INVESTIGATION OF A NEW TYPE OF OSCILLATIONS IN THE MAGNETORESISTANCE

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A new type of oscillations in the transverse magnetoresistance of nondegenerate semiconductors due to inelastic scattering of electrons by optical phonons was theoretically predicted by Gurevich and Firsov.[1] This new effect can be observed if the phonon spectrum of the crystal has an optical branch and if the magnetic field is sufficiently strong to satisfy the condition $\Omega\tau = \mu H/c = (e\tau H/m^*c) \gg 1$, where Ω is the cyclotron frequency, τ is the electronic relaxation time, and μ is the electronic mobility. Later Efros[2] generalized the Gurevich-Firsov theory for degenerate statistics.

The physical nature of these oscillations can be explained as follows. At very high magnetic field the distance between the adjacent Landau levels, $\hbar\Omega$, exceeds the longitudinal optical phonon energy, $\hbar\omega_0$, and the probability of electron-phonon scattering is relatively small. When the magnetic field decreases, the Landau splitting energy $\hbar\Omega$ becomes equal to $\hbar\omega_0$. Then the probability of electron-phonon scattering sharply increases, causing the ρ_{xx} component of the resistivity tensor to increase (the magnetic field H is supposed to be oriented along the z axis).

Further decrease of the magnetic field breaks the resonance condition, and the number of transitions induced by optical phonons is decreased until a new resonance is approached. The resonance condition is $\omega_0 = M\Omega$, where M is an integer. Thus the part of the magnetoresistance due to scattering by optical phonons should oscillate with a period

$$\Delta(1/H) = e/m^*\omega_0 c, \tag{1}$$

depending on the effective mass m^* and ω_0.

We have also investigated theoretically similar oscillations of the longitudinal magnetoresistance for the case of low temperatures, where $(\hbar\omega_0/kT)$

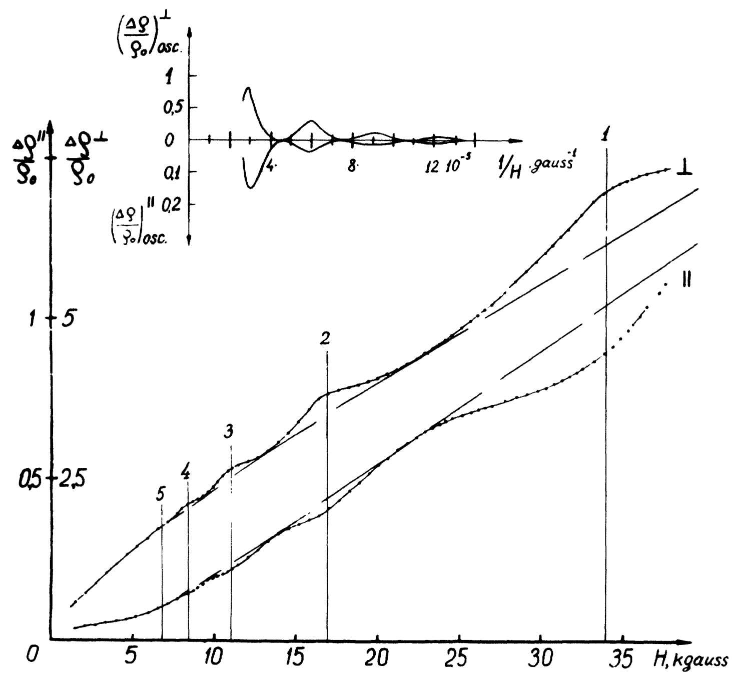

FIG. 1. The curves of the transverse $(\Delta\rho_\perp/\rho_0)$ and longitudinal $(\Delta\rho_\parallel/\rho_0)$ magnetoresistance for n-InSb samples with carrier concentrations 6×10^{13} cm^{-3} and 4.1×10^{13} cm^{-3} and mobilities 6.7×10^5 cm^2/V-sec and 5.5×10^5 cm^2/V-sec, respectively, at 90°K. The broken lines correspond to the monotonic background on these curves. The oscillatory part of the transverse and longitudinal magnetoresistance as function of the inverse magnetic field is given in the upper part of the figure. The vertical lines correspond to the resonance condition $\omega_0 = (1-5)\Omega$.

$\gg 1$.[3] If only scattering by optical phonons is essential, the oscillating part of the magnetoresistance should have a maximum near the resonance. But if some mechanism of elastic scattering predominates, for instance scattering by acoustical phonons, the shape of the function $\Delta\rho_{zz}(H)$ near the resonance should depend strongly on the ratio Γ of the probability of scattering by acoustical phonons to the probability of scattering by optical phonons. If $\Gamma \gg 1$, a minimum of $\Delta\rho_{zz}$ should exist near the resonance, but when Γ decreases [assuming the condition $(\hbar\omega_0/kT) \gg 1$ still holds], the minimum should transform into a maximum.

The first brief communication on the observation of new type oscillations in n - InSb was reported by Puri and Geballe.[4] The results of our detailed experimental investigation of the transverse and longitudinal magnetoresistance in n - InSb, shown in the Fig. 1, confirm the theory.

The maxima of the oscillations in the transverse magnetoresistance curve are located at $H_{max} = 34$, 17, ~11.3, ~8.5, and ~6.7 kilogauss. In the longitudinal magnetoresistance, minima are found at $H_{min} = 32.5$, 16.5, ~11, ~8.3, and ~6.7 kilogauss. The existence of the minima is in satisfactory agreement with the theory, since the intensity of acoustical scattering in this case was rather high. The fourth and fifth extrema on the magnetoresistance curves were obtained in a special investigation in a magnetic field weaker than 15 kilogauss.

The separation of the monotonic background on these curves was made according to the theoretical conclusion that the oscillatory part of the resistance at low temperatures should be added to the transverse magnetoresistance and should be subtracted from the longitudinal magnetoresistance. The maximum of the ratio of the oscillatory part to the monotonic background is approximately the same both for the transverse and for the longitudinal effect and is about 15%. The experimental value of H_{max1} and the period of oscillation $[\Delta(1/H) = (3.0 \pm 0.2) \times 10^{-5}\ \text{gauss}^{-1}]$ are consistent with their theoretical values calculated using available data for the effective mass[5] ($m^* = 0.016$ at $H \approx 34$ kilogauss) and optical phonon limiting frequency[6] ($\omega_0 = 3.7 \times 10^{13}$ sec^{-1}).

It is clear from physical arguments only that an optimum temperature exists where the oscillatory part of the magnetoresistance reaches a maximum. An optimum condition for observing the oscillations occurs when the phonon occupation number and the mobility are sufficiently large. The experimental curves of the transverse effect for one n - InSb sample at different temperatures are presented in Fig. 2. The oscillatory part reaches a maximum value at 104°K and diminishes when the temperature is either decreased or increased. A set of curves of the transverse magnetoresistance measured for different carrier concentrations, which is not shown here, demonstrates that the period and the phase of the transverse oscillations are independent of the concentration in the range $5.2 \times 10^{13}\ \text{cm}^{-3}$ to $1.3 \times 10^{15}\ \text{cm}^{-3}$. In addition it is noted that the ratio of the oscillatory part to the background diminishes as the mobility decreases. We did not observe any oscillation on the specimens of n - InSb with carrier concentration greater than $5 \times 10^{15}\ \text{cm}^{-3}$. Figure 3 demonstrates that the phase but not the period of longitudinal oscillations changes when the temperature is changed. The fact that the phase varies with temperature agrees qualitatively with the theoretical conclusion that the phase of the oscillations of the longitudinal magnetoresistance

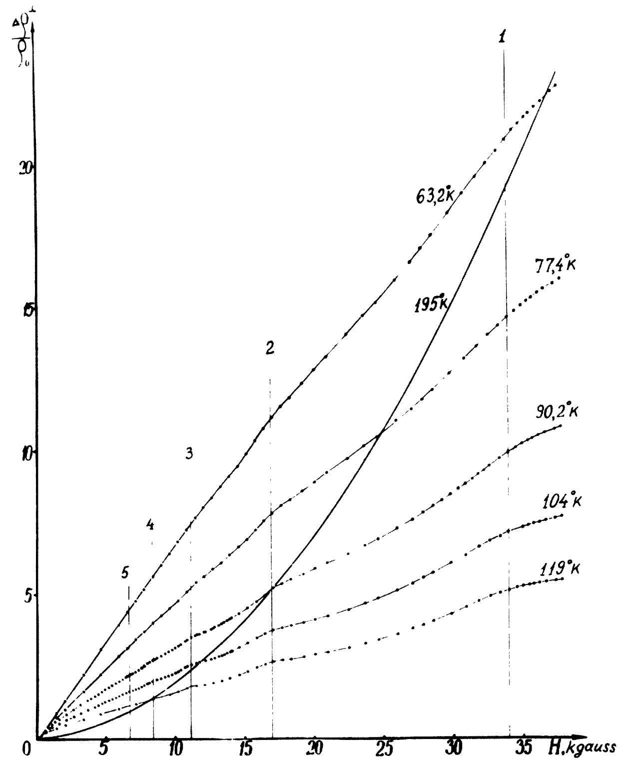

FIG. 2. The plots of the transverse magnetoresistance for n-InSb sample with carrier concentration $5.2 \times 10^{13}\ \text{cm}^{-3}$ at different temperatures.

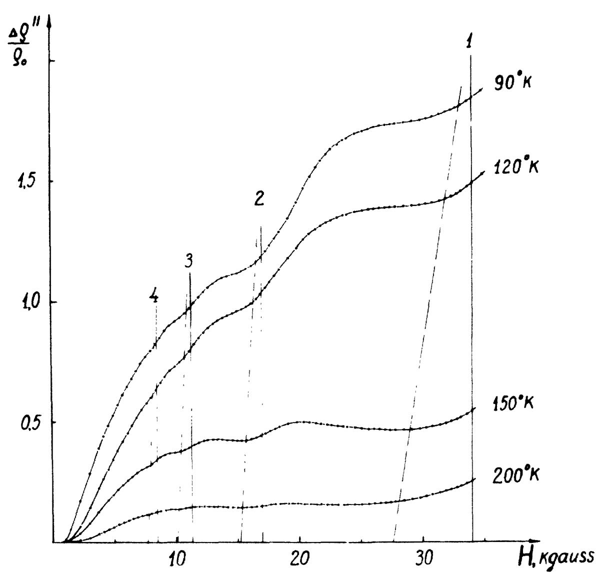

FIG. 3. The curves of the longitudinal magnetoresistance for n-InSb sample with carrier concentration 4×10^{13} cm^{-3} at different temperatures. The broken inclined lines show the displacement of the minimum positions when the temperature is changed.

should change when the relative intensity of acoustical and optical scattering varies. The curves obtained demonstrate the difference between this new oscillatory effect and the well known Shubnikov–de Haas oscillations. As we have seen, the period of the new type of oscillations is independent of the carrier concentration and the amplitude decreases with temperature in the region of liquid nitrogen and below. However, the period of the Shubnikov–de Haas oscillations is determined by the carrier concentration only and these oscillations can be observed at very low temperatures and only under degenerate conditions. The new oscillatory effect can be observed for any statistics. The specimens investigated in the present work were nondegenerate.

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EVIDENCE FOR A NEW COLLECTIVE RESONANCE IN A "FREE-ELECTRON" METAL*

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From cyclotron resonance[1] and de Haas–van Alphen studies,[2] the Fermi surface of K is known to be spherical within 1% with an effective mass of 1.21. Band studies[3] show that the energy gaps at Brillouin zone edges are $\mathcal{E}_g \lesssim 0.2$ eV compared to the Fermi energy $E_F = 2.2$ eV. The direct interband optical threshold would arise from transitions in the Brillouin zone near N. To second order in $\mathcal{E}_g/E_F$, the theoretical threshold energy E_t is given by the free-electron model: $E_t = 1.2$ eV.

Mayer and El Naby[4] have studied the reflectance of polarized light from mirror surfaces of metallic K in the temperature range -183°C to >85°C (the melting point) under conditions of high vacuum. We believe their data to be the best yet obtained[5] on the spectra of the alkali metals within their spectral range of 0.5-2.6 eV.

From their data [see Fig. 1(b)] the following salient results emerge:

(1) There is a sharp absorption threshold in $\mathcal{E}_2$ at $\hbar\omega \leq 0.5$ eV.

(2) Beyond the threshold $\mathcal{E}_2$ rises sharply to a peak at 0.6 eV and then falls gradually out to 2.0 eV.

(3) At their lowest temperature (-183°C), $\mathcal{E}_2$ drops to zero (within experimental error) for $0.5 \leq \hbar\omega \leq 0.7$ eV. This observation rests on three experimental points. Moreover, in Fig. 2 we show that as the temperature is lowered, the difference D between the total $\mathcal{E}_2$ and the Drude background diminishes monotonically as well as finally reversing sign at -183°C.

(4) At the peak, the excess absorption (over