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1958

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PHYSICS

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INVESTIGATION OF THE LONGITUDINAL AND TRANSVERSE GALVANOMAGNETIC EFFECTS IN AN n-TYPE GERMANIUM SINGLE CRYSTAL ALONG THE PRINCIPAL CRYSTALLOGRAPHIC AXES

Introduction. The relative change in the specific resistance in a magnetic field of germanium crystals of n- and p-types in specimens cut along the axes [100] and [110], at temperatures of 77 and 300°K, was investigated by Pearson and Suhl ([2]). Recently ([1]), all the magnetoelectric properties of ultrapure germanium single crystals of three different specimens, having the form of parallelepipeds cut respectively along the axes [100], [110], [111], were investigated at room temperature. In particular, the presence of anisotropy of the galvanomagnetic effect in the objects studied was established. However, the question of whether the anisotropy of the magnetoelectric properties is a consequence of nonuniformity of the density of the specimens remains unclear, since the specimens were cut along the principal crystallographic axes from different ultrapure single crystals.

The aim of the present work was to investigate in detail the relative change in electrical resistance in a magnetic field (longitudinal and transverse effects) with respect to the crystallographic axes [100], [110], and [111] in the diagonal plane (110) of an ultrapure germanium single crystal (with purity up to $10^{-8}\%$) on one and the same specimen, having the form of a sphere. Here we call the effect longitudinal if the vectors of the current $\mathbf{i}$, the measurement $\mathbf{r}$ (directions of the axes), and the magnetic field $\mathbf{H}$ are parallel to one another, i.e. $\mathbf{i} \parallel \mathbf{r} \parallel \mathbf{H}$. If the magnetic-field vector $\mathbf{H}$ is perpendicular to two mutually parallel vectors $\mathbf{i}$ and $\mathbf{r}$, i.e. $\mathbf{i} \parallel \mathbf{r} \perp \mathbf{H}$, the effect is called transverse.

From the known formula of Seitz ([3]) for the current density in semiconductors of the cubic system in the presence of electric and weak magnetic fields, one can derive a formula for the galvanomagnetic effect ($\Delta R/R$) in the form

$$\frac{\Delta R}{R} = \left(K_0 + K_1 \sum_{i=1}^{3} g_i^2 h_i^2 + 2K_2 \sum_{i \neq j = 1}^{3} g_i g_j h_i h_j \right) H^2. \tag{1}$$

Fig. 1. Crystallographic axes [100], [110], and [111] in the diagonal plane (110) of a germanium crystal in the form of a sphere

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In this formula g_i and h_i are the direction cosines, respectively, of the unit vector of the current **i** and of the magnetic field **H** with respect to the tetragonal axes of the crystal of the cubic system; K_0, K_1, and K_2 are constants which, according to ([3]), may be expressed as follows:

$$K_0 = \frac{9\pi neu^3}{16c^2}\left[1+\frac{532}{231}\left(\frac{\tau_1}{\tau_0}\right)^2\right]\rho_0 = \frac{9\pi u^2}{16c^2}\left[1+\frac{532}{231}\left(\frac{\tau_1}{\tau_0}\right)^2\right];$$

$$K_1 = -\frac{9\pi neu^3}{16c^2}\left[1+\frac{452}{231}\left(\frac{\tau_1}{\tau_0}\right)^2\right]\rho_0 = -\frac{9\pi u^2}{16c^2}\left[1+\frac{452}{231}\left(\frac{\tau_1}{\tau_0}\right)^2\right]; \quad (2)$$

$$K_2 = -\frac{9\pi neu^3}{16c^2}\left[1+\frac{212}{231}\left(\frac{\tau_1}{\tau_0}\right)^2\right]\rho_0 = -\frac{9\pi u^2}{16c^2}\left[1+\frac{212}{231}\left(\frac{\tau_1}{\tau_0}\right)^2\right],$$

where u and n are, respectively, the mobility and concentration of current carriers; e is the electron charge; c is the speed of light; ρ_0 is the resistivity; τ_0 and τ_1 are two different functions of the relaxation time τ on the wave vector **k**.

As is seen from (1), for weak H the magnitude of the effect is proportional to the square of the magnetic-field strength, i.e. $\Delta R/R = bH^2$. Calculations by formula (1), for a given value of H, taking (2) into account, give for the longitudinal galvanomagnetic effect $b_{[110]\|} = 2.5\, b_{[100]\|}$ and $b_{[111]\|} = 3\, b_{[100]\|}$. For the transverse effects, in the case where the vectors **i**, **r**, and **H** lie in the plane (110), theoretically from formula (1) we find $b_{[100]\perp} = b_{[110]\perp} \neq b_{[111]\perp}$.

Fig. 1. Crystallographic axes [100], [110], and [111] in the diagonal plane (110) of a germanium crystal in the form of a sphere.

Object and method of investigation

A single crystal of germanium was grown from the melt in a vacuum furnace by the Czochralski method in the laboratory of Prof. D. A. Petrov of the Institute of Metallurgy of the Academy of Sciences of the USSR. To relieve internal stresses in the single crystal, it was boiled for 2 min in hydrogen peroxide and then in distilled water. From the obtained germanium single crystal, in the form of a rod (about 60 mm in diameter and 180 mm long), a specimen was cut in the form of a sphere 33.25 mm in diameter.

Fig. 2

Figure 2: Fig. 2

With the aid of a thermoprobe, the electronic conductivity of the specimen was established. By the X-ray method, on a URS-55 apparatus, using back-reflection photography, one of the diagonal planes (110) of the crystal was determined; this plane at the same time is a diametral plane of the sphere (Fig. 1). Then three principal axes were determined: one of the tetragonal axes [100], one of the diagonal axes [110], and one of the trigonal axes [111], lying in the plane (110).

To place the specimen between the poles of the electromagnet, a special device was made, consisting of a movable and a fixed part. The movable part could rotate about a vertical axis relative to the fixed part of the apparatus. The sphere was fastened to the movable part of the apparatus in a special socket in such a way that in all its positions the magnetic-field vector lay in the plane (110) of the specimen. The specimen, together with the attached part of the apparatus, was placed in a Dewar vessel, and the temperature of the specimen was kept constant. The apparatus was provided with a pointer and a scale, which made it possible successively to measure both longitudinal-transverse effects and the dependence of the effect on the angles between $\mathbf{H}$ and $\mathbf{i} \parallel \mathbf{r}$ at a constant magnetic field in the plane (110).

Copper wires were soldered to the specimen along predetermined directions; their ends went to the measuring circuit (the soldering points had been copper-plated by electrolysis). A DC bridge of the MTV type, class 0.02, was used, to which a mirror galvanometer M21 with a sensitivity of 10^{-9} A/mm was connected.

Results of the investigation

All measurements were made at a temperature of 29°C. Preliminary measurement gave the following initial values of the electrical resistance of the specimen in three directions: $R_{[100]} = 372.5\ \Omega$, $R_{[110]} = 423\ \Omega$, and $R_{[111]} = 340\ \Omega$.

The results obtained in the study of the longitudinal and transverse galvanomagnetic effects as functions of the external magnetic field are presented in Fig. 2. As is seen from Fig. 2, in weak fields the points lie on the parabola $\Delta R/R = bH^2$, which had earlier been obtained by N. S. Akulov ([4]) for ferromagnetic crystals of the cubic system under weak–

magnetic fields. If, however, the squares of the values of the external magnetic field are plotted along the abscissa axis, then at small values of H the dependence of $\Delta R/R$ on H^2 is represented by straight lines (Fig. 3), from whose slope tangent one can calculate the coefficient of proportionality b.

Fig. 2. Curves of the dependence of $\Delta R/R$ on H along the principal crystallographic axes. I—longitudinal effect: a–$\mathbf{i} \parallel [100] \parallel \mathbf{H}$; b–$\mathbf{i} \parallel [110] \parallel \mathbf{H}$; c–

Fig. 3

Figure 3: Fig. 3

i ‖ [111] ‖ **H**. II—transverse effect: a—**i** ‖ [100] ⊥ **H**; b—**i** ‖ [110] ⊥ **H**; c—**i** ‖ [111] ⊥ **H**. $T = 302°$K

Fig. 3. Dependence of the galvanomagnetic effect on the square of the magnetic field along different crystallographic axes of a germanium single crystal. The notation is the same as in Fig. 2

Table 1 gives the theoretical values of the coefficient of proportionality (b_{theor}), calculated by formula (1), and those obtained from experiment (b_{expt}) with respect to the axes [100], [110], and [111] in the (110) plane.

The experimental ratios between the coefficients differ from the theoretical ones obtained: for the longitudinal effect it was found that $b_{[110]\|} = 0.93\, b_{[100]\|}$ and $b_{[111]\|} = 0.89\, b_{[100]\|}$, while for the transverse effect $b_{[100]\perp} \simeq b_{[110]\perp} < b_{[111]\perp}$.

Figure 4 presents the dependence of $\Delta R/R$ on the angles between the vectors **i** ‖ **r** and **H** at a constant magnetic field ($H = 2426$ oersted) in the (110) plane of a germanium single crystal. As can be seen, with respect to the [100] axis the largest longitudinal effect and the smallest transverse effect are observed, whereas the [111] axis, conversely, corresponds to the smallest longitudinal and the largest transverse effects.

Some difference is found between our results and the theory of the galvanomagnetic effect for semiconductors of the cubic system ([3]), which was also noted in work ([1]). Nevertheless, formula (1), derived from a vector series for the expressions for the current in semiconductors of the cubic system in the presence of electric and magnetic fields,

Table 1

Arrangement of vectors in the plane (110)	b_{theor}	$b_{\text{exp}} \cdot 10^0$
i ‖ [100] ‖ **H**	$K_0 + K_1$	3.411
i ‖ [100] ⊥ **H**	K_0	3.167
i ‖ [110] ‖ **H**	$K_0 + \frac{1}{2}(K_1 + K_2)$	3.185
i ‖ [110] ⊥ **H**	K_0	3.170
i ‖ [111] ‖ **H**	$K_0 + \frac{1}{3}(K_1 + 2K_2)$	3.06
i ‖ [111] ⊥ **H**	$K_0 + \frac{1}{3}(K_1 - K_2)$	3.25

Fig. 4. Dependence of the galvanomagnetic effect on the angle between the vectors **i** ‖ **r** and **H** at $H = 2426$ oersted in the plane (110). $T = 302°$K

can quite well serve as a formula for the anisotropy of the galvanomagnetic effect for semiconductors of the cubic system.

Thus, we have experimentally shown that the initial electrical conductivity and the magnitude of the galvanomagnetic effect depend on the crystallographic direction of the germanium single crystal. This confirms our assumption concerning the presence of anisotropy of the galvanomagnetic effect in the object studied.

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Received
7 IX 1957

CITED LITERATURE

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Note: Figure translations are in progress. See original paper for figures.