Aharonov–Bohm oscillations in a 2D electron gas with a periodic lattice of scatterers

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(Submitted 28 November 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **55**, No, 2, 129–132 (25 January 1991)

Oscillations have been observed in the magnetoresistance of a 2D electron gas in an artificial 2D periodic lattice of scatterers. The period of these oscillations along the magnetic field scale is $hc/(2eS)$, where S is the area of the square associated with the lattice period. This oscillation period is determined by the Aharonov–Bohm effect of electrons which interfere as they are scattered by the lattice.

The interference of electrons plays an important role in transport processes in conductors containing impurities, determining the temperature dependence of the conductivity of these systems at low temperatures and the behavior of the systems in magnetic fields. In particular, it is responsible for a negative magnetoresistance.[1] A new entity has recently arisen in the physics of 2D systems: a 2D electron gas in a periodic lattice of antipoints.[2,3] The antipoints determine the scattering of the carriers

 0021-3640/92/020123-04$03.00

in the absence of the magnetic field and also in weak magnetic fields.[4,5] In this case, one should observe an interference of electrons as they are scattered by the antipoints.

In this letter we are reporting the observation of oscillations in the magnetoresistance of a 2D electron gas in a lattice of antipoints with a period along the magnetic field scale which depends on the period of this lattice.

The test samples were Hall bridges based on GaAs/AlGaAs heterostructures with a 2D electron gas. The distance between the potential probes was 500 μm, and the width of the bridge was 200 μm. In the initial heterostructures, the electron density was $n_s \simeq (4\text{–}5)\times 10^{11}$ cm^{-2}, and the electron mobility was $\mu = (1.5\text{–}5)\times 10^5$ cm^2/(V·s). A lattice of antipoints produced by electron-beam lithography and reactive ion etching covered part of the sample between the potential probes (Fig. 1). Samples with lattice periods $d = 0.6$, 0.7, 0.8, 0.9, 1, and 1.3 μm and with antipoint diameters $2r = 0.15\text{–}0.2$ μm were studied. The magnetoresistance was measured by the four-probe method with an active ac bridge at frequencies of 70–700 Hz in magnetic fields up to 8 T at temperatures of 1.3–4.2 K.

In strong and comparatively weak magnetic fields we observed, along with the

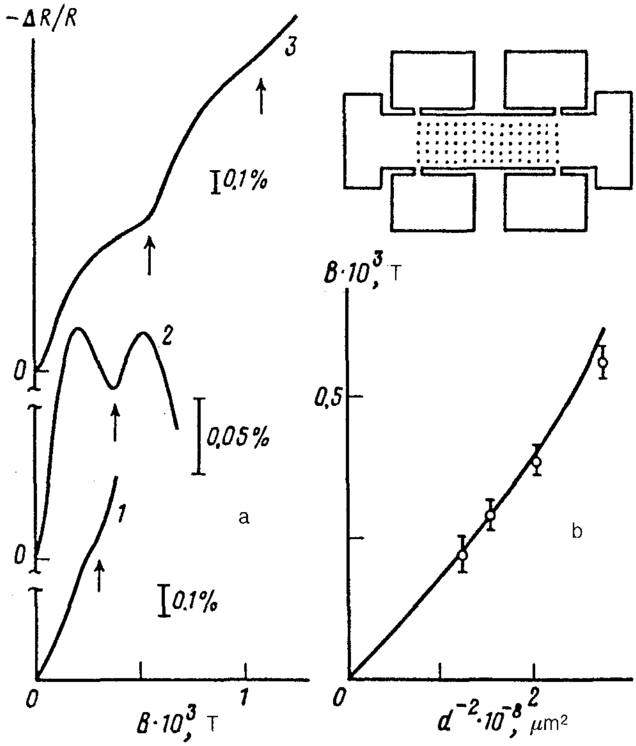

FIG. 1. a: Magnetoresistance of samples with various periods (d) of the lattice of antipoints. 1—$d = 0.8$ μm; 2—0.7 μm; 3—0.6 μm, $T = 1.7$ K). b: Period of the magnetoresistance oscillations versus $1/d^2$. The solid line is a calculation from the formula $B = hc/(2eb^2)$. The inset is the schematic diagram of a sample.

Shubnikov–de Haas oscillations, some additional oscillations, whose behavior is described in Ref. 5. In this case, we made a detailed study of the magnetoresistance at magnetic fields up to 200 G. Figure 1a shows the magnetoresistance $\Delta R(B)$ for the samples with the smallest superlattice periods. Against the background of the negative magnetoresistance there are some structural features whose positions depend on d. In a sample with a period $d=0.6$ μm, we see two structural features. This result is evidence that their behavior is of an oscillatory nature. The second oscillation is not seen in sample 2 because of the positive magnetoresistance associated with the formation of closed orbits near the antipoints.[4,5] The observed oscillations, like the negative magnetoresistance, depend on the temperature. Specifically, they decrease as T is raised to 4.2 K. There are no oscillations in the samples with a large period.

Let us discuss the results. The observed oscillations can be linked most clearly with the Aharonov–Bohm effect, in which electron waves moving along different trajectories interfere. This effect was originally predicted for disordered conductors in Ref. 6. It was observed in Ref. 7 in measurements of the magnetoconductivity of thin-walled metal cylinders of small dimensions. In this case, electrons moving around the cylinder in opposite directions interfere, and the period is determined by the flux quantum $\Phi_0 = hc/(2e)$. In order to observe these oscillations, it is necessary to arrange the conditions $l_e \ll L_\varphi \sim L$, where l_e is the mean free path, L_φ is the phase coherence length, and L is the circumference of the cylinder. A different sample geometry, similar to that used in the present study, has been used[8] in a study of these oscillations in thin films. In that study the sample was a grid with a period $d = 1.5$ μm. In all these cases, the conditions corresponded to the "dirty" limit, with $l_e \ll L_\varphi$, and the electron trajectories interfered near an aperture. In our case, there are nearly no impurities, and the role of scatterers is played by the periodic lattice of antipoints. In weak magnetic fields, it is thus possible to select from all possible electron trajectories those which form a closed loop. One possible trajectory is shown in Fig. 2. An electron emerging from point A can move clockwise or counterclockwise; the interference between these trajectories in the magnetic field gives rise to oscillations with a period $hc/(2eb^2)$. We believe that these trajectories are responsible for the magnetoresistance

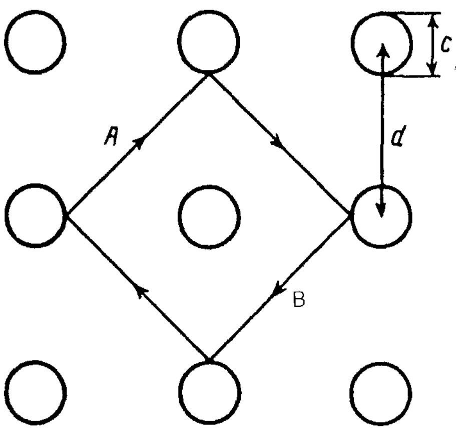

FIG. 2. Schematic diagram of the electron trajectories which contribute to the Aharonov–Bohm oscillations.

oscillations shown in Fig. 1a. Oscillations with a smaller period ΔB are not visible, since the associated trajectories have a perimeter larger than L_φ. Oscillations with large values of ΔB, corresponding to trajectories within one cell, are not visible against the background of the classical magnetoresistance, which dominates the situation in strong magnetic fields. Lower temperatures are required in order to observe oscillations associated with other trajectories. Figure 1b shows the magnetic field values at which the oscillations are observed. The solid line shows the results of calculations based on the geometric model in Fig. 2. In determining the oscillation period we allowed for the antipoint diameter c; in the calculations, it turned out to be twice the geometric size of the antipoints. The size of these regions can be found independently, from the magnetoresistance oscillations in weak magnetic fields.[5] In our case the width of the depletion regions turns out to be $t = 0.1\ \mu$m, which corresponds to the antipoint diameter $c = 2r + 2t$ found above.

It can be seen from Fig. 2b that the oscillation period is described satisfactorily by the formula $\Phi_0 = hc/(2eb^2)$. In making the comparison with the theory, we use the superconductivity flux quantum, which incorporates the interference of the trajectories during backscattering at point A (Refs. 1 and 6). The interference during forward scattering averages out, since the sample has macroscopic dimensions.[9]

It is difficult to determine L_φ in our case, because the B dependence of the negative magnetoresistance cannot be adequately described by the expressions for the 2D case.[10] If we nevertheless use those expressions to estimate L_φ, we find a value of 1–2 μm, which corresponds to the condition for the observation of Aharonov–Bohm oscillations: $L \sim L_\varphi$.

In summary, these experiments have revealed oscillations in the magnetoresistance which are due to the Aharonov–Bohm effect involving electron trajectories which arise during the elastic scattering of 2D carriers by a periodic lattice of scatterers created artificially by electron-beam lithograpy.

We wish to thank V. G. Plyukhin for carrying out the reactive ion etching.

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Translated by D. Parsons