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Investigation of the influence of isovalent impurity of silicon and γ-irradiation (^{60}Co) on electrophysical parameters of *n*-Ge ⟨Sb⟩

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Abstract. The influence of isovalent impurity of Si on the kinetics of electron processes in *n*-Ge ⟨Sb⟩ single crystals has been investigated. It has been shown that in the region of predominant impurity scattering (at $T \approx 77.4$ K), the presence of isovalent impurity significantly reduces the mobility of charge carriers and changes the sign of inequality $n_{e_{300\mathrm{K}}} / n_{e_{77.4\mathrm{K}}} > 1$ characteristic of *n*-Ge ⟨Sb⟩ single crystals to the opposite one. It has found that in *n*-Ge ⟨Sb⟩ samples irradiated by γ-rays (^{60}Co) with the dose $1.23 \cdot 10^8$ R, the charge carrier mobility has low radiation stability and decreases with increasing the magnetic field, while remaining practically unchanged in the region of the intermediate *H* values.

Keywords: germanium, isovalent impurity, silicon, γ-irradiation, Hall effect, charge carrier mobility, electron concentration.

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1. Introduction

For most of problems of the applied character, it is important not only a high degree of homogeneity of the crystal, but what kind and state of impurity are available in its bulk, since all this, ultimately, influences the concentration of charge carriers and their mobility. These problems can be solved by investigating crystals in various aspects:

a) by direct studying the influence of certain chemical elements on their electrical properties;
b) by revealing features of the influence of semiconductor compensating impurities on these properties;
c) by analyzing various schemes of complexing and its consequences to which it leads in the crystal bulk.

Concerning electrically active impurities, at least, basic properties of almost every element leading to formation of singly and multiply charged centers in Ge and Si were studied. More difficult is the situation with the so-called electrically passive impurities of different elements in these crystals. When considering that according to the data of mass-spectroscopic analysis, the content of oxygen in Ge is about $2 \cdot 10^{18}$ cm^{-3}, and the contents of hydrogen and carbon in it are about the same [1], then, naturally, a question arises, what features of charge carrier scattering, for example, may be associated with these impurities, since in other experiments (e.g. when studying absorption of infrared radiation [2]), the presence of these impurities in the crystal bulk is easily singled out. The question concerning the interaction of these impurities with other impurities that are in the *n*-Ge crystal bulk and resulting formation of various complexes is of particular interest. For example, the impurity atoms of Si in Ge, which are isovalent impurities, may affect transport phenomena occurring in germanium not only as electrically neutral elementary scatterers, but also in the form of neutral or charged complexes. These complexes may arise during interaction of silicon atoms with the atoms of electrically neutral or active impurities that are in the crystal bulk. This fact combined with very little data in the literature

Table. Electrophysical parameters of *n*-Ge single crystals for unitary (Ge ⟨Sb⟩) and double doping (Ge ⟨Sb+Si⟩).

Dopant	Number of n-Ge sample	$T \approx 300$ K			$T \approx 77.4$ K			$r = \frac{n_{e_{300K}}}{n_{e_{77.4K}}}$
		R, cm^3/Coul	n_e, cm^{-3}	μ, cm^2/V·s	R, cm^3/Coul	n_e, cm^{-3}	μ, cm^2/V·s	
Sb+Si	1	$5.09 \cdot 10^5$	$1.23 \cdot 10^{14}$	2960	$4.70 \cdot 10^5$	$1.33 \cdot 10^{14}$	23100	0.925
	2	$3.70 \cdot 10^4$	$1.69 \cdot 10^{14}$	2680	$3.65 \cdot 10^4$	$1.76 \cdot 10^{14}$	19600	0.960
	3	$2.86 \cdot 10^4$	$2.18 \cdot 10^{14}$	3200	$2.54 \cdot 10^4$	$2.46 \cdot 10^{14}$	20500	0.886
Sb	1'	$9.04 \cdot 10^5$	$6.92 \cdot 10^{13}$	3070	$1.08 \cdot 10^5$	$5.78 \cdot 10^{13}$	29200	1.197
	2'	$8.09 \cdot 10^4$	$7.74 \cdot 10^{13}$	3050	$9.70 \cdot 10^4$	$6.90 \cdot 10^{13}$	28300	1.122
	3'	$6.90 \cdot 10^4$	$9.08 \cdot 10^{13}$	2560	$8.15 \cdot 10^4$	$7.68 \cdot 10^{13}$	27000	1.182

relative to the problem of complex formation in Ge (the situation with Si containing isovalent impurity of Ge is somewhat better [3-6]) important in general for physics and chemistry of solids have prompted to undertake studying the influence of Si isovalent impurities on the Hall mobility of charge carriers in *n* – Ge.

Back in the sufficiently early studies (see, e.g. [7]), it was shown that Si is an electrically neutral impurity relative to Ge, i.e., its atoms found in the bulk of Ge do not lead to appearance of additional charge carriers. However, it can be assumed that the impurity atoms of Si (even in the case of its electrical neutrality) influence on the mobility of charge carriers in the area of impurity scattering. The aim of this study was to experimental determine contribution of this scattering in a resultant value of the mobility. For this goal, comparative experiments using the reference samples of Ge doped with Sb and samples of Ge doped with Sb and Si were carried out.

The scientific literature, as far as it is known [8-12], is very poor in sources related to the study of the kinetics of the electron gas in crystals grown at combined doping (i.e., when doping more than one impurity).

2. Results and discussion

To study the influence of Si isovalent impurity on electrophysical properties of *n*-Ge doped with an electrically-active impurity of antimony (Sb), ingots, some of which were doped only with Sb impurity (unitary doping) and others besides the Sb impurity were doped with silicon with approximately the same concentration (double or combined doping), were used. From these ingots, two groups of samples (three samples in each group) were prepared. The obtained samples possess suitable sizes and shapes for measurements of the resistivity and Hall effect both at room temperature and at liquid nitrogen one (Fig. 1). The samples in both cases were cut from ingots in the direction of their growth, which coincided with the crystallographic orientation [110]. The magnetic field oriented in the crystallographic direction $\vec{H} \parallel [001]$ was applied perpendicular to the lateral surface of the samples. All the measurements were performed at $H = 2340$ Oe.

Before soldering current contacts and contacts to the measuring probes, the samples were polished and etched for about 2 min in a boiling solution of 30 % hydrogen peroxide, and then they were washed with distilled water. After the contacts were soldered using pure tin (Sn), the samples were etched again. Before the measurements, the ohmic regime of current contacts was tested at the current values that by several times exceeded the values used in our experiments.

The results of the measurements carried out using the samples of germanium both at 300 K and at 77.4 K are presented in Table.

The results obtained by the experiments (Table) show that the insertion of isovalent impurity of Si in Ge crystals (even more heavily doped with antimony than the 1'–3' samples) leads to a significant change in electrophysical properties of these crystals, which finds its expression in a number of features. For example, the sign of inequality $n_{e_{300K}} / n_{e_{77.4K}} > 1$, which is typical for the initial samples (i.e., for *n*-Ge ⟨Sb⟩), changes to the opposite one when introducing isovalent silicon atoms into the germanium crystal in addition to doped Sb atoms.

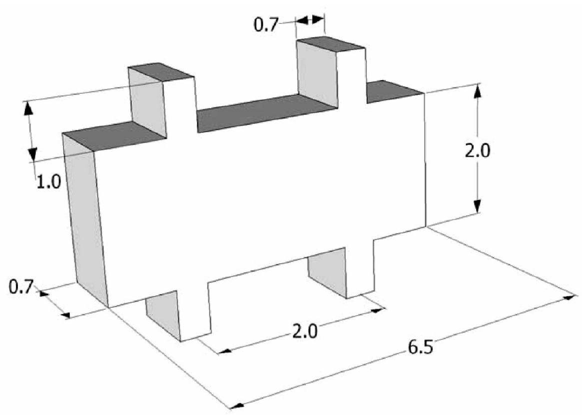

Fig. 1. External view, shape and dimensions (in millimeters) of investigated *n*-Ge samples.

Table shows that at dominant scattering by the lattice vibrations (i.e., at 300 K), in the samples of unitary and double doping, the values of mobility $\mu_{300\,K}$ are conventional for *n*-Ge with the concentration of charge carriers $10^{13}\ldots10^{14}$ cm^{-3} and are about 2700...3000 cm^2/V·s. However, in the region of predominant impurity scattering (i.e., at 77.4 K), in the crystals of double doping (*n*-Ge ⟨Sb+Si⟩), values of the charge carrier mobility $\mu_{77.4\,K}$ are considerably lower than those in the samples of unitary doping. Thus, the isovalent impurity of Si atoms, being electrically passive, significantly reduces the mobility of charge carriers in Ge crystals, doped with electrically active impurity of Sb as a consequence of manifestation of the additional scattering of charge carriers by neutral centers [13]. This result may be caused by some difference in the tetrahedral radii of Si and Ge (r_{Si} = 1.17 Å; r_{Ge} = 1.22 Å) and, therefore, the emergence of local internal stresses of the lattice around Si atoms. It can also be a manifestation of imperfections of the Ge lattice doped with Si, which is caused, in turn, by non-uniformity in distribution of Si impurity in the bulk of the studied crystals.

The values of the mobility of charge carriers in the samples of double doping were not only smaller than the values $\mu_{77.4\,K}$, typical for samples of unitary doping, but they were also less sensitive (by approximately 1.3 times) to the concentration of dopant in the bulk of the samples. This is clear from the fact that, at the temperature 77.4 K, an increase of the concentration of dopant n_e in *n*-Ge ⟨Sb⟩ crystals by 33 % results in a decrease of the charge carrier mobility in these crystals by 8 %, while in the crystals of double doping (*n*-Ge ⟨Sb+Si⟩), an increase of the concentration of electrically active impurity almost twice (or, more precisely, by 85 %) provides a reduce of the mobility only by 13 %.

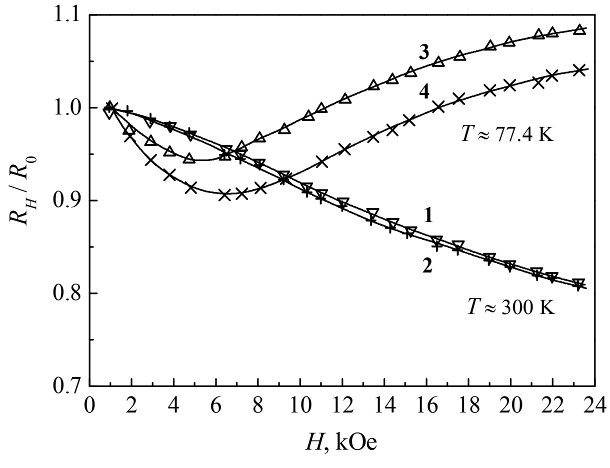

Fig. 2. Dependences $R_H/R_0 = f(H)$ obtained in the experiments with *n*-Ge crystals doped with Si at $T \approx 300$ K (curves *1* and *2*) and at $T \approx 77.4$ K (curves *3* and *4*). Curves *1* and *3* for the sample 2 ($\rho_{300\,K}$ = 11.8 Ohm·cm), curves *2* and *4* for the sample 3 ($\rho_{300\,K}$ = 7.6 Ohm·cm) (see Table).

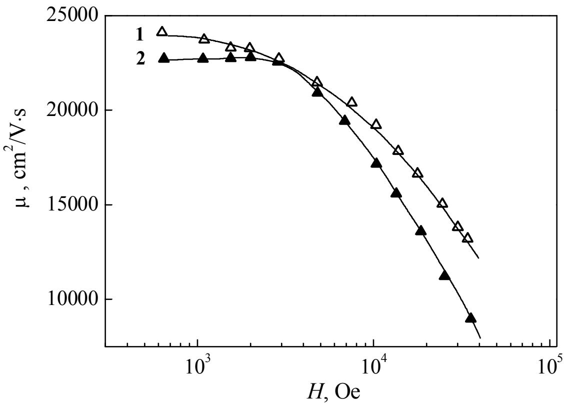

Fig. 3. Dependences μ = μ (*H*) of *n*-Ge ⟨Sb⟩ crystals before (*1*) and after (*2*) γ-irradiation (^{60}Co) with the dose $1.23\cdot10^8$ R. The current and the magnetic field were directed as follows: $\vec{J}$ ∥ [110], $\vec{H}$ ∥ [001].

The fact that well-known literature lacks data on the dependence of the Hall coefficient on the magnetic field value in Ge doped with Si causes not only a technical difficulty in the processing of Hall data, but also a substantial obstacle in obtaining unambiguous results for the Hall mobility of charge carriers in these crystals. In relation with it, the measurements of the dependence of the Hall coefficient on the magnetic field value in Ge samples doped with Sb and Si were carried out.

The results of these experiments fulfilled both at room temperature and at 77.4 K (Fig. 2), in fact, are typical for *n*-Ge (free from the Si impurities), which was studied in similar conditions [14].

In samples prepared from the ingot of unitary doping *n*-Ge ⟨Sb⟩ (with antimony impurity doped in melt $N_{Sb} = n_e = 1.2\cdot10^{14}$ cm^{-3}), in which the concentration of atomically dispersed oxygen (determined by IR-absorption spectra) was $\approx 1.2\cdot10^{17}$ cm^{-3}, the study of the dependence of Hall mobility on the magnetic field value before (initial three samples) and after γ-irradiation (^{60}Co) with the dose $1.23\cdot10^8$ R was carried out. The vectors of the current $\vec{J}$ and magnetic field $\vec{H}$ in the samples were directed as follows: $\vec{J}$ ∥ [110], $\vec{H}$ ∥ [001].

The dependences of the mobility of charge carriers on the magnetic field intensity in *n*-Ge ⟨Sb⟩ crystals before and after γ-irradiation are presented in Fig. 3.

Fig. 3 shows that the mobility under the influence of γ-irradiation significantly changed only in weak and strong magnetic fields *H*, while in the intermediate fields this parameter (with respect to the used dose) was almost unchanged. However, the decrease in the carrier mobility with increasing the magnetic field in the samples before and after γ-irradiation had progressive character.

Thus, from the results of our measurements, it can be concluded that in the initial samples Ge ⟨Sb⟩ of *n*-type with atomically dispersed (electrically neutral) oxygen impurity, the mobility of charge carriers has low radiation resistance (mobility μ decreases under the influence of γ-irradiation).

3. Conclusions

In this paper, the influence of Si isovalent impurity on the Hall effect and electrical conduction in *n*-Ge single crystals doped with electrically active impurity of Sb has been investigated. It has been shown that mainly in the field of impurity scattering (at $T \approx 77.4$ K), the presence of electrically passive impurity of silicon in the germanium bulk significantly reduces the mobility of charge carriers, which is, probably, the result of a manifestation of both additional carrier scattering by neutral centers and changes in scattering caused by lattice vibrations owing to violation of its structure as a result of some difference in the covalent radii of matrix atoms (Ge) and isovalent impurity (Si).

It has been found that in the crystals of double doping (*n*-Ge ⟨Sb+Si⟩), the sign of inequality $n_{e_{300\mathrm{K}}} / n_{e_{77.4\mathrm{K}}} > 1$ characteristic of *n*-Ge ⟨Sb⟩ single crystal changes to the opposite one.

It has been found that in the unitary doped *n*-Ge ⟨Sb⟩ samples irradiated by γ-quanta (^{60}Co) with the dose $1.23 \cdot 10^8$ R, the mobility of charge carriers has low radiation stability, and it decreases with increasing the magnetic field value. The changes are more significant in weak and strong magnetic fields *H*, while for the intermediate *H* values this parameter remains practically unchanged.

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