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Symmetric, gated, ballistic rings as tunable electron interferometers

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Abstract

In the present work we investigate the coherent electron transport in a symmetrically designed ballistic ring uniformly covered by a top metal gate. We find that as the Fermi energy is varied, the phase of Aharonov–Bohm (AB) oscillations near zero magnetic field switches between 0 and π. It seems unlikely that this behaviour can be explained by some accidental asymmetry in the structures. We give a qualitative explanation of our results using a model where the ring is considered to be weakly coupled to the leads and the conductance is calculated on the basis of an exact energy spectrum of an ideal ring. This model predicts that a variation of the phase of AB oscillations with gate voltage may be observed in a symmetrical ring. © 2000 Elsevier Science B.V. All rights reserved.

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Ever since the start of the mesoscopic physics, the properties of quantum ring interferometers have been intensively studied [1–4]. In the present work we investigate the effect of the gate voltage on electron interference in a symmetric ring interferometer uniformly covered by a top metal gate. The problem is closely related to the concept of the quantum interference device [5], in which the electron wave is split into two and then recombines again after a phase difference has been added between the two partial waves. If the waves are in phase, they interfere constructively to give a large amplitude (low resistance). When out of phase, destructive interference yields a high resistance. In general, there exist only two principal ways in which a controllable variation of the transmission of the device can be accomplished. The first is the use of a variable external magnetic field normal to the ring which gives rise to AB oscillations. The other is changing the Fermi wave vector in the ring conducting channels by means of an electrostatic gate. The effect of the top gate voltage on the AB oscillations in a ring interferometer will depend on the strength of

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the coupling of the ring to the leads. If the coupling is good (no scattering in the couplers) one would need to introduce an appreciable asymmetry in the structure in order to be able to vary the phase of the oscillations with gate voltage. If, on the other hand, there is a noticeable scattering of the incident wave in the couplers, then it should be possible to tune the transmission of the ring even in the absence of any asymmetry. In earlier experiments [6–8] on ring interferometers it was implicitly assumed that the coupling is strong and so the tuning of the phase of AB oscillations with gate voltage was thought to be possible and was looked for only in asymmetrical structures. In the present work we study the effect of the variation of gate voltage on AB oscillations in uniformly gated rings of symmetrical design. As the gate voltage is varied, the phase of the h/e oscillations in magnetic field switches between 0 and π. We find that the asymmetry factor needed to explain this variation of phase in the frames of the waveguide model (strong coupling) is too big to be considered realistic. We therefore opt for the model of a weakly coupled ring which gives a qualitative explanation of our results and shows that the variation of the phase of AB oscillations with gate voltage does not necessarily require asymmetry and may be observed in a symmetrical ring uniformly covered by gate.

The samples (see the insets to Fig. 1) were four- and two-terminal ring interferometers fabricated from AlGaAs/GaAs heterolayers with the 2D electron density $n_s = (1.5 - 6) \times 10^{11}$ cm^{-2} and mobility $\mu \approx (0.5 - 1) \times 10^6$ cm^2/Vs. The average radius of the rings was $r_0 = 0.35$ μm, and the lithographical width of the channels $W_{\text{lith}} = (0.5–0.3)$ μm. The structures were entirely covered by Au/Ti gate. The measurements were performed at $T \approx 100$ mK by a conventional lock-in technique with an AC current 1 nA at a frequency of 13 Hz.

The typical magnetoresistance of our devices is presented in Fig. 1. As expected, the magnetoresistance is dominated by AB-h/e oscillations, whose regularity and beating indicate that the devices are in a single or a few-mode regime. Figs. 2a and b show the modification of AB oscillations with gate voltage in a four-terminal and a two-terminal structure. A qualitatively similar behaviour has been observed in all our structures. The oscillations are symmetrical with respect to $B = 0$ indicating that the phase coherence length is smaller than the distance between the probes used to measure the voltage drop across the ring. The symmetry of the oscillations also means that no other phase except 0 and π should be possible at $B = 0$. As the gate voltage is varied, the phase of the h/e oscillations switches irregularly between 0 and π. Because of the condition of symmetry imposed on the oscillations near $B = 0$, oscillations with $\varphi = 0$ can evolve continuously into oscillations with $\varphi = \pi$ via an intermediate state with h/2e oscillations [8], which is observed experimentally. The experimental structures, although symmetrical in design, can still have some individual accidental asymmetry. This asymmetry will result in a variation of the phase of AB oscillations if the integral $\int \boldsymbol{k}_F \cdot d\boldsymbol{l}$ in the two channels of the ring changes unequally when the gate voltage is varied. Using the approach developed in Refs. [9,10] we have estimated the degree of asymmetry needed to account for the change of phase in Fig. 2a and found it to be about 100%, which we believe unrealistic in our case. In the present work we attempt to give a qualitative explaination of the observed behaviour using the model proposed recently by Tan and Inkson [11] which is based on the exact energy spectrum of an isolated ring in magnetic field. The spectrum (Fig. 3a) consists of subbands originating from the quantization of the radial motion of electron. The energy levels in each subband correspond to the clockwise and anticlockwise motion along the channel of the ring.

The ring is considered to be weakly coupled to two leads. An electron can reach from one lead to the other by tunneling though the quasibound states in the ring which are approximated by broadened energy levels of an isolated ring. Let us consider the situation where only the first subband in the ring is occupied. The oscillations in the conductance arise when the Fermi level is aligned with one of the energy levels of the quasibound states in the ring. As can be seen from Fig. 3b, the phase of the AB oscillations in magnetic field depends on the position of the Fermi level relative to the energy levels in the ring. Shifting the Fermi level by $\Delta = hv_F/(2\pi r_0)$ (the distance between the energy levels in the ring in zero magnetic field) changes the phase of the AB oscillations by 2π. Whenever the Fermi level lies between the positions corresponding to the states with $\varphi = 0$ and $\varphi = \pi$ one observes h/2e oscillations. It is also interesting to note that when the Fermi energy is var-

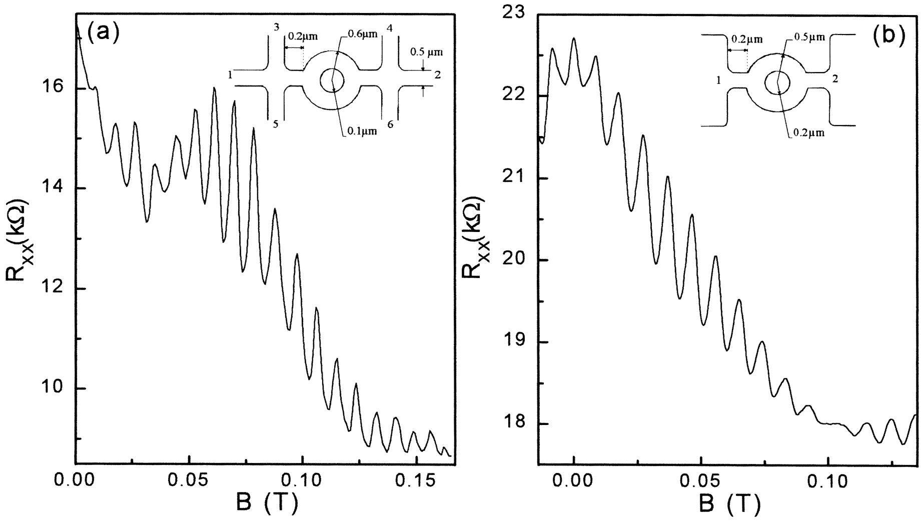

Fig. 1. Typical magnetoresistance curves and the schematic top view of the ring interferometer ((a)-type 1; (b)-type 2).

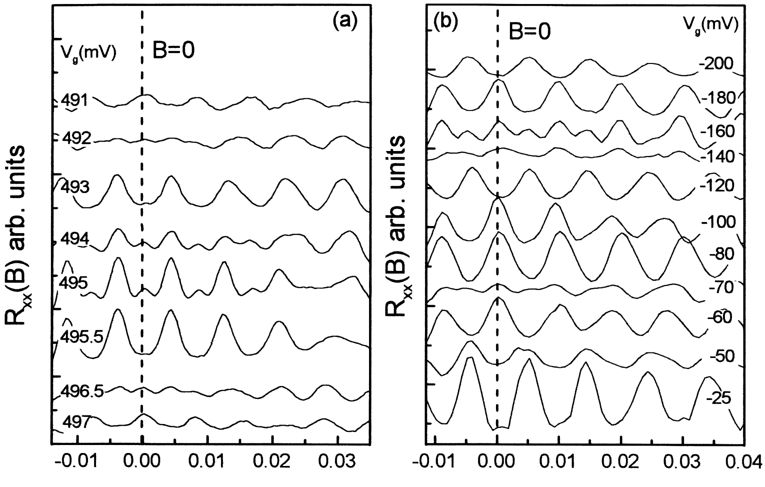

Fig. 2. The variation of the phase of the Aharonov–Bohm oscillations with gate voltage in symmetrical ballistic rings uniformly covered by gate ((a)-type 1; (b)-type 2).

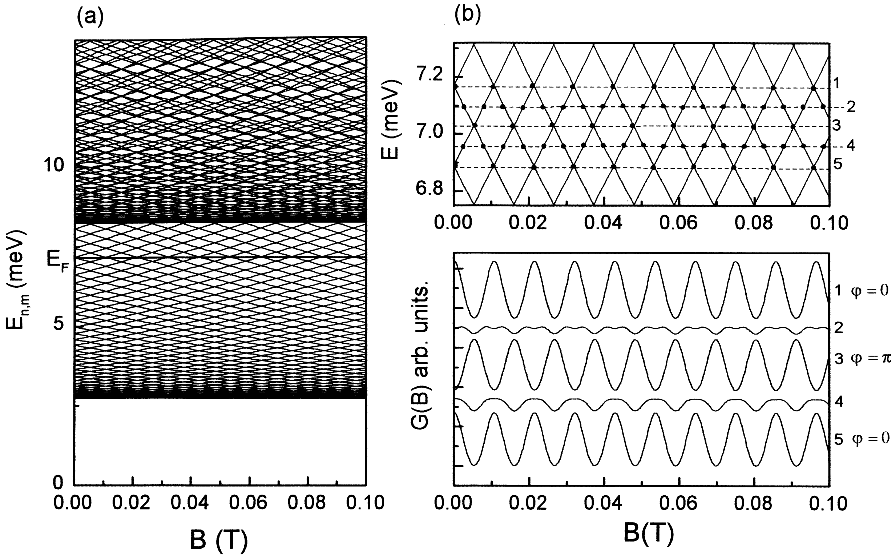

Fig. 3. (a) The energy spectrum in the 4-leads ring calculated after [11]; the energy levels of the first two radial energy subbands are shown. (b) The phase of Aharonov–Bohm oscillations (below) for different positions of the Fermi energy with respect to the energy levels in the ring (above).

ied, each time the phase of AB oscillations changes by π the number of occupied energy levels in the ring changes by one. That leads to a quite universal conclusion that in a single-mode ring the addition or removal of only two electrons would be sufficient to change the phase of AB oscillations by π. We get a surprisingly close result $\Delta N \approx 3$ from our estimates based on the data presented in Fig. 2a.

Although all the main features of the behaviour discussed above are present in the experimental results, there is also a certain difference. The phase of AB oscillations is not a simple periodical function of the gate voltage as one would expect it to be in the case of a single-mode ring for relatively small variations of the Fermi energy. A possible explanation of this fact can be that the characteristics of the ring necessarily undergo certain modifications as the gate voltage is varied. That means that at each new gate voltage we have a slightly different ring and this might account for the lack of the expected periodicity in the variation of the phase. One can also consider a situation when two radial subbands in the ring are occupied instead of one. In that case, the energy spectrum is more complicated as the energy levels of the two subbands are intermixed. We have checked that under these circumstances the modification of AB oscillations with gate voltage can look very similar to what we find in the experiment.

To conclude, in the present work we report the modification of phase of the Aharonov–Bohm oscillations in a symmetrical ballistic ring interferometer uniformly covered by top metal gate. As the Fermi energy is varied the phase of the AB oscillations near zero magnetic field switches between 0 and π. We show that these results can be qualitatively explained using a model where the conductance of the interferometer is calculated on the basis of an exact energy spectrum in an ideal ring which is considered to be weakly coupled to the leads.

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