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Coherent properties of in plane gated submicron rings in a small-signal regime

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Abstract

We report the results of experimental investigation of coherent properties of in plane gated InGaAs/AlGaAs submicron rings in a small-signal regime. The magnetic field dependences of the differential resistance dR_{SD}/dV_G (V_G is the gate voltage) and the microwave EMF dV_{EMF}/dV_G were measured in magnetic fields up to 2 T at temperatures $T = 4.2$ K. It was shown that for the coherent processes the conditions of small signal were met when the Fermi energy modulation amplitude (δE_F) in the channels of the ring did not exceed the correlation energy E_c, $\delta E_F < E_c$. Under these conditions the averaged component in $dR_{SD}(B)/dV_G$ dependences (in contrast to $R_{SD}(B)$ dependences) was comparable with the interference component involving aperiodic fluctuations and *h*/*e* oscillations.

Keywords: Electron interferometer; Aharonov–Bohm effect; Heterojunction

1. Introduction

Coherent properties of a ring solid state analog to the optical Mach–Zender interferometer – a so called interference transistor, have been experimentally investigating for more than 10 years [1,2]. Nevertheless the magnetotransport properties of submicron rings with metallic conductivity in a small-signal regime remains unstudied up to now. In the present work it is shown that such investigations make it possible, on one hand, to estimate the transistor properties of such devices, and on the other hand, to study coherent processes in solid state structures in detail.

2. Experimental

Experimental samples have been fabricated on the basis of InGaAs/AlGaAs heterojunctions grown by molecular beam epitaxy by means of electron lithography and subsequent reactive ion etching. The parameters of a two-dimensional electron gas (2DEG) in the initial InGaAs/AlGaAs heterojunctions at $T = 4.2$ K were $N_s = (7–10) \cdot 10^{11}$ cm^{-2}, $\mu = (5–10) \cdot 10^4$ cm^2/V s. The effective geometrical radius of rings determined from the period of *h*/*e*-oscillations was $r_{eff} \approx (0.2–0.35)$ μm.

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A schematic view of in plane gated ring is presented in the inset of Fig. 1(a). Black regions in the figure are the etched areas. The rings have current and voltage probes and two gate electrodes situated by the conducting channels.

The magnetic field dependences of differential (with respect to the gate voltage V_G) resistance dR_{SD}/dV_G and microwave EMF dV_{EMF}/dV_G in magnetic fields $B \leqslant 2$ T at $T = 4.2$ K have been investigated. A sinusoidal signal $V_{G1} = V_0 \sin(2\pi f t)$ was applied at one of the gate electrode, while the other one was either grounded or held at a constant potential V_{G2}. A signal proportional to dR_{SD}/dV_{G1} or to dV_{EMF}/dV_{G1} was measured from the ohmic contacts to a ring at the frequency f of sinusoidal modulation of the gate voltage. In the first case the sample was held at a constant voltage $V_{SD} \leqslant kT/e$, and in the second case it was subjected by the microwave irradiation in the frequency range $\omega/2\pi = (1–145)$ GHz. In the low-frequency range (1–10) GHz the coaxial cable was used to apply the microwave irradiation, while in the high-frequency range (37–145) GHz the wave guide was used. The value of the microwave power was chosen such that overheating of electron gas was much less than equilibrium temperature ($\Delta T_e \ll T$).

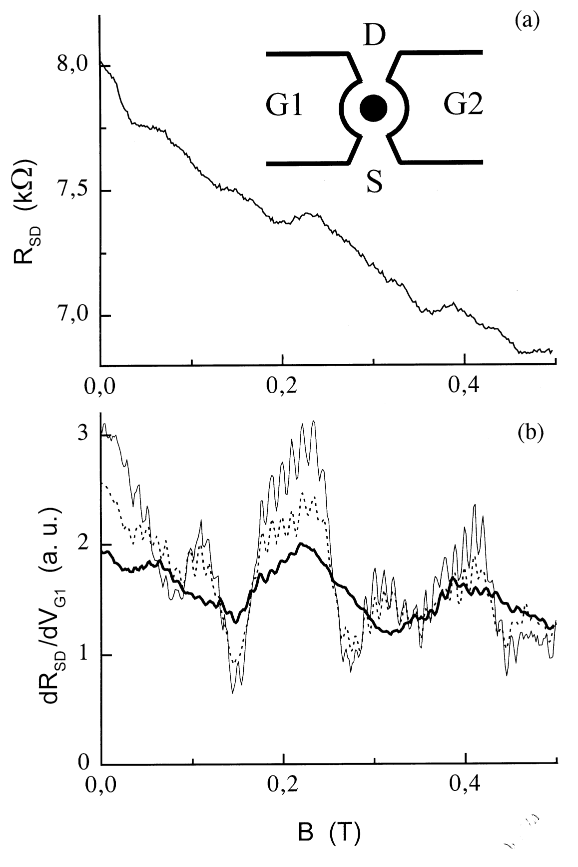

Fig. 1. (a) Magnetic field dependence of the ring resistance R_{SD}. (b) Magnetic field dependences of dR_{SD}/dV_{G1} for three different amplitudes of sinusoidal voltage: thick line $V_0 = 0.28$ V, dotted line $V_0 = 0.07$ V, thin line $V_0 = 0.014$ V. Temperature $T = 4.2$ K. Inset shows the schematic top view of the device.

3. Results and discussion

A typical magnetic field dependence of InGaAs/AlGaAs-ring resistance is presented in Fig. 1. In the dependence $R_{SD}(B)$ an aperiodic component is clearly seen due to the interference of electron waves on the scattering potential of the conducting channels of the ring, while the h/e-oscillations are practically not observed on the background of the big classical component. Fig. 1(b) shows $dR_{SD}(B)/dV_{G1}$ curves for different values of the amplitude of sinusoidal voltage (V_0) applied across the gate G1. It is seen that magnetic field dependences $dR_{SD}(B)/dV_{G1}$ as well as the $R_{SD}(B)$ dependence contain averaged and aperiodic components. Besides, in contrast to $R_{SD}(B)$, in the $dR_{SD}(B)/dV_{G1}$ dependences h/e-oscillations are well-advanced.

Magnetic field dependences of different components of $dR_{SD}(B)/dV_{G1}$ for the minimal value of V_0 are presented in Fig. 2(a), while the dependences of their mean-square amplitudes on V_0 are shown in Fig. 2(b). The observed behavior of the components of $dR_{SD}(B)/dV_{G1}$ as functions of B and V_0 allow us to conclude that there are at least two mechanisms of the influence of V_G on the ring conductivity. One of them results from the classical modulation of conductivity of the ring channels due to the change in the electron density. This mechanism shows itself in dR_{SD}/dV_G as magnetic field averaged component, the amplitude of which is practically independent of the value of V_0 in the voltage region investigated. The other mechanism is of the quantum-mechanical origin, and is

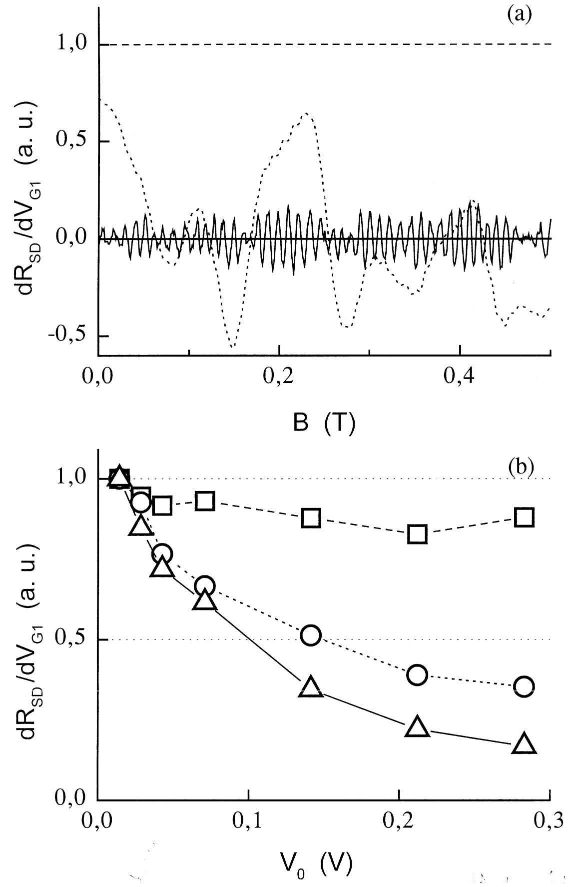

Fig. 2. (a) Magnetic field dependences of the components of dR_{SD}/dV_{G1}. Dashed line is the averaged component, dotted line is the aperiodic one, and the solid line is *h*/*e*-oscillations. (b) Mean square amplitudes of dR_{SD}/dV_{G1} as functions of V_0. Squares correspond to the averaged component, circles – to the aperiodic one, triangles – to the periodic one.

connected with the gate voltage modulation of the interference conditions for the electron waves in the ring. As in Refs. [1,2] the variation of V_G can affect the phase of the electron wave function in the ring in two ways. It can change the form of the electron trajectories in the ring and also change the electron density and hence the Fermi wavelength. The overall phase shift is given by the expression: $\Delta\varphi_G \approx 2\pi r_{rm}\ \Delta k_F + k_F\ \Delta L$, where Δk_F is the corresponding variation of the Fermi wave vector, ΔL is the variation of a typical electron trajectory in the ring and r_{rm} is the average radius of the ring. The magnetic field also makes a contribution to the phase shift $\Delta\varphi_B \approx 2\pi\Phi e/h$, where Φ is the magnetic flux through the area of the ring. It is clear that the small-signal condition is fulfilled when $\delta\varphi_G \ll 2\pi$, where $\delta\varphi_G$ is the amplitude of the phase shift variation produced by the variation of the gate voltage. Since $\delta\varphi_G \sim V_0$, the decrease of the mean square amplitudes of periodic and aperiodic components with the increase of V_0 (Fig. 2(b)) means the breaking of the small-signal conditions. Arbitrarily, the small-signal condition can be considered as fulfilled for the values of V_0 lower than V_0^c, where V_0^c corresponds to the half-fall of the curves in Fig. 2(b). It should be noted that the values of V_0^c for periodic and aperiodic components differ not more than by a factor of 1.5, while the magnetic field scales of fluctuations of dR_{SD}/dV_{G1} and of *h*/*e*-oscillations differ at least by a factor of 10. Such behavior can be explained by the quasiballistic regime of electron transport when the mean free path is comparable with the length of interferometer arms, $l_p \sim \pi r_{eff}$. This is in agreement with initial parameters of 2DEG and interferometer dimensions. In spite of the quasibalistic regime of electron transport, the presence of the aperiodic component in dR_{SD}/dV_{G1} exceeding the periodic one in amplitude point to the dominating role of the scattering potential in coherent processes in the rings investigated. This should give rise to the effects connected with the absence of the inversion symmetry, such as rectification [3] and mesoscopic photovoltaic effect [4,5]. The difference of the dR_{SD}/dV_{G1} dependences measured for different directions of current I_{SD} (Fig. 3(a)) resulted from the rectification effect support this fact. Fig. 3(b) shows the differential microwave EMF for $\omega/2\pi = 2$ GHz as the function of B. One can see a complete correlation between the rectification and EMF at the frequency of 2 GHz, which is absent for higher frequencies.

Correlational characteristics of the curves dV_{EMF}/dV_{G1} measured at different $\omega/2\pi$ and V_{G2} are presented in Fig. 4. The comparison of Fig. 2(b) and Fig. 4 leads to conclusion that the small-signal condition connected with quantum-mechanical mechanism is fulfilled when the Fermi energy modulation by the gate voltage does not exceed the correlation energy of the system, which is of the order of kT (70 GHz) for our case.

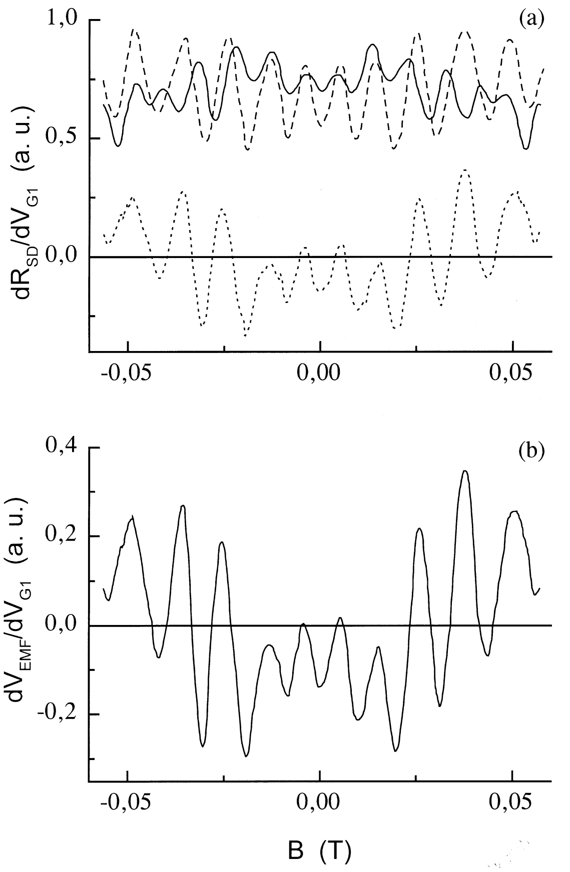

Fig. 3. (a) Magnetic field dependences of dR_{SD}/dV_{G1} for positive (solid line) and negative (dashed line) signs of current I_{SD}. Dotted line is the difference between them. (b) Magnetic field dependence of dV_{EMF}/dV_{G1} at $\omega/2\pi = 2$ GHz. Temperature $T = 4.2$ K.

4. Conclusion

It was shown that the small-signal condition for InGaAs/AlGaAs in plane gated rings is met if the value of the Fermi energy modulation due to the gate voltage variations does not exceed the correlation energy of the system. Under these conditions the modulation technique can be used to investigate coherent processes. By means of the modulation technique it was established that for the

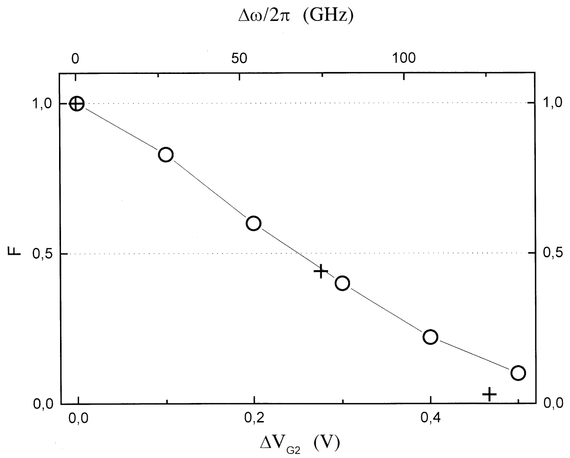

Fig. 4. The value of correlation (F) between the $dV_{EMF}(B)/dV_{G1}$ curves measured at different frequencies $\omega/2\pi$ (crosses) and gate voltages V_{G2} (circles).

microwave quantum energies lower than kT the mesoscopic photovoltaic effect results from the rectification effect inherent in a mesoscopic system.

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References

[1] S. Washburn, H. Schmid, D. Kernaud, R.A. Webb, Phys. Rev. Lett. 59 (1987) 1791.

[2] C. Ford, A. Fowler et al., Surf. Sci. 229 (1990) 307.

[3] D.E. Khmel'nitskii, A.I. Larkin, Sov. Phys. JETP Lett. 64 (1986) 1075.

[4] V.I. Fal'ko, D.E. Khmel'nitskii, Sov. Phys. JETP Lett. 68 (1989) 186.

[5] A.A. Bykov, G.M. Gusev et al., JETP Lett. 49 (1989) 13.