance of *n*-Ge at $\vec{X} \parallel \vec{J} \parallel [100]$, this effect differs by the beginning of its growth under the fairly negligible mechanical stresses. Since the Hall measurements clearly indicate the independence of *X* for the complete charge carrier concentration in *n*-Si, which is deformed in the direction [111], and the interminimum redistribution in these conditions is excluded, in principle, then the cause for change of $\rho_X/\rho_0 = f(X)$ observed experimentally can be only the dependence of electron mobility μ on deformation. Both the theory [6], and the data on cyclotron resonance in uniaxially deformed *n*-Si [9] show that at presence of the component of shear deformation (which is characteristic for $\vec{X} \parallel [111]$) the transverse effective mass $m_\perp$ increases linearly with *X* growth (approximately by 1% per every 0.25 GPa).

Removal of degeneration of bands Δ_1 and Δ_2' for *n*-Si in the point X_1 at the expense of shear deformation is accompanied by the change in the curvature $E(\vec{k})$ in the area of acting minimum (Fig. 1). Therefore, the “blurring” of the charge carrier distribution over the energy levels in the conduction band (*c*-band) under the temperature increase must be accompanied by amplification of these changes manifestation, which results in the growth of ρ_X/ρ_0 as compared to the value of this relationship obtained at a lower temperature. Therefore, the tensoresistance satisfies the inequality $\frac{\rho_X}{\rho_0}(300\,\text{K}) > \frac{\rho_X}{\rho_0}(78\,\text{K})$ with the direction of the inequality sign opposite to that characteristic to the Smith–Herring tensoresistance.

Thus, in the many-valley semiconductors such as *n*-Si, besides the well-known Smith–Herring tensoresistance, appearance of tensoresistance associated with changing the charge carrier mobility $\mu = \mu(X)$ is possible, which is caused by growing $m_\perp$ with increasing *X* for these orientations of the mechanical stresses, at which it is possible to manifest the shear deformation components. In addition, there appears the tensoresistance component associated with the deformation removal of degeneracy of *n*-Si zones in the point X_1 and with manifestation of nonparabolicity of Δ_1-valleys in its surroundings.

The aim of this study is to investigate the dose dependences of tensoresistance ρ_X/ρ_0, which was measured at orientation of the pressure axis symmetrically with respect to all isoenergetic ellipsoids both in the initial and in γ-irradiated silicon crystals, and the research of tensoresistance features (at a fixed temperature) in the



(a) (b)

Fig. 1. Schematic image: *a*) the band structure of Si; the widths of band gaps are equal ΔE = 1.12 eV; ΔE_0 = 3.4 eV; ΔE_s = 0.035 eV; ΔE_1 = 1.2 eV; $\Delta E_1'$ = 3.1 eV; ΔE_2 = 1.9 eV; $\Delta E_2'$ = 2.2 eV ([10]); *b*) the removal of degeneracy of the bands Δ_1 and Δ_2' of *n*-Si in the neighborhood of points X_1 at the expense of the directional deformation (solid lines – in the absence of deformation $X = 0$, dashed lines – for $X \neq 0$).

irradiated semiconductors depending on the crystallographic directions, along which the samples were cut and the mechanical stress *X* was applied.

2. Results and discussion

The influence of γ-irradiation and level of the initial compensation in the *n*-Si crystals on the field dependences of magnetoresistance and Hall coefficient within the range of magnetic fields $5850 \le H \le 18000$ Oersted were studied in Ref. [11]. There was also shown a slight increase of the ratio $\alpha = R_H / R_{H_{\min}}$ with the growth of the magnetic field *H*. An interesting result was that, in both compensated and uncompensated crystals, the ratio $\rho(H)/\rho_0$ (within the accuracy of measurements carried out there) showed its independence of γ-irradiation, although the radiation dose ($D \approx 10^7$ R) used in these experiments exceeded by an order of magnitude the radiation dose used in studying the Hall effect in the same samples. This fact was also explained there.

Both in the cognitive and practical aspects, the study of the γ-irradiation influence on *n*-Si tenso-resistance was interesting, particularly, the study of tensoresistance effect features at presence in the band gap of silicon the deep levels belonging to the radiation defects. A- or E-centers can serve as examples in the γ-irradiated *n*-Si. Silicon crystals grown from the melt, as a rule, have a high content of the oxygen impurity, therefore, A-centers (as the complexes of the vacancies and oxygen atoms) [12] should be taken into account in the first place.

In this paper, to measure the tensoresistance and Hall effect the dislocation-free *n*-Si crystals were used with the relatively low level of doping by As impurity (the initial concentration of charge carriers $n_e = 7.19\cdot10^{13}$ cm^{-3}) and the background concentration of oxygen impurities up to $1.9\cdot10^{18}$ cm^{-3}, as well as the samples *n*-Ge⟨Sb⟩ with the initial concentration of charge carriers $n_e = 4\cdot10^{13}$ cm^{-3}. For the purpose of comparative experiments, the samples were cut along the main crystallographic directions ⟨100⟩, ⟨110⟩, ⟨111⟩, along which the mechanical stress *X* was applied. When measuring the tensoresistance in conditions of $\vec{X} \parallel \vec{J} \parallel [111]$ on *n*-Si samples and under conditions of $\vec{X} \parallel \vec{J} \parallel \langle 100 \rangle$ on *n*-Ge samples with longitudinal orientation along the crystallographic directions ⟨111⟩ and ⟨100⟩, respectively, the usual tensoresistance associated with intervalley migration of electrons has been completely ruled out.

Irradiation of crystals by γ-quanta was carried out from ^{60}Co sources at room temperature. In the case of *n*-Si, the γ-irradiation dose ($D_1 = 3.3\cdot10^7$ R) was chosen so that the energy level $E_c - 0.17$ eV, belonging to A-center [13], clearly manifested in the temperature dependence of the charge carrier concentration. In the case of *n*-Ge, the γ-irradiation dose ($D = 6\cdot10^7$ R) was chosen so that the energy level $E_c - 0.2$ eV manifested in the temperature dependence of the carrier concentration.

Fig. 2 shows the results of measurements of the longitudinal tensoresistance of γ-irradiated *n*-Si and *n*-Ge samples at the fixed temperatures and for different directions of applying the mechanical compression stress ($\vec{X} \parallel \vec{J} \parallel [100], [111], [110]$). We can see from Fig. 2 that the obtained dependences for irradiated silicon and germanium samples are qualitatively similar to each other both in the case of unsymmetrical (curves *1*, *3* and *1**, *3**) and symmetrical (curves *2* and *2**) arrangement of the deformation axis relatively to all isoenergetic ellipsoids of the conduction band.

It is known [14] that in the unirradiated *n*-Ge crystals without deep levels, the resistivity for crystallographic direction [111] first increases with the increasing mechanical stress that is applied along this direction, and then goes to saturation, similarly as in *n*-Si, when the pressure is applied along the [100] direction.

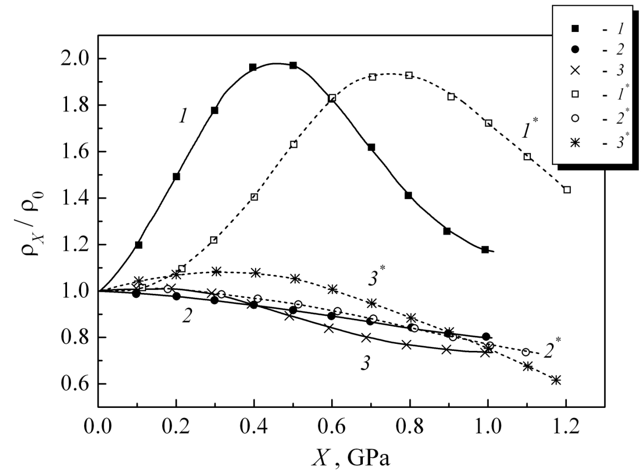


Fig. 2. Dependences $\rho_X/\rho_0 = f(X)$, measured at T = 125 K in n-Si (*1–3*) after γ-irradiation by the dose D_1 = 3.3·10^7 R and at T = 160 K in n-Ge (1^*–3^*) after γ-irradiation by the dose D = 6·10^7 R, under conditions $\vec{X} \parallel \vec{J} \parallel [100]$ ($1, 2^*$), $\vec{X} \parallel \vec{J} \parallel [111]$ ($2, 1^*$) and $\vec{X} \parallel \vec{J} \parallel [110]$ ($3, 3^*$).

For the γ-irradiated n-Ge crystals in the temperature range, where the level of radiation-induced defects E_c – 0.2 eV [15, 16] is manifested, the character of tensoresistance dependence changes qualitatively: the decrease in resistivity appears with increasing the mechanical stress after the passage of curves through the maxima (curves 1^*, 3^* in Fig. 2). This is true both for the direction [111] and for [110]. On the dependence (curve 2^*, Fig. 2) obtained for n-Ge with the pressure applied in the [100] direction, the maximum is absent, as on curve *2* obtained for n-Si under the conditions $\vec{X} \parallel \vec{J} \parallel [111]$, however, with increasing pressure, the resistivity decreases in both cases.

As is known [2], in the non-irradiated n-Si crystals (without deep levels) the presence of tensoresistance in conditions of $\vec{X} \parallel \vec{J} \parallel [100]$ is caused by migration of the charge carriers from four rising valleys (with greater mobility $\mu_\perp$) into two valleys with $\mu_\parallel << \mu_\perp$, descending on the energy scale, which leads first to an increase of dependence $\rho = f(X)$ and then to saturation. However, this dependence can also be observed at room temperature, when the deep center with E_c – 0.17 eV level is almost completely ionized. With decreasing temperature, when the level of radiation defects begins to appear, behavior of $\rho_X/\rho_0 = f(X)$ dependence becomes qualitatively different (Fig. 2, curve *1*). Passage of tensoresistance through the pronounced maximum with a further decrease in resistivity under increasing the mechanical stresses is a characteristic feature of dependence (Fig. 2, curve *1*) obtained under the condition $\vec{X} \parallel \vec{J} \parallel [100]$.

A comparison of curves *1* and *3* in Fig. 2 shows that the dependences $\rho = \rho(X)$ under the conditions $\vec{X} \parallel \vec{J} \parallel [100]$ and $\vec{X} \parallel \vec{J} \parallel [110]$ are qualitatively similar, although in the latter case the maximum is expressed not so clear and the region characterized by the decrease of resistivity with deformation begins to emerge at less mechanical stresses. The shape of dependences $\rho = \rho(X)$ obtained in these experiments for both crystallographic directions can be explained by the presence of two competing mechanisms of resistivity change with pressure:

1) redistribution of the charge carriers between the valleys that are deformation-shifted (in the energy scale) in opposite directions (two valleys shift down, and four – shift up at $\vec{X} \parallel \langle 100 \rangle$), which leads to growth of ρ with increasing X;

2) increasing the total concentration of charge carriers in the conduction band at the expense of deformation diminution of the energy gap between the deep level and the conduction band bottom, which leads to decrease of ρ with growth of X.

Since under the asymmetric placement of the deformation axis relative to the isoenergetic ellipsoids in n-Si redistribution of charge carriers between the valleys practically ends at the mechanical stresses about X ~ 0.7 GPa (in the temperature range 77…300 K) [2], then at higher values of X only the second of the above mechanisms of tensoresistance remains active.

At the symmetrical placement of the deformation axis relatively to all isoenergetic ellipsoids in γ-irradiated n-Si ($\vec{X} \parallel \vec{J} \parallel [111]$) on the curve *2* (Fig. 2), the maximum of dependence $\rho = \rho(X)$ is not observed, since the reason for the growth of ρ_X/ρ_0 with increasing pressure X is absent under these conditions (no interminimum redistribution of charge carriers).

The increase of ρ_X/ρ_0, starting with the lowest mechanical compression stress X due to the presence of the component of shift deformation is the characteristic feature of unirradiated n-Si tensoresistance in the case of $\vec{X} \parallel \vec{J} \parallel [111]$ (Fig. 3, curve *1*). This feature, in principle, distinguishes the n-Si tensoresistance from that, arising in unirradiated n-Ge at the symmetrical placement of the deformation axis relatively to all isoenergetic ellipsoids (Fig. 3, curve 1^*). Taking into account this circumstance and data about the band structure of silicon (the energy gap between Δ_1- and L_1-valleys is about 1.1 eV), we cannot apply the same representations that were used in the case of n-Ge, to explain tensoresistance that arises in n-Si at $\vec{X} \parallel \vec{J} \parallel [111]$.

Since when applying the mechanical stress X in conditions $\vec{X} \parallel \vec{J} \parallel [111]$ the relative displacement of valleys is absent in n-Si, then the presence of tensoresistance in unirradiated crystals (Fig. 3, curve *1*) can be explained by the change in mobility due to increase of $m_\perp$ at simultaneous manifestation of the deformation-induced nonparabolicity of the conduction band. In fact, at the pressure X angularly to the long axis of the ellipsoid the shape of its cross-section changes, which is equivalent to changes in the acting effective masses. In contrast to n-Si, for unirradiated n-Ge samples with uniaxial pressure applied under the conditions $\vec{X} \parallel \vec{J} \parallel [100]$ (the symmetric arrangement of the deformation axis with respect to all isoenergetic

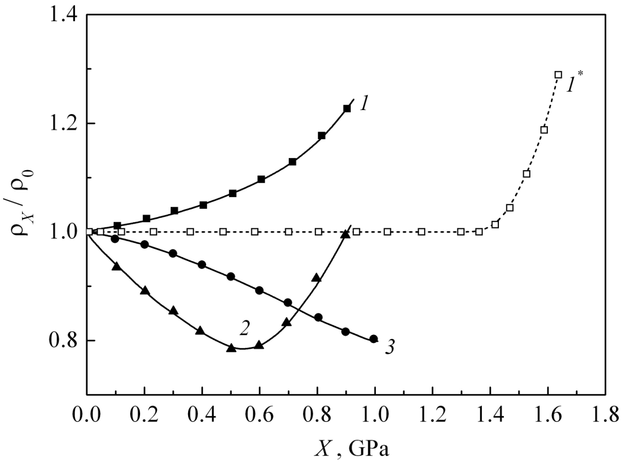


Fig. 3. Dependences $\rho_X/\rho_0 = f(X)$, measured at $T = 125$ K in n-Si under conditions $\vec{X} \parallel \vec{J} \parallel [111]$ before (*1*) and after γ-irradiation with the doses $D_1 = 3.3 \cdot 10^7$ R (*2*) and $D_2 = 8 \cdot 10^7$ R (*3*); as well as the dependence $\rho_X/\rho_0 = f(X)$, measured at 77 K in unirradiated n-Ge under the conditions $\vec{X} \parallel \vec{J} \parallel [100]$ (1^*).

ellipsoids of the conduction band), the tensoresistance effect associated with deformation redistribution of charge carriers between minima of the same type (the Smith–Herring tensoresistance) will be absent up to the pressures of the order of 1.5 GPa (Fig. 3, curve 1^*).

After n-Si irradiation with different doses of γ-quanta, the dependences of $\rho_X/\rho_0 = f(X)$ are qualitatively changed (Fig. 3, curves *2* and *3*) as compared to the curve *1* obtained before irradiation. The rising mechanical load X is accompanied not by increase (at least, initially) but by decrease of ρ_X/ρ_0. This indicates the emergence as a result of irradiation of deep centers in silicon, which at the measurement temperature (125 K) without mechanical load on the crystal were not completely ionized. Thus, the curve *2* represents the dependence $\rho_X/\rho_0 = f(X)$ obtained at $T = 125$ K, when the level $E_c - 0.17$ eV actively appears. It can be seen that (unlike the impurity states), for the level belonging to A-center, the decrease in the energy gap between the deep level and the bottom of conduction band is observed with increasing the mechanical load $\vec{X} \parallel \vec{J} \parallel [111]$, which provides (at $T = 125$ K = const) additional ionization of these centers and increase in the concentration of charge carriers inside the conduction band, thus causing the decline of ρ_X/ρ_0 with increasing the mechanical stress. After a complete ionization of deep centers, the mechanism that causes the growth of curve *1* (Fig. 3) with pressure (associated with the deformation restructuring of the isoenergetic ellipsoids) begins to show itself. Thus, the curve *3* (Fig. 3) passes through the minimum with increasing the mechanical stress X.

Increasing the irradiation dose from $3.3 \cdot 10^7$ up to $8 \cdot 10^7$ R promoted not only the increase in concentration of the centers of radiation origin in the irradiated crystals, but also changed their ability to ionization, as could be seen from the shape of curves *2* and *3* in Fig. 3 and their relative arrangement in coordinates (ρ_X/ρ_0; X).

It should be noted that in n-Si the above mentioned radiation-induced changes turned out rather stable over time (under conditions of finding the objects in the air at room temperature), like to previously investigated changes in n-Ge crystals [17], as well as in hetero-systems and nanostructures created on the basis of elementary semiconductors and semiconductor compounds [18].

3. Conclusions

The tensoresistance measurements in n-Si crystals irradiated with different doses of γ-radiation (^{60}Co) showed that:

– under conditions of the symmetric arrangement of deformation axis relatively to all isoenergetic ellipsoids ($\vec{X} \parallel \vec{J} \parallel [111]$) at the fixed temperature $T = 125$ K [in contrast to n-Si tensoresistance in the initial state, when the function $\rho_X/\rho_0 = f(X)$ was characterized by some (up to 20%) increase], irradiation of samples by the dose $D_1 = 3.3 \cdot 10^7$ R ensures its monotonic decrease, and for the dose $D_2 = 8 \cdot 10^7$ R the nonmonotonic change of the investigated function ρ_X/ρ_0 is manifested with the monotonic increase of the mechanical load X;

– sequential raising of γ-irradiation dose (from $3.3 \cdot 10^7$ up to $8 \cdot 10^7$ R) provides the qualitatively distinct (between themselves) change of $\rho_X/\rho_0 = f(X)$ function, which is the evidence not only about quantitative changes (*i.e.*, in concentration) of the radiation electrically-active defects, but also points to the qualitative change in the structure of these defects at dose increase of the radiation treatment of crystals;

– dependences of tensoresistance $\rho_X/\rho_0 = f(X)$ measured at $T = 125$ K in γ-irradiated n-Si samples by the dose of $3.3 \cdot 10^7$ R, when applying the mechanical stress along the crystallographic directions $\vec{X} \parallel \vec{J} \parallel [100]$ and [110], are characterized by a pronounced maximum, which is explained by manifestation of two main mechanisms for changing the resistivity with pressure. In the case of $\vec{X} \parallel \vec{J} \parallel [111]$, the similar maximum of ρ_X/ρ_0 is not observed, since one of the mechanisms of changing ρ, associated with the interminimum migration of charge carriers, is absent.

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