THE DEPENDENCE OF THE HALL CONSTANT OF p-TYPE GERMANIUM ON THE MAGNETIC FIELD STRENGTH

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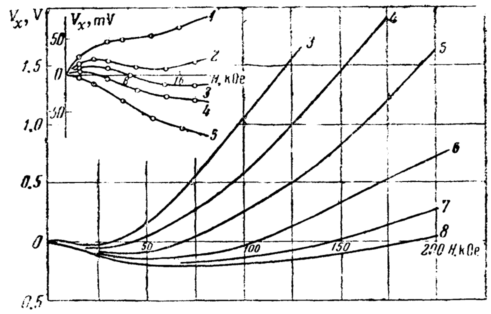
THE dependence of the Hall constant of hole type semiconductors on the strength of the magnetic field has been studied several times. The experimental investigations of the field dependence of the Hall constant in p-type InSb[1,2] showed good qualitative agreement between the results of measurements and the deductions from classical theory.[3] This agreement consists in the change of sign of the Hall constant with increasing magnetic field in the temperature region where the Hall effect has the electronic sign. However, the Hall constant of p-type germanium in weak fields changes sign from positive to negative. Willardson, Harman, and Beer[4] used a model with three types of current carriers (electrons, ordinary holes and "light" holes) to explain the field dependence of the Hall constant in p-type germanium, and obtained good agreement between the deductions from the theory and the experimental results in weak fields up to 8 koe. Measurements of the Hall effect in p-type germanium by Stafeev and Tuchkevich in fields up to 20 koe[5] did not show a second change in sign of the Hall constant, which they interpreted as a disagreement between the results and the deductions from the theory. In addition, Orlova and Tuchkevich[6] suggested that the disagreement between the theoretical and experimental values of the Hall constant lies in the incorrectness of the energy model of germanium. It is thus of great interest to measure the Hall effect in p-type germanium specimens in the region of stronger magnetic fields and to compare the results obtained with the theoretical predictions.

The aim of the present work is to measure the Hall effect in p-type germanium over a wide range of magnetic fields. The measurements were made on a p-type specimen with room temperature resistivity 25 ohm-cm (specimen No. 1) in pulsed magnetic fields up to 200 koe, and also on a specimen with room temperature resistivity 58 ohm-cm (specimen No. 2) in fields up to 300 koe).

The high pulsed magnetic field generator described earlier[7] was used in the measurements. The specimens had dimensions $8 \times 2.5 \times 0.8$ mm and were placed in the uniform field region of the solenoid with the help of a special holder. The ohmic contacts were fixed with indium, followed by heating in vacuum. The temperature was regulated by a thermostat and was controlled by a copper-constantan thermocouple. The measuring system made it possible to obtain the field dependence of the Hall voltage directly on the oscilloscope screen.



Field dependence of the Hall voltage for specimen No. 1. Curve 1 corresponds to a temperature of 50°C; 2 – 53.5°C; 3 – 55°C; 4 – 58.5°C; 5 – 62.5°C; 6 – 68.5°C. 7 – 76°C; 8 – 85°C.

The figure shows the results for specimen No. 1. The curves, obtained in pulsed field, were not plotted point by point, as they are enlarged oscillograms. The initial part of the dependence $V_x(H)$ (up to 20 koe) was measured in the constant field of an electromagnet.

The results can be explained by a model in which the resultant Hall field is made up of components produced by separate types of current carriers. The relation between the separate components of the Hall effect changes with changing temperature and field strength.

In specimen 1, the ratio of mobilities and concentrations of the separate types of current carriers is such that for $t < 60°$ C the Hall constant in weak fields becomes positive. On increasing the magnetic field, the ratio of the components changes, owing to the bending of the lines of current flow. Since the bending of the lines is determined by the parameter uH (where u is the mobility of the current carriers and H is the field strength), an increase in the field decreases first the contribution of the most mobile fast holes and then that of the electrons. This leads to a double change in sign of the Hall constant with a change in field strength in the temperature interval between 56 and 60° C. The first time that $V_x(H)$ passes through zero is connected with the reduction in the contribution of fast holes, and the second with that of electrons.

The form of the $V_X(H)$ dependence also changes with changing temperature. On increasing the temperature, the field corresponding to the first change decreases, while the field corresponding to the second increases. There is thus no first passing of the Hall constant through zero for $t > 60°C$ (curve 5). A decrease in the temperature leads to a reduction in the number of free electrons and to an increase in the mobility of the current carriers. As a result, the role of electrons in the Hall effect decreases, and the field range in which the influence of fast holes becomes appreciable narrows. Our results agree with the deductions from classical theory of galvanomagnetic phenomena not only qualitatively but quantitatively. In fact, if we take the concentration of light holes to be 5% of that of heavy holes, and the ratio of their mobilities to be 8.0, then the experimental field dependence of the Hall constant agrees well with theory. Numerical comparison was made for specimen No. 1 at 55, 62.5, and 76° C. The experiments show that in the temperature range studied the ratio of mobilities of "light" and "heavy" holes does not change, while the ratio of their concentrations is, to a first approximation, proportional to the absolute temperature.

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THE WEIZSÄCKER-WILLIAMS RELATION FOR MATRIX ELEMENTS

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FERMI[1] was evidently the first to use the analogy between the electromagnetic field of a moving charge and a radiation field. This method was developed by Weizsäcker[2] and Williams,[3] who obtained the spectrum of photons equivalent to the field of a charge. Recently there have been a number of papers in which authors have used this method (cf. Low,[4] and especially Pomeranchuk and Shmushkevich[5]).

In these papers, however, the method is applied only to cross sections averaged over polarizations. We shall show how a virtual quantum can be replaced by a real one directly in the matrix element.

Let us consider a diagram describing some process that occurs in the field of another particle (and with the diagram connected with the source of the field by one photon line). The momentum of the virtual photon is $q = P_1 - P_2$ (the difference of the four-momenta of the heavy particle before and after the collision). The Fourier components of such a field are given by

$$A(q) = -2\pi Zeq^{-2}P\delta(qP), \qquad (1)$$

where $P = P_1 + P_2$, and the δ function expresses the obvious relation $(P_1 - P_2)(P_1 + P_2) = 0$; we use throughout $ab = \mathbf{a}\cdot\mathbf{b} - a_0b_0$. In the system in which $\mathbf{P} = 0$, Eq. (1) goes over into the Fourier component of index 4 for the static Coulomb field.

We call one of the external lines of the diagram the incident particle [momentum $p(p_0, \mathbf{p})$, mass m]. In order for the expression (1) to go over into a free field, we must choose a new gauge. In the calculation of formulas with a free photon one usually chooses the gauge so that the photon will have no scalar component in some chosen coordinate system (usually in the system $\mathbf{p} = 0$). This condition can be written in the form $ep = 0$. Therefore let us choose a new polarization vector $\tilde{e}$ by the formula

$$\tilde{e} = [P - q(qp)^{-1}(pP)]f^{-1}, \quad f^2 = P^2 + q^2(qp)^{-2}(pP)^2, \qquad (2)$$

so that $\tilde{e}p = 0$. Then the field (1) is replaced by

$$A(q) = -2\pi Zeq^{-2}\delta(qP)f\tilde{e}. \qquad (3)$$