NEW MAGNETOCONCENTRATION EFFECT IN GERMANIUM

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The temperature dependence of the Hall coefficient of germanium with a low impurity content was investigated at liquid-helium temperatures in various magnetic fields. A magnetoconcentration effect,[1] associated with a redistribution of carriers localized at impurity centers, was observed at T ~ 7–4.2° K. The experimental results were in good agreement with a theory given in [1]. A method is suggested for estimating the compensating impurity concentration from the magnitude of the magnetoconcentration effect at T = 4.2° K.

1. INTRODUCTION

GALVANOMAGNETIC effects in semiconductors at temperatures which are low compared with the impurity exhaustion temperature are considered theoretically in [1]. It is shown there that the Hall field, which appears in a semiconductor sample placed in crossed electric (E) and magnetic (H) fields, is due to a redistribution of carriers localized at impurity centers, provided

$$\varepsilon E\mu / 8\pi e d n_0 c \gg 1, \qquad (1)$$

where ϵ is the permittivity; μ and n_0 are, respectively, the mobility and equilibrium density of carriers; e is the absolute value of the electronic charge; c is the velocity of light; 2d is the thickness of the semiconductor plate along the Hall direction.

Physically, this effect can be explained as follows. At temperatures considerably lower than the impurity exhaustion temperature, most electrons in a semiconductor are localized at impurity centers. At low impurity concentrations, the density of free electrons may be far too low to establish the polarization which balances the Lorentz force. Consequently, free carriers become concentrated at one of the lateral faces of the plate and the volume density of free carriers falls to a low value.

This disturbs the dynamic equilibrium between the free and localized electrons: the free electrons are generated in the carrier-depleted region and these electrons move to the opposite face and recombine there. The redistribution of electrons continues until a sufficiently strong polarization is established and the motion of electrons along the Hall direction stops. The total number of free electrons in the plate increases because of a strong rise of their density in a thin layer near one of the lateral faces. This gives rise to the magnetoconcentration effect, as the result of which the conductivity of the plate may increase by several orders of magnitude.

Let N_0 be the equilibrium number of carriers in a sample. According to [1], the number of carriers in mutually perpendicular fields E and H becomes

$$N = N_0\left[1 + (1-K)^{-1/K}\frac{ckT}{4e\mu dHE}\exp\frac{\varepsilon\mu^2H^2E^2}{4\pi c^2N_2kT}\right]. \qquad (2)$$

Here, $K = N_2/N_1$ is the degree of compensation of the sample; N_1 and N_2 are the concentrations of the main and compensating impurities. In the derivation of Eq. (2) it is assumed that the free-carrier density n always remains quite small, namely

$$n \ll N_1, \quad N_1 - N_2. \qquad (3)$$

The purpose of our investigation was to study experimentally the magnetoconcentration effect predicted in [1].

2. EXPERIMENTAL RESULTS

We investigated n- and p-type germanium samples in which the total impurity concentration ranged from 2×10^{14} to 7×10^{11} cm^{-3} and the degree of compensation ranged from 9 to 85%. All the measurements were carried out using dc [2] at temperatures of 4.2–20° K in magnetic fields H up to 5000 Oe.

The parameters of the samples are given in Table I. The values of N_2 and K were deduced from the values of the Hall coefficient measured at temperatures and in fields such that the concentration effect was not observed.

Figure 1 shows the dependences of log $R_H T^{3/2}$ on T^{-1} (R_H is the Hall coefficient) for several samples. All the

Sample No.	Type	$N_2 \cdot 10^{-17}$, cm^{-3}	K	U, V	N/N_0	N/N_0 calc	2d, cm	N_2 calc · 10^{-12}
1	p	0.56	0.25	2.1	$1.03 \cdot 10^4$	$2.9 \cdot 10^4$	0.182	0.65
2	p	1.56	0.28	2.56	$5.8 \cdot 10^3$	$3.1 \cdot 10^3$	0.202	1.15
3	p	2.18	0.62	3.15	$9.8 \cdot 10^3$	$9.3 \cdot 10^3$	0.157	2.6
4	p	2.39	0.096	3.25	$1.33 \cdot 10^3$	$1.8 \cdot 10^3$	0.18	2.5
5	p	2.8	0.42	2.6	$4.6 \cdot 10^3$	$3.5 \cdot 10^3$	0.19	1.1
6	p	6.3	0.71	5.6	$9.7 \cdot 10^3$	$1.1 \cdot 10^4$	0.189	6.9
7	p	15.3	0.85	—	$1.9 \cdot 10^2$	$2.1 \cdot 10^2$	0.18	—
8	n	16.3	0.22	4.8	50	62.5	0.139	12.6
9	n	210	0.097	—	4.2	—	0.19	—

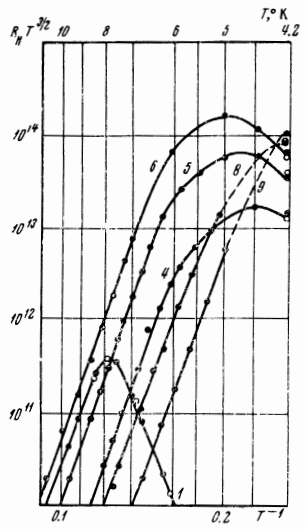

FIG. 1. Temperature dependence of R_H for several samples. The black dots are the experimental results and the open circles are the values calculated using Eq. (2).

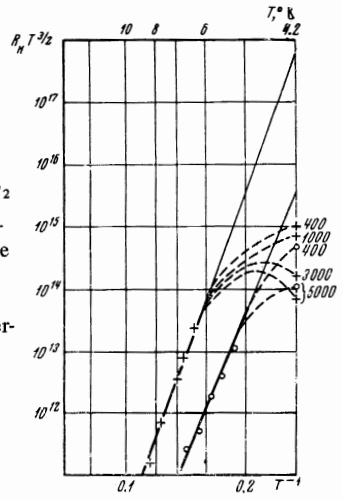

FIG. 2. Dependence of $R_H T^{3/2}$ on T^{-1} for two samples of Ge, obtained using different values of the magnetic field: O—sample No. 8; +—sample No. 3. The intensity of the magnetic field H is given in oersteds alongside the curves.

measurements were carried out in a magnetic field H = 5000 Oe. At high temperatures, the obtained dependences were linear, in agreement with the exponential temperature dependence of the carrier density. When the temperature was lowered, the exponential dependence of $R_H T^{3/2}$ on T^{-1} broke down for all samples. The curves of some of the samples had maxima.

We extended the straight lines in Fig. 1 in the direction of low temperatures. We used R_{H_0} to denote the Hall coefficient obtained through such extrapolation. It was obvious that $N/N_0 = R_{H_0}/R_H$.

It is evident from Fig. 1 and Table I that the magnitude of the effect (N/N_0) and the temperature at which the dependences $\log R_H T^{3/2} = f(T^{-1})$ became nonlinear depended mainly (for a constant value of HE and a given thickness of the sample) on the concentration of the compensating impurity. Thus, for sample No. 1 with $N_2 = 5.6 \times 10^{11}$ cm^{-3} a departure from the exponential dependence was observed at $T \sim 8°$ K, and we found that $N/N_0 = 10^4$ at $T = 6.1°$ K; for sample No. 9 with $N_2 = 2.1 \times 10^{14}$ cm^{-3} a linear temperature dependence of the Hall coefficient was observed right down to $T \sim 4.2°$ K, and we found that $N/N_0 \approx 4$ at $T = 4.2°$ K.

Figure 2 shows the dependences $\log R_H T^{3/2} = f(T^{-1})$ for samples Nos. 8 and 3, obtained using various values of the magnetic field intensity H. Evidently, the value of N/N_0 at a fixed temperature (in the range of temperatures at which the magnetoconcentration effect was observed) increased with increasing magnetic field intensity. We should mention here that all the measurements were carried out using the same value of the current through the sample.

Using Eq. (2) and bearing in mind that $N/N_0 = R_{H_0}/R_H$, we could calculate R_H as a function of E, H, and T. In these calculations, we took the Hall emf U to be $2d\mu HE/c$. The values of U were experimental. Such a calculation was carried out for sample No. 1 in the temperature range 9–6° K and at one temperature, $T = 4.2°$ K, for all the other samples. The calculated values of N/N_0 are compared with the experimental values both in Table I and in Fig. 1 (for sample No. 1 the value of N/N_0 given in Table I corresponds to a temperature of 6.1°K). It is evident from these results that the theory and experiment are in good agreement.

3. ANALYSIS OF THE RESULTS

The presence of maxima in the $R_H T^{3/2} = f(T^{-1})$ curves (cf. Fig. 1) for the majority of samples indicates that, at some temperature T_m, the free-carrier density reaches its minimum value and begins to rise when the temperature is lowered still further. We shall now find the conditions for a minimum at given values of E and H. In finding the minimum of N(T) we must take into account that

$$N_0 \propto T^{3/2} \exp(-\varepsilon_i / kT),$$

where ϵ_i is the ionization energy of the main impurity.

For simplicity, we shall assume that all the pre-exponential factors are independent of T. Then, assuming that $\mu \propto T^{\beta}$ and bearing in mind that $N(T_m) \gg N_0(T_m)$, we obtain the condition for the minimum in the following form:

$$(2\beta - 1)\frac{\varepsilon\mu^2 H^2 E^2}{4\pi c^2 N_2 \varepsilon_i} = (2\beta - 1)\frac{\varepsilon U^2}{16\pi d^2 N_2 \varepsilon_i} = -1. \qquad (4)$$

In our experiments, the mobility was close to the lattice value ($\beta = -3/2$) and the product EH was approximately constant. Therefore, the various samples should, as indicated by Eq. (4), obey approximately the following relationship

$$N_2 T_m^3 = \text{const}.$$

In fact, we can easily show, using Fig. 1 and Table I, that, for example, the product $N_2 T_m^3$ for samples Nos. 4 and 1 is, respectively, 2.7×10^{14} and 2.5×10^{14} deg$^3 \cdot$ cm^{-3}.

It is evident from Eq. (2) that the dependences of N on N_2 and on the degree of compensation K are quite different. N_2 occurs in the denominator of the argument of the exponential function and K appears only in the pre-exponential factor, which is not much greater than unity for $0 < K < 0.9$. It follows that N/N_0 is, other conditions being equal, almost independent of N_1 and increases exponentially when N_2 is reduced. Therefore, when

$N \gg N_0$, expression (2) can be written in the form

$$\frac{N-N_0}{N_0} \approx \frac{kT}{2eU} \exp\left(\frac{\varepsilon U^2}{16\pi d N_2 kT}\right). \quad (5)$$

The above relationship can be used to calculate N_2. The values of the concentration of the compensating impurity calculated in this way are listed in Table I (they are denoted by N_{2calc}). We can see that these calculated values agree very well with the values of N_2 deduced from $R_H(T)$ in the range of temperatures at which the magnetoconcentration effect is absent.

In conclusion, we must note the following points.

1. In the derivation of Eq. (2), we have assumed that, in the absence of external fields, free carriers are in thermodynamic equilibrium with carriers localized at centers of a given type. The equilibrium number of free carriers in a sample is N_0. From the definition of R_{H_0}, it follows that $R_{H_0}/R_H = N/N_0$. However, we may find that R_H and N do not tend to R_{H_0} and N_0 when HE $\rightarrow$ 0. Thus, for example, we carried out experiments in H = 400 Oe and found that the difference between R_H and R_{H_0} (cf. Fig. 2) was greater than that predicted by Eq. (2). This shows that, even in the absence of external fields, the free-carrier density is higher than the equilibrium value. The most likely cause of this effect is the thermal radiation of the upper part of the cryostat, a fraction of which reaches the sample, in spite of the precautionary measures, and produces a background free-carrier density. However, this circumstance should not prevent us from comparing Eq. (2) with the experimental results if the magnetoconcentration effect is sufficiently large, i.e., when N is large compared with the number of free carriers in the absence of external fields.

2. When $N \gg N_0$ the current in the semiconductor plate flows in a thin layer, $\sim L = kT/eU$ thick, near one of its faces. Under the experimental conditions we find that $L \sim 10^{-4}$ cm. The good agreement between the theory and experiment indicates that, if a surface layer with properties different from the volume properties (for example, if the carrier mobility is different in the surface layer) does exist, the thickness of such a layer is much less than 10^{-4} cm.

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