Quantum "zero-point oscillations" in structures with a 2D electron gas

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Voltage oscillations having the period of Shubnikov–de Haas oscillations have been observed in structures with a 2D electron gas in a quantizing magnetic field. These oscillations are unrelated to the current flow through the sample.

We studied selectively doped AlGaAs/GaAs heterostructures fabricated by molecular-beam epitaxy, with an electron mobility $\mu = (3 - 15) \times 10^4$ cm^2/(V·s) at $T = 4.2$ K and with a 2D gas of density $n = (4 - 8) \times 10^{11}$ cm^{-2}. Measurements were taken from samples with the Hall geometry and also from samples of arbitrary shape (by the van der Pauw method). The magnetic field is produced by a superconducting solenoid ($H \leqslant 5$ T) and an electromagnet ($H \leqslant 1.2$ T). The voltage is measured by potentiometric and electrometric methods.

Figure 1 shows the doubled amplitude of the Shubnikov–de Haas oscillations, ΔV_{SH}, versus the current through the sample at a fixed magnetic field. The amplitude ΔV_{SH} falls off linearly with decreasing current, indicating that there is no heating of the electron gas; for this particular sample [$\mu = 1.5 \times 10^5$ cm^2/(V·s), $n = 6.1 \times 10^{11}$ cm^{-2}] this heating would set in at currents[1] $I \geqslant 100$ μA. It can be seen from Fig. 1, however, that an extrapolation of the line to $I = 0$ results in a nonzero intercept on the voltage axis. This result forces the unexpected conclusion that the voltage oscillations should be observed even in the absence of a current through the sample. Indeed, we see in Fig. 2 that in quantizing magnetic fields there are oscillations in the voltage when the current circuit is opened ("zero-point oscillations"; curve 2). Their period is the same as that of Shubnikov–de Haas oscillations (curve 1). It follows from Fig. 1 that the experimental curves recorded at low currents consist of the sum of additive contributions from Shubnikov–de Haas and zero-point oscillations.

Zero-point oscillations of this sort were observed in essentially all of the (more than ten) samples which we studied. The amplitude of these oscillations varies from sample to sample and also depends on the particular pair of contacts chosen. The peak-to-peak amplitude of these oscillations in a field $H \simeq 4$ T reaches ~ 10 mV. The effect is influenced by neither the rate at which the magnetic field is swept (which ranged from 0 to 0.5 kG/s in our experiments) nor the direction of this sweep. The sign of the zero-point oscillations does not depend on the direction of the magnetic field. The voltage taken from the sample at a fixed magnetic remains constant over the measurement time (~ 1 h).

Illumination of a sample with a source of "type A" (illumination = 500 lx) caused no significant change in the amplitude of the zero-point oscillations. The temperature dependence of the amplitude of these oscillations is similar to that of Shubni-

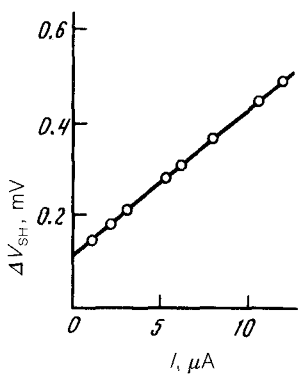

FIG. 1. Amplitude of Shubnikov–de Haas oscillations versus the current through the sample in a static magnetic field $H = 9.5$ kG.

kov–de Haas oscillations and can be used to determine the effective mass of the 2D electrons in GaAs: $m^* = (0.069 \pm 0.002)m_0$. This result agrees well with data in the literature. The period is equal to the period of the Shubnikov–de Haas oscillations, and it gives us the concentration of 2D electrons. In a magnetic field directed parallel to the heterojunction, the zero-point oscillations disappear, as do the Shubnikov–de Haas oscillations. Heating the electron gas by passing an alternating current results in a decay of the zero–point oscillations. Along with these identical features of the zero-point and Shubnikov–de Haas oscillations, there are also some significant differences.

It follows from Fig. 1 that for a given sample the amplitude of the zero-point oscillations corresponds to the amplitude of the Shubnikov–de Haas oscillations at a current $I \simeq 4$ μA. As can be seen from Fig. 2 (curve 1), however, the Shubnikov–de Haas oscillations occur against the background of a huge positive magnetoresistance, $\Delta R / R_0 \sim 500\%$, which is essentially not manifested in measurements of the zero-point oscillations in weak magnetic fields (curve 2). Furthermore, there is usually a phase shift between the zero-point and Shubnikov–de Haas oscillations. This phase shift

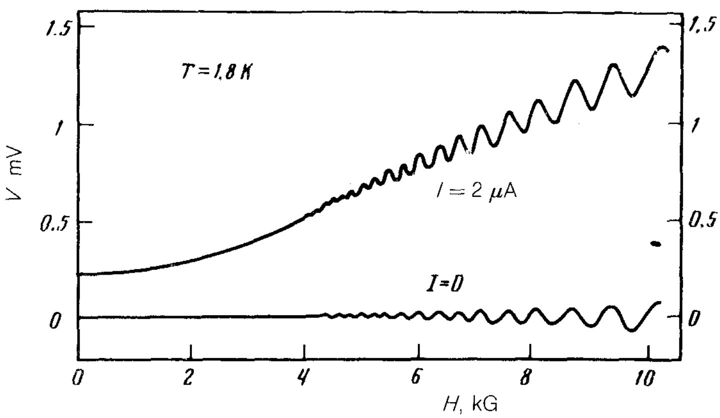

FIG. 2. Shubnikov–de Haas oscillations and oscillations in the voltage with an open current circuit.

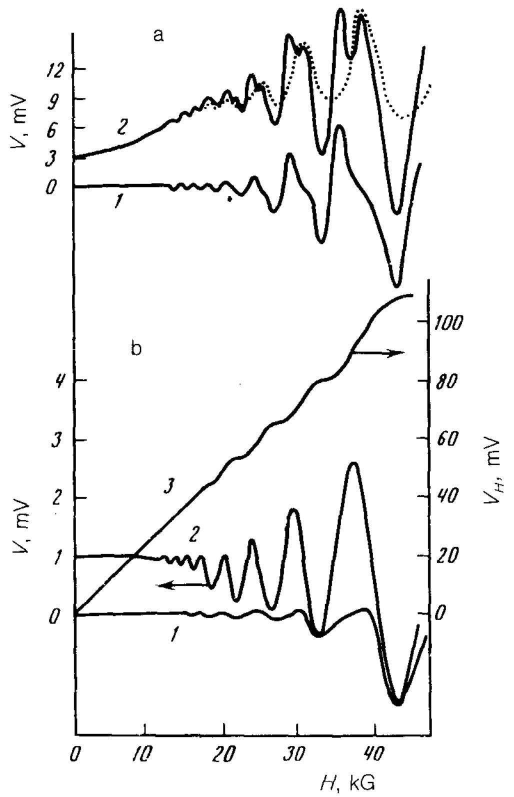

FIG. 3. Voltage oscillations versus the magnetic field. a: For a sample in which the quantum Hall effect does not occur [$\mu = 5\times10^4$ cm(V·s), $n = 8\times10^{11}$ cm^{-2}]. 1—$I = 0$ μA; 2—$I = 100$ μA. The dotted line shows the Shubnikov–de Haas oscillations, found by subtracting curve 1 from curve 2. b: For a sample in which a quantization of the Hall resistance is observed [curve 3; $\mu = 4.30\times10^4$ cm^2/(V·s); $n = 6.4\times10^{11}$ cm^{-2}]. 1—$I = 0$ μA; 2,3— $= 25$ μA.

substantially distorts the resultant curves of $V(H)$, to the point that additional maxima appear.

The picture of the oscillations here is similar to that which is observed during pronounced spin splitting of Landau levels (Fig. 3).

It can also be seen from Fig. 3 that the experimental curves for the Shubnikov–de Haas oscillations may intersect the line of the instrumental zero, but in our experiments they never intersect the zero-point oscillations. Under conditions of a quantum Hall effect, the curves of the Shubnikov–de Haas and zero-point oscillations touch each other (Fig. 3b). Consequently, the zero-point oscillations may be thought of as a change in the reference point or "zero" for Shubnikov–de Haas oscillations in a quantizing magnetic field. The effect results from the additivity of the Shubnikov–de Haas and zero-point oscillations.

Shunting the sample with an external resistance upon the appearance of the zero-point oscillations results in the flow of a current through the sample and thus the dissipation of a power, whose magnitude is $\sim 10^{-13}$–10^{-12} W. When the current circuit is opened, and we have $dH/dt = 0$, one possible source might be, for example, the generation of a noise power in electric circuits which are moving away from the sample and which are at room temperature.

We believe that the "topological" potential difference which was recently observed in Ref. 2 at the contacts of a metal-insulator-semiconductor structure in the form of a corbino disk, under conditions of the quantum Hall effect, is of the same nature as the zero-point oscillations.

The possible interpretation offered in Ref. 2, on the basis of the existence of frozen charges, would seem, however, to be inapplicable in the case $\rho_{xx} = 0$, since the zero-point oscillations are definitely observed not only under conditions of the quantum Hall effect (Fig. 3b) but also in its absence, with $\rho_{xx} \neq 0$ (Figs. 2 and 3a).

Consequently, at the moment there is no theoretical interpretation of the zero-point oscillations.

We wish to stress that this phenomenon is quite general in nature. It is observed in samples with various configurations (a double Hall cross, a corbino disk, and samples of arbitrary shape) and in 2D channels synthesized from AlGaAl/GaAs heterojunctions and silicon metal-insulator-semiconductor structures.[2] Furthermore, preliminary measurements on InGaAs/InP heterostructures have demonstrated an effect similar to that described above.

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[2]V. G. Veselago, V. N. Zavaritskiĭ, M. S. Nunuparov, and A. B. Berkut, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 382 (1986) [JETP Lett. **44**, 490 (1986)].

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