# Experimental determination of the compensation of neutron-doped germanium

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A "semiconductor" method is proposed and implemented for solving the problem of determining the compensation of neutron-doped germanium.

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1. As established in the works of Lark-Horovitz (see, for example, Ref. 1), the neutron doping of Ge by irradiation with slow reactor neutrons consists of the transmutation of the $Ge^{70}$, $Ge^{74}$, and $Ge^{76}$ isotopes, which is caused by (n, $\gamma$) radiation capture reactions, with the formation of the electrically active impurities Ga, As, and

Se:

$$Ge^{70}(n, \gamma)\, Ge^{71} \xrightarrow{\text{Э.З.}} Ga^{71} \tag{1}$$

$$Ge^{74}(n, \gamma)\, Ge^{75} \xrightarrow{\beta} As^{75} \tag{2}$$

$$Ge^{76}(n, \gamma)\, Ge^{77} \xrightarrow{\beta} As^{77} \tag{3a}$$

$$As^{77} \xrightarrow{\beta} Se^{77} \tag{3b}$$

Interest in this method of doping Ge is due to the highly uniform distribution of impurities introduced by the irradiation, the ability of precise determination of the doping level, and the independence of this level from the ratio between the number of donor $N_D = N_{As} + 2N_{Se}$ (Se is a doubly charged center) and acceptor $N_A = N_{Ga}$ states, i.e., due to the constant, steady-state compensation

$$K = (N_{As} + 2N_{Se})/N_{Ga}\,. \tag{4}$$

Until now, however, this compensation has been unknown, since the literature contains only the absorption cross sections of thermal neutrons for the Ge isotopes, and even these values are not adequately precise. Thus, even if it is assumed that in the presence of a good moderator the doping is caused only the thermal neutrons, then the spread in the cross-section values taken from various sources[2–5] with the quoted error taken into account leads to a wide range of possible $K$ values: $50\% \gtrsim K \gtrsim 17\%$. The goal of this paper is to solve the problem of determining $K$ by a purely "semiconductor" method—from an analysis of the kinetics of neutron doping of Ge.

2. These kinetics are determined by the half-life $T$ of the $Ge^{71}$, $Ge^{75}$, $Ge^{77}$, and $As^{77}$ isotopes. $Ge^{71}$ has the longest half-life, which ranges from 10.5 to 12.5 days according to various data.[6] $T = 82$ min[2–5] for $Ge^{75}$, and the rate of the reaction (3) is limited by the reaction (3b) with $T = 38.8$ hours. As a result of irradiation, therefore, donors (As and then Se) are formed first, and the quantity $N_A$ of acceptor impurity reaches the values of $N_D$ only after the time $t = t_0$ of the order of several days after the start of irradiation. If the original density of uncompensated carriers in the Ge is much less than $N_D$, then $K(t) \underset{t \to t_0}{\longrightarrow} 1$ and the $n \to p$ conversion must occur at $t = t_0$, after which the compensation will decrease with time and approach asymptotically the steady-state value of K [Eq. (4)].

We are interested in sufficiently long times $t \gtrsim t_0$, those of reactions (2) and (3a) and primarily the reaction (3b). The density of donor states at time $t_0$, which are still not the result of the reaction (3b), does not exceed $0.01N_D$, according to our estimate. Thus, at $t \geqslant t_0$ in the case of complete ionization of the acceptors the time dependence of the hole density $p(t)$ in the valence band of $p$-Ge is determined only by the Ga formation rate, i.e., by the half-life $T_{Ge^{71}}$. We shall also assume that irradiation time $t_1 < < T_{Ge^{71}}$. In this case the decay of $Ge^{71}$ during irradiation can be ignored at $t \geqslant t_0$:

$$p(t) = N_A[1 - \exp(-\lambda t)] - N_D, \tag{5}$$

where $\lambda = ln2/T_{Ge^{71}}$ is the decay constant.

TABLE I.

| Sample No. | $T_{\mathrm{Ge}^{71}}$ days | $K$(Refs. 8 and 9) % | $t_0$ days | $K$ (Ref. 6) % | $\lambda t_1$ | $N_A/r$, cm$^{-3}$ |
|---|---|---|---|---|---|---|
| 1 | 11.44 | 30.3 | 5.85 | 29.9 | 0.0008 | $1.06\times10^{14}$ |
| 2 | 11.42 | 30.4 | 5.82 | 29.7 | 0.0013 | $3.04\times10^{14}$ |

Since $p(t_0) = 0$ at the moment of conversion,

$$K = 1 - \exp(-\lambda t_0) . \tag{6}$$

The large error in the quantity $\lambda$ prevents direct use of the Eq. (6) obtained by us. We shown $K$ can be determined by another method, while at the same time obtaining a more accurate value of $\lambda$. If the hole density is found from Hall-effect measurements, then, as is known,

$$p(t) = r/qR(t), \tag{7}$$

where $r$ is the Hall factor, which does not depend on $p$ and $N_A$ at weak doping levels for a constant temperature, since the hole-scattering mechanism does not depend on

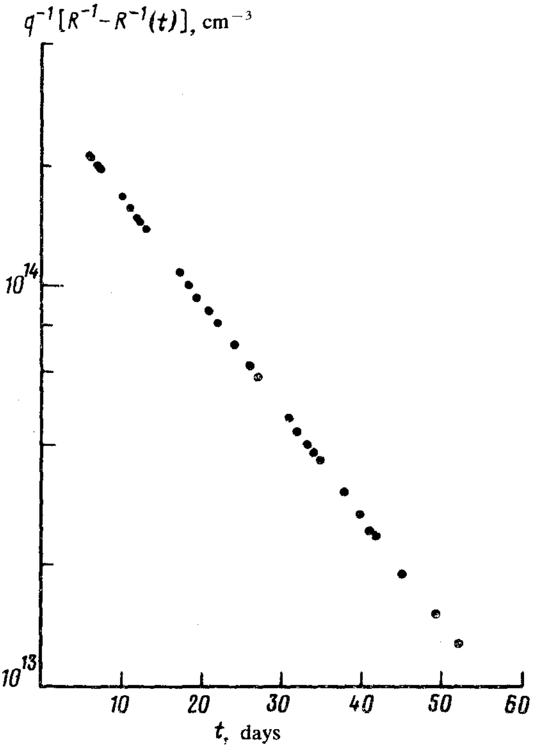

FIG. 1. Analysis of experimental data for sample No. 2 in accordance with Eq. (9).

these quantities: $q = |e|$, where $e$ is the electron charge, and $R(t)$ is

$$R \equiv \lim_{t \to \infty} R(t) = r/qN_A(1 - K)\,. \tag{8}$$

We obtain from Eqs. (5), (7), and (8)

$$\ln\{q^{-1}[R^{-1} - R^{-1}(t)]\} = \ln(N_A/r) - \lambda t. \tag{9}$$

By analyzing the experimental data using Eq. (9), we can determine, first, the precise value of $\lambda$ and, second, the ratio $N_A/r$, and we can then determine $K$ from Eq. (8).

3. In view of the comment about the quantity $r$ and the requirement of low activity for the test samples, i.e., small $N_D$ and $N_A$, ultrapure Ge was used for the experiments. The irradiation was done in a channel of the LIYaF [Leningrad Institute of Nuclear Physics] reactor in which the ratio of the thermal-neutron flux to the flux of fast neutrons with an energy $E \gtrsim 0.5$ MeV amounted to 30–50. The radiation defects were annealed at a temperature[1] of 450 °C for 7–12 hours, followed by a slow cooling in order not to introduce thermodefects. For this same reason, a gettering coating was deposited on the sample surfaces beforehand; this coating was ground off after annealing. The Hall emf was measured at a temperature of 77.4 $K$ with an error not exceeding 0.3%. The results of two experiments are summarized in Table I. As seen from the

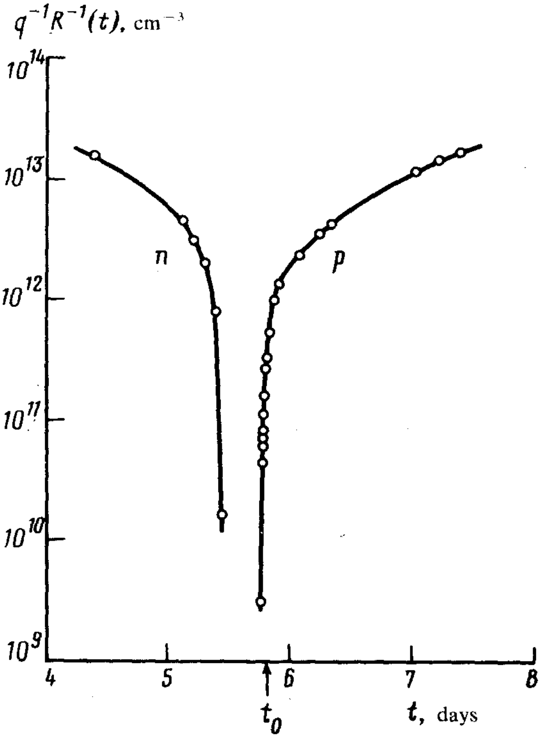

FIG. 2. Variation of density of majority carriers in $n$- and $p$-Ge near the $n \to p$ conversion in sample No. 2.

table, the parameter $\lambda t_1$ in our case is actually very small and $N_A$ corresponds,to a low level of doping.

Figure 1 shows an analysis of the data for one of the samples by means of Eq. (9). The half-life, which was refined in this manner, is $T_{\text{Ge}^{71}} = 11.43 \pm 0.09$ days. The value of $K$, determined from Eqs. (8) and (9), is 30.3%.

Figure 2 illustrates the variation of majority-carrier density in $n$- and $p$-Ge (relative and the corresponding Hall factor) near the $n \rightarrow p$ conversion. The observed "dip" is due to the fact that the Fermi level passes successively through the deep Se levels. The moment of conversion corresponds to the right-hand wall of the "dip": $t_0 = 5.84 \pm 0.05$ days. Substituting this value of $t_0$ and the above-determined half-life $T_{\text{Ge}^{71}}$ in Eq. (6), we find that $K = 29.8\%$.

As is seen, both methods gave similar results in the two experiments. The error of the first method is determined by the accuracy of the Hall measurements, while for the second method it is determined by the errors in $\lambda$ and $t_0$. In both cases the absolute error $\Delta K$ is of the order of $\pm 0.5\%$, and the relative error is $\Delta K / K \approx 0.02$.

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