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# INFLUENCE OF GAMMA IRRADIATION ($^{60}$Co) ON THE ELECTROPHYSICAL PARAMETERS OF $n$-Ge WITH A DIFFERENT DOPING LEVEL AND WITH OXYGEN IMPURITY IN DIFFERENT STATES

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On the basis of the measurements of the Hall effect, the specificity of the influence of $\gamma$-irradiation ($^{60}$Co) on changes in the charge carrier concentration $\Delta n$ and their mobilities was investigated in the $n$-Ge single crystals of different levels of doping by the antimony impurity. The dependences of $\Delta n$ on the initial Sb impurity concentration in the crystals for two temperatures (room and liquid nitrogen) have been established, and changes in the charge carrier mobility (in the impurity scattering region) that correlate with changes in the carrier concentration have been revealed. At the liquid nitrogen temperature, the influence of $\gamma$-irradiation on the Hall parameters of $n$-Ge ⟨Sb⟩ crystals with an oxygen impurity (atomically dispersed and in the form of oxygen complexes) was investigated. Changes in the electron mobility, which are opposite in sign, were detected in the initial and heat-treated (400°C; 100 h) germanium samples under the effect of irradiation. It was shown that the change in the scattering anisotropy under the influence of irradiation depends on the state of the oxygen impurity in Ge.

**Key words**: germanium, gamma irradiation, thermal treatment, charge carrier concentration, mobility, scattering anisotropy.

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## I. INTRODUCTION

Single-crystal germanium had been for a long time and remains today a promising semiconductor material for the manufacture of power diodes, transistors, dosimetry devices, the creation of precision nuclear radiation detectors, the application in micro- and nanoelectronics [1–4]. In radio communication devices, the alloy of germanium with silicon begins to gradually displace the gallium arsenide. Germanium is widely used for the manufacture of details of optical systems of infrared technology, in particular in infrared spectroscopes and other optical equipment that requires the extremely sensitive infrared sensors [5–8]. Obtaining multilayered arrays of quantum dots of germanium in the silicon matrix is promising with a view to using them in solar cells [9].

The germanium single crystals substantially change their physical characteristics under the action of different physical influences [10, 11]. Their comprehensive use under such conditions as high loads, rapidly changing temperature regimes, significant electric, magnetic and radiation fields requires a detailed study of the germanium properties, which will subsequently create prerequisites for taking into account the indicated effects when designing semiconductor devices with the purpose to increase their reliability and extend the term service [12, 13]. Thus, investigations into the transport phenomena of charge carriers, as well as the processes of the generation and transformation of the radiation defects that arise in germanium samples under the influence of thermal and radiation treatments, are not only of considerable scientific interest. Such studies are no less important in terms of application, since they allow predicting the changes occurring in the material during the process of manufacturing electronic devices, with high probability [14].

It should be noted that for most applied problems, not only the doping method or the degree of homogeneity of the crystal is of great importance, but also what background impurities are contained in its volume and in what state they seat. Both the concentration and the mobility of charge carriers ultimately depend on these circumstances [15, 16]. These problems can be solved by examining the crystals in various aspects: by directly studying the influence of individual chemical elements on their electrical properties [17]; by revealing the features of the effect of compensating impurities on the properties of semiconductors [18]; by analyzing the various variants of complexation in the volume of the crystals and the consequences to which they lead [19, 20]; by investigating the anisotropy of the main electrophysical parameters of the crystals (that is, their discrepancy in the different crystallographic directions) [21]; by studying the changes in the electrical parameters of the crystals in fields of effective external action [12].

Among the basic impurities that determine the structural perfection and properties of germanium single crystals, an oxygen impurity is released. According to [22–

24], thermal annealing of germanium in the temperature range 350–450°C leads to the formation of precipitates of a special type, which are characterized by electrical activity, namely, thermodonors based on interstitial oxygen. A majority of modern models of thermodonors represent such centers in the form of complexes consisting of an electrically active nucleus with different numbers of oxygen atoms attached to it.

It is known [25] that in $n$-Ge doped with a shallow donor impurity (such as antimony or phosphorus), the Hall mobility of charge carriers, as well as the Hall coefficient, are isotropic in weak magnetic fields and anisotropic in intermediate magnetic fields. However, when germanium is doped with donors of another nature (for example, by oxygen complexes that arise during the thermal treatment process of crystals [26]), a number of peculiarities appear that depend not only on the oxygen concentration, but also on the state of this impurity in the volume of the crystal, as was shown in [27, 28]. Thus, with the help of Hall measurements, an anomalous increase in the charge carrier mobility from irradiation dose in the mixed-scattering region was observed in [27] when irradiating the oxygen-containing $n$-germanium and $n$-silicon crystals. Meanwhile the crystals, grown by the floating-zone method, which had a low content of background oxygen impurity, did not exhibit the radiation-induced increase in mobility. The influence of irradiation on samples with the approximately equal dopant concentration was investigated in [27].

The aim of the paper was to establish the regularities of the influence of $\gamma$-irradiation on changes of Hall parameters in the $n$-Ge crystals of different levels of doping and with the oxygen impurity in the different states.

## II. SPECIFICITY OF THE INFLUENCE OF $\gamma$-IRRADIATION ON THE HALL PARAMETERS OF $n$-Ge WITH DIFFERENT CONCENTRATIONS OF DOPANT

While interacting with solids, gamma quanta, like fast electrons, cause mainly point type defects, which can change electrophysical characteristics of the material. When studying the energy structure of defects in $\gamma$-irradiated germanium, it was found that the interpretation of the obtained data is largely hampered both by the migration processes of primary defects arising upon irradiation, and by the manifestation of their interaction with impurities and structural imperfections of the initial crystals, and the annealing kinetics of radiation-induced defects depends on the presence of chemical impurities and structural defects in the volume of the crystals under study [29]. Meanwhile the annealing processes of radiation defects occur differently not only in samples with different chemical impurities but also in samples with the same impurity but different contents of it. In addition, the formation of defects under $\gamma$-irradiation of Ge in the region of moderately high temperatures ($\sim 300$ K) is accompanied by the process of their annealing, which occurs simultaneously. Taking into account both of these circumstances, it was possible to assume that the change in the charge carrier concentration in the samples as a result of irradiation will depend (with other equal conditions) on the initial impurity concentration $N \equiv n_0$ in the crystals under study. This section of the work is devoted to an experimental check of the indicated assumption, as well as to answering related questions concerning, in particular, the change in the charge carrier mobility in $n$-Ge as a result of $\gamma$-irradiation.

The changes in the charge carrier concentration $\Delta n$, arising as a result of $\gamma$-irradiation $^{60}$Co at the temperature of 30°C, were investigated in the germanium samples with antimony impurity $n$-Ge $\langle$Sb$\rangle$ ($3.49 \times 10^{14} \leq N_{\mathrm{Sb}} \equiv n_0 \leq 1.92 \times 10^{18}$ cm$^{-3}$) at room temperature (300 K) and liquid nitrogen temperature (77 K). Carrying out the measurements only at two fixed temperatures eliminated the possibility of performing the analysis directly from the standpoint of changing the concentration of radiation defects, but this task was not contemplated here. The measurements were carried out on the sufficiently homogeneous samples with the dislocation density of $N_{\mathrm{D}} = 10^3 - 10^4$ cm$^{-2}$. The power of the source was $4.8\times 10^{12}$ $\gamma$-quanta/(cm$^2$·s), and the fluences of the gamma-quanta used in the experiments were as follows: $D_1 = 1.6 \times 10^{18}$; $D_2 = 1.6 \times 10^{17}$; $D_3 = 1.6 \times 10^{16}$; $D_4 = 1.6\times 10^{15}$ $\gamma$-quanta/cm$^2$. The data analyzed in this study were related to the irradiation stage, which does not yet change the type of crystal conductivity.

The charge carrier concentrations before ($n_0$) and after ($n$) $\gamma$-irradiation were obtained on the results of Hall measurements from the expression $n = r/(eR_0c)$, where $r = R_0/R_\infty$ is the Hall factor, whose concentration dependence is known from [30], $R_0$ and $R_\infty$ are the limiting values of the Hall coefficient for the magnetic field strengths $H \to 0$ and $H \to \infty$, respectively.

The dependences of the changes in the concentration $\Delta n = n_0 - n$ obtained under the $\gamma$-irradiation of the samples with different values of $n_0$ in the initial state by three different fluences ($D_1$, $D_2$ and $D_3$) are presented in Fig. 1. When processing the data, the concentration dependence of the Hall factor was not taken into account only in the case of the straight line *0*. The consequences of taking into account the Hall factor, which was used in the paper, can be seen from the comparison of the straight lines *1′* and *0* (Fig. 1), constructed from the same experimental data, respectively, with and without the Hall factor. It was found that the slope of the straight line *0* is 1.63 times less than the slope of the straight line *1′*. Therefore, for the accurate determination of the occurrence depth of the levels from the dependences $n = f(1/T)$, it is also necessary to take into account changes in the Hall factor with temperature and concentration.

Figure 1 shows that the dependences of $\Delta n = f(n_0)$, represented at the double logarithmic scale, have the form of straight lines both at room temperature and at liquid-nitrogen temperature, that is, in both cases they can be described by the relation $\Delta n = \eta n_0^{\xi}$ (where $\eta = \mathrm{const}$). The value of the parameter $\xi$ was cal-

culated, averaged every time along the slopes of three straight lines: $\xi_{300\ \mathrm{K}} = 0.34 \pm 0.01$ for straight lines *1–3*; $\xi_{77\ \mathrm{K}} = 0.13 \pm 0.03$ for straight lines *1′–3′*. The results obtained show that in both cases (at 300 and 77 K) the changes in the charge carrier concentration under the action of $\gamma$-quanta depend significantly on the concentration of the dopant Sb in the initial crystals; meanwhile, the large changes in the concentration $\Delta n$ correspond to the large values $n_0$.

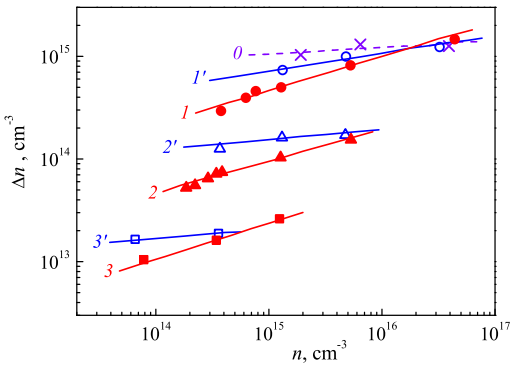


Fig. 1. Dependences of the changes of charge carrier concentration in the conduction band $\Delta n = n_0 - n$ on the values of $n_0 \equiv N_{\mathrm{Sb}}$ in the initial state, which appear in $n$-Ge ⟨Sb⟩ crystals as a result of $\gamma$-irradiation by different fluences $D$, $\gamma$-quanta/cm$^2$: *0*, *1*, *1′* — $D_1$; *2*, *2′* — $D_2$; *3*, *3′* — $D_3$. The measurements were carried out at temperatures $T$, K: *1*, *2*, *3* — 300; *0*, *1′*, *2′*, *3′* — 77. When processing the data, the Hall factor was taken into account everywhere except for the straight line *0*.

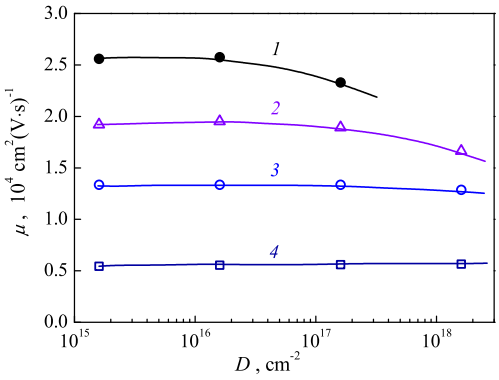


Fig. 2. Dependences of the charge carrier mobility at 77 K on the fluence of $\gamma$-irradiation in $n$-Ge ⟨Sb⟩ samples with different initial concentration of charge carriers $n_0$, cm$^{-3}$: *1* — $3.49 \times 10^{14}$; *2* — $1.21 \times 10^{15}$; *3* — $4.90 \times 10^{15}$; *4* — $3.92 \times 10^{16}$.

Figure 2 shows the dependences of the charge carrier mobility, measured at 77 K, on the irradiation fluence in the samples having the initial concentrations $n_0$ in the interval $3.49 \times 10^{14} - 3.92 \times 10^{16}$ cm $^{-3}$.

The reason for the observed dependence of mobility on the irradiation fluence is the change in the concentration of the scattering (primarily charged) centers in the crystal as a result of irradiation. It was established that in the samples with the initial concentration $n_0 \geq 4 \times 10^{16}$ cm$^{-3}$, the irradiation fluences $D \leq 1.6 \times 10^{18}$ $\gamma$-quanta/cm$^2$ practically did not change the value of mobility (Fig. 2). According to the results of mobility measurements at the temperature of 300 K (on the sufficiently homogeneous samples), the last conclusion remained valid for the whole range of the concentrations studied (Table 1).

| Sample number | $n_0$, cm$^{-3}$ | $\mu_0$, cm$^2$/(V·s) | $\mu$ after irradiation, cm$^2$/(V·s) | | | |
|---|---|---|---|---|---|---|
| | | | $D_1$ | $D_2$ | $D_3$ | $D_4$ |
| 1 | $3.49 \times 10^{14}$ | 3290 | — | 3250 | 3380 | 3360 |
| 2 | $1.21 \times 10^{15}$ | 3120 | 3090 | 3130 | 3140 | 3140 |
| 3 | $4.90 \times 10^{15}$ | 2890 | 2920 | 2940 | 2970 | 2930 |
| 4 | $3.92 \times 10^{16}$ | 2670 | 2690 | 2680 | 2680 | 2720 |
| 5 | $1.92 \times 10^{18}$ | 875 | 883 | 878 | 880 | 890 |

Table 1. The values of charge carrier mobility, measured at 300 K, in $n$-Ge crystals with different levels of doping with antimony impurity before ($\mu_0$) and after ($\mu$) irradiation by different fluences $D$ of $\gamma$-quanta.

## III. INFLUENCE OF THERMAL AND RADIATION TREATMENTS ON ELECTROPHYSICAL PARAMETERS OF OXYGEN-CONTAINING $n$-Ge ⟨Sb⟩ CRYSTALS

The magnitude of changes in the Hall coefficient upon application of the magnetic field is determined by the carrier-charge scattering efficiency, and the anisotropy of the Hall coefficient in the intermediate magnetic fields $H$ depends completely on the anisotropy of this scattering. Therefore, we will try, using the Hall effect method, to clarify the role of oxygen in the variation of the galvanomagnetic properties of the $\gamma$-irradiated germanium crystals. The present section of the work is devoted to the study of this question.

The electroconductivity and the Hall effect in $n$-Ge crystals doped with antimony (Sb) through melting and saturated with oxygen during their growth were investigated at 77 K before and after $\gamma$-irradiation by fluence $2.62 \times 10^{17}$ $\gamma$-quanta/cm$^2$. The measurements were carried out over a wide range of the magnetic field strengths (up to 35 kOe). The oxygen content in the ingots was estimated from the magnitude of optical absorption (at $\lambda = 11.7$ $\mu$m), taking into account the calibration factor 1 cm$^{-1}$ $\equiv 1.25 \times 10^{17}$ atom/cm$^3$. The concentration of atomically dispersed oxygen in the initial ingot *a* was $N_{\mathrm{O}} = 1.4 \times 10^{17}$ cm$^{-3}$. After the thermal treatment of a part of this ingot (which will be denoted by letter *b*) at the temperature of $T = 400$°C during 100 h, the amount of the optically active oxygen decreased in it to the magnitude of $1.2 \times 10^{17}$ cm$^{-3}$, and the charge carrier concentration increased by $\Delta n_e \approx 1.8 \times 10^{15}$ cm$^{-3}$ due to the formation of thermal donors.

Two groups of samples were prepared from each ingot (initial $a$ and heat-treated $b$), which were conditionally designated by letters $A$ and $B$ (before $\gamma$-irradiation), $A'$ and $B'$ (the prime ($'$) denotes the same sample and orientaion after $\gamma$-irradiation). All samples were cut in the [110] direction. The current $j$ and the magnetic field $H$ were directed as follows: $A \rightarrow \mathbf{j} \parallel [110]$, $\mathbf{H} \parallel [001]$; $B \rightarrow \mathbf{j} \parallel [110]$, $\mathbf{H} \parallel [1\bar{1}0]$.

The results of the experiments carried out at 77 K with these samples in the weak magnetic fields ($H \rightarrow 0$) before and after irradiation are given in Table 2 and Table 3, respectively. The approximate value of the coefficient at $1/(enc)$ was 0.82 [30].

Dependences of the charge carrier mobility on the value of the magnetic field strength applied in different directions with respect to the current direction (orientations $A$ and $B$), before and after $\gamma$-irradiation are presented in Fig. 3 for initial samples (from ingot $a$) and in Fig. 4 for heat-treated samples (from ingot $b$).

| Ingot | $N_O$ $\times 10^{-17}$, $cm^{-3}$ | Orientation | Before $\gamma$-irradiation | | | |
|---|---|---|---|---|---|---|
| | | | $R_0 \times 10^{-4}$, $cm^3/C$ | $\rho$, Ohm·cm | $n_e \times 10^{-14}$, $cm^{-3}$ | $\mu \times 10^{-4}$, $cm^2/(V \cdot s)$ |
| $a$ | 1.4 | $A$ | 4.57 | 1.62 | 1.12 | 2.40 |
| | | $B$ | 4.27 | 1.47 | 1.20 | 2.47 |
| $b$ | 1.2 | $A$ | 0.26 | 0.14 | 19.50 | 1.55 |
| | | $B$ | 0.27 | 0.14 | 19.10 | 1.62 |

Table 2. The values of the Hall parameters measured at 77 K and $H \rightarrow 0$ on the oxygen-containing $n$-Ge ⟨Sb⟩ crystals, initial (ingot $a$) and annealed at 400°C during 100 h (ingot $b$), before $\gamma$-irradiation.

| Ingot | $N_O$ $\times 10^{-17}$, $cm^{-3}$ | Orientation | After $\gamma$-irradiation | | | |
|---|---|---|---|---|---|---|
| | | | $R_0 \times 10^{-4}$, $cm^3/C$ | $\rho$, Ohm·cm | $n_e \times 10^{-14}$, $cm^{-3}$ | $\mu \times 10^{-4}$, $cm^2/(V \cdot s)$ |
| $a$ | 1.4 | $A$ | 8.90 | 3.27 | 0.58 | 2.31 |
| | | $B$ | 8.72 | 3.38 | 0.59 | 2.19 |
| $b$ | 1.2 | $A$ | 0.28 | 0.15 | 18.50 | 1.58 |
| | | $B$ | 0.38 | 0.17 | 13.60 | 1.84 |

Table 3. The values of the Hall parameters measured at 77 K and $H \rightarrow 0$ on the oxygen-containing $n$-Ge ⟨Sb⟩ crystals, initial (ingot $a$) and annealed at 400°C during 100 h (ingot $b$), after $\gamma$-irradiation.

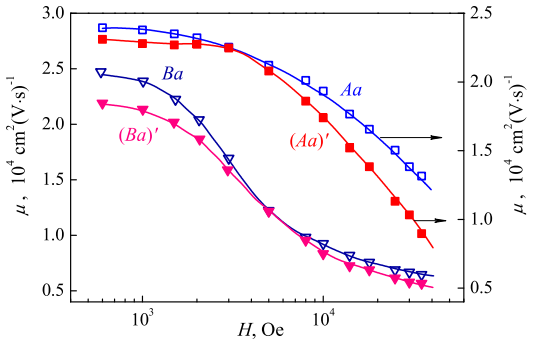


Fig. 3. Dependences of the charge carrier mobility on the value of the magnetic field strength for the unannealed oxygen-containing $n$-Ge ⟨Sb⟩ samples from ingot $a$ with orientations $A$ and $B$ before ($Aa$, $Ba$) and after (($Aa$)′, ($Ba$)′) $\gamma$-irradiation.

The following conclusions can be made from the results of the measurements. In both types of samples ($A$ and $B$), made from the initial (Fig. 3) and heat-treated (Fig. 4) ingots of germanium, the decrease in the charge carrier mobility with increasing magnetic field strength both before and after $\gamma$-irradiation turned out to be progressively decreasing.

The absolute magnitude of the change in the Hall mobility as a result of the $\gamma$-irradiation depends on the orientation of the samples being studied: samples of type $A$, initial (Fig. 3) and heat-treated (Fig. 4), were less sensitive to radiation than samples of type $B$.

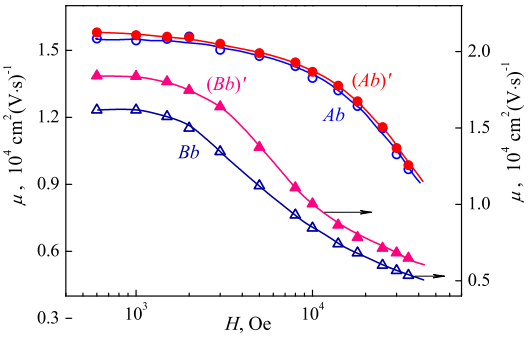


Fig. 4. Dependences of the charge carrier mobility on the value of the magnetic field strength for the oxygen-containing $n$-Ge ⟨Sb⟩ samples (heat-treated at 400°C during 100 h) from ingot $b$ with orientations $A$ and $B$ before ($Ab$, $Bb$) and after (($Aa$)′, ($Ba$)′) $\gamma$-irradiation.

In the general case, the Hall mobility of carriers in $n$-Ge crystals with the oxygen impurity is radiation-low stable. Herewith, the changes in the mobility of electrons under the action of $\gamma$-irradiation, which appear in the initial crystals (Fig. 3) and in the crystals subjected to thermal annealing (Fig. 4), turn out to be opposite in sign. In the initial germanium crystals with atomically dispersed (electrically neutral) oxygen impurity (ingot $a$), the mobility of electrons under the influence of irradiation is traditionally reduced (and for some values of $H$ practically does not change) for both types of samples (Fig. 3). That is, in the initial $n$-Ge crystals, the behaviour of the carrier mobility is qualitatively similar for samples of type $A$ and type $B$. In germanium crystals with electrically active oxygen complexes that arise as a result of thermal treatment at 400°C for 100 h (ingot $b$), the mobility of electrons in $B$-type samples increases under the influence of $\gamma$-irradiation, while for samples of $A$-type it remains almost insensitive to irradiation in the entire range of the applied magnetic field strengths $H$ (Fig. 4, the curves $Ab$ and $(Ab)'$ practically coincide). It is necessary to emphasize the decisive role of oxygen complexes and local mechanical lattice stresses in their vicinity for the manifestation of the effect of radiation-stimulated increase in mobility (due to the introduction of point defects of acceptor type under $\gamma$-irradiation) in the heat-treated germanium crystals (in particular, in samples of type $B$).

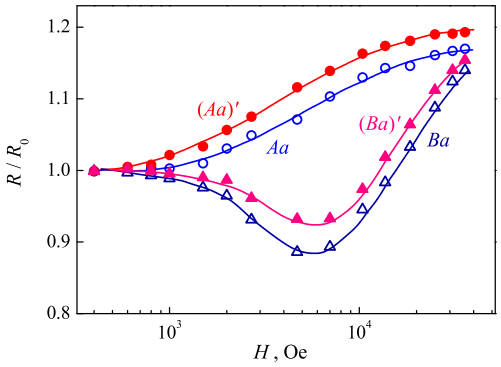


Fig. 5. Dependences $R/R_0 = f(H)$ for the unannealed oxygen-containing $n$-Ge ⟨Sb⟩ samples from ingot $a$ with orientations $A$ and $B$ before ($Aa$, $Ba$) and after ($(Aa)'$, $(Ba)'$) $\gamma$-irradiation.

Thus, the changes in the mobility of charge carriers, which turned out to be opposite in sign, were established in the initial and heat-treated crystals under $\gamma$-irradiation (in the initial crystals, the mobility decreased, and in the annealed crystals it increased). A substantial dependence of the changes in the function $\mu = \mu(H)$ on the orientation of the samples ($A$ or $B$) in heat-treated germanium crystals has been also revealed (in samples of type $B$, the mobility of electrons increases under the influence of irradiation, whereas for samples of type $A$ it remains practically unchanged in the entire range of used magnetic field strengths).

Dependences of the Hall coefficient $R$ on the magnetic field strength $R/R_0 = f(H)$ (where $R_0 = \lim_{H\to 0} R$) for the same samples in the region of the weak and intermediate $H$ are given for the initial ingot $a$ in Fig. 5, and for the heat-treated ingot $b$ are shown in Fig. 7.

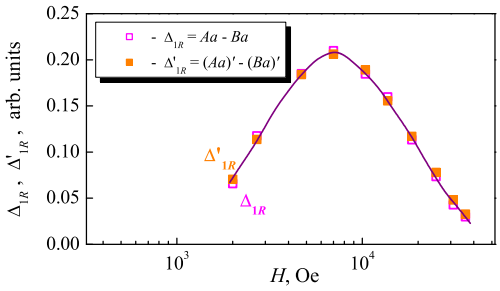


Fig. 6. The difference dependences $\Delta_{1R}$ and $\Delta'_{1R}$ on the magnetic field strength $H$ for the unannealed oxygen-containing $n$-Ge ⟨Sb⟩ samples from ingot $a$, obtained before ($\Delta_{1R} = Aa - Ba$) and after ($\Delta'_{1R} = (Aa)' - (Ba)'$) $\gamma$-irradiation (see Fig. 5).

The difference dependences $\Delta_{1R}$ and $\Delta'_{1R}$ on the magnetic field strength $H$ for ingot $a$, obtained before ($\Delta_{1R} = Aa - Ba$) and after ($\Delta'_{1R} = (Aa)' - (Ba)'$) $\gamma$-irradiation, are shown in Fig. 6. Similar dependences for ingot $b$ before ($\Delta_{2R} = Ab - Bb$) and after ($\Delta'_{2R} = (Ab)' - (Bb)'$) $\gamma$-irradiation are shown in Fig. 8.

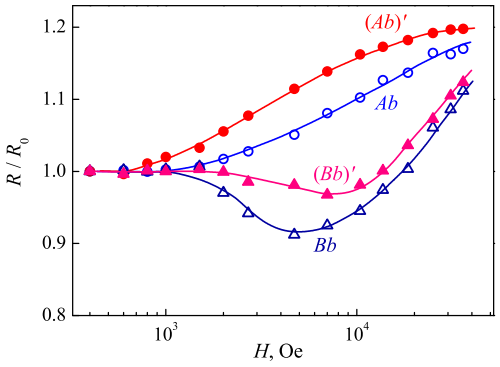


Fig. 7. Dependences $R/R_0 = f(H)$ for the oxygen-containing $n$-Ge ⟨Sb⟩ samples (heat-treated at 400°C during 100 h) from ingot $b$ with orientations $A$ and $B$ before ($Ab$, $Bb$) and after ($(Ab)'$, $(Bb)'$) $\gamma$-irradiation.

The tendency of the mobility to decrease in samples from ingot $a$ after irradiation (see Table 3) is more likely due to changes in the lattice scattering than an increase in the contribution of scattering on the ionized impurities. This is supported by the fact that, with a noticeable shift in the $R/R_0 = f(H)$ curves along the ordinate axis after irradiation, the anisotropy of the Hall coefficient (and, consequently, the scattering anisotropy as a result of $\gamma$-irradiation of these samples) did not change (the difference curves $\Delta_{1R}$ and $\Delta'_{1R}$ in Fig. 5 completely coincide).

We have a different picture in the case of ingot $b$. When annealing, as can be seen from the comparison of the data of Table 2 for samples $a$ and $b$ (obtained before irradiation), the charge carrier concentration $n_e$ sharply increases due to the formation of oxygen (electrically active) complexes. The scattering on these complexes became determinative, given the sharp decrease in the electron mobility from $\sim (2.4-2.5)\times 10^4$ to $(1.5-1.6)\times 10^4$ cm$^2$/(V·s). Under these conditions, however, the anisotropy of the Hall coefficient $R$ almost did not change, which is evident from a comparison of the height of the maxima of the curves $\Delta_{1R}$ and $\Delta_{2R}$ (Figs. 6 and 8, respectively). The indicated circumstance testifies to the fact that the scattering on electrically active (charged) oxygen complexes is less anisotropic than on ionized donors or acceptors of the usual type.

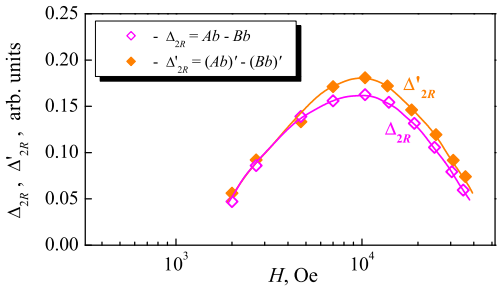


Fig. 8. Difference dependences $\Delta_{2R}$ and $\Delta'_{2R}$ on the magnetic field strength $H$ for the heat-treated (400°C; 100 h) oxygen-containing $n$-Ge ⟨Sb⟩ samples from ingot $b$, obtained before ($\Delta_{2R} = Ab - Bb$) and after ($\Delta'_{2R} = (Ab)' - (Bb)'$) $\gamma$-irradiation (see Fig. 7).

The results of the interaction of impurity oxygen atoms with radiation defects in Ge (ingot $a$) were presented in Fig. 5. Now let us analyze, using the example of experiments with samples from ingot $b$, a somewhat specific case of the interaction of radiation defects with oxygen (electrically active) complexes that were formed in the annealing process of ingot $b$ at 400°C for 100 h. As can be seen from Table 3, the irradiation of the samples of both types prepared from ingot $b$ led to an increase in the charge carrier mobility. The mobility of electrons especially noticeably increases in the heat-treated samples of type $B$ (Fig. 4). The obtained result was different from the data for the samples from ingot $a$ with dispersed oxygen atoms in the Ge volume (Fig. 3), as well as from typical results for $n$-Ge with Sb impurity (see Section II of the present work) when the $\gamma$-irradiation of the samples caused only a decrease in mobility. It should be noted that the observed increase in mobility occurred under conditions of a marked decrease in the charge carrier concentration due to the acceptor action of radiation defects, which became negatively charged as a result of this. The increase in the total number of charged scatterers due to this should lead to a decrease in mobility. However, in the experiment we observed an increase in mobility. Therefore, it remains to be assumed that the interaction of positively charged oxygen complexes with radiation defects of the acceptor type (which captured electrons from the conduction band) leads to their mutual neutralization and to the formation of the structurally more complex center with lower scattering efficiency. It should be noted that positively charged oxygen complexes are neutralized by acceptor centers of radiation origin even at room temperature (in the irradiation process) without special heating. If such neutralization does occur in the crystal, this should lead to a decrease in the scattering anisotropy (decrease in $K_\tau$), an increase in the mobility anisotropy parameter $K$ ($K = K_m/K_\tau = f(T)$, where $K_m$ is the anisotropy parameter of effective mass) and an increase (after $\gamma$-irradiation) in the anisotropy of Hall coefficient, associated with the parameter $K$ [31]. The carried out experiments confirmed this, as can be seen from the comparison of curves $\Delta_{2R}$ and $\Delta'_{2R}$ (Fig. 8).

Thus, it was experimentally established that unlike Ge with atomically dispersed oxygen impurity (ingot $a$), in the heat-treated crystals (ingot $b$) the scattering anisotropy $K_\tau$ decreases due to a decrease of anisotropically scattering (charged) centers under the action of $\gamma$-irradiation. This fact, in turn, leads (in samples from ingot $b$) to an increase in the charge carrier mobility, which is unusual for the action of irradiation (Table 3, Fig. 4).

## IV. CONCLUSIONS

1. As a result of the experiments carried out, the type of dependences of changes in charge carrier concentration on the initial concentration of antimony dopant in $\gamma$-irradiated $n$-Ge crystals was established for two measurement temperatures ($\Delta n = \eta n_0^{\xi}$, where $\eta = \text{const}$, $\xi_{300\,\text{K}} = 0.34 \pm 0.01$; $\xi_{77\,\text{K}} = 0.13 \pm 0.03$); also the changes in charge carrier mobility that are correlated with changes in the carrier concentration were revealed in the impurity scattering region.
2. The changes in charge carrier mobility that are opposite in sign were revealed in oxygen-containing initial and heat-treated (400°C; 100 h) $n$-Ge ⟨Sb⟩ samples under the influence of $\gamma$-irradiation: in the initial samples, the mobility decreases, whereas in the heat-treated samples it increases.
3. The essential dependence of the changes in the function $\mu = \mu(H)$ under the influence of $\gamma$-irradiation on the orientation of the samples was established in the heat-treated germanium crystals: in the samples of type $B$, the mobility of electrons increases, while for the samples of type $A$ it remains little sensitive to irradiation in the entire range of used magnetic field strengths $H$.
4. It was shown that the change in the anisotropy of scattering under the influence of $\gamma$-irradiation depends on the state of the oxygen impurity in Ge. A decrease in anisotropy of scattering due to a decrease of the anisotropically scattering (charged) centers under the influence of $\gamma$-irradiation was found in heat-treated crystals with electrically active oxygen complexes (in contrast to $n$-Ge with atomically dispersed oxygen impurity). The decrease in scattering anisotropy led to an increase in the anisotropy of Hall coefficient and to an increase in charge carrier mobility, which is unusual for the action of radiation.
5. It was found that the scattering on the electrically active (charged) oxygen complexes is less anisotropic than on the ionized donors or acceptors of the usual type.

6. The essential dependence of the absolute value of the change in the Hall mobility as a result of $\gamma$-irradiation on the orientation of the samples under investigation was established: samples of type $A$, initial and heat-treated, proved to be more resistant to radiation than samples of type $B$. The results obtained can be practically useful both in the development and operation of a certain class of radiation-resistant semiconductor devices.


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# ВПЛИВ ГАММА-ОПРОМІНЕННЯ ($^{60}$Co) НА ЕЛЕКТРОФІЗИЧНІ ПАРАМЕТРИ $n$-Ge РІЗНОГО РІВНЯ ЛЕГУВАННЯ ТА З ДОМІШКОЮ КИСНЮ В РІЗНИХ СТАНАХ

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У монокристалах $n$-Ge різного рівня леґування домішкою сурми на основі вимірювань ефекту Голла досліджено специфіку впливу гамма-опромінення кобальтом-60 на зміни концентрації носіїв заряду $\Delta n$ і їх рухливості. Установлено залежності $\Delta n$ від вихідної концентрації домішки Sb у кристалах для двох температур (кімнатної та рідкого азоту), а також виявлено зміни рухливості носіїв заряду (в зоні домішкового розсіяння), які корелюють зі змінами концентрації носіїв. За температури рідкого азоту досліджено вплив $\gamma$-опромінення на голлівські параметри кристалів $n$-Ge з домішкою кисню, атомарно дисперґованою та у вигляді кисневих комплексів. Виявлено у вихідних і термічно оброблених (400°C; 100 год) зразках германію протилежні за знаком зміни рухливості електронів під дією опромінення, а саме: у вихідних зразках рухливість зменшується, а в термооброблених — зростає. Установлено вирішальну роль кисневих комплексів і локальних механічних напружень ґратки в їхній околиці для прояву ефекту радіаційно-стимульованого підвищення рухливості (за рахунок введення під час $\gamma$-опромінення точкових дефектів акцепторного типу) у термооброблених кристалах германію. Показано, що зміна анізотропії розсіяння під впливом опромінення залежить від стану домішки кисню в Ge. Установлено, що, на відміну від Ge з атомарно дисперґованою домішкою кисню, в термічно оброблених кристалах анізотропія розсіяння зменшується за рахунок зменшення під дією $\gamma$-опромінення анізотропно розсіювальних (заряджених) центрів, що, своєю чергою, призводить до невластивого для дії радіації підвищення рухливості носіїв заряду.