Interference and backscattering by edge current states in a quantum interferometer

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Oscillations of the magnetoresistance due to an interference and backscattering of edge current states have been observed in a quantum interferometer. Oscillations are also caused by resonant tunneling through a current state closed along an inner circle of the interferometer.

Interference effects in nanostructure solid-state systems rank among the most interesting topics of research in solid state physics. Aharonov–Bohm oscillations play an important role in these studies. For a long time these oscillations were studied in ring and multiply connected systems, in which the interfering trajectories are completely determined by the geometry of the conductor. In some recent studies, in contrast, Aharonov–Bohm oscillations have been observed to result from a quantization of magnetic flux in an area specified not by the geometry of the conductor but by tunneling-coupled edge current states[1,2] or by scattering processes.[3]

In this letter we are reporting the first observation of oscillations in the magnetoresistance of an electron interferometer under the conditions of the quantum Hall effect. Our study shows that these oscillations stem from interference and backscattering of tunneling-coupled edge current states and also from a resonant tunneling through a current state closed along an inner circle of the interferometer. Such effects have previously been observed only at quantum point contacts.[1,2]

The test samples are ring interferometers based on AlGaAs/GaAs heterojunctions. The method for fabricating them and their basic parameters are described in Ref. 4. In the present study we investigated the magnetoresistance of two ring interferometers with identical effective diameters $d \approx 650$ nm and different widths of the conducting channels. The measurements were carried out at temperatures $T = 20$ mK–4.2 K in magnetic fields up to 12 T at an ac frequency of 30 Hz in a four-point arrangement with the help of a phase detector.

The behavior of these interferometers in magnetic fields up to 1 T is characterized by high-amplitude Aharonov–Bohm oscillations with a period corresponding to a quantization of the magnetic flux, with a flux quantum $\Phi_0 = h/e$, through an area of $\pi d^2/4$ (Ref. 4). At magnetic fields for which the magnetic length is comparable to the width of the conducting channel, i.e., at which there is a transition to the conditions of a quantum Hall effect, we observe a more complex behavior of the magnetoresistance. Figure 1 shows experimental results for an interferometer with a smaller effective channel width, $W \approx$ 30 nm, determined from the period of the beats of the

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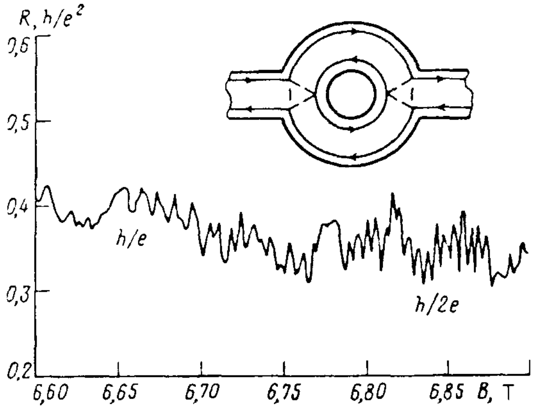

FIG. 1. Aharonov–Bohm h/e and $h/2e$ oscillations in strong magnetic fields at $T \approx$ 20 mK (sample 1). The inset is a diagram of the interfering electron trajectories.

oscillations in weak magnetic fields (sample 1). It can be seen from this figure that at $B \leqslant 6.65$ T there are aperiodic fluctuations in the magnetoresistance. These oscillations then give way to some well-defined h/e oscillations, which convert into $h/2e$ oscillations at $B \approx 6.8$ T. As the magnetic field is increased further, oscillations of a new type arise against the background of the $h/2e$ oscillations, which persist. The period and amplitude of these new oscillations are larger by nearly an order of magnitude (Fig. 2). The amplitude of the large oscillations then begins to fall off monotonically, without a noticeable change in the amplitude of the $h/2e$ oscillations. At $B > 7.5$ T, the oscillations of all types in the magnetoresistance disappear essentially completely, and a plateau $R_L = h/4e^2$ is reached. Against the background of this plateau, series of oscillations with a considerably smaller amplitude arise at certain values of the magnetic field. The value of the resistance in this region can be used to determine the number of edge states which pass through the interferometer, from the expression

$$R_L = (h/e^2)(1/N_{\text{int}} - 1/N_{\text{wide}}),$$

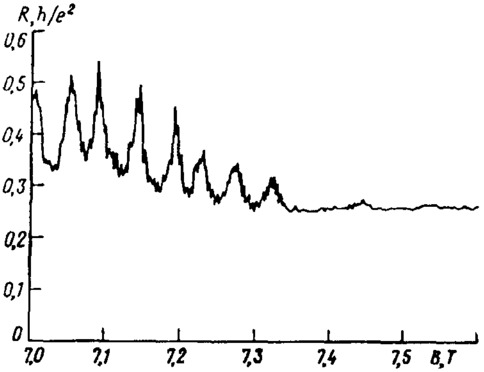

FIG. 2. Long-period $h/2e$ oscillations in strong magnetic fields at $T \approx$ 20 mK (sample 1).

where R_L is the measured resistance, N_{int} is the number of edge states which pass through the interferometer, and N_{wide} is the number of edge states in the macroscopic part of the test sample. In this region of magnetic fields, we have $N_{\text{int}}=2$, with spin splitting being taken into account.

To interpret the results we consider the particular features of electron transport in a ring interferometer for various magnetic fields. In weak fields, at which the magnetic length of the electrons is considerably greater than the width of the conducting channels, the oscillations with a period of h/e are a consequence of a direct interference of independent electron trajectories passing through different arms of the interferometer. With increasing field, the magnetic length of the electrons approaches $W/2$. According to our estimates, for sample 1 this event corresponds to a field $B \approx 2.5$ T. At these magnetic fields, the Aharonov–Bohm effect should arise because of the appearance of edge current states,[5,6] and a plateau should set in for our samples. In the experiments in these fields, the h/e oscillations did indeed disappear initially, but the resistance did not reach a constant quantized value, in contrast with Ref. 6. Instead, we observe oscillations of the magnetoresistance as described above (Figs. 1 and 2). We regard this behavior of the interferometer as resulting from a backscattering and an interference between tunneling-coupled edge current states. In the samples studied, the conducting channels may be of nonuniform width because of fluctuations in the potential of the randomly positioned impurities. As a result, the interferometer contains regions in which, because of a contraction of the channel, an overlap of the wave functions of opposite edge states increases sharply, in addition to regions in which the edge states are well separated. These factors account for the transitions of electrons from one edge to the other through a tunneling accompanied by simultaneous scattering by potential fluctuations. The probability for such processes is high if the length scale of the variations, L, is comparable to the channel width; alternatively, it can be small in the case $W \gg L$. It is for this reason that oscillations of the magnetoresistance under the conditions of Hall quantization were not observed in Ref. 6, where the interferometers had $W \gg L$, in contrast with the samples of the present study. Under our conditions we can expect an interference of electrons on trajectories passing around different areas; the effect should lead to the simultaneous observation of oscillations at several frequencies in the magnetoresistance. The inset in Fig. 1 is a diagram of possible interference processes. If the tunneling probability is not very high, the oscillations caused by this interference will be observed near the plateau, and the minimum of these oscillations cannot be smaller than the value of R_L on the plateau. This was the situation in the experiments (Figs. 1 and 2).

Another backscattering mechanism is a resonant tunneling of electrons between current-carrying edge states through discrete levels of a closed current state at the center of the interferometer. In this case a tunneling exchange is allowed only when an integer number of magnetic flux quanta pass through the closed loop of this edge current. This effect leads to an oscillatory dependence of the magnetoresistance with a period of h/e (Ref. 2). If there are no other backscattering mechanisms, the observed oscillations will be seen as peaks with a base lying on the plateau and with a period of h/e. The periodicity of the oscillations in this case may be disrupted, since the appearance of these oscillations is determined not by the probability for tunneling ex-

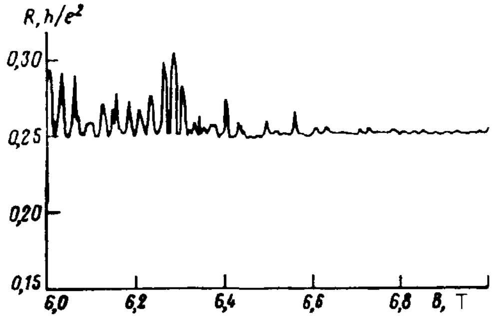

FIG. 3. "Peak-shaped" oscillations against the background of a plateau of the quantum Hall effect at $T \approx 20$ mK (sample 2).

change but by the probability for backscattering, which also depends on the magnetic field. This behavior is seen most clearly in sample 2 (Fig. 3).

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