AN EXPERIMENTAL CONFIRMATION OF MAGNETOPHONON RESONANCE IN n-TYPE InSb

R. V. PARFEN'EV, S. S. SHALYT, and V. M. MUZHDABA

Institute of Semiconductors, Academy of Sciences, U.S.S.R.

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Experimental data on the transverse and longitudinal magnetoresistance of n-InSb are presented and confirm the new type of oscillation of these galvanomagnetic effects first predicted by Gurevich and Firsov. The physical nature of the new phenomenon is related to the resonant character of the scattering of carriers by optical phonons in strong magnetic fields. Weak but noticeable oscillations of the predicted type were observed on the longitudinal magneto-resistance curve of InAs.

GUREVICH and Firsov [1] laid the theoretical groundwork for the phenomenon of the magnetophonon resonance, which manifests itself in a new type of oscillations of the magneto-resistance of a semiconductor. The direct cause of this effect is inelastic scattering of the carriers by optical phonons.

The choice of a conductor in which to observe the new physical phenomenon is determined by the requirement that the carrier mobility u be high at a temperature that ensures a sufficiently intense excitation of the optical branch of the crystal vibration spectrum. The larger the coupling between the carriers and the polarization optical vibrations of the crystal lattice, the more manifest will be the magnetophonon resonance in the magnetoresistance of such a conductor. The main experimental requirement is that the effective magnetic field be strong in the classical sense, $uH/c \gg 1$. If the foregoing requirements are satisfied, and if the resonance condition $\omega_0 = M\Omega$ is fulfilled (signifying that the limiting frequency of the optical phonons ω_0 is a multiple of the cyclotron frequency $\Omega = eH - m^*c$, which depends on the field H), then the plots of the transverse and longitudinal magnetic resistance of such a conductor vs. the field can exhibit nonmonotonic singularities in the form of convex or concave sections.

In our first communication [2] we presented some experimental data on the transverse magnetoresistance of n-InSb, confirming the existence of a new type of oscillation, and indicated that the first brief report of this new effect is due to Puri and Geballe [6]. In the present article we describe the results of a detailed experimental investigation of the transverse and longitudinal magnetoresistance of various samples of n-InSb, confirming in great detail the physical picture represented in the theoretical papers of Gurevich, Firsov, and Éfros [4].

EXPERIMENTAL RESULTS

The investigated samples of n-InSb, in the form of rectangular parallelepipeds measuring (2—3) × (2—3) × (10—20) mm, were cut from single-crystal ingots perpendicular to the growth direction. Such samples, as is well known, have a more uniform carrier distribution, a very important factor in the measurements of magnetoresistance of semiconductors [5]. The polished samples were etched for 10 seconds in a solution of $2HF + 1HNO_3 + 3H_2O$.

To reduce the geometrical effects that distort the magnetoresistance measurement results, the potential probes were soldered to the sample at a distance exceeding double the width of the sample away from the current probes, and the current probes covered the entire end-surface area of the sample. To reduce the monotonic part of the longitudinal magnetoresistance, which determines the relative magnitude of the oscillating part, it was necessary to locate with great care the potential zones along the current lines on the sample, and to pay close attention to its correct placement in the magnetic field. These experimental precautions greatly reduce the parasitic emf of the even plane Hall effect, which cannot be eliminated by reversing the field and is therefore superimposed on the monotonic part of the longitudinal magnetic resistance.

It must be borne in mind, however, that, owing to the resonant nature of the investigated phenomenon, these parasitic effects, which are imposed on the measured value of the magnetic resistance, can influence only the sensitivity of the method used to observe the oscillations, but cannot noticeably distort the results of interest to us, namely the period and the phase of the oscillations.

The measurements were made with a low-resistance potentiometer in fields up to ~38 kOe.

The table lists data on the concentrations and mobilities of the electrons in the investigated n-InSb samples at T = 90°K.

Sample No.	$10^{-13}n$, cm^{-3}	10^{-5} u, cm^2/V·sec	Sample No.	$10^{-13}n$, cm^{-3}	10^{-5} u, cm^2/V·sec
1	5.2	5.7	5	130	2.8
2	6.5	6.7	6	4.1	5.5
3	8.3	6.1	7	5.5	5.6
4	24	4.4			

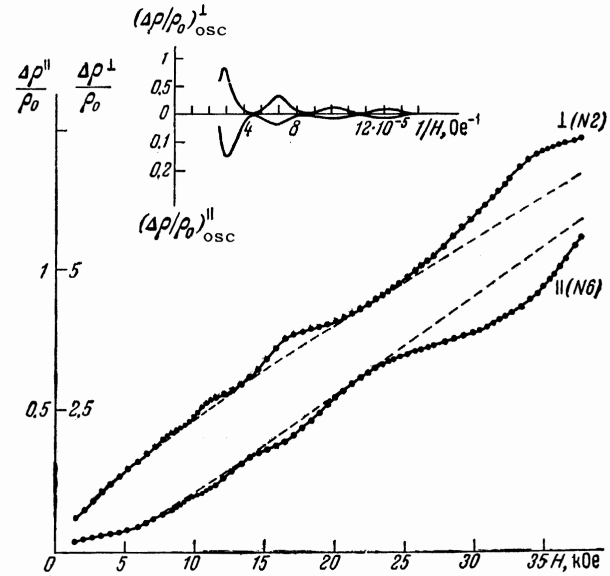

FIG. 1. Curves showing the transverse ($\Delta\rho_{\perp}/\rho_0$) and longitudinal ($\Delta\rho_{||}/\rho_0$) magnetoresistance, obtained in the investigation of samples of n-InSb (No. 2 and No. 6) at T = 90°K. The dashed lines represent the monotonic background, on which the resonant oscillations are superimposed. In the upper part of the figure is shown the oscillating part of the magnetoresistance as a function of the reciprocal field intensity.

The experimental results presented below for the transverse ($\Delta\rho_{\perp}/\rho_0$) and longitudinal ($\Delta\rho_{||}/\rho_0$) magnetoresistance of InSb confirm the following deductions of the Gurevich-Firsov theory.

A. The theory predicts that the oscillation extrema on the magnetoresistance curves should have, accurate to the dependence of the effective mass on the fields, a periodic dependence on the reciprocal field with a period

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

determined by the charge of the electron e, the effective mass m*, and the end-point frequency ω_0 of the longitudinal optical phonons interacting with the current carriers.

1. Transverse effect. If the resonance condition $\omega_0 = M\Omega$ is satisfied, a system of maxima should appear on the transverse magnetoresistance curve. The corresponding experimental ($\Delta\rho_{\perp}/\rho_0$) curves, shown in Figs. 1 and 2, confirm this conclusion: the system of five maxima at H_{max} = 34, 17, 113.3 ~ 8.5, and ~6.7 kOe discloses a periodicity with period $\Delta(1/H) = (3.0 \pm 0.2) \times 10^{-5}$ Oe^{-1}, in good agreement with the value $\Delta(1/H) = 2.9 \times 10^{-5}$ Oe^{-1} calculated from the theoretical formula (1). From the position of the first maximum on the strong-field side, which is clearly pronounced on the experimental curve, we can determine the value of m*, from the known published value [6] $\omega_0 = 3.7 \times 10^{13}$ sec^{-1}. The value $m^* = 0.016m_0$ obtained in this manner is in good agreement with the value of the cyclotron mass at H ≈ 34 kOe, determined by Palik et al. [7] The

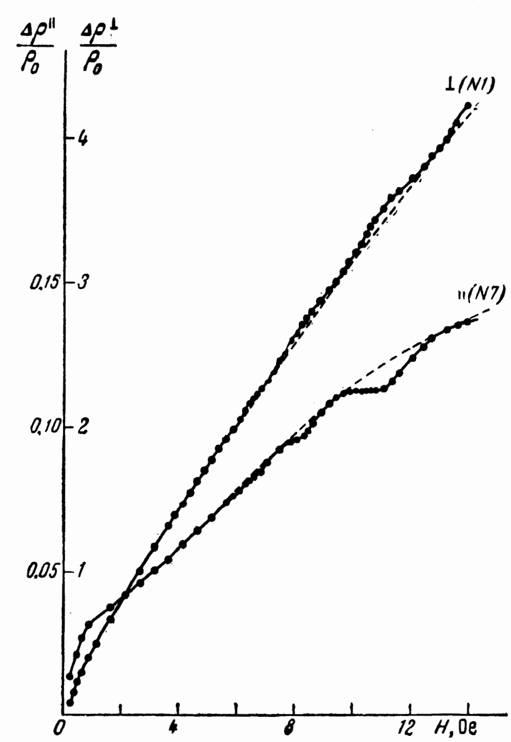

FIG. 2. Curves of transverse and longitudinal magnetoresistance, obtained in the investigation of samples n-InSb No. 1 and No. 7 at T = 90°K.

oscillating part of the transverse effect, shown in the upper part of Fig. 1, was determined from the difference between the experimental curve and the curve of monotonic background. This background is shown in Figs. 1 and 2 in the form of the envelopes of the minima of experimental curves. The basis for this was the theoretical deduction of Gurevich and Firsov that maxima can appear on the monotonic curve of the transverse effect when the resonant condition $\omega_0 = M\Omega$ is satisfied. Figure 2 shows the variation of the transverse magnetoresistance in relatively weak magnetic fields, from which we can deduce the additional maxima at H = 11.3, ~8.5, and ~6.7 kOe, which are difficult to distinguish on Fig. 1.

2. Longitudinal effect. According to the theory of galvanomagnetic phenomena in strong fields, the curves of the transverse and longitudinal magnetoresistance should be smooth if the carriers are scattered only by acoustic phonons. Gurevich and Firsov have shown that if the main contribution to the scattering process is made by optical phonons, oscillating peaks of additional resistance should appear on both monotonic curves if the resonance condition $\omega_0 = M\Omega$ is satisfied.

The situation is different when the participation of the optical phonons in the scattering of the carriers is not the main factor. We have demonstrated above that in this case a system of maxima appears on the curve of the transverse effect. According to Gurevich and Firsov, a system of minima having the same form periodicity in H^{-1} as in (1) can appear in this case on the longitudinal-effect curve.

The corresponding experimental curves for the longitudinal effect $\Delta\rho_{||}/\rho_0$ shown in Figs. 1 and 2 disclose a system of five minima with H_{min} = 32.5, 16.5, ~11.0, ~8.3, and ~6.7 kOe, with a periodicity of the form (1). Some discrepancy in the phases of the minima of the longitudinal effect, compared with the phases of the transverse effect, can be related to the dependence of the former on the relative contribution of the optical phonons during the scattering process. This question was not investigated in the theory. The physical picture of the mechanism of formation of maxima on the transverse-effect curve is simpler. Therefore, in the case of a non-quadratic dispersion law, when the effective mass depends on the field and the best approximation is to determine m* or ω_0 not from the period of the oscillations but from the position of the individual extrema on the magnetic-field scale, more reliable initial data for the determination of m* and ω_0 are gained from the maxima of the transverse effect.

The oscillating part of the longitudinal effect, shown in the upper part of Fig. 1, was determined by subtracting from the experimental curve the background, which varies monotonically with the field and which is represented by the dashed curve enveloping the maxima of the experimental curve.

B. From the general physical picture of the Gurevich-Firsov effect it follows that there should exist an optimal temperature at which the oscillating part of the magnetoresistance curves is maximal. The depth of modulation of these curves by the magneto-phonon resonance depends both on the degree of excitation of the optical branch of the crystal vibration spectrum and on the carrier mobility. Therefore the optimal temperature is the one at which there is a sufficiently high mobility in a sufficiently excited crystal. Experimental curves of the transverse effect, obtained for one sample of n-InSb at different temperatures, are shown in Fig. 3. We see that the depth of modulation is maximal at T = 104°K and decreases away from this temperature in both directions on the temperature scale.

To understand the curves of Fig. 3 it must be borne in mind that at T = 200°K the investigated sample goes into the intrinsic-conductivity region, and that in the interval 80—130°K the mobility

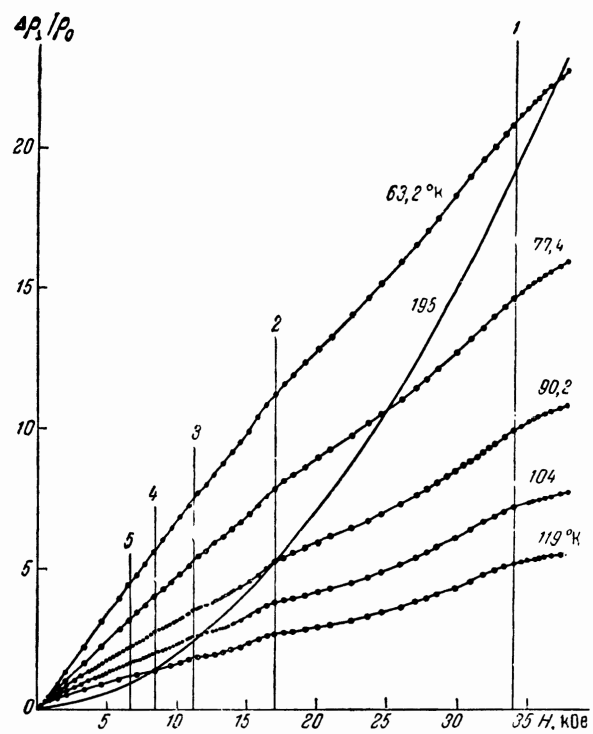

FIG. 3. Curves of transverse magnetoresistance, obtained in the investigation of sample No. 1 of n-InSb at different temperatures. The vertical lines with integer indices M = 1 – 5 indicate the magnetic field intensity values corresponding to the resonant condition $\omega = MeH/m^*c$.

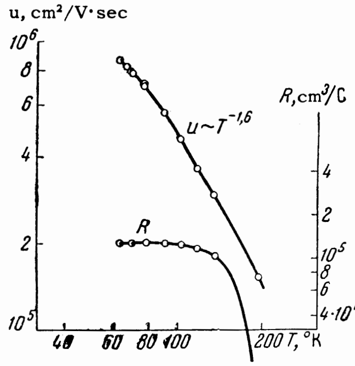

FIG. 4. Temperature dependence of the electron mobility and of the Hall coefficient for sample No. 1.

changes like $u \sim T^{-1.6}$ (Fig. 4). The decrease in the oscillating part of the magnetoresistance with increasing temperature can also be due to the increasing thermal scatter of the electrons in the Landau energy bands. The minimum relative depth of modulation of the curves of longitudinal and transverse effects is approximately the same and amounts to 15%.

C. From the theoretical formula (1) we see that the period of the Gurevich-Firsov oscillations should not depend on the carrier density. The series of experimental curves shown in Fig. 5, obtained for n-InSb samples with carrier densities ranging from 5.2×10^{13} to 1.3×10^{15} cm^{-3}, demonstrates the correctness of the theoretical deduction that the period and the phase of the modulation do not depend on the carrier density. The same figure shows also that this depth decreases with the mobility decrease that accompanies usually the increase in density. Therefore the oscillation effect is already quite indistinguishable in our n-InSb samples with density $n > 5 \times 10^{15}$ cm^{-3}.

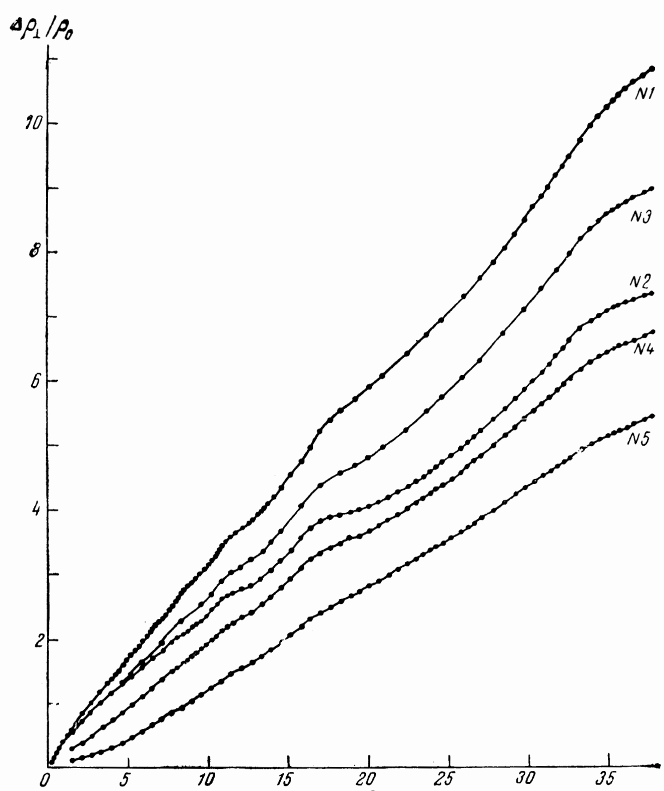

FIG. 5. Transverse magnetoresistance curves obtained at T = 90°K, for n-InSb samples with different carrier densities. The curves demonstrate the independence of the period and of the phase of the modulation of the concentration.

D. The curves of Figs. 3 and 5 show the characteristic differences between the new type of oscillations and the long-known Shubnikov-deHaas quantum oscillations. Whereas the period of the Gurevich-Firsov oscillations does not depend on the density and the amplitude attenuates with decreasing temperature even on the lower boundary of the nitrogen temperature interval, the period of the Shubnikov-deHaas oscillation

$$\Delta(1/H) = (2e/\hbar c)(3\pi^2 n)^{-2/3}$$

is determined only by the density, and the effect itself is observed only at very low temperatures, mostly in the helium range. Another important difference between these two types of magnetoresistance oscillations is that the Shubnikov-deHaas effect can be observed only in a degenerate electron gas. The Gurevich-Firsov effect, as shown by Éfros [4], can appear for any electron gas statistics. The n-InSb samples investigated in the present work were in a nondegenerate state.

In order to observe the new type of magnetoresistance oscillations in other semiconductors, we investigated the transverse and longitudinal magnetoresistance of a polycrystalline sample of indium arsenide at T = 90°K with an electron density $n = 1.25 \times 10^{16}$ cm^{-3} and a mobility $u = 6.4 \times 10^4$ cm^2/V-sec. The curve of the transverse effect remains smooth over the entire field interval from 1 to 34 kOe. The curve of the longitudinal effect, for which $(\Delta\rho_{||}/\rho_0)$ did not exceed 20% in a field $H \approx 34$ kOe, had two concave sections with minima (with depth 1% of the smooth background) at $H_{min} \approx 33$ kOe and $H_{min} \approx 22$ kOe. To determine the numbers of these minima we can use the magnetophonon resonance condition $\omega_0 = M\Omega$, from which it follows that $M = \omega_0 m^* c/eH_{min}$. Assuming for InAs that $\omega_0 = 4.6 \times 10^{13}$ sec^{-1} [6] and $m^* = 0.25\ m_0$ (at $H \approx 35$ kOe) [7] we obtain 1.98 for H = 33 kOe, which corresponds to M = 2. The minimum at $H \approx 22$ kOe corresponds to M = 3. The first minimum on the strong-field side should be observed at a field $H \approx 68$ kOe, which cannot be attained with our electromagnet.

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