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# Changes in Hall parameters after γ-irradiation ($^{60}$Co) of n-Ge

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**Abstract.** Studying the γ-irradiation influence on the properties of *n*-type germanium ($n\text{-Ge}\langle\text{As}\rangle$) within the interval of concentrations of the doping arsenic impurity $7.79\times10^{13} \le N_{\text{As}} \equiv n_e \le 6.36\times10^{16}\,\text{cm}^{-3}$ has shown that the initial resistivity of single crystals with concentrations $N_{\text{As}} \ge 5\times10^{15}\,\text{cm}^{-3}$ remains constant within the accuracy of measurements carried out. Only in weakly doped crystals (with $N_{\text{As}} \approx 7.79\times10^{13}\,\text{cm}^{-3}$ and less), the used doses of γ-irradiation cause appreciable reduction both in the carrier concentration $n_e$ and their mobility μ.

**Keywords:** germanium, γ-irradiation, Hall effect, resistivity, electron concentration, charge carrier mobility.

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## 1. Introduction

Irradiation by high energy particles and γ-quanta is very effective mean to influence on the physical properties of semiconductors. Investigation of the crystal lattice defects that arise under irradiation and ascertaining the relations between properties of a crystal and defects created in it represents large scientific interest and belongs to the major problems of the modern physics of solids. Advantages of radiation treatment lie in the opportunity to introduce a certain kind of defects into crystals in controllable conditions and with strictly specified concentrations. Applying different particles gives us the possibility to change properties of materials over a wide range.

The practical aspect of this problem, which stimulates studying the influence of the nuclear radiation on properties of semiconductors, is the creation of semiconductor materials and devices with the increased radiation hardness, and also the development of devices with new properties that are determined by stable radiation defects.

Germanium and silicon are the most widely studied, since these single crystals are obtained in the sufficiently pure and perfect form, and most semiconductor devices are made on the basis of them.

Influence of nuclear radiation on solids is accompanied by losses of energy not only on the ionization, but also on formation of various kinds of structural damages. When the energy transferred from the bombarding particles to the atom of a crystal lattice exceeds the threshold energy, necessary to displacement of an atom from the lattice site, the simple defects (Frenkel pairs, and also the spatially-separated vacancies and interstitial atoms) are mainly generated. In the case when the knocked-on atoms possess a sufficient energy to create the whole cascade of displaced atoms, the disordered regions surrounded by the space charge are formed. These regions are called defect clusters. Under irradiation, the Frenkel pairs and their components (vacancies and interstitial atoms) are mobile even at very low temperatures [1, 2]. They interact with such impurities as interstitial oxygen, carbon, doping atoms, and also among themselves. Meanwhile radiation defects of the point type stable at a room temperature are formed, for example, in silicon: A-centers ($VO_i$), E-centers (PV), divacancies ($V_2$), di-interstitials ($I_2$). The energy levels of point defects in the forbidden band is usually determined from the Hall-effect measurements, photoconductivity spectra, infrared absorption, luminescence, DLTS, analysis of the lifetime of non-equilibrium charge carriers depending on temperature.

High-energy γ-quanta ($E > 0.5$ MeV) are capable to create radiation defects in solids. As a result of the direct interaction of γ-quanta with crystal, the probability of occurrence of the displaced atoms is very small. The major role in creation of defects in this case belongs to fast electrons formed as a result of photoeffect and Compton effect, as well as to the pairs of electrons and positrons, which arise at rather high energies of γ-quanta. The pair generation cross-section ($\sigma_p$) is proportional to the square of the nuclear number of atoms in the irradiated material.

If the energy of γ-quanta is less than 1 MeV, then under interaction of this irradiation with *K*, *L*, *M*, ... atomic shells of substance the photoelectrons will be mainly formed. The cross-section for emission of *K*-electrons is maximal at the energies of γ-quanta equal to the energy of *K*-electrons and steadily decreases with increasing the γ-quanta energy.

For γ-quanta with energies from 1 up to 2 MeV, the process of Compton scattering is the most significant. Its cross-section is proportional to the atomic number *Z* of the irradiated substance, since the value of *Z* determines the number of electrons that can take part in this scattering. Compton's effect leads to the formation of electrons with a sufficiently high energy, which are capable to displace atoms from their lattice sites in crystal. It is this process that promotes uniform formation of radiation damages in the crystal bulk under irradiation (such as by γ-quanta $^{60}$Co) of semiconductor crystals. This is the main advantage of γ-rays over the primary fast electron irradiation. For irreversibility of the displacement of atoms, the distance between the vacancy and the interstitial atom should be sufficiently large, otherwise the spontaneous recombination can occur. Certainly, this distance will depend on the orientation of Frenkel pair relative to a crystal lattice. According to [3], for supporting the stability, the distance between the vacancy and interstitial atom must be of the order of several lattice constants, especially along the directions of close packing the atoms.

Thus, γ-quanta, as well as fast electrons, during interaction with solids cause mainly the appearance of the point type defects, which can change the electrophysical characteristics of material.

A significant amount of the different type of semiconductor devices, due to the certain circumstances, is used in the fields of the nuclear radiation [4, 5]. To guarantee the reliable operation of such devices during long time, it is necessary to provide a sufficiently high stability of their parameters in the process of operation. For this purpose, it is necessary to know what doses of irradiation (when using different kinds of nuclear radiation, in particular of γ-irradiation) can essentially influence on device functioning.

The aim of this work is to study the radiation-induced changes of main parameters of $n\text{-Ge}\langle\text{As}\rangle$ single crystals (resistivity ρ, concentration $n_e$ and the mobility μ of charge carriers) under the influence of γ-irradiation ($^{60}$Co), and to investigate the dependences of the Hall coefficient on the magnetic field $R_H = f(H)$ measured both at room temperature and liquid nitrogen one in samples of germanium with different values of the initial resistivity.

## 2. Results and discussion

The studies were carried out on three series of samples (three samples in each series) of *n*-type germanium doped with arsenic impurity ( $n\text{-Ge}\langle\text{As}\rangle$ ), grown from the melt (Cz), which covered the concentration range of $7.79\times10^{13} \le N_{As} \equiv n_e \le 6.36\times10^{16}\,\text{cm}^{-3}$ and irradiated with two doses of γ-quanta: $D_1 = 1\times10^6$ R and $D_2 = 5\times10^6$ R. Measurements of parameters (both in the initial state and after irradiation) was carried out using the method of the Hall effect on the samples of the cruciform shape with dimensions of 1×2.5×9 mm$^3$.

The results of the measurements carried out in the magnetic field $H = 5850$ Oe at $T = 77$ K are shown in Table 1.

The obtained results indicate that:

– even in the least doped samples (series № 3 with $n_e \approx 7.79\times10^{13}\,\text{cm}^{-3}$) the $D_1$ dose of irradiation practically does not cause any significant changes in the magnitude of measured parameters;
– starting with the concentration of $n_e \approx 5.42\times10^{15}\,\text{cm}^{-3}$ (series № 2) and below (series № 3) the dose $D_2$ results in the appreciable changes in the magnitudes of measured mobilities, and in the series № 3 under the influence of this dose not only μ, but also the carrier concentration $n_e$ essentially changes.

It is interesting that in the experiments with more heavily doped crystals (№ 1 and 2), i. e. up to the concentration $n_e \ge 5\times10^{15}\,\text{cm}^{-3}$ inclusive, at both doses of irradiation the weakly expressed tendency to changes of $n_e$ and μ in the opposite directions is found: $n_e$ shows the tendency to growth, and μ shows the opposite one. It is this fact that certify the constancy (within the accuracy of the experiments carried out) of the resistivity values ρ in the crystals № 1 and № 2. And only from the doping level lower (or equal to) $N_{As} \le 7.79\times10^{13}\,\text{cm}^{-3}$ there begin to appear the unidirectional changes of $n_e$ and μ in the direction of reducing the value of these parameters at both doses of irradiation.

Our investigations of the least doped samples (series № 3) show that under the influence of γ-irradiation the concentrations of charge carriers only decreases with decreasing of their mobility for both used doses ($D_1$ and $D_2$).

There is no doubt that irradiation by these doses of samples № 1 and № 2 must be also accompanied by some decrease in the concentration of carriers in their volume. The fact that the calculated concentrations (from the experimental data) in these samples not only did not decrease, but even showed the indistinctly expressed (however reliably registered) the tendency to growth, can only be explained by radiation-induced changes of the Hall factor.

The expression for the Hall factor has the following form [6]:

**Table 1. Changes in the Hall parameters (measured at 77 K) as a result of irradiation of $n$-Ge⟨As⟩ samples by using two different doses of γ-quanta ($^{60}$Co).**

| № series of samples | Before irradiation | | | After irradiation by different doses of γ-quanta ($^{60}$Co): $D_1 = 10^6$ R / $D_2 = 5\times10^6$ R | | |
|---|---|---|---|---|---|---|
| | $n_e$, cm$^{-3}$ | μ, cm$^2$/V·s | ρ, Ohm·cm | $n_e$, cm$^{-3}$ | μ, cm$^2$/V·s | ρ, Ohm·cm |
| 1 | $6.36\times10^{16}$ | 3690 | 0.0266 | $6.47\times10^{16}$ / $6.46\times10^{16}$ | 3670 / 3660 | 0.0266 / 0.0264 |
| 2 | $5.42\times10^{15}$ | 15180 | 0.076 | $5.47\times10^{15}$ / $5.45\times10^{15}$ | 15130 / 14910 | 0.0755 / 0.0769 |
| 3 | $7.79\times10^{13}$ | 28260 | 2.836 | $7.51\times10^{13}$ / $7.3\times10^{13}$ | 28240 / 27860 | 2.946 / 3.070 |

$$r = \frac{\Gamma\left(\frac{5}{2}-2s\right)\Gamma\left(\frac{5}{2}\right)}{\left[\Gamma\left(\frac{5}{2}-s\right)\right]^2} \cdot \frac{3\mathrm{K}(\mathrm{K}+2)}{(2\mathrm{K}+1)^2}, \qquad (1)$$

where $\Gamma\left(\frac{5}{2}-2s\right)$, $\Gamma\left(\frac{5}{2}\right)$, $\Gamma\left(\frac{5}{2}-s\right)$ are the gamma-functions of different (shown in parentheses) arguments (in general, the gamma-function is defined by the expression $\Gamma(x) = \int_0^\infty t^{x-1}e^{-t}dt$; $\mathrm{K} = \frac{m_\parallel^*}{m_\perp^*}$ is the anisotropy parameter of the effective mass; $s$ is the exponent in the formula that bind the relaxation time with energy $\tau = aE^{-s}$, and $s$ is some constant, and the magnitude of $a$ can depend on the temperature). The value of $s$ in a general case is obtained from the experimental dependence of the mobility on temperature and, depending on the type of scattering, it acquires different values (such as $s = +1/2$ for the scattering on the lattice vibrations, and for the impurity scattering $s = -3/2$).

As seen from (1), the Hall factor depends not only on the effective masses but also on the scattering of the charge carriers. Effective masses remain unchanged not only in the presence of a magnetic field, which is necessary to carry out the Hall effect measurements. They also do not change under the elastic uniaxial deformation of the crystal, which in $n$-Ge allows to prove migration of the carriers from all isoenergetic ellipsoids to the one that falls in the energy scale under the influence of the deforming effort $X$ oriented in parallel to the crystallographic direction ⟨111⟩. Thus, the radiation-induced changes of the Hall factor, which occur under the influence of γ-irradiation, are not associated with changes in the effective masses, but these changes are connected with the variations in the scattering of charge carriers on the point defects introduced by irradiation. Under the influence of γ-irradiation, not only the point defects are introduced into the crystal matrix, but also the structure of the environment of these defects is changed and, consequently, the scattering of the charge carriers is changed.

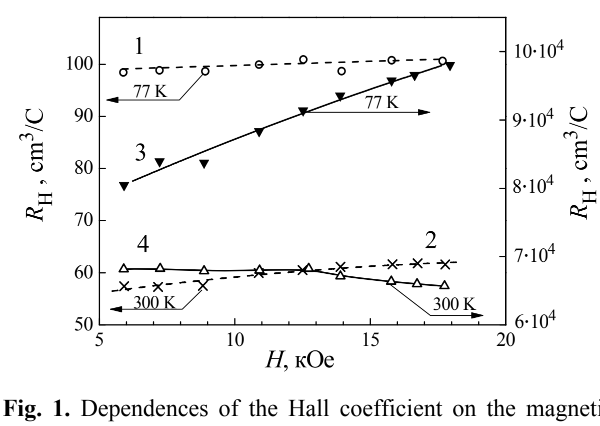


**Fig. 1.** Dependences of the Hall coefficient on the magnetic field $R_H = f(H)$ measured at 77 K (*1*, *3*) and 300 K (*2*, *4*) in samples of $n$-Ge⟨As⟩ with two different values of initial resistivity: *1*, *2* – $\rho_{300\,K} \approx 0.027$ Ohm·cm; *3*, *4* – $\rho_{300\,K} \approx 19.81$ Ohm·cm.

The study of the dependences of the Hall coefficient $R_H$ on the magnetic intensity within the range $5850 \le H \le 17680$ Oe shows that neither at room temperature nor at 77 K the Hall coefficient measured in the heavily doped samples of $n$-Ge⟨As⟩ ($\rho_{300\,K} \approx 0.027$ Ohm·cm) practically does not depend on $H$ (see Fig. 1), whereas on the less doped samples ($\rho_{300\,K} \approx 19.81$ Ohm·cm), the Hall coefficient at the temperature of liquid nitrogen increases at $H = 17680$ Oe approximately by 20-22 % in comparison with $R_H$ measured at $H = 5850$ Oe. This effect can also be explained just by the changes in the processes of scattering of charge carriers.

### 3. Conclusions

The studies of γ-irradiation influence (with doses $D_1 = 1\times10^6$ R and $D_2 = 5\times10^6$ R) on electro-physical characteristics of single crystals of $n$-Ge⟨As⟩, carried out within the concentration range of the dopant $7.79\times10^{13} \le N_{As} \equiv n_e \le 6.36\times10^{16}\,\text{cm}^{-3}$, showed that:

– within the limits of the used doses of irradiation the initial resistivity of the more heavily doped single crystals (series № 1 and № 2) practically remains constant;
– the specified doses lead to the appreciable changes in the values of $n_e$ and μ under irradiation of the germanium single crystals at the concentration of dopant $N_{As} \le 7.79\times10^{13}\,\text{cm}^{-3}$;
– the checking measurements of the investigated parameters performed on the samples of series № 3 (with the minimal charge carrier concentration $n_e \approx 7.79\times10^{13}\,\text{cm}^{-3}$) show that significant changes have not detected during the storage of samples for more than half of the year at temperature of about 300 K. So, caused by γ-irradiation (in the specified doses) changes of $n_e$ and μ parameters have stable character.

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