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Kh. I. AMIRKHANOV, R. I. BASHIROV, and Yu. E. ZAKIEV

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Abstract

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GALVANOMAGNETIC PHENOMENA IN n-InSb IN PULSED MAGNETIC FIELDS

The classical theory of transport phenomena ([1]), based on the Boltzmann kinetic equation, in the case of strong magnetic fields leads to the following relations for the galvanomagnetic coefficients:

$$R = \frac{1}{nec}; \qquad \frac{\Delta\rho}{\rho_0} \perp = \beta; \qquad \frac{\Delta\rho}{\rho_0} \parallel = 0, \tag{1}$$

where R is the Hall constant; n is the carrier concentration; e is the elementary charge; c is the speed of light; $\frac{\Delta\rho}{\rho_0} \perp$ is the transverse magnetoresistance; $\frac{\Delta\rho}{\rho_0} \parallel$ is the longitudinal magnetoresistance; β is a constant determined by the mechanism of carrier scattering. These formulas were derived under the assumption of a unipolar semiconductor with spherical isoenergetic surfaces.

However, the classical theory of galvanomagnetic phenomena does not take into account the quantum character of electron motion in a magnetic field. Therefore, for $\hbar\omega_0 \gg kT$ and $\omega_0\tau \gg 1$, the classical treatment is invalid because of the quantization of the energy spectrum of the carriers in the magnetic field (here $\hbar = h/2\pi$; h is Planck' s constant; k is Boltzmann' s constant; τ is the carrier relaxation time; $\omega_0 = eH/m^*c$ is the cyclotron frequency; m^* is the effective mass of the carrier; H is the magnetic field). Taking into account the quantization of electron orbits in a magnetic field changes the kinetics of galvanomagnetic phenomena ([2–5]) and leads to results substantially different from those of the classical theory. In this connection it is of interest to carry out an experimental verification of the conclusions of the quantum theory of galvanomagnetic phenomena.

Quantum effects in semiconductors, as in metals, may be especially significant at low temperatures. But in strong magnetic fields, created by pulsed techniques, in certain semiconductors of the n-InSb type quantum effects may appear even at room temperatures and dominate at the temperature of liquid nitrogen.

Galvanomagnetic phenomena in semiconductors in pulsed magnetic fields have been little studied. Germanium was investigated by Fakidov and Zavadsky ([6]), and by Furt and Vaněk ([7]). The transverse magnetoresistance in n-InSb in magnetic fields up to 100 kgauss was measured by Busch and Luthi ([8])*.

Fig. 1

Figure 1: Fig. 1

Below we report the results of experimental investigations of the Hall effect and of transverse and longitudinal magnetoresistance, carried out on 5 samples of electron-type indium antimonide in pulsed magnetic fields with strengths up to 900 kgauss. The dependence of the effects both on the magnetic field and on temperature was measured.

* After the present work had been prepared for publication, we had the opportunity to become acquainted with work ([9]), in which the longitudinal magnetoresistance was investigated in the temperature range 3.9–78°K in magnetic fields up to 160 kgauss.

Samples for the study were cut from an InSb ingot purified by repeated zone recrystallization, in a direction perpendicular to the motion of the zone. The sample dimensions were $1 \times 1 \times 5$ mm^3; in measurements in fields above 400 kgauss the samples were shortened in length to 3.5 mm. All samples were checked for homogeneity. The potential and current electrodes were soldered to the sample with pure indium or welded on by the discharge of a capacitor bank; in the latter case, platinum wire 0.03 mm in diameter was used for the probes. In both cases there was no rectification. It was also established that the results did not depend on the current density passing through the sample, up to $j = 10$ A/cm^2.

Fig. 1. Dependence of the transverse (a) and longitudinal (b) magnetoresistance on the magnetic-field strength for n- and p-InSb samples.

The sample in the magnetic field was oriented by a special readout device. In measurements of the longitudinal magnetoresistance, the sample was usually set in such a position that the Hall effect was zero. The transverse magnetoresistance was measured at sample positions corresponding to the maximum value of the Hall field. In the present work pulsed magnetic fields were produced and measured in the same way as in other works ([10–13]). The inhomogeneity of the field in the volume occupied by the sample at H up to 400 kgauss varied within 1%; at higher fields the inhomogeneity of the magnetic field was 3%.

The degree of purity of the samples studied is characterized by the following data: at $T = 77$°K, in InSb No. 1 $n = 6 \cdot 10^{15}$ cm^{-3}, in InSb No. 2 $n = 1.0 \cdot 10^{16}$ cm^{-3}, in InSb No. 3 $n = 10^{16}$ cm^{-3}, in InSb No. 4 $n = 10^{17}$ cm^{-3}, and in InSb No. 5 $n = 10^{18}$ cm^{-3}.

The carrier concentration was determined from measurements of the Hall effect in a constant magnetic field at $H = 5000$ gauss. The following were measured: in samples InSb Nos. 1, 2, 3, 4—the dependence of the transverse magnetoresistance on the magnetic-field strength (Fig. 1); in InSb No. 1—the longitudinal magnetoresistance in different magnetic fields (Fig. 1); in InSb No. 4—the depen-

Fig. 2

Figure 2: Fig. 2

dence of the Hall constant on the magnetic field (Fig. 2). These measurements were carried out at $T = 77^{\circ}$K. In addition, the temperature dependence of the transverse magnetoresistance in InSb No. 2 and of the longitudinal magnetoresistance in InSb No. 1 was measured at $H = 340$ kgauss (Fig. 3).

Fig. 2. Dependence of the Hall constant on the magnetic-field strength for the InSb No. 4 sample.

It follows from the graphs presented that the longitudinal magnetoresistance in InSb No. 1 is appreciable and increases linearly with increasing magnetic field. The dependence of the transverse magnetoresistance on the magnetic-field strength for samples InSb Nos. 1 and 2 is $\frac{\Delta\rho}{\rho_0}_{\perp} \sim H$ over the whole interval of fields studied, and for samples InSb Nos. 3 and 4 $\frac{\Delta\rho}{\rho_0}_{\perp} \sim H^2$ at $H > 250$ kgauss. The Hall constant in sample No. 4 also increases rapidly···

increases with increasing H and only at $H > 400$ kilogauss begins to tend toward saturation. In sample InSb No. 5, within the sensitivity limits of our circuit, no change in the resistance was detected either in transverse or in longitudinal magnetic fields.

These results are completely inexplicable from the standpoint of the classical theory of galvanomagnetic phenomena. As follows from formulas (1), the Hall constant and the transverse magnetoresistance should not depend on the magnitude of the magnetic field, while the longitudinal magnetoresistance for an isotropic semiconductor, which n-InSb apparently is [14], should be absent.

It is obvious that the obtained dependences of $\dfrac{\Delta\rho}{\rho_0}$ on H and of R on H are connected with the quantum character of electron motion in a magnetic field. This is confirmed by the fact that for sample InSb No. 1 at 77° K and at $H > 100$ kilogauss the "quantum" conditions are satisfied as follows: $\hbar\omega/kT > 13$ and $\omega_0\tau > 60$.

For a nondegenerate electron gas in the quantum limit, Argyres [4,5] derived the following formulas:

$$\frac{\rho_H}{\rho_0} \parallel = \frac{1}{3}\left(\frac{n_0}{n_H}\right)\left(\frac{\hbar\omega_0}{kT}\right),$$

$$\frac{\rho_H}{\rho_0} \perp = \frac{2}{3}\left(\frac{\hbar\omega_0}{kT}\right)\left(\frac{I_1(\gamma)}{I_1^2(\gamma) + I_2^2(\gamma)}\right). \quad (2)$$

Here n_0, n_H are the carrier concentrations without a field and in the presence of a magnetic field, respectively; ρ_H is the resistance in a magnetic field;

Fig. 3. Dependence of the transverse (a) and longitudinal (b) magnetoresistance on temperature for samples InSb No. 2 and InSb No. 1

Figure 3: Fig. 3. Dependence of the transverse (a) and longitudinal (b) magnetoresistance on temperature for samples InSb No. 2 and InSb No. 1

Fig. 3. Dependence of the transverse (a) and longitudinal (b) magnetoresistance on temperature for samples InSb No. 2 and InSb No. 1

$$I_1(\gamma) = \frac{\gamma}{\pi^{1/2}} \int_0^\infty \frac{e^{-t}\,dt}{t+\gamma}; \qquad I_2 = \left(\frac{\gamma}{\pi}\right)^{1/2} \int_0^\infty \frac{e^{-t} t^{1/2}\,dt}{t+\gamma}; \qquad \gamma = \frac{1}{4}\,[kT\tau_0(kT)/\hbar]^{-2}.$$

As is seen from Fig. 1, the magnetoresistance in InSb Nos. 1 and 2 depends on H in the way that follows from (2), with the transverse magnetoresistance being an order of magnitude greater than the longitudinal one, which indicates the sphericity of the energy surfaces in n-InSb.

To explain the change of $\dfrac{\Delta\rho}{\rho_0}$ with H in InSb No. 4, it should be taken into account that the electron concentration in this sample at 77° K is $n = 10^{17}$ cm^{-3}, i.e., the sample at this temperature is degenerate. In this case quantization is significant only when $\hbar\omega_0 > E_0$, where E_0 is the limiting Fermi energy. Since in degeneracy $E_0 > kT$ (for InSb No. 4, $E_0 = 8kT$), the magnetic fields at which quantization is significant must be higher. For InSb No. 4 at $H > 300$ kilogauss $\dfrac{\Delta\rho}{\rho_0} \perp\sim H^2$, which is also predicted by theory [5] for the degenerate case. An analogous phenomenon also occurs in InSb No. 3. As E_0 increases, higher fields are required to satisfy the condition $\hbar\omega_0 > E_0$. The absence of transverse and longitudinal magnetoresistance in the strongly degenerate sample InSb No. 5 is explained by the fact that the quantum condition $\hbar\omega_0/E \gg 1$ is not fulfilled. Thus, for this sample the classical case is realized, and the magnetoresistance should be equal to zero.

The Hall constant for sample InSb No. 4 increases rapidly with increasing H up to 400 kilogauss, and then tends toward saturation (Fig. 2). Theoretical calculations [3] lead only to an increase of the Hall constant with increasing H.

The curve of the temperature dependence of $\dfrac{\Delta\rho}{\rho_0}\perp$ for InSb sample No. 2 (Fig. 3) falls with increasing temperature less steeply than follows from theory ([5]); in the interval 77–200°K,

$$\frac{\Delta\rho}{\rho_0} \perp\sim T^{-0.4}.$$

The longitudinal magnetoresistance $\frac{\Delta\rho}{\rho_0}\parallel$ changes still more weakly up to 250°K, and then decreases sharply.

The discrepancies between theory and experiment that are observed for the dependences of R on H and of $\frac{\Delta\rho}{\rho_0}$ on T are apparently connected with the circumstance that in the region 77—200°K two scattering mechanisms operate —lattice and ionic—whereas the theory has been developed only for the case in which a single scattering mechanism acts.

The dependences of galvanomagnetic effects on magnetic field presented in this work were also observed by us in other substances, in particular in electron samples of HgTe and InAs.

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Academy of Sciences of the USSR

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