QUANTUM OSCILLATIONS OF PHOTOMAGNETIC EFFECTS AND PHOTOCONDUCTIVITY IN InSb *AND* InAS

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An investigation was made of quantum oscillations of the photomagnetic effects in degenerate n-type samples of InSb and InAs semiconductors in magnetic fields up to 50 kOe at temperatures 1.8—4.2°K. In the range of magnetic fields in which the photomagnetic emf changed its sign (the anomalous region) the photomagnetic effects exhibited a strong nonlinear dependence on the intensity of weak incident illumination ($\Delta n \ll n$). When the illumination intensity was increased the photomagnetic emf passed through a maximum and then changed its sign. The photoconductivity in a magnetic field was investigated in the same samples. It was found that the photoconductivity was negative in a transverse magnetic field. The role of hot electrons had to be taken into account in a theoretical interpretation of the investigated anomalies.

THE results of investigations of quantum oscillations of the odd and even photomagnetic emf's are reported in[1-5]. The most important feature of the oscillations is a change of sign of the photomagnetic emf (Fig. 1) in a certain range of magnetic fields. Attempts to explain this change of sign within the framework of the available theory of the photomagnetic effects[6] have not been successful. Abakumov, Lyagushchenko, and Yassievich[7] have developed a theory of the photomagnetic effects in which the heating of electrons by illumination plays an important role. Estimates of the energy relaxation time of electrons interacting with other electrons, τ_{ee}, show that in semiconductors such as n-type InSb and n-type InAs this relaxation time is much shorter than the time τ_{ac} governed by the interaction of electrons with acoustical phonons. Moreover, the relaxation time τ_{ee} is much shorter than the lifetime τ_n. Consequently, the interaction between electrons themselves is so strong that a considerable fraction of the energy of photoelectrons is distributed between all conduction electrons and we may assume that the Fermi distribution of electrons corresponds to an electron temperature $T_e(x)$ which is not equal to the equilibrium temperature T_0.

Illumination of a semiconductor establishes not only a carrier concentration gradient but also a temperature gradient. The presence of an electron temperature gradient gives rise to the Nernst effect in an illuminated sample placed in a magnetic field. Thus, the measured emf is the sum of the Nernst emf, due to this temperature gradient, and a photomagnetic emf, due to the carrier concentration gradient. According to Abakumov, Lyagushchenko, and Yassievich,[7] the observed change in the sign of the photomagnetic effect is due to a change of the sign of the Nernst emf in the relevant range of magnetic fields. A comparative experimental investigation of the photomagnetic effect and of the ordinary Nernst effect, carried out on the same sample, was reported in[8]. The dependences of the two effects on the magnetic field were similar, which confirmed qualitatively the theoretical conclusion given in[7]. However relationships representing the behavior of the photomagnetic effects in the quantum region require further theoretical and experimental investigations.

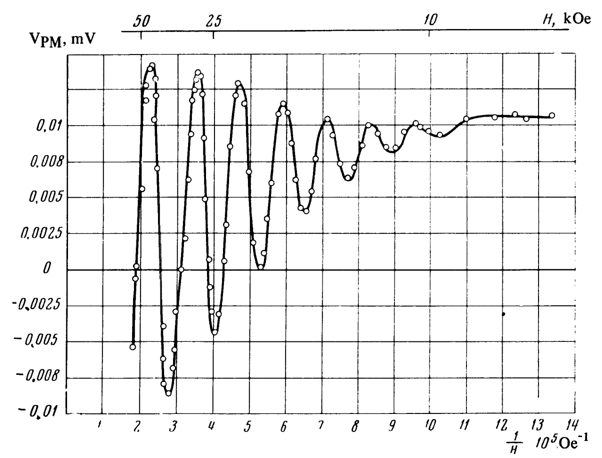

FIG. 1. Dependence of the odd photomagnetic effect (V_{PM}) on the reciprocal of the magnetic field for a sample of n-type InAs ($n = 9.2 \times 10^{16}$ cm^{-3}).

The present paper reports an investigation of the photomagnetic effect in the range of magnetic fields where it has the anomalous sign. We studied the dependence of the photomagnetic emf on the illumination intensity and we investigated the photoconductivity of the same samples in a magnetic field.

EXPERIMENTAL METHOD

Experiments were carried out on single-crystal samples of n-type InSb and n-type InAs with carrier concentrations $n = 10^{15}-10^{17}$ cm^{-3}. These samples were ground and etched in standard solutions. A metal cryostat with fluorite windows was employed. Samples were placed directly in liquid helium. Measurements were carried out during illumination of a sample with light of constant intensity as well as with light modulated at a frequency of 700 Hz. An incandescent lamp or a helium-neon laser was used as the source of light. The illumination intensity was measured with a thermopile and was varied by means of special stops and grid filters. In the modulated illumination case the measurements were carried out using a resonance amplifier and a phase-sensitive detector. Under constant illumination conditions the photomagnetic emf, amplified by means of an F-116 photoamplifier, was plotted by an X-Y automatic recorder. The second coordinate was a Hall-probe signal which was proportional to the magnetic field. In some experiments the photomagnetic emf was determined by the standard compensation circuit.

Measurements of the photoconductivity had to be more accurate because the amplitude of the photoconductivity was only 0.1% of the dark conductivity. The conductivity was deduced from the voltage across a sample when a constant electric current of a few milliamperes was passed through the sample. The constancy of this current was checked by measuring the voltage drop across a standard resistor connected in series with the investigated sample. The voltage across this resistor was determined by a potentiometer circuit to the fifth significant figure. Since the photomagnetic emf exceeded considerably the ohmic voltage drop across a sample (the photoconductivity voltage of an illuminated sample), we had to suppress this emf. This could be done either by commutation of the current in the sample or by simultaneous illumination of the sample from two opposite sides. We used both these methods to eliminate the photomagnetic emf. Measurements were carried out in magnetic fields up to 27 kOe at temperatures 1.8–4.2°K. The illumination intensity was varied within the range 10^{15}–10^{18} quanta-cm^{-2} sec^{-1}.

RESULTS OF MEASUREMENTS

1. Dependence of the Photomagnetic EMF on Illumination Intensity

Figure 2 shows the dependence of the photomagnetic emf on the illumination intensity. Curve 1 corresponds to a magnetic field in which the photomagnetic emf has its normal sign. This curve is nearly linear. Curves 2–4 correspond to values of the magnetic field in which the photomagnetic emf has the anomalous sign [points 2–4 on the V_{PM} = f(H) dependence shown in the top right-hand corner of Fig. 2]. It is evident from Fig. 2 that the photomagnetic emf in the anomalous region increases with increasing illumination intensity only at relatively low intensities. At higher intensities the photomagnetic emf reaches a maximum, passes through zero and changes its sign. Comparison of curves 2–4 shows that the magnetic field affects strongly the value of the illumination intensity at which the photomagnetic emf changes its sign.

Figure 3 shows the dependences of the photomagnetic emf on the magnetic field for various intensities of illumination incident on a sample of n-type InSb with a carrier concentration n = 5.5×10^{15} cm^{-3}. It can be seen that, at sufficiently high illumination intensities, the photomagnetic emf has the normal sign at all values of the magnetic field up to 27 kOe. Similar curves are obtained also for the even photomagnetic effect in the same samples. The dependences of the photomagnetic emf on the magnetic field are of the same nature for illumination with white light from an incandescent lamp as well as for illumination with monochromatic light of a helium-neon laser (λ = 0.63 μ).

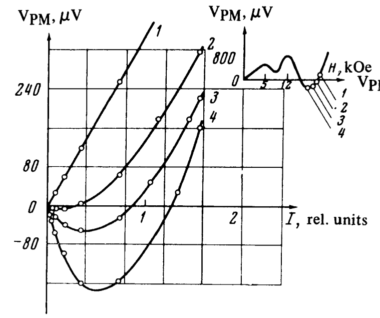

FIG. 2

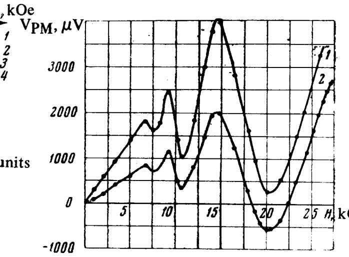

FIG. 3

FIG. 2. Dependence of the odd photomagnetic effect (V_{PM}) on the intensity of illumination of a sample of n-type InSb (n = 5.5×10^{15}cm^{-3}). Curves 1-4 correspond to different values of the magnetic field [points 1-4 on the V_{PM} = f(H) curve].

FIG. 3. Dependence of the odd photomagnetic effect (V_{PM}) on the magnetic field for various intensities of illumination of a sample of n-type InSb (n = 5.5×10^{15} cm^{-3}). Curve 1 correspond to a higher intensity.

We also illuminated a sample with pulsating light. The light was passed through a rotating disk with apertures. The pulsating photomagnetic emf was amplified and recorded using a two-beam oscillograph. One beam was used for the photomagnetic emf and the other represented a signal of a vacuum photocell illuminated with the same pulsating light. Figure 4 shows an oscillogram of the photomagnetic emf (in a magnetic field in which this emf has the anomalous sign) and of the signal generated by the vacuum photocell (proportional to the intensity of incident light). Oscillograms A, B, and C show the time dependences of the photomagnetic emf and the oscillograms a, b, c show the time dependences of the incident light. The sequence A, B, C corresponds to increasing intensity of illumination. It is evident from these oscillograms that at low illumination intensities (oscillogram A), the photomagnetic emf varies monotonically with the illumination intensity. The oscillogram B shows that the emf passes through a maximum and decreases to zero and the oscillogram C demonstrates a change in the sign of the photomagnetic emf caused by an increase in the illumination intensity.

2. Influence of Surface Recombination Rate

It is known that the photomagnetic emf usually decreases when the recombination rate of the illuminated surface is increased. We investigated this effect by repeating our experiments on samples whose illuminated surfaces were ground. Figure 5 shows the dependences of the photomagnetic emf on the magnetic field for the same sample of n-type InAs. Curve 1 represents a sample with an etched surface and curve 2 represents the same sample with a ground surface. As expected, the photomagnetic emf is less for the ground surface (higher surface recombination rate) and the magnetic field at which the photomagnetic emf has the anomalous sign is also different. The absolute value of the anomalous component of the photomagnetic emf depends on the ratio of the oscillatory and monotonic parts of the emf. The anomalous photomagnetic emf may increase when the surface recombination rate is increased if the

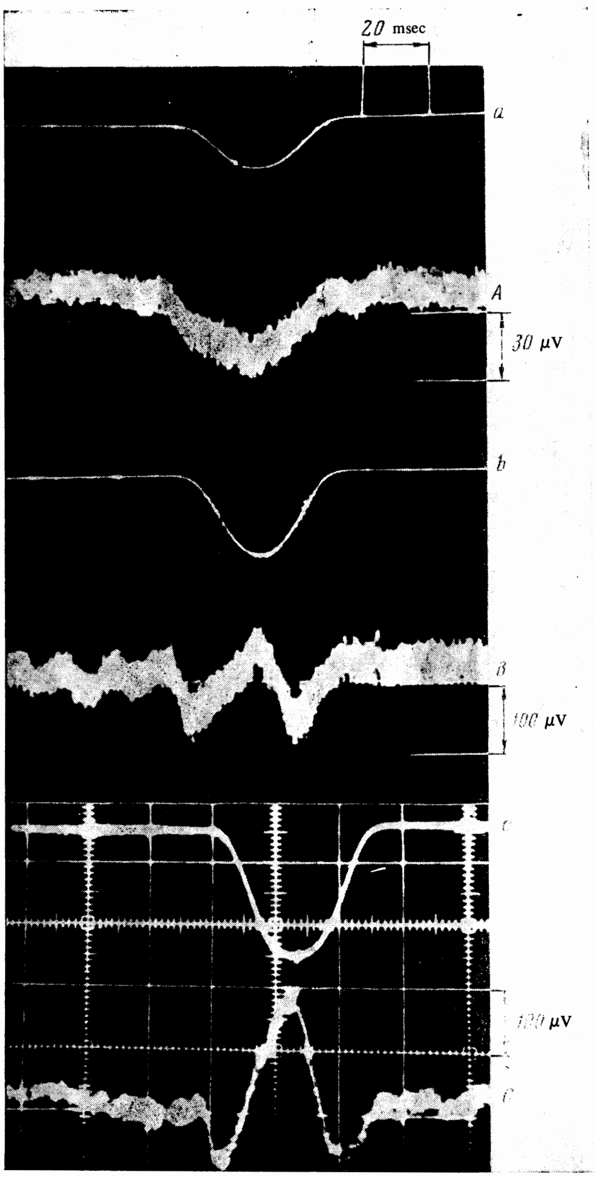

FIG. 4. Oscillograms of the photomagnetic emf (in the anomalous region) for different intensities of illumination of a sample of n-type InSb ($n = 3.7 \times 10^{16}$ cm^{-3}). A, B, and C are oscillograms of the photomagnetic emf; a, b, c are oscillograms of the corresponding illumination intensities. The sequence A, B, C corresponds to increasing illumination intensity.

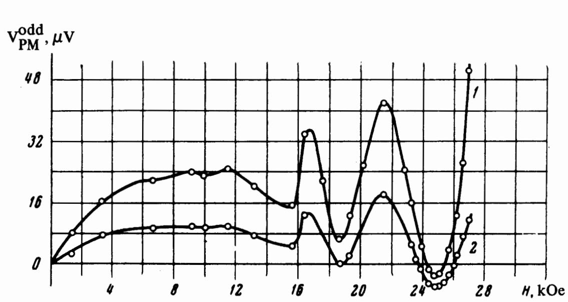

FIG. 5. Influence of surface recombination on the oscillations of the photomagnetic effect. Sample of n-type InAs ($n = 9.2 \times 10^{-16}$ cm^{-3}). Curve 1 represents a sample whose illuminated surface is etched. Curve 2 represents the same sample but with a ground surface.

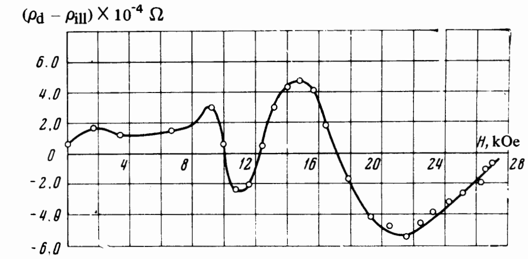

FIG. 6. Photoconductivity in a transverse magnetic field for a sample of n-type InAs ($n = 1.8 \times 10^{16}$ cm^{-3}). The ordinate represents the difference between the dark resistivity of the sample, $\rho_d(H)$, and the resistivity during illumination in a transverse magnetic field, $\rho_{ill}(H)$.

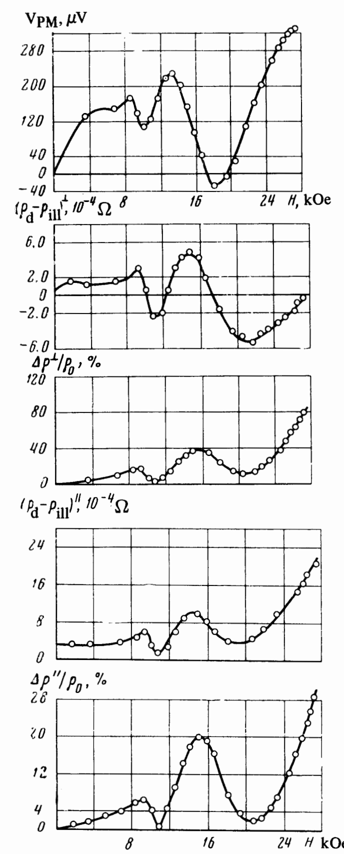

FIG. 7

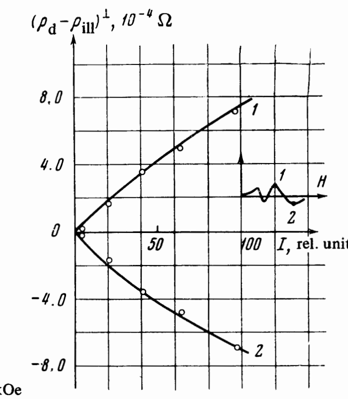

FIG. 8

FIG. 7. Comparison of the experimentally obtained oscillatory dependences, on the magnetic field, of the following quantities: the photoconductivity in transverse $(\rho_d - \rho_{ill})^{\perp}$ and longitudinal $(\rho_d - \rho_{ill})^{\parallel}$ magnetic fields, the longitudinal $(\Delta\rho^{\parallel}/\rho_0)$ and transverse $(\Delta\rho^{\perp}/\rho_0)$ magnetoresistances, and the odd photomagnetic effect (V_{PM}).

FIG. 8. Dependence of the photoconductivity in a transverse magnetic field, $(\rho_d - \rho_{ill})^{\perp}$, on the intensity of illumination of a sample of n-type InAs ($n = 1.8 \times 10^{16}$ cm^{-3}). Curves 1 and 2 correspond to different values of the magnetic field [points 1 and 2 on the curve representing the dependence of $(\rho_d - \rho_{ill})^{\perp}$ on H].

monotonic component of the photomagnetic emf is stronger than the oscillatory component; when the relationship between these components is reversed, the anomalous emf may decrease.

3. Investigation of Dependences of the Photoconductivity on the Magnetic Field and Illumination Intensity

Figure 6 shows the results of an investigation of the photoconductivity in a transverse magnetic field, carried out on a sample of InAs with a carrier concentration $n = 1.8 \times 10^{16}$ cm^{-3}. The photoconductivity oscillates in a magnetic field and, in the $H \geq 10$ kOe range, the photoconductivity changes its sign. This means that, in these magnetic fields, illumination of a sample increases its resistance. The negative photoconductivity is not observed in a longitudinal magnetic field. Figure 7 compares the dependences of the longitudinal and transverse photoconductivity on the magnetic field with curves representing the magnetoresistance in darkness and the photomagnetic effect in the same sample. The oscillation periods of all these effects are the same. However, the phase of the photomagnetic emf differs by a quarter of a period from the phases of the photoconductivity and dark magnetoresistance curves. Figure 8 shows the dependences of the photoconductivity on the illumination intensity. It is evident from this figure that the photoconductivity increases with increasing illumination intensity.

These experiments cannot be explained using the conventional diffusion theory of the photomagnetic effects. It is likely that the theory developed in[7] can explain the anomalous effects reported in the present paper. This is supported by measurements of the microwave photomagnetic effects which have been carried out in our laboratory.

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