SHUBNIKOV - DE HAAS OSCILLATIONS IN p-InSb

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The main result of the present investigation is the observation of Shubnikov - de Haas (SH) quantum oscillations and the determination of the singularities in a semiconductor having degenerate bands (p-InSb). Quantum oscillation effects in kinetic phenomena in p-InSb have not been investigated before[1].

Characteristic features of semiconductors with degenerate bands are the presence of several types of carriers (light and heavy holes in p-InSb) and the possibility of interband transitions upon scattering (transformation of light holes into heavy ones and vice versa in p-InSb). The light-hole concentration (p_2) is usually smaller by two orders of magnitude than the heavy-hold concentration (p_1), but nevertheless the light holes make a noticeable contribution to the galvanomagnetic effects in p-InSb, owing to the higher mobility of the light holes ($u_2 \simeq 10u_1$).

The quantum oscillations of the kinetic coefficients of n-InSb have been thoroughly investigated. Since the parameters of the light holes in InSb are close to those of the electrons, one should expect to satisfy in suitable magnetic fields the conditions necessary for the observation of SH oscillations, namely $u_2H/c \gg 1$, $\hbar\Omega_2/kT \gg 1$, and $\zeta/kT \gg 1$ (Ω_2 is the cyclotron frequency for the light holes and ζ the chemical potential).

We investigated degenerate p-InSb samples doped with germanium, with hole density[2] $p_1 = 8 \times 10^{17} - 1 \times 10^{19}$ cm^{-3} in stationary magnetic fields up to 75 kOe at helium temperatures. The magnetoresistance and the Hall effect were measured by a standard potentiometer method using an automatic x-y recorder.

The measured plots of the transverse magnetoresistance and of the Hall coefficient revealed oscillations constituting small increments to a strongly varying background. More distinct SH oscillations were obtained by investigating the longitudinal magnetoresistance ($\vec{H} \parallel \vec{J}$) of p-InSb (Fig. 1). Figure 2 shows the oscillating parts of the plots of the longitudinal magnetoresistance, obtained by subtracting the signal linear in H.

As seen from Fig. 1, the oscillations of the longitudinal magnetoresistance have the following singularities: a relatively large oscillation amplitude, reaching 50% of the background for the lower levels, and oscillatons corresponding to the lower Landau levels a_0 and b_0 of the light holes. These cannot be explained if it is assumed that only the electric conductivity $\sigma_{zz}^{(1)}$ of the light holes oscillates, since the light holes constitute 1% of the heavy holes and their contribution to the conductivity at H = 0 is of the order of 10%. In addition, according to the theory [2], 0^+ and 0^- maxima of ρ_{zz} (corresponding to the b_0 and a_0 maxima in the notation of [3]), which are observed in the experiment, should not exist for simple bands.

These singularities are attributed to the fact that quantum oscillations of the electric conductivity $\sigma_{zz}^{(2)}$ of the heavy holes occur in a longitudinal

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[1] After the experimental part of this investigation was completed, a brief communication [1] reported observation of SH oscillations in p-InSb.

[2] The heavy-hole concentration was calculated from the Hall coefficient in a strong magnetic field ($H \to \infty$), determined from the $R = f(H^{-2})$ dependence.

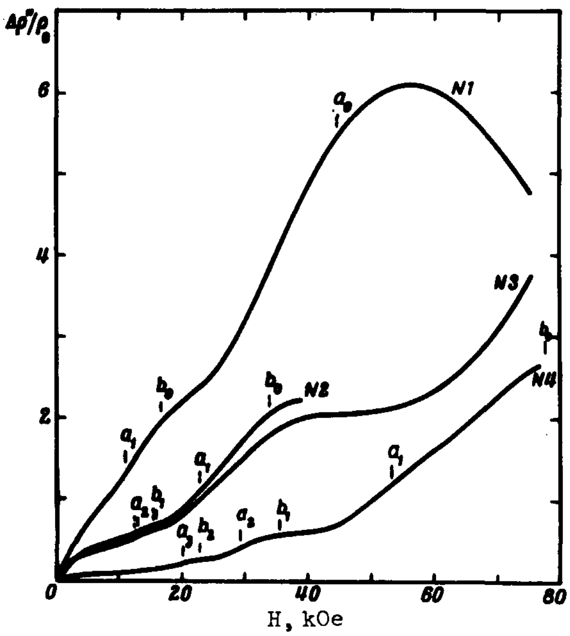

Fig. 1

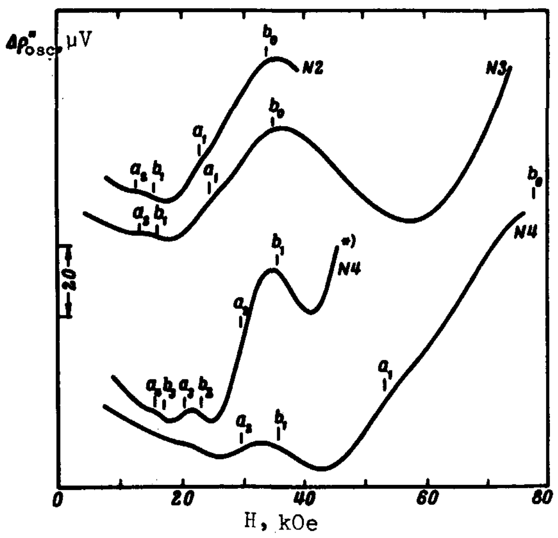

Fig. 2

Fig. 1. Experimental plots of the longitudinal magnetoresistance of p-InSb samples at T = 1.6°K and $\vec{H} \parallel$ [111] for samples No. 1, 3, and 4 and $\vec{H} \perp$ [111] for sample No. 2. The Hall coefficients in a weak field are R_0 = 15, 3.7, 3.6, and 10 cm^3/C, and the electric conductivity is σ_0 = 54, 203, 200, and 625 ohm^{-1}cm^{-1} for samples 1, 2, 3, and 4, respectively.

Fig. 2. Oscillating parts of the longitudinal-magnetoresistance curves, obtained by subtracting the signal linear in H, for p-InSb samples 2, 3, and 4 at T = 1.6°K (* - magnification 5×).

magnetic field owing to the quantization of the energy of the light holes, even if there is no quantization of the energy of the heavy holes themselves. The reason is that when a heavy hole is scattered it can fall not only into the heavy band but also in the light one, and the scattering probability is $W_1 = W_{11} + W_{12}$, where W_{11} and W_{12} are the probabilities of scattering into the heavy and light bands, respectively. In the absence of a magnetic field we have $W_{11} > W_{12}$, owing to the larger density of states in the heavy-hole band, but in a quantizing magnetic field this inequality is reversed ($W_{12} > W_{11}$) for heavy holes having an energy equal to the bottom of the Landau light-hole subband (transitions of the type 1, 2 in Fig. 3), owing to the singularities in the density of state of the light holes. Therefore if the Fermi level coincides with the bottom of the Landau light-hole subband, the electric conductivity of the heavy holes, $\sigma_{zz}^{(2)}$, has a minimum, and ρ_{zz} a maximum. Although the collision smearing of the Landau levels and the thermal smearing of the Fermi level limit the oscillation amplitude, this explains the rather large ρ_{zz} oscillations.

A detailed analysis (which will be reported in a separate article) shows that transitions from the heavy-particle states are allowed to all the states of the light particles, thus explaining the existence of ρ_{zz} oscillations corresponding to the lower levels of the light holes.

Thus, the observed oscillations of the longitudinal magnetoresistance of p-InSb are due mainly to the oscillatory behavior of the conductivity of the heavy holes, with a period determined by the Landau levels of the light holes.

In other words, a strong enhancement of the interband scattering of the heavy holes is observed whenever the Fermi level coincides with the bottom of the Landau light-hole subband. To determine the theoretical positions of the maxima of the longitudinal magnetoresistance, the Landau levels were determined at $k_z = 0$ for the light holes in InSb. The interaction between the conduction and the valence bands was considered exactly, and the influence of the more remote bands was taken into account by perturbation theory. The InSb valence-band parameters, in Luttinger's notation [4], were assigned the values obtained by Pidgeon and Brown from magneto-absorption data [3] and satisfying the cyclotron-resonance data for the heavy holes [5]: $P^2 = 0.403$ at. un., $\gamma_1^L = 32.5$, $\gamma_2^L = 14.3$, $\gamma_3^L = 15.4$, $k^L = 13.4$, and $\varepsilon_g = 0.2355$ eV ($T = 4.2$°K). The best agreement between the observed maxima of ρ_{zz} and the values of H corresponding to agreement of the Fermi level with the Landau levels a_n and b_n of the light holes was obtained at $\zeta = 9.5$, 19, 19.5, and 40.5 meV for samples 1, 2, 3, and 4, respectively. The theoretical values of H for given ζ are indicated in Figs. 1 and 2 by vertical lines with indices a_n and b_n. It is seen that the agteement is good. The heavy-hole concentration calculated from the value of the chemical potential for each of the samples agrees well with the data determined from the Hall coefficient in a strong field. It should be noted that owing to the smearing of the Landau levels, due in turn to the collisions, the nearby maxima of ρ_{zz}, corresponding to the neighboring levels b_n and a_{n+1}, overlap to form a single maximum in the experiment. Splitting of the maxima could be observed at $T = 1.6$°K only for the lowest Landau levels and grids a and b (Fig. 2).

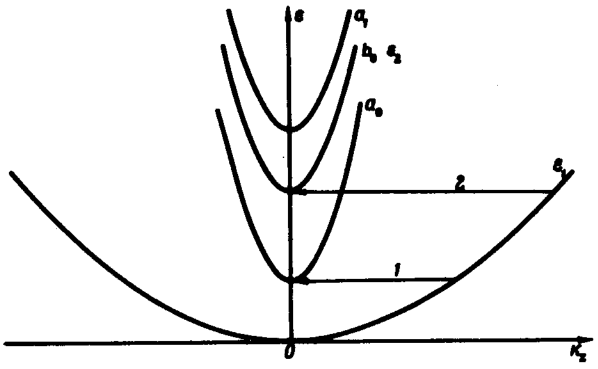

Fig. 3. Transitions in the valence band of InSb in a magnetic field that is quantizing for the light holes.

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ELECTRON-CYCLOTRON HEATING IN THE TOKAMAK TM-3 INSTALLATION

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Using the Tomamak TM-3 installation [1], we investigated the possibility of additionally heating a plasma in a high-frequency (HF) field in the