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Abstract

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QUANTUM OSCILLATIONS OF MAGNETORESISTANCE IN n-InSb IN STRONG PULSED MAGNETIC FIELDS

The energy spectrum of charge carriers in a solid upon application of a strong magnetic field is quantized. Landau levels appear, the spacings between which are determined by the quantity

$$\hbar\omega_0 = \frac{\hbar e H}{m^* c}.$$

Here $\hbar = h/2\pi$, h is Planck' s constant, e is the electron charge, H is the magnetic-field strength, m^* is the effective mass, and c is the speed of light. If $\hbar\omega_0 > E$, where E is the characteristic energy of the electron, the quantum limit is realized. For $\mu_0 > \hbar\omega_0 \gg kT$, where μ_0 is the chemical potential, oscillations should arise in transport phenomena that depend quasiperiodically on the magnitude $1/H$.

In order to study the Shubnikov-de Haas effect in strong magnetic fields, and also to determine the dependence of the magnetoresistance on the magnetic field in the quantum limit, we measured the longitudinal and transverse magnetoresistance in InSb samples of different purity in the range 20-77° K in pulsed magnetic fields up to 400 kOe. The measurements were carried out by the method of time sweeps of the field and of the phenomenon considered in (1), and by the method of direct recording on an oscilloscope of the measured phenomenon as a function of the field (2). The results obtained by these two methods coincided within the experimental error. A typical oscillogram of the recording of the phenomenon as a function of the field is given in Fig. 3a.

The article presents data obtained by the second method. Samples measuring $5.2 \times 0.4 \times 0.4$ mm^3 were cut from single-crystal ingots and were sufficiently homogeneous. It was established that the value of the magnetoresistance does not depend on the dimensions of the sample if the ratio of the sample length to its width is greater than 12. Measurements were carried out at current densities that did not lead to violation of Ohm' s law. The maximum field was 0.05 V/cm.

The characteristics of the investigated samples are given in Table 1 ($T = 77°$K). In samples 265 and 410 the longitudinal magnetoresistance was measured; in all the others—the transverse magnetoresistance.

Table 1

Sample	$n \cdot 10^{-17}$, cm^{-3}	σ, $\mathrm{ohm}^{-1} \cdot \mathrm{cm}^{-1}$
265	6.6	2700
182	4.08	2560
184	2.04	1830
410, 411	0.89	704

From the experimental results (Figs. 1 and 3) it is evident that the resistance in a magnetic field in all samples undergoes oscillations quasiperiodic in $1/H$. The oscillations disappear as the magnetic field increases. This transition into the region of the extreme quantum limit occurs at fields that are the higher, the higher the concentration of charge carriers.

To determine the oscillation period, Fig. 2 gives plots of N versus $10^6/H$, constructed from the extrema of the oscillations and the points of intersection of the oscillating part with the monotonically varying part of the magnetoresistance (N is the number of the oscillation period). The periods are determined from the slope of the straight lines obtained. The maximum error in such ···

determination of the periods was 10%. It follows from Fig. 2 that the period of the longitudinal oscillations is constant, whereas the period of the transverse magnetoresistance decreases with increasing magnetic field at $H > 10^5$ oerst.

Table 2 gives the values of the periods calculated from

$$\Delta\left(\frac{1}{H}\right)_{\mathrm{theor}} = \frac{\hbar e}{\mu_0 m^* c}, \tag{1}$$

and $\Delta(1/H)_{\mathrm{exp}}$, determined from Fig. 2; for the transverse magnetoresistance the period is determined from the rectilinear initial portions of the curves up to $(10^6/H) = 10$, which corresponds to $H = 100$ kOe. The authors of Ref. [3] showed that, for the transverse magnetoresistance, comparison of theory and experiment should be made by the oscillation maxima, and not by the minima, as had been done previously [4].

Table 2

Sample	$\left(\frac{10^3}{H}\right)_{\mathrm{exp}}$, oerst^{-1}	$\left(\frac{10^3}{H}\right)_{\mathrm{theor}}$, oerst^{-1}
182	6.0	5.8
184	8.0	9.2

Fig. 1

Figure 1: Fig. 1

Sample	$\left(\frac{10^3}{H}\right)_{exp}$, oerst^{-1}	$\left(\frac{10^3}{H}\right)_{theor}$, oerst^{-1}
411	7.2	16
265	3.3	4.2

Table 3 gives the experimental and theoretical, according to [3], values of $(1/H)_{max}$ for the first three maxima (from the side of strong magnetic fields). The theoretical values $(1/H)_{theor.\ max}$ were obtained by multiplying the quantity $(1/H)_{theor}$ by 1.31; 2.36; 3.38 [3]; $T = 20°$K. It follows from Table 3 that

Fig. 1. Dependence of the magnetoresistance on the inverse magnetic field. 1 –sample 182 ($T = 20°$K), 2 –sample 184 (20°K), 3 –sample 265 (77°K), 4 –sample 265 (20°K).

the positions of the maxima of the transverse-magnetoresistance oscillations, determined experimentally and calculated theoretically according to [3], differ substantially. It was shown above that the periods of the transverse magnetoresistance depend on the magnetic field (at $H > 100$ kOe); this also disagrees with theory. Thus, comparison of our results in the oscillatory region with the theory [3], which is based on a quadratic dispersion law and does not take into account the splitting of Landau levels in a magnetic field, leads to discrepancies.

The splitting of the Landau levels for InSb in fields $\sim 10^5$ oerst is comparable with the distances between diamagnetic quantum levels. This is connected with the large g-factor in InSb. According to the data of Ref. [5], $g = -50$ at

Table 3

		$\left(\frac{10^3}{H}\right)^{I}_{max}$, oerst^{-1}	$\left(\frac{10^6}{H}\right)^{II}_{max}$, oerst^{-1}	$\left(\frac{10^6}{H}\right)^{III}_{max}$, oerst^{-1}
Sample 182,$I \perp H$	Theory[3]	7.7	13.7	–
Sample 182,$I \perp H$	»	3.9	6.7	–
Sample 182,$I \perp H$	Experiment[6]	3.5	7.9	–
Sample 184,$I \perp H$	Theory[3]	12.2	21.7	31.2

		$\left(\frac{10^3}{H}\right)^{\mathrm{I}}_{\max}$, oerst^{-1}	$\left(\frac{10^6}{H}\right)^{\mathrm{II}}_{\max}$, oerst^{-1}	$\left(\frac{10^6}{H}\right)^{\mathrm{III}}_{\max}$, oerst^{-1}
Sample 184,$I \perp H$	»	6.1	10.9	17.8
Sample 184,$I \perp H$	Experiment(6)	4.7	10.5	18
Sample 411,$I \perp H$	Theory(3)	21.0	–	–
Sample 411,$I \perp H$	»	10.5	–	–
Sample 411,$I \perp H$	Experiment(6)	10	–	–
Sample 265,$I \parallel H$	Theory(3)	5.52	10	14.2
Sample 265,$I \parallel H$	»	2.3	4.7	8.2
Sample 265,$I \parallel H$	Experiment(6)	6.0	9.3	–

77°K. If it is assumed that the Landau levels, beginning with the lowest one, split, then the entire picture of the magnetoresistance oscillations may be complicated. When the Landau level with quantum number $N = 0$ is split, a zero maximum of the oscillations also appears.

L. E. Gurevich and A. L. Efros theoretically calculated* (6) the influence of spin on the transverse magnetoresistance for a quadratic spectrum and obtained the following formulas for the zero maximum and the first maxima with different spin orientations in the case when m^*/m_0 is not small:

$$\left(\frac{1}{H}\right)^{0}_{\max} = n^{-2/3}\left(\frac{1}{2}\right)^{0}\left(\frac{1}{\pi^2}\right)^{1/3}\frac{e}{\hbar c}\left(\frac{m^*}{m_0}\right)^{1/3}; \quad (2)$$

$$\left(\frac{1}{H}\right)^{-\mathrm{I}}_{\max} = n^{-2/3}\left(\frac{1}{2}\right)^{1/3}\left(\frac{1}{\pi^2}\right)^{2/3}\frac{e}{\hbar c}\left[1+\sqrt{1-\frac{m^*}{m_0}}\right]^{2/3}; \quad (3)$$

$$\left(\frac{1}{H}\right)^{+\mathrm{I}}_{\max} = n^{-2/3}\left(\frac{1}{2}\right)^{1/3}\left(\frac{1}{\pi^2}\right)^{2/3}\frac{e}{\hbar c}\left[1+\sqrt{1+\frac{m^*}{m^*}}+\sqrt{\frac{m^*}{m_0}}\right]^{2/3}. \quad (4)$$

Here m_0 is the spin mass of the electron.

The values of the magnetoresistance maxima calculated from formulas (2)–(4) [6] are given in Table 3. The ratio m^*/m_0 was taken to be 0.5, i.e., $|g| = 50$; $m^*/m = 0.02$. It is seen from Table 3 that, when the spin influence according to [6] is taken into account, the discrepancies between our experimental data and theory are substantially reduced. The small discrepancies that continue to be observed between the theoretical and experimental positions of the maxima may be connected with the nonparabolicity of the conduction band of InSb. In addition, it should be borne in mind that, as the magnetic field changes, the g-factor does not remain constant. It is interesting to note that in the case of longitudinal magnetoresistance (sample 265) the experimental results agree satisfactorily also with the theory [3], which does not take the spin influence into account.

Fig. 2. Dependence of the position of the oscillation periods on the inverse field. 1 –sample 265, 2 –sample 184, 3 –sample 182.

* We express our deep gratitude to L. E. Gurevich and A. L. Efros for acquainting us with the results of work [6] before their publication, and also for communicating the results in the case when m^*/m_0 is not small.

Let us turn to a discussion of the results in the region $\hbar\omega_0 > E$, presented in Fig. 3. In the region of the extreme quantum limit in sample 184 at 20°K, where, apparently, the principal scattering mechanism is ionic,

$$\frac{\Delta\rho}{\rho_0} \perp \sim H^3.$$

According to Adams and Holstein [7], for a degenerate electron gas in the case of the extreme quantum limit, i.e., when $\hbar\omega_0 \gg \mu_0 > kT$, with scattering of carriers by ionized impurities,

$$\frac{\Delta\rho}{\rho_0} \perp \sim H^3.$$

Thus, for sample 184, quite satisfactory agreement between theory [7] and experiment is observed. In samples 410 and 411, also degenerate but with a lower carrier concentration,

$$\frac{\Delta\rho}{\rho_0} \perp, \ \| \sim H^2.$$

It may be assumed that the difference in the dependences in sample 184 and in samples 410 and 411 is connected with the fact that the condition for preservation of degeneracy in a strong magnetic field [8] is only weakly fulfilled in samples 410 and 411.

Fig. 3. Dependence of the resistance on the magnetic field.
1 –sample 184, **2** –sample 411, **3** –sample 410. $J \parallel H$

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