Aharonov–Bohm effect in a quasiballistic electronic interferometer in a transverse electrostatic field

A. A. Bykov,[1] L. V. Litvin, and S. P. Moshchenko
Institute of Semiconductor Physics, Siberian Branch of the Russian Academy of Sciences, 630090 Novosibirsk, Russia

(Submitted 11 April 1995; resubmitted 4 May 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **61**, No. 12, 974–979 (25 June 1995)

The effect of a transverse electrostatic field on the interference of electronic waves in a submicron GaAs/AlGaAs loop was investigated. It was found that the mesoscopic microwave emf is a periodic function of the gate voltage. The experimental results are explained by an increase of the phase difference between the components of the electronic wave function in the channels of the interferometer under the action of an electrostatic field on one of the channels. © *1995 American Institute of Physics.*

One method for investigating coherent processes in submicron conductors is the mesoscopic photovoltaic effect.[1-3] This effect arises under the action of microwave radiation in disordered conductors whose dimensions are smaller than or comparable to the phase coherence length L_{ph} of the electrons. In such conductors, which are called mesoscopic, there is no inversion center because of the random arrangement of the scattering impurities and a microwave field produces an emf. The magnitude of this emf is determined by the specific arrangement of the scattering centers, and in simply connected mesoscopic conductors it is a random function of the magnetic field (B) and the Fermi energy (E_F),[1,4] and for the same realization of the random potential it is always reproduced. The microwave emf is more sensitive to coherent processes in mesoscopic systems than is the resistance, and the use of the microwave emf for the investigation of these processes is justified under conditions where the interference component in the conductivity is small.

Investigations of the mesoscopic photovoltaic effect in a quasiballistic electronic interferometer have shown that in contrast to simply connected microconductors, the microwave emf in submicron loops has also an aperiodic dependence on B a periodic dependence whose period corresponds to the change in the magnetic flux through the area of the loop by an amount equal to the flux quantum[5] $\Phi_0 = h/e$. However, the dependence of the emf on the gate voltage (V_g), with the gate arranged along one of the channels of the interferometer, was aperiodic.[6] The periodic component could not be observed in a narrow range of gate voltages, since the characteristic scale of the aperiodic fluctuations was of the same order of magnitude as the period of the oscillations as a function of V_g.

In the present work the effect of both magnetic and transverse electrostatic fields on coherent processes in a quasiballistic electronic interferometer was investigated by means of the mesoscopic photovoltaic effect. It was found that the dependence of the microwave emf on the electrostatic field, just as on a magnetic field, has both aperiodic and periodic components. A method is proposed for separating these components in a narrow range of values of V_g.

The quantum-mechanical effect of electrostatic and magnetic fields on the interference of electronic waves is that the electromagnetic potential shifts the phase of the wave function of an electron by the amount $\Delta\phi = e/\hbar \int(\varphi dt - A ds)$, where φ and A are, respectively, the scalar and vector potentials, and dt and ds are the elements of the time and path along the trajectory of the electron. According to this formula, both a transverse electrostatic field applied to one channel of the loop and a magnetic field directed perpendicular to the plane of the loop should lead to a periodic change in the conditions of interference and, correspondingly, to oscillations of the resistance and microwave emf in submicron loops. In addition, the magnetic-field h/e oscillations should change phase under the action of the gate voltage, and the oscillations as a function of V_g should be shifted under the action of a magnetic field, as was recently determined in an investigation of the interference of ballistic electrons on two slits in a GaAs/AlGaAs microstructure.[7] However, such a complete and symmetric picture of the effect of electrostatic and magnetic fields on the direct interference in submicron loops has not been observed in experimental studies of the electrostatic Aharonov–Bohm effect.[8-10] This is associated mainly with electron scattering by the random potential of the impurities and defects and with the multimode regime in the interferometer channels.[6,8-10] The imperfection of the conducting channels of the loop causes not only h/e oscillations but also aperiodic mesoscopic fluctuations to appear in the magnetic-field dependences of the resistance (R) or microwave emf (V). Their characteristic scale δB as a function of the magnetic field is comparable to or greater than the period of the h/e oscillations. To separate these components correctly by numerical methods (for example, by Fourier analysis), magnetic fields $\Delta B \gg \delta B$ are required. This is easily achievable experimentally. In this range the aperiodic and periodic components can be separated even when the amplitude of the aperiodic fluctuations is much greater than the amplitude of the h/e oscillations.[11]

A somewhat different situation arises when a gate voltage is applied. The scale δV_g of the aperiodic fluctuations and the expected period of the oscillations as a function of V_g were found to be comparable to the range of admissible gate voltages which is limited by the condition that when the voltage is removed, the initial $V(B)$ curve is once again obtained. In this case, the different components in the dependences on V_g cannot be separated by Fourier analysis.[6] This problem can be solved by making use of the fact that the oscillations arising in an electrostatic field as a result of the direct interference in the loop for magnetic fluxes Φ differing by $\Phi_0/2$ should be out of phase. Within the change of the aperiodic component in the interval of magnetic fields $\pi r^2 \Phi_0/2$ (where r is the radius of the loop), the periodic and aperiodic components in the gate-voltage dependences $V(V_g)$ are therefore determined by the following expressions: $[V(V_g,\Phi) - V(V_g,\Phi+\Phi_0/2)]/2$ and $[V(V_g,\Phi)+V(V_g,\Phi+\Phi_0/2]/2$, respectively.

The accuracy of this method depends on the ratios of the amplitudes of the components and on the ratios of the quantities r and W (where W is the width of the loop). For the experimental samples used in this work $r \gg W$. For this ratio of the geometric dimensions of the loop the aperiodic component in a magnetic field changes little over the period of the h/e oscillations, since the scale of the aperiodic fluctuations $\delta B \gg \pi r^2 \Phi_0$, and therefore this method can be used to separate the components. The acceptable conditions for separating the components can be obtained by finding a realization of the random potential for which there are sections of magnetic fields with comparable amplitudes of the components by repeatedly heating the sample to room temperature and cooling it again. This approach can be easily implemented by performing experiments at $T=4.2$ K. At this temperature, however, the amplitude of the h/e oscillations in the resistance of the loops is small and it is better to use the more sensitive microwave emf to investigate coherent processes.

The experimental samples used in this work were fabricated on GaAs/AlGaAs heterojunctions with the following parameters of the two-dimensional electron gas at $T=4.2$ K: electron mobility $\mu=10^5$ cm^2/Vs and electron density $N_s=(7-9)\times 10^{11}$ cm^{-2}. The loops were fabricated by electron-beam lithography and reactive ion etching. The electronic lithography was conducted in a scanning electron microscope using the PROXY scanning system. The effective diameter of the loops and the effective width, determined experimentally,[5,12] were as follows: $d_{\text{eff}}=600-700$ nm and $W_{\text{eff}}=15-60$ nm. The topology and the electrical properties of such interferometers were described in Refs. 6 and 12. The samples had two ohmic contacts to the loop and two gates, arranged, as in Ref. 8, along the conducting channels of the interferometer. The gates were formed on the basis of the two-dimensional electron gas in the GaAs/AlGaAs heterojunction.

The measurements of the microwave emf were performed at $T=4.2$ K in magnetic fields up to 1.5 T at frequencies f from 8 to 12 GHz. The microwave radiation was fed to the sample by a coaxial cable. The measurement procedure was as follows. One ohmic contact and the gate were grounded. The emf signal (V) was obtained from the other ohmic contact and recorded with a phase-sensitive nanovoltmeter. A constant voltage V_g was applied to the second gate. The resistance R_0 of the loop in a zero magnetic field at $T=4.2$ K was equal to approximately 10 kΩ. In the cycles of heating up to 300 K and cooling to 4.2 K, R_0 changed by several kΩ. The realization of the random potential also changed. The magnetic-field dependences $R(B)$ at $T=4.2$ K were similar to those presented in Ref. 5. The amplitude of the h/e oscillations was small and equal to a fraction $\sim 5\times 10^{-3}$ of the resistance R_0.

Just as in Refs. 5 and 6, the magnetic-field dependences $V(B)$ had periodic and aperiodic components. The amplitude of the aperiodic component was three to four times greater than the h/e oscillations in a wide range of magnetic fields. However, narrow sections of magnetic fields, where the amplitude of the h/e oscillations predominated, were present. The gate-voltage dependences $V(V_g)$ were measured for values of V_g from 0 to -0.3 V, where the resistance of the loop changed very little. In this range of V_g the fluctuations of $V(V_g)$ at $T=4.2$ K were reproduced consistently. When the range of gate voltages V_g was extended, an irreversible change of the random potential occurred. This was confirmed by the change in the form of the magnetic-field dependences $V(B)$. The realization of the random scattering potential could also be changed by illuminating the sample with the help of a light-emitting diode.

Figure 1 shows the function $V(B)$ for a realization of the scattering potential for which this dependence initially exhibits predominantly h/e oscillations. The aperiodic component for this realization of the random potential is virtually independent of B. As

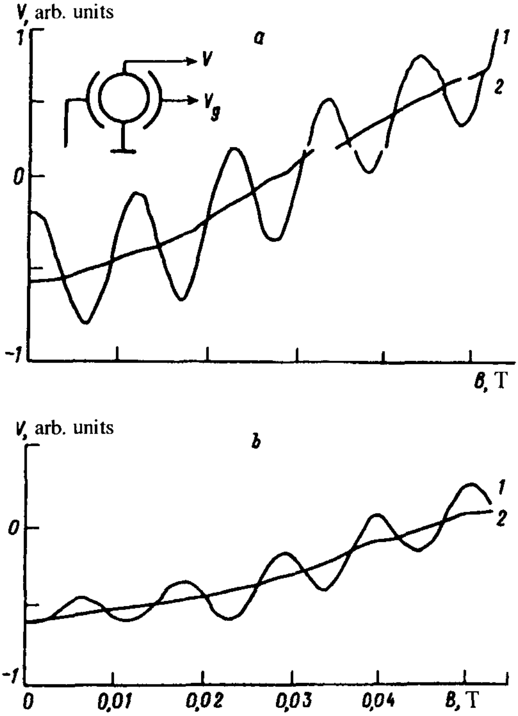

FIG. 1. Electromotive force versus B for different values of V_g ($T=4.2$ K, $f=9$ GHz): a — $V_g=0$ V, *1* — experimental curve, *2* — aperiodic component; b — $V_g=-0.1$ V, *1* — experimental curve, *2* — aperiodic component. Inset: Measurement scheme.

one can see from the figure, the gate voltage $V_g \approx -0.1$ V produces a shift of the magnetic-field oscillations by apporoximately π and leads to a very small transformation of the aperiodic component. Similar behavior has been observed in submicron metal loops.[8]

The functions $V(V_g)$ for different magnetic fields and the same configuration of the scattering potential are shown in Fig. 2a. The functions $V(V_g)$ for magnetic fluxes differing by one quantum h/e are identical within the increment associated with the aperiodic component in the $V(B)$ curve, and they are out of phase for magnetic fluxes through the loop which differ by $h/2e$. The distance between the points of intersection of the out-of-phase functions is equal to half the period of the oscillations as a function of V_g. The aperiodic and periodic components, separated from the curves $V(V_g,\Phi)$ and $V(V_g,\Phi+\Phi/2)$ by the method described above, are shown in Fig. 2b. Within the experimental error, the periodic component is a sine curve with the period $V_g \approx 0.24$ V.

Acceptable conditions for separating the periodic component in the functions $V(V_g)$ for other sections of the magnetic field also can be obtained by illuminating the sample or heating it up to 300 K and again cooling it to 4.2 K. Such conditions are realized on magnetic-field sections where the aperiodic component on the curve $V(B)$ is

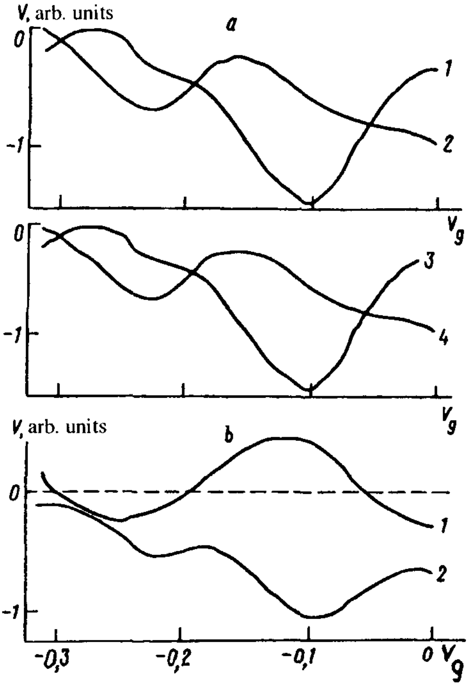

FIG. 2. Electromotive force versus V_g for different values of B ($T=4.2$ K, $f=9$ GHz): a — Measured gate voltage dependences $V(V_g)$: *1* — $\Phi=0$, *2* — $\Phi=\Phi_0/2$, *3* — $\Phi=\Phi_0$, *4* — $\Phi=\frac{3}{2}\Phi_0$; b — Periodic *(1)* and aperiodic (2) components.

small and changes very little when the voltage V_g is applied. The curves shown in Fig. 3a correspond to one such section of the magnetic field. In this case we were able to separate the periodic component in a somewhat larger range of values of V_g. The functions $V(V_g)$ for magnetic fluxes differing by $h/2e$ are out of phase, just as in the preceding case. The period and aperiodic components are shown in Fig. 3b. The period of the

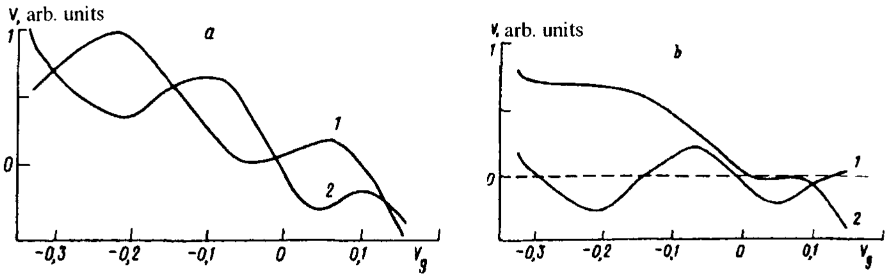

FIG. 3. Electromotive force versus V_g for different values of B and a different realization of the scattering potential ($T=4.2$ K, $f=9$ GHz): a — Measured curves $V(V_g)$. *1* — $\Phi=10.5\Phi_0$, *2* — $\Phi=11\Phi_0$; b — periodic *(1)* and aperiodic *(2)* components.

oscillations is somewhat larger: $V\approx 0.28$ V. This can be explained by the fact that in this case, as compared to the preceding one, not only the realization of the random potential changed but the geometry of the conducting channels of the loop and of the gates changed because of the irreproducibility of the depletion regions.

The fact that the gate-voltage dependences in Fig. 2a are in-phase for magnetic fluxes differing by h/e and out of phase for fluxes differing by $h/2e$ indicates that we are observing the effect of V_g on the direct interference of electronic waves propagating along different channels of the loop. This is also confirmed by the magnetic-field dependences in Fig. 1. As one can see from the figure, the h/e oscillations are in out of phase for gate voltages differing by 0.1 V, which approximately corresponds to the half-period of the curve $V(V_g)$ in Fig. 2b.

In contrast to Refs. 13 and 14, in the geometry of our experiment the mechanism of the action of an electrostatic field on the direct interference in a loop can be not only a change in E_F in one of the electronic channels but also a change in the length of the channel. Since the gate voltage acts directly on one arm of the interferometer, the phase difference between the wave functions in channels which are not equivalent with respect to the electrostatic field will be determined by the expression $\Delta\phi\approx\pi r_{\mathrm{eff}}\Delta k_F+k_F\Delta L$, where Δk_F is the change in the wave number of the electrons at the Fermi surface, and ΔL is the change in the length of the arm under the action of the gate voltage. If it is assumed that $\Delta\phi$ is determined by the second term, then the gate voltage corresponding to $\Delta\phi\sim 2\pi$ should change the area of the loop as a result of a change in the length of the channel by an amount of the order of 10^{-2}. However, our investigations of the periodic component under the conditions when the magnetic flux through the loop was $\Phi>100\Phi_0$ did not give an appreciable change in the period as a function of V_g. This shows that the gate voltage does not change the length of the arm appreciably but that it changes only E_F.

In summary, coherent processes in a submicron GaAs/AlGaAs loop in the presence of a transverse electrostatic field were studied by using the mesoscopic microwave emf. It was found that the microwave emf as a function of the gate voltage, just as the magnetic-field dependence, has aperiodic and periodic components. It was determined that the action of an electrostatic field on one channel of the interferometer changes the phase difference between the electron waves in different arms of the interferometer by at least 2π, i.e., it has been shown experimentally that there are no fundamental obstacles to producing a quantum interference transistor.

In conclusion, we wish to thank A. L. Aseev and M. R. Baklanov for encouragement. We also thank E. B. Ol'shanetskiĭ, Z. D. Kvon, and A. Govorov for a helpful discussion of the results, and A. O. Minaev for technical assistance in the experiments.

The investigations whose results are reported in this paper were made possible by a grant (No. U84000) from the International Science Foundation and grant No. 95-02-04409-a from the Russian Fund for Fundamental Research.

[1] e-mail:byko@ispht.nsk.su

---

[1] V. I. Fal'ko and D. E. Khmel'nitskiĭ, Zh. Éksp. Teor. Fiz. **95**, 328 (1989) [Sov. Phys. JETP **68**, 186 (1989)].

[2] A. A. Bykov, G. M. Gusev, Z. D. Kvon *et al.*, JETP Lett. **49**, 13 (1989).
[3] J. Liu, M. A. Pennington, and N. Giordano, Phys. Rev. B **45**, 1267 (1992).
[4] A. A. Bykov, G. M. Gusev, Z. D. Kvon, and B. I. Fomin, Zh. Éksp. Teor. Fiz. **97**, 251 (1990) [Sov. Phys. JETP **70**, 140 (1990)].
[5] A. A. Bykov, Z. D. Kvon, L. V. Litvin *et al.*, JETP Lett. **58**, 543 (1993).
[6] A. A. Bykov, Z. D. Kvon, L. V. Litvin *et al.*, JETP Lett. **60**, 809 (1994).
[7] A. Yacoby, M. Heiblum, V. Umansky *et al.*, Phys. Rev. Lett. **73**, 3149 (1994).
[8] S. Washburn, H. Schmid, D. Kern, and R. Webb, Phys. Rev. Lett. **59**, 1791 (1987).
[9] C. J. B. Ford, A. B. Fowler *et al.*, Surf. Sci. **229**, 307 (1990).
[10] J. Liu, W. X. Gao, K. Ismail *et al.*, Phys. Rev. B **48**, 15148 (1993).
[11] R. A. Webb, S. Washburn, C. P. Umbach, R. B. Laibowitz *et al.*, Phys. Rev. Lett. **54**, 2696 (1985).
[12] A. A. Bykov, Z. D. Kvon, E. B. Ol'shanetskiĭ *et al.*, JETP Lett. **57**, 613 (1993).
[13] S. Bandyopadhyay and W. Porod, Appl. Phys. Lett. **53**, 2323 (1988).
[14] S. Data, Superlattices and Microstructures **6**, 83 (1989).

Translated by M. E. Alferieff