Effect of an electrostatic field on the interference of electron waves in a quasiballistic interferometer

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The mesoscopic microwave emf has been used to study the effect of an electrostatic field on coherent processes in submicron GaAs/AlGaAs rings. In contrast with magnetic-field fluctuations, in which case one observes an aperiodic component and h/e oscillations, the dependence of the emf on the gate voltage has only a random component. The reason is that a random scattering potential plays a dominant role in the coherent processes in a quasiballistic interferometer, and the correlation energies of the aperiodic mesoscopic fluctuations of the Aharonov–Bohm oscillations are comparable in magnitude. © *1994 American Institute of Physics.*

At least three mechanisms are involved in the effect of an electrostatic field on coherent processes in mesoscopic conductors. The first is the effect of the field on the realization of the random scattering potential. The second stems from the change in the carrier density and, correspondingly, the Fermi energy of the interfering electrons. Both of these mechanisms have been studied experimentally in some detail in submicron silicon field-effect transistors.[1,2] There has been less study of the third mechanism, which stems from the quantum-mechanical phase shift ϕ of the electron wave function due to the electromagnetic potential. Such an effect of an electromagnetic field on the interference of electron waves is known in quantum mechanics as the Aharonov–Bohm effect.[3]

One distinguishes between magnetic and electrostatic Aharonov–Bohm effects, depending on which component of the electromagnetic potential leads to the shift ϕ. Both of these effects have been studied in vacuum, in which case electrons move ballistically.[4,5] In the diffusion and quasiballistic regimes, which prevail in submicron rings with a metallic conductivity, only the magnetic Aharonov–Bohm effect has been studied in detail. It is seen as a periodic change in the magnetoresistance of submicron cylinders[6] and rings.[7]

The electrostatic Aharonov–Bohm effect, like the magnetic one, should lead to a periodic change in the interference conditions and, correspondingly, to a periodic dependence of the conductivity of a ring on the strength of the electrostatic potential. However, this dependence on the voltage (V_g) on special gates along the conducting channels, has not been observed in submicron metal rings.[8,9] Furthermore, a periodic dependence of the resistance on the gate voltage has not been observed in submicron GaAs/AlGaAs rings

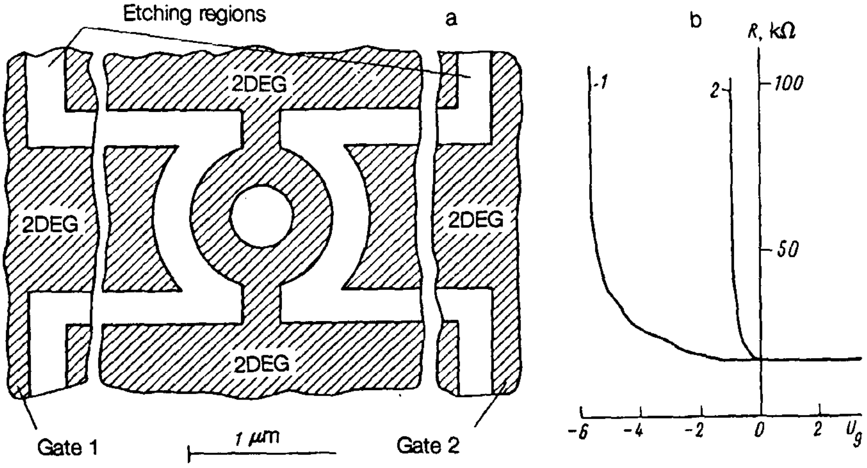

FIG. 1. a: Schematic diagram of the electron interferometer. b: Resistance of the interferometer versus the gate voltage at $T=4.2$ K. 1—Plot of R versus the voltage on gate 1; 2—R versus the voltage on gate 2.

with a planar gate.[10] Experimentally, the effect of the gate voltage is seen as a reversible shift of the h/e oscillations in the magnetic-field dependence on the voltage V_g (Refs. 8 and 10). This effect might be caused by not only the electrostatic Aharonov–Bohm effect, but also an effect of the gate voltage on the realization of the scattering potential and on the electron Fermi energy.

In this letter we are reporting the use of a mesoscopic microwave emf to study the effect of an electrostatic field on electron interference in submicron GaAs/AlGaAs rings. The microwave emf differs from the conductance in having a higher sensitivity, since in our case there is no average component, and this emf can be used successfully to study coherence properties in submicron conductors.[2,11,12]

The test samples were prepared from GaAs/AlGaAs heterojunctions in which the 2D electron gas had an electron density $N_s=(7-9)\times 10^{11}$ cm^{-2} and a mobility $\mu=10^5$ cm^2/(V·s) at $T=4.2$ K. The rings were fabricated by electron-beam lithography and reactive ion etching. The lithographic dimensions of the interferometer are shown in Fig. 1a. The effective diameter of the rings and the effective width of the conducting channels were determined experimentally:[12,13] $d_{\mathrm{eff}}=600$ –700 nm and $W_{\mathrm{eff}}=15-60$ nm. Electrical properties of similar interferometers were described in Ref. 13. The samples had two ohmic contacts to the ring and two gates, positioned along conducting channels of the interferometer. The gates were formed on the basis of a 2D electron gas (2DEG) in the heterojunction and were fabricated along with the ring in the same technological process.

Figure 1b shows the resistance R of one of the test samples versus the voltage on the gates with respect to the grounded ohmic contact. These measurements were carried out in a two-point arrangement. The resistance R includes the total resistance of the two ohmic contacts, of the conducting lines, and of the ring itself. The total resistance of the two ohmic contacts was about 10 kΩ. At gate voltages $V_{g1}<-1$ V and $V_{g2}<-6$ V, the

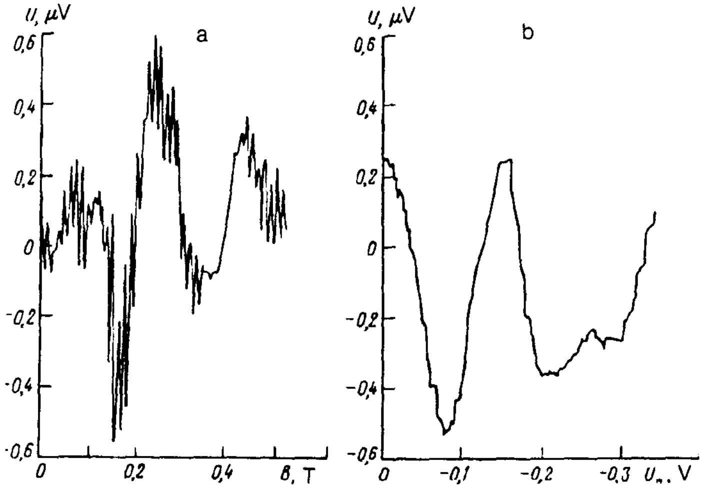

FIG. 2. a: Microwave voltage versus the magnetic field. $f = 9$ GHz, $T = 1.6$ K. b: Microwave voltage versus the voltage on gate 2. $f = 9$ GHz, $T = 1.6$ K.

interferometer went into a nonconducting state with $R > 100$ kΩ. The particular features of the individual gates are apparently responsible for the difference between the $R(V_{g1})$ and $R(V_{g2})$ curves. Qualitatively, the same behavior was observed on another interferometer. During cyclic heating (to $T = 300$ K) and cooling (to $T = 4.2$ K), the resistance of the interferometers changed by a few kilohms. The realization of the random scattering potential changed in the process.

The curves of the magnetic-field dependence $R(B)$ in the temperature interval $T = 1.6-4.2$ K are similar to those reported in Ref. 12. The interference component of the resistance is small, on the order of 5×10^{-3} of the resistance at $B = 0$ T. We were not able to detect reproducible fluctuations of R as a function of V_g because of the small signal-to-noise ratio.

The microwave voltage was measured at temperatures of 1.6–4.2 K in magnetic fields B up to 1 T at microwave frequencies from 8 to 80 GHz. The microwave power in the frequency range 8–12 GHz was fed to the sample by coaxial cable, while that in the range 37–80 GHz was fed by a waveguide. The voltage signal was taken from ohmic contacts and measured by a phase-sensitive nanovoltmeter.

Figure 2 shows the voltage V as a function of B and the voltage on the second gate, V_g. On the magnetic-field dependence there are a periodic component (h/e oscillations) and an aperiodic component. The average amplitude of the aperiodic fluctuations is 3–4 times that of the periodic ones. The curves of $V(V_g)$ have only an aperiodic component, with an amplitude comparable to that of the aperiodic component on the $V(B)$ curve.

The measurements of $V(V_g)$ were taken over the voltage interval from -0.3 to 0 V, in which R remained essentially constant. In this interval of gate voltages, at liquid-helium temperatures, the fluctuations of $V(V_g)$ are reproducible many times. A broaden-

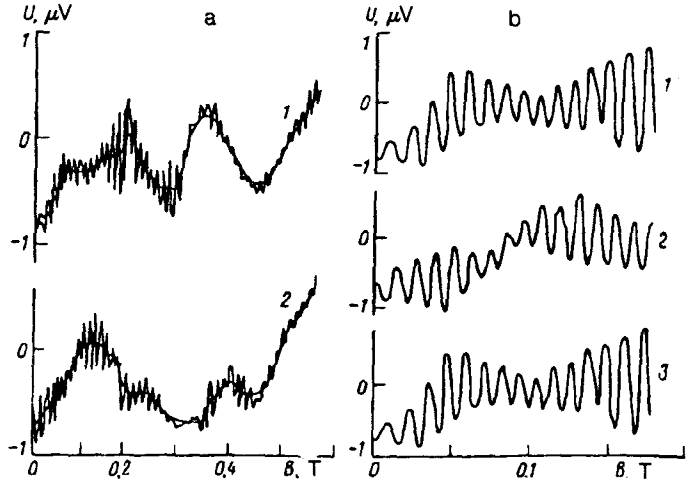

FIG. 3. a: Microwave voltage versus the magnetic field for various gate voltages. 1—$V_g=0$ V; 2—-0.1 V. $f=9$ GHz, $T=1.6$ K. b: Reversible shift of the h/e oscillations in a magnetic field versus the gate voltage. 1—$V_g=0$ V; 2—-0.1 V; 3—0 V. $f=9$ GHz, $T=1.6$ K.

ing of the V_g interval to -0.8 V resulted in a hysteresis on the plot of $V(V_g)$. This hysteresis is evident of an irreversible change in the realization of the random scattering potential in the channels of the ring due to the electrostatic field. After the V_g interval is narrowed to -0.3 V, the fluctuations become reproducible again, but now for a different configuration of the scattering potential. This conclusion is supported by the curves of the magnetic-field dependence $V(B)$. The $V(B)$ curves in Figs. 2a and 3a correspond to different realizations of the scattering potential. The resistance of the interferometer is essentially the same for these realizations.

Figure 3 demonstrates the effect of the gate voltage on the aperiodic and periodic components of the magnetic-field fluctuations. The aperiodic component was singled out numerically with the help of a binomial filter. It can be seen from Fig. 3a that the application of V_g results in a transformation of the aperiodic fluctuations. After the gate voltage is turned off, the $V(B)$ curve reverts to its original shape. For the periodic component we observe a reversible shift of the h/e oscillations in a magnetic field as a function of V_g, as shown in Fig. 3b. A similar behavior of the h/e oscillations as a function of V_g has been seen previously for metallic submicron rings with charge carriers in a diffusive transport regime. In this case the fluctuation potential in the coherent processes is the governing factor.[8]

Let us examine the experimental data. It can be seen from the magnetic-field dependence that the aperiodic component is larger than the periodic one by a factor of 3 or 4. This result indicates that, again in the quasiballistic regime, the random scattering potential has the governing effect on the electron interference. Although the amplitude of the aperiodic component is considerably smaller than that of the periodic one, the h/e oscillations in the magnetic field can be seen clearly. They are evidence of a magnetic

Aharonov–Bohm effect in the quasiballistic interferometer. It is observed because the correlation magnetic fields B_c for the periodic and aperiodic components of the microwave voltage differ by nearly an order of magnitude, in accordance with the areas of a circle with a diameter of 600–700 nm and of a ring 15–60 nm wide, of the same diameter. This relationship between the correlation magnetic field of the aperiodic component and the period of the h/e oscillations makes it possible to correctly separate the components in the curves of the emf versus B.

The aperiodic nature of the dependence of the emf on the gate voltage (on the one hand) and the fact that the average fluctuation amplitude $V(V_g)$ has approximately the same value as the amplitude of the aperiodic magnetic-field fluctuations (on the other) indicate that we are observing only a random dependence of the emf on V_g. The periodic component should be smaller by a factor of 3 or 4, according to the relationship between the amplitudes of the components on the $V(B)$ curves. The apparent reason why it is not seen on the $V(V_g)$ curves is that, in contrast with plots versus the magnetic field, on which the correlation magnetic fields of the components are quite different in magnitude, the correlation gate voltages for the different mechanisms for the effect on the electron interference—these voltages are proportional to the correlation energies E_c—are approximately the same. For quasi-1D mesoscopic systems we have $E_c \sim 1/L_\phi$ if $L_\phi < L$ and $E_c \sim 1/L$ if $L_\phi > L$, where L is the length of the conductor, and L_ϕ is the coherence length.[14] The conducting channels of the interferometer are quasi-1D channels. In this case the correlation energy of the electrons for the different mechanisms by which V_g affects the coherent processes will be determined by the value of L_ϕ ($E_c \sim 1/L_\phi$), since the condition $L_\phi < d_{\text{eff}}$ holds in the temperature range studied.

The arguments above are supported by the following experimental results. The value found for $\Delta V_g \sim E_c$ from the decay half-life of the autocorrelation function $F(\Delta V_g)$ of the $V(V_g)$ curve is about 0.1 V. The same gate voltage is required for a shift of the h/e oscillations by an amount π (Fig. 3b) and for a halving of the correlation function $F(B,\Delta V_g)$ of the aperiodic components of the magnetic-field dependence $V(B)$.

In summary, this study has shown that the effect of an electrostatic field on electron interference in a quasiballistic interferometer stems from the dominant role played by the fluctuation potential, because of the comparable correlation energies for different mechanisms by which the gate voltage affects coherent processes.

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