

QUANTUM OSCILLATIONS OF THE CURRENT IN AN ELECTRON-HOLE CONDENSATE IN GERMANIUM

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Using laser radiation to produce a high photocarrier density in germanium, we succeeded in observing quantum oscillations of the photocurrent as a function of the magnetic field. The presence of such oscillations confirms the existence of a two-phase system, namely an electron-hole condensate with exciton "vapor" [1]. The oscillations are apparently due to the heavy holes. Their period in terms of the reciprocal field determines the carrier density N in the condensate and the Fermi energies E_e and E_h of the electrons and holes.

The experiment was performed in the following manner. The germanium samples (p-type, total content of electrically-active impurities about 10^{13} cm^{-3} , [100] axis normal to the surface of plates measuring $4 \times 4 \times 0.3 \text{ mm}$) were etched in CP-4A. Two strips of an indium-gallium alloy were then deposited on each sample in such a way that a band of pure germanium surface, with approximate width 1 mm, remained between these electrodes. Sample 1 (see Fig. 1), which was freely placed in mount 2 in the center of a superconducting solenoid, was immersed directly in superfluid helium ($T = 1.5^\circ\text{K}$). The beam 4 from an He-Ne laser ($\lambda = 6328 \text{ \AA}$, approximate power 10 mW) was focused with a short-focus ($f = 7 \text{ mm}$) cylindrical lens 3 into a strip approximately 20μ wide that crossed the gap between the electrodes 6. A constant voltage V was applied to the sample, and the current I was measured as a function of the field H . Usually I ranged from $0.05 - 0.1$ to $1 - 2 \mu\text{A}$. To compensate at least partially for the monotonic course of the $I(H)$ curve and to increase the gain thereby, a signal $i = \alpha H$ from a Hall pickup, also placed inside the solenoid, was applied to the x-y recorder in series with the measured signal. The proportionality coefficient α was regulated by the current through the pickup.

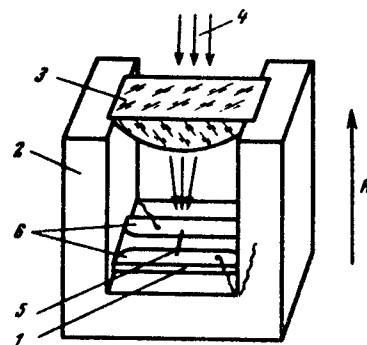


Fig. 1

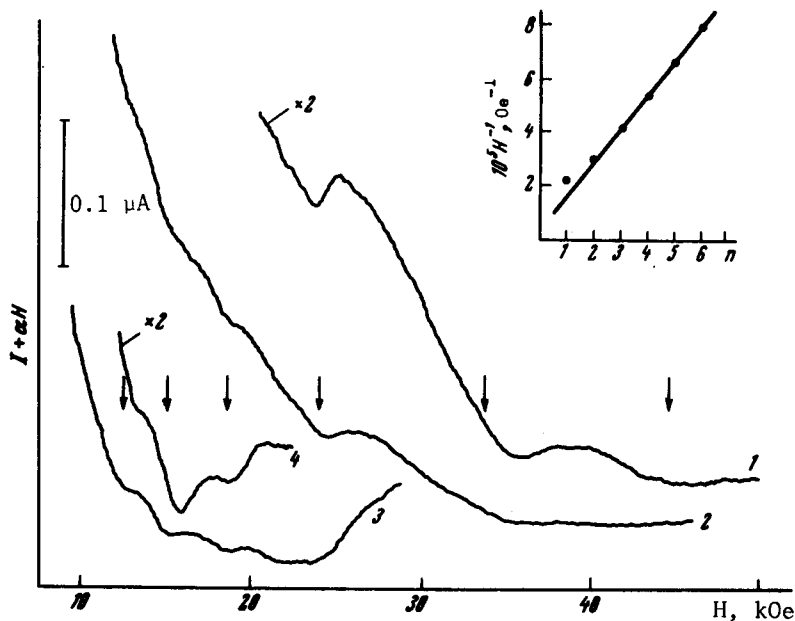


Fig. 2. Dependence of the photocurrent on the magnetic field. The vertical scale pertains to curves 2 and 3 (curves 1 and 4 were recorded with double the magnification). $V = 1$ volt. Variation of the value of the compensating signal makes it possible to reveal more distinctly the extrema in different sections. Curves 1, 2: $\alpha = 3.5 \times 10^{-3} \mu\text{A}/\text{kOe}$, curve 3: $\alpha = 9 \times 10^{-3} \mu\text{A}/\text{kOe}$, curve 4: $\alpha = 4.5 \times 10^{-2} \mu\text{A}/\text{kOe}$.

ted with the Landau quantization of the photocarrier spectrum. Such a quantization of the excitation spectrum in the condensate was already observed by spectroscopic methods both in germanium [2] and in silicon [3].

As is clear from the description of the experiment, the electron-hole pairs were produced in the surface layer of a very small part of the sample, the greater part of the latter serving only as a radiator to transfer the heat to the helium. Observation of quantum oscillations of the current under these conditions, especially the fact that the period of the oscillations is independent of the intensity of the light, is convincing proof of the presence of a two-phase system of excitations. Indeed, were there no interphase boundary, the carrier density would decrease away from the axis of the illuminated strip towards the interior and along the surface. Then the period of the oscillations, if observed at all, would be determined by the maximum value of the concentration near the axis of the strip, and could therefore be varied by varying the pump. Owing to the presence of the two-phase system, only the depth of the strip occupied by the condensate changes with changing pump, while the Fermi energy of the carriers, which is determined by the thermodynamic relations, remains constant over the entire volume of the condensate. The minimum possible strip thickness d_0 is determined by the depth of concentration of the light, and also by the diffusion of the electrons and of the holes during the time of their cooling. From the minimum value of the illumination, at which the oscillations were observed, we obtain the estimate $d_0 \approx 1 - 2 \mu$. (We note for comparison that estimates of the radius of the electron-hole drops give values from 2 to 8 μ [4]).

Generally speaking, one can imagine two mechanisms through which the Landau quantization causes oscillations of the current: the Shubnikov-de Haas effect (oscillations of the bulk conductivity), and phenomena occurring in the region near the contacts, e.g., oscillations of the probability of tunneling through the Schottky barrier. The contact phenomena should be quite complicated in our case, since we have on one side of the boundary two degenerate groups of carriers with different Fermi quasilevels. By producing contacts known to be non-ohmic with the aid of a conducting adhesive based on colloidal silver, we also observed oscillations in fields 20 - 45 kOe, but we have seen also intermediate minima in addition to the minimum noted

Figure 2 shows typical curves obtained with one of the three investigated samples. Six distinct minima on these curves are marked by arrows. The accuracy with which the positions of the minima were established is apparently $\pm 5\%$. The positions of the minima remained constant, with the same accuracy, from sample to sample, did not depend on the sign and magnitude of V in the range from 0.3 to 3 V, and remained practically the same when the illumination intensity was decreased by at least a factor of 30. With further decrease of the intensity, the amplitude of the oscillations decreased and vanished, while their period remained the same. The oscillations vanished also when the beam was defocused into a strip wider than 0.5 mm.

The insert of the diagram shows clearly the periodicity of the minima as a function of the reciprocal field; deviations for the periodicity appear only for the first numbers. This indicates that the oscillations are connected

in Fig. 2, and the entire picture was less distinct. The ohmic character of the indium-gallium contacts used by us and the complete reproducibility of the curves after repeated heating of the sample to room temperatures and using different samples give grounds, in our opinion, that the oscillations in Fig. 2 are due precisely to the Shubnikov-de Haas effect.

There are few experimental facts concerning the parameters of the excitation spectrum and the condensate. It is clear, however, that this spectrum should be close to the initial spectrum of the electrons and holes in germanium. It cannot be determined beforehand whether the observed period $P = 1.3 \cdot 10^{-5} \text{ Oe}^{-1}$ is due to electrons or heavy holes. For both variants, it is possible to determine first the Fermi energy $E = \hbar v / P m_c c$ of the carriers causing the oscillations (m_c is the cyclotron mass at $\vec{H} \parallel [100]$), and then their concentration $N = v(2mE)^{3/2} / 3\pi^2 \hbar^3$ (v is the number of valleys and m is the mass determining the density of states) and the Fermi energy of the carriers of opposite sign. If the oscillations were due to electrons, the values obtained would not agree with the spectroscopic data [4, 5]. On the other hand, the assumption that the oscillations are determined by holes ($m = 0.347m_0$, $m_c = 0.28m_0$) leads to values that agree splendidly with [4, 5]:

$$N = 1.75 \cdot 10^{17} \text{ cm}^{-3}, \quad E_e = 2 \text{ meV}, \quad E_h = 3.2 \text{ meV}.$$

It is understandable here why no oscillations due to electrons are observed, since their period is too large to be recorded by such a crude method.

It is known that for the heavy holes in germanium the magnetic levels corresponding to small quantum numbers are not equidistant [6]. The experimental accuracy, however, is insufficient as yet to investigate this circumstance.

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