QUANTUM OSCILLATIONS OF THE PHOTOELECTRIC COEFFICIENTS OF *n*-TYPE InSb IN A STRONG MAGNETIC FIELD

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Submitted June 22, 1967

Zh. Eksp. Teor. Fiz. 53, 1571–1581 (November, 1967)

Quantum oscillations arising out of the discrete structure of the electron energy spectrum in a high magnetic field were detected in an investigation of the photomagnetic effect and photoconductivity in n-type InSb at helium temperature. Two types of oscillations are observed, depending on the electron concentration. One of these is the Shubnikov–de Haas type, where the period is governed by the electron concentration. The second type, which appears only in weakly doped samples, exhibits a period corresponding to Gurevich–Firsov magnetophonon resonance. In theoretical interpretations of the oscillations it must be remembered that electrons excited by light are hot electrons whose excess energy can be transferred to the lattice through the excitation of optical phonons. The effects of electric fields and temperature on the oscillation amplitude are investigated.

WE know that the electron energy spectrum acquires a discrete Landau level structure in a magnetic field. In a sufficiently strong field H ($uH/c \gg 1$, where u is the electron mobility) the quantum structure of the Landau spectrum is manifested in the oscillatory field dependence of several kinetic and thermodynamic coefficients that describe the electronic properties of semiconductors. The corresponding oscillatory curves are characterized by periodic arrangements of their extrema along the abscissal axis representing the reciprocal magnetic field (when spin splitting of the Landau levels is not observed experimentally).

Two types of oscillations in transfer processes are being studied at the present time. In connection with one type, when the electron gas is degenerate (with a chemical potential $\zeta \gg kT$) and the experimental temperature is very low ($kT \ll \hbar\Omega$) oscillations result from shifts of the Landau levels, represented by

$$\varepsilon_{N^\pm} = \hbar\Omega(N + 1/2) \pm 1/2|g|\mu_B H \quad (1)$$

relative to the Fermi level as the magnetic field is varied. Here $\Omega = eH/m^*c$ is the cyclotron frequency; N = 0, 1, 2, 3, ... enumerate the Landau levels; g is the spectroscopic splitting factor; m* is the effective electron mass; μ_B is the Bohr magneton. The oscillations of the kinetic coefficients that arise in this way are designated as the Shubnikov–de Haas (SH) effect. In the simplest case of a spherical equal-energy surface, with which the present study is concerned, the SH oscillation period depends only on the electron concentration n:

$$\Delta(1/H) = 3.18\cdot 10^6 n^{-2/3}\,\mathrm{Oe}^{-1}, \quad (2)$$

and the extrema are located according to the formula

$$1/H_N = 3.18\cdot 10^6 A_N n^{-2/3}\,\mathrm{Oe}^{-1}, \quad (3)$$

where A_N equals 1.31, 2.36, 3.38, 4.40, 5.41, ... etc. for N = 1, 2, 3, 4, 5, ..., respectively.[1]

Landau-level spin splitting results[2] in a doublet structure of the extrema and in the appearance of an additional extremum (0^+), at positions given by the following formulas (allowing for incomplete degeneracy):

$$\frac{1}{H_{N^-}} = \frac{e}{\hbar c}\left(\frac{1}{2\pi^4}\right)^{1/3} n^{-2/3}\left\{\sum_{i=1}^{N}[i^{1/2} + (i-\beta)^{1/2}] + 0.53\sqrt{\frac{kT}{\hbar\Omega_{N^-}}}\right\}^{2/3},$$

$$\frac{1}{H_{N^+}} = \frac{e}{\hbar c}\left(\frac{1}{2\pi^4}\right)^{1/3} n^{-2/3}\left\{\sum_{i=0}^{N}[i^{1/2} + (i+\beta)^{1/2}] + 0.53\sqrt{\frac{kT}{\hbar\Omega_{N^+}}}\right\}^{2/3}, \quad (4)$$

where $\beta = |g|m^*/2m_0$. The extremum associated with the intersection of the Fermi level and the Landau level $\varepsilon_0^- = 1/2\hbar\Omega - 1/2|g|\mu_B H$ does not appear in the oscillatory effects because of weak degeneracy in this instance.

The easily achieved modification of the electron concentration n in semiconductors permits shifts of SH oscillation curve extrema along the abscissal axis representing the magnetic field. In an easily achievable magnetic field it also becomes possible to enter the region of the quantum limit ($\hbar\Omega > \zeta$), where the experimental field dependence of the kinetic coefficients is usually represented by smooth curves.[1]

The second type of oscillations exhibited by the kinetic coefficients was predicted by Gurevich and Firsov (GF) and results from the resonant character of inelastic electron scattering on optical lattice vibrations in a strong magnetic field ($u/Hc \gg 1$). In this case the period of the oscillations and the locations of the extrema do not depend on the concentration of the electrons but on their effective mass m* and on the frequency ω_0 of longitudinal optical phonons:

$$\Delta(1/H) = e(m^*\omega_0 c)^{-1}\,\mathrm{Oe}^{-1}, \quad (5)$$

$$1/H_M = Me(m^*\omega_0 c)^{-1}\,\mathrm{Oe}^{-1}, \quad M = 1, 2, 3, \ldots \quad (6)$$

The possibility of observing the second type of oscillations is not subject to the condition of strong degeneracy but requires an optimum experimental temperature permitting sufficiently intense excitation of optical crystal vibrations in a strong effective magnetic field.[3] Consequently, the SH and GF oscillations of the kinetic coefficients are usually observed in different temperature ranges. Thus, in detailed studies of the n-type semiconductors InSb and InAs the first type of oscillations is observed in galvanomagnetic and thermomagnetic effects when $T \leq 20°K$, while the second type is observed when $T \geq 60°K$.[1,3] It should be noted that in these instances the effects are induced by thermalized electrons characterized by the lattice temperature.

It is shown in the present work that both types of oscillations can appear simultaneously in n-type InSb in connection with the Kikoin-Noskov photomagnetic effect, and also photoconduction, when the photoexcited carriers are hot but the experimental temperature does not exceed 20°K. Kikoin and Lazarev[4] were the first to observe photomagnetic-effect oscillations in n-type InSb at helium temperature. In our laboratory, the SH type of oscillations of the photomagnetic effect have recently been observed in Te and in n-type InAs, HgSe, and GaSb.

EXPERIMENT

The photomagnetic effect, photoconduction, and galvanomagnetic effects were investigated in single-crystal parallelepipeds of n-type InSb. Samples were ground and then polished in SR-rA etchant. The potential probes were placed on unilluminated surfaces of the samples. The accompanying table gives the principal characteristics of our samples.

Principal Characteristics of Investigated n-Type InSb Single Crystals

Number of sample	$T = 4.2°$ K: n, cm^{-3}	$T = 4.2°$ K: u, cm^2/V-sec	Dimensions of sample, mm^3
1	$2.2 \cdot 10^{14}$	$1.1 \cdot 10^5$	1.9×2.8×36
2	$8.1 \cdot 10^{14}$	$5.8 \cdot 10^4$	1.9×4.0×26
3	$1.36 \cdot 10^{15}$	$1.2 \cdot 10^5$	2.1×2.7×15
4	$2.7 \cdot 10^{15}$	$5.5 \cdot 10^4$	0.9×4.0×25
5	$8 \cdot 10^{15}$	$1 \cdot 10^5$	1.2×2.6×20
6	$3.5 \cdot 10^{16}$	$8.5 \cdot 10^4$	1.3×3.0×40
7	$1.1 \cdot 10^{17}$	$6 \cdot 10^4$	1.7×3.3×28
8	$8 \cdot 10^{15}$	$1 \cdot 10^5$	0.18×2.0×7
9	$3.9 \cdot 10^{15}$	$1.3 \cdot 10^5$	0.19×2.2×7

Measurements of the photomagnetic effect and photoconductivity were obtained under both constant and modulated (at 400 and 600 cps) white light that traversed two to four walls of glass dewars; the wavelengths impinging on the samples were in the range $0.5-2.8\,\mu$. The samples were in direct contact with a heat bath of liquid helium, hydrogen, or nitrogen. The measured signals were amplified by an F-116/1 photoelectric galvanometer, and the magnetic-field dependence of the signals was registered with a two-coordinate recorder. For the experiment with modulated light we used an U2-6 narrow-band amplifier and a phase detector.

EXPERIMENTAL RESULTS

The curves in Fig. 1 show the experimental dependence of voltage induced by the odd photomagnetic effect (V_{PM}^{odd}) on the magnetic field strength at 4.2°K for samples of n-type InSb having different electron concentrations ($n = 2.2 \times 10^{14} - 1.1 \times 10^{17}/cm^3$) when subjected to identical light intensity.1) These experimental curves

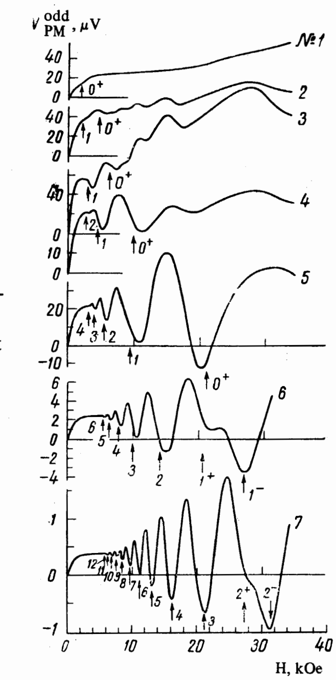

FIG. 1. Experimental curves representing magnetic-field dependence of odd photomagnetic effect for n-type InSb single crystals having different carrier concentrations at 4.2°K.

exhibit the following characteristics.

1. V_{PM}^{odd} has an oscillatory dependence on the magnetic field; two types of oscillations appear, depending on the electron concentration. The location and period of one of these types depends only on the electron concentration as in Eq. (2), like Shubnikov–de Haas oscillations. For $n \geq 8 \times 10^{15}/cm^3$ (samples Nos. 5–7 in Fig. 1) this type occupies the entire investigated magnetic field region. [The arrows in Fig. 1 show the locations of the extrema for Shubnikov–de Haas oscillations calculated from (3) and (4) using $m^* = 0.013\, m_0$[5] and $|g| = 50$.[6]] For samples with $n < 8 \times 10^{15}/cm^3$ (Nos. 1–4) the SH oscillations are shifted towards weak magnetic fields and an additional group of oscillations is observed in the region of the quantum limit. This latter group exhibits almost no observable shift and fails completely to obey Eq. (3). However, when the concentration is reduced to $2 \times 10^{14}/cm^3$ (sample No. 1) the amplitude of this type decreases rapidly and the curve representing $V_{PM}^{odd}(H)$ becomes almost smooth.

2. The initial segment of the curve for $V_{PM}^{odd}(H)$ is smooth and exhibits saturation that is characteristic for a classically strong field ($uH/c \gg 1$). The maximum in the saturation region is reached at $n \approx 10^{15}/cm^3$; decreases occur with both increasing and decreasing concentrations.

3. The SH oscillations in the photomagnetic effect have such large amplitudes that the sign of the effect is reversed near magnetic field strengths corresponding to crossing of the Fermi level by Landau quantum levels. This characteristic indicates that the "giant" oscillations of the photomagnetic effect do not result simply from resistivity oscillations of the sample in a magnetic field. Evidence for this conclusion is found in results obtained (but not presented in the present work) by investigating the short-circuit photomagnetic current I_{SC}, whose magnetic field dependence $I_{SC}(H)$ has the same form as the $V_{PM}(H)$ curves including the reversal of sign.

1)The experimental work was performed using weak illumination of the samples.

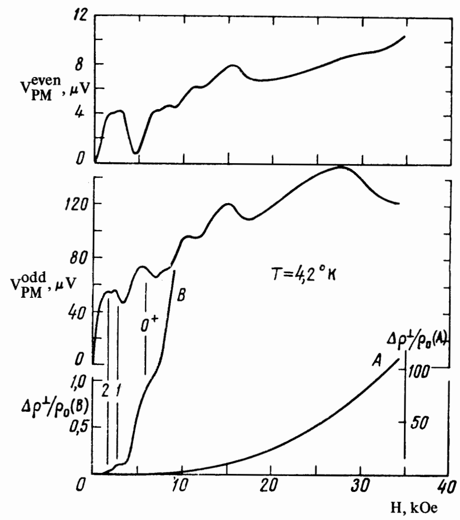

FIG. 2. Experimental curves of the even and odd photomagnetic effects and transverse magnetoresistance (A and B) for sample No. 3 at 4.2°K. Curve B is a greatly enlarged portion of curve A. As in Figs. 4, 5, and 8, the vertical straight lines indicate field strengths corresponding to Eqs. (3) and (4). Here $m^* = 0.013\ m_0$ and $|g| = 50$.

4. Spin splitting of the Landau levels appears in SH oscillations of the photomagnetic effect at maximum values of the magnetic field.

The character of the observed quantum oscillations of the photomagnetic effect was determined by comparing the curves representing $V_{PM}(H)$ with well-studied SH oscillations of magnetoresistance. In Fig. 2 transverse magnetoresistance curves are compared with both odd and even photomagnetic effects in sample No. 3 at 4.2°K. We here observe that in fields $H < 7$ kOe, where the conditions $uH/c \gg 1$ and $\hbar\Omega/kT \gg 1$ are fulfilled, SH oscillations appear in magnetoresistance and also in both odd and even V_{PM}.

In the region of the quantum limit, $\hbar\Omega > \zeta$ ($H > 7$ kOe for sample No. 3), where the magnetoresistance curve (A) is smooth, the curves for V_{PM}^{odd} and V_{PM}^{even} both reveal an additional series of oscillations, which are periodic in the reciprocal field, as is illustrated in Fig. 3 for the case of the odd photomagnetic effect. The period of this group of oscillations is $\Delta(1/H) = 3 \times 10^{-5}$/Oe, which is a characteristic period for the Gurevich–Firsov magnetophonon oscillations of the kinetic coefficients that have previously been observed in n-type InSb only at higher temperatures $T \geq 60°K$.[3] Equation (5) for the period of Gurevich–Firsov oscillations enables us to determine the effective mass of carriers participating in the effect when the frequency ω_0 is known. Assuming $\omega_0 = 3.7 \times 10^{13}$/sec, we obtain $m^* = 0.016\ (\pm 0.001) m_0$. Figure 3 shows that the resonant fields in Gurevich–Firsov oscillations that are determined from (6) correspond to minima of the oscillatory curve $V_{PM}^{odd}(H)$ and also of the curve $V_{PM}^{even}(H)$ (see Fig. 2).

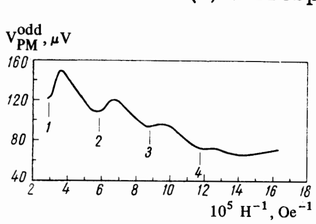

FIG. 3. The portion of the oscillatory curve of V_{PM}^{odd} in Fig. 2 where Gurevich–Firsov oscillations are observed. The vertical bars (M = 1,2,3,4) denote magnetic field resonances calculated from Eq. (6) with $\omega_0 = 3.7 \times 10^{13}$/sec and $m^* = 0.016\ m_0$.

In Fig. 3 the amplitude of Gurevich–Firsov photomagnetic oscillations is seen to reach 20–30% of the background at helium temperatures. With rising temperature up to 20°K this amplitude drops sharply. In samples with $n > 10^{15}/cm^3$ at 77°K the photomagnetic effect signal did not lie within the limits of experimental accuracy. It has been shown previously that in n-type InSb samples with $n \approx 10^{14}/cm^3$ at nitrogen temperatures magnetophonon oscillations of the kinetic coefficients are observed very clearly. Under these conditions the amplitude of V_{PM} oscillations does not exceed 2–3% of the background; they are in phase with the oscillations of magnetoresistance and can be attributed entirely to the latter.

Figure 1 shows that at 4.2°K the most pronounced Gurevich–Firsov oscillations of the photomagnetic effect are observed in samples having $n \approx 10^{15}/cm^3$. With increase of the electron concentration the largest-amplitude SH oscillations of the photomagnetic effect are shifted to the strong magnetic field region and form a background against which the Gurevich–Firsov oscillations are not observed.

Quantum oscillations of the SH type have also been observed in connection with photoconductivity; here the Gurevich–Firsov oscillations have been relatively weak. Figure 4 shows the quantum oscillations of several kinetic coefficients for sample No. 8 of n-type InSb at 1.6°K. The photoconductivity was measured for modulated light, with the current direction parallel to the magnetic field in order to reduce the photomagnetic emf at the potential contacts. The direct current passing through the sample was reversed for the purpose of discriminating V_{PC} from the photomagnetic effects. Figure 4 shows that the SH oscillations of photoconductivity are in phase with the oscillations of longitudinal magnetoresistance ($\Delta\rho''/\rho_0$). We must here note the trivial result that in the photoconductivity oscillations with $J \parallel H$ the zeroth maximum (0^+) is not observed clearly. This peculiarity had previously been observed in oscillations of the longitudinal magnetoresistance and had been explained theoretically in [7].

In Figs. 4 and 5 the investigated photomagnetic ef-

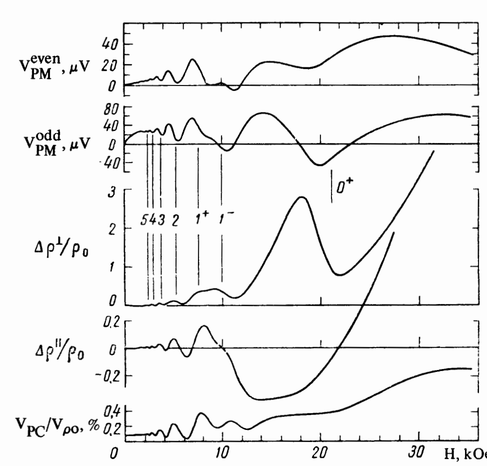

FIG. 4. Experimental oscillation curves for different kinetic coefficients versus magnetic field for sample No. 8 at 1.6 K.

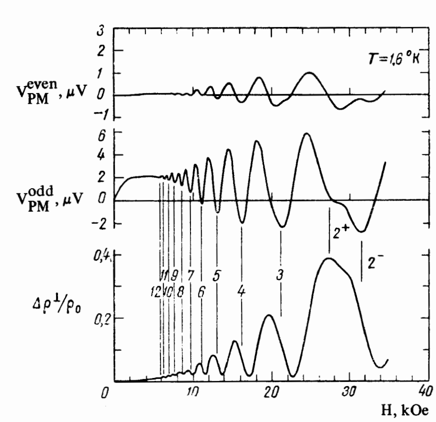

FIG. 5. Experimental oscillatory curves for the even and odd photomagnetic effects and transverse magnetoresistance vs. magnetic field for sample No. 7 at 1.6°K.

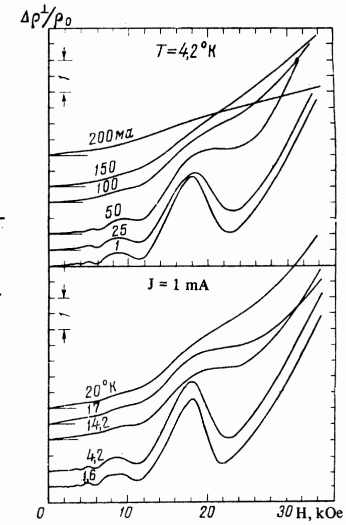

FIG. 7. Influence of a high electric field and of temperature on oscillations of transverse Magnetoresistance in sample No. 8. The effective electric field is the same as in Fig. 6.

fects are compared with magnetoresistance oscillations for samples of n-type InSb with $n = 8 \times 10^{15}/cm^3$ and $1.1 \times 10^{17}/cm^3$, when SH oscillations corresponding to the first Landau levels are shifted into the highest magnetic field region. Figures 4 and 5 show that the periods of photomagnetic and magnetoresistance oscillations coincide, and that maxima of the transverse magnetoresistance and minima of odd and even photomagnetic effects are located close to magnetic field strengths (4) corresponding to crossing of the Fermi level by Landau quantum levels $N^{\pm}$. The spin splitting of the first Landau levels, which had been discovered previously in a study of magnetoresistance in n-type InSb, was exhibited more clearly in photomagnetic oscillations, especially in the even effect.

It was noted in [1] that the spin splitting of the first maximum of transverse magnetoresistance (from the ratio H_1^-/H_1^+) yields the value $|g| \approx 35$ (for $m^* = 0.013\ m_0$). It follows from Figs. 1, 4, and 5 that the spin splitting of the minima $N = 1^+$, 1^-, 2^+, and 2^- of the photomagnetic curves indicate a value close to $|g| = 50$, which has been determined by means of paramagnetic resonance in InSb.[6] Thus the investigation of photomagnetic effects represents a more sensitive method for studying the fine structure of quantum oscillations than the study of the other kinetic coefficients.

It was of interest to investigate the influence of different factors on the quantum oscillations of photoelectric coefficients. For this purpose we measured photomagnetic effects in samples of different thicknesses down to 15 μ having an electron concentration $n \sim 3 \times 10^{15}/cm^3$; in this case both types of oscillations are manifested on the $V_{PM}(H)$ curves, without being affected by the given reduction of sample thickness.

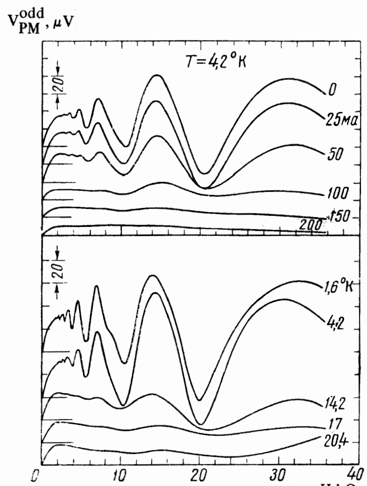

FIG. 6. Influence of a high electric field and of temperature on oscillations of the odd photomagnetic effect in sample No. 8 E ≈ 1.5 J (mV/cm) at H = O; J is the current in milliamperes.

We also investigated the influence of an electric field on oscillations of the photomagnetic effect in n-type InSb. An electric field E was generated in a sample by transmitting a direct current parallel to the magnetic field. Modulated light was used for the purpose of discriminating the photomagnetic effect. At the same time we investigated the influence of a high electric field on SH oscillations of the transverse ($\mathbf{H} \perp \mathbf{J}$) and longitudinal ($\mathbf{H} \parallel \mathbf{J}$) magnetoresistance as well as the Hall effect. Figures 6 and 7 show curves of the odd photomagnetic effect and transverse magnetoresistance $\Delta\rho^{\perp}/\rho_0$ plotted for different electric currents and temperatures. We here observe that an increase of the electric current, and consequently of the electric field, produces the same effect as a temperature rise. In the photomagnetic effect and magnetoresistance the amplitude of the oscillations decreases and the extrema are shifted into a higher magnetic field region.

We discovered a similar effect produced by high electric fields in our investigation of longitudinal magnetoresistance and the Hall effect. By comparing the amplitudes and shifts for the extrema of the oscillatory photomagnetic effect and transverse magnetoresistance at different values of E and T, we were enabled to determine the effective temperature of the electron gas as had been done for transverse magnetoresistance in [8]. Figure 6 shows that both a high electric field and a temperature rise can reduce the amplitude of photomagnetic effect oscillations and also the V_{PM}^{odd} signal.

Figure 8 shows the influence of electric fields on the quantum oscillations of the photomagnetic effect for a sample that exhibited both SH and GF oscillations simultaneously. This series of $V_{PM}^{odd}(H)$ curves shows that a high electric field influences the amplitude of GF oscillations less strongly than it influences the SH oscillations.

Oscillations of the photomagnetic effect were not observed when a sample of p-type InSb with the concen-

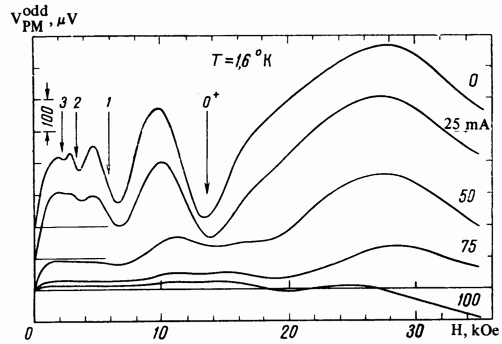

FIG. 8. Influence of a high electric field on oscillations of the odd photomagnetic effect in sample No. 9 at 1.6°K. E ≈ 2.8 J (mV/cm) at H = 0.

tration $p_{4.2°K} = 4 \times 10^{13}/cm^3$ was studied in the temrange 1.5° –80°K.

CONCLUSION

The oscillatory magnetic-field dependence of the photoelectric coefficients under our experimental conditions could have been anticipated, because the magnitudes of these coefficients depend on the electrical conductivity of the crystal, and for n-type InSb an oscillatory field dependence of the electrical conductivity at helium temperature had been established a long time previously. However, the "giant" amplitude of SH photomagnetic oscillations, even accompanied by a sign reversal of the signal in a high field, and the oscillatory curves for a short-circuit current indicate that oscillations of the photomagnetic coefficients do not result simply from oscillations of magnetoresistance. For the technique of investigating the Landau level fine structure and determining the g factor, it was important that the modulation of the photomagnetic effect was more pronounced than for the other kinetic coefficients (under identical experimental conditions).

It was not a trivial circumstance that under our experimental conditions the decisive role in the photomagnetic effect is played in the case of n-type InSb by electrons which are the majority carriers, rather than by holes as in the conventional theory of the photomagnetic effect, which does not take into account the effective electron temperature. This circumstance was manifested as follows:

1) The curves representing $V_{PM}^{odd}(H)$ enter the saturation region at values of the effective field (uH/c) that are consistent with electron mobility but not with hole mobility.

2) The condition for the strong degeneracy required to permit observation of SH oscillations is fulfilled in n-type InSb only for the majority carriers (electrons).

3) The period of SH oscillations in the photomagnetic effect corresponds to the electron concentration.

We can now account for the absence of photomagnetic oscillations in p-type InSb. In a theoretical study (private communication) by R. I. Lyagushchenko and I. K. Yassievich, the governing role of the majority carriers (electrons) in the photomagnetic effect induced by "hot" electrons is explained as follows: If the momentum relaxation time of the electrons is energy dependent, then the opposing photomagnetic currents of hot and cold electrons flowing in the magnetic field are not mutually compensating as in the case of completely thermalized electrons having the lattice temperature. We can hope that these authors will be able to extend their theory to the region of quantum oscillations in the photomagnetic effect and to account for all experimental characteristics observed in the present work. In his theoretical study of the oscillatory photomagnetic effect Sobakin[9] disregarded the fact that the light-excited electrons are hot.

A completely unexpected result of the present work was the appearance of magnetophonon oscillations at helium temperatures, when the optical branch of crystal vibrations is not excited in the normal (thermal) manner. It is entirely clear that the appearance of these oscillations at helium temperatures is associated with the fact that the light-excited electrons are hot (while the holes, with their much greater mass, are cold) and these electrons can become thermalized by emitting optical phonons. Each hot electron can thus emit several tens of optical phonons. Supporting evidence is found in experiments that revealed the oscillatory dependence of photoconduction on the wavelength of exciting light at $T < 10°K$.[10] However, if this mechanism of optical phonon excitation were sufficient for the production of magnetophonon oscillations, the latter would also be observed in samples of n-type InSb with low electron concentrations.[2)] However, the GF oscillations were observed to vanish when the concentration was reduced to $10^{14}/cm^3$, although at higher temperatures, when optical vibrations are excited, magnetophonon oscillations of kinetic effects in these samples of n-type InSb are stronger than in more heavily doped samples. Therefore we still do not understand even qualitatively how we should treat the mechanism that induces magnetophonon oscillations of the photomagnetic effect in n-type InSb when optical phonons are excited in a very thin layer of a light-absorbing sample. Any theory that can claim to describe this type of oscillations at helium temperatures must account for the sharp drop in amplitude both when the concentration of majority carriers is reduced to $10^{14}/cm^3$ and when the temperature is raised from 4° to 20°K.

We are indebted to Yu. A. Firsov and A. R. Aronov for discussions of theoretical questions, to I. N. Yassievich for communicating results before publication, and to M. S. Bresler, V. A. Noskin, and A. V. Matveenko for experimental assistance.

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Translated by I. Emin
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