kW cm^{-2} at 300 K) in (Zn, Mg) (S, Se) lasers with a CdSe FM active region. (Be, Mg, Zn)Se/ZnCdSe SL QW heterostructure lasers possess the highest characteristic temperature ($T_0 = 340$ K at 300 K) and operating temperature (140°C) in the pulsed mode among those reported in the literature. All the lasers with a CdSe FM active region and SL waveguide exhibited enhanced degradation stability compared to conventional DHS SC QW lasers.

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One-electron transistors based on Coulomb blockade and quantum interference

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The subject of the report are two limiting cases of 'one-electronics'. In the first part, we present the results of the development and study of a type of transistor based on Coulomb blockade, and in the second part, we discuss the concept of a one-electron interference transistor and the first experiments with it.

Transistor based on Coulomb blockade

The basic part of the channel of all the transistors discussed below is a conductor with capacitance C_g that is low compared to the gate capacitance. When the conductor is isolated from the main circuit by tunneling barriers, the conductivity peaks correspond to the removal of the Coulomb blockade of tunneling $C_g V_g + q = (n + 1/2)e$, where n is an integer and q is the constant polarization charge of the Coulomb island [1]. Therefore, to switch the transistor to the neighboring open state, it is necessary to add an elementary charge C_g to the capacitance e. Because the necessary condition for operation of a transistor has the form $e^2/2(C_1 + C_2 + C_g) \gg k_B T$, the capacitances C_1 and C_2 of tunneling transitions should be made as low as possible. The use of a conventional method of shadow masks gives an operating temperature for the transistor of 0.2 K for a lithographic size of 100 nm, while to achieve $T = 4.2$ K, lithography with a resolution of 30 nm would be required. We overcame this difficulty by breaking a titanium nanowire with a rectangular projection, which was previously made on a dielectric substrate (Fig. 1a). Tunneling transitions with a small barrier height (~ 10 meV) were formed by oxidation of a thin titanium film at two 10-nm steps under conditions of oxygen deficiency. For a lithographic size of 150 nm, the capacitances of tunneling transitions decreased to $(10-30)\times10^{-18}$ F due to deviation from the flat condenser geometry. The geometry of the device was controlled by means of a transmission electron microscope with a resolution of several A; for this purpose, the structures were manufactured on thin membranes of silicon nitride on silicon. Figure 1c shows that the transistor exhibits distinct oscillations of the current as a function of the gate voltage at 4.2 K. In accordance with the theory [1] and numerical calculations [2], the peak-to-valley ratio for oscillations increases with decreasing pulling voltage. Thus, the one-electron charging of the Coulomb island and Coulomb blockade were clearly observed (Fig. 1b). Also, random switchings of the conductivity were observed, which corresponded to a change in the polarization charge of the Coulomb island by a few tenths of the elementary charge. Thus, it has been shown that the device operates as a one-electron transistor and its stability has been studied. Note that the rupture of nanowires by a step on the dielectric surface has already been used for manufacturing one-electron diodes, however, this is the first fabrication of a transistor by this method.

Interference two-electron oscillations

A one-electron transistor usually means a transistor based on Coulomb blockade. However, it can be easily shown that interference transistors based on one-dimensional Fermi systems also allow one to realize a mode of counting of electrons added to the active region of the device. Indeed, consider a quantum wire of length L, in which only one miniband of transverse quantization is filled. At zero temperature, the relation between the Fermi wave vector k_F and the electron concentration N_w has the simple form

$$k_F = \frac{\pi}{2} N_w \,. \tag{1}$$

The number of electrons in the wire is $N_L = N_w L$. Taking into account Eqn (1), we obtain that a change in the number of

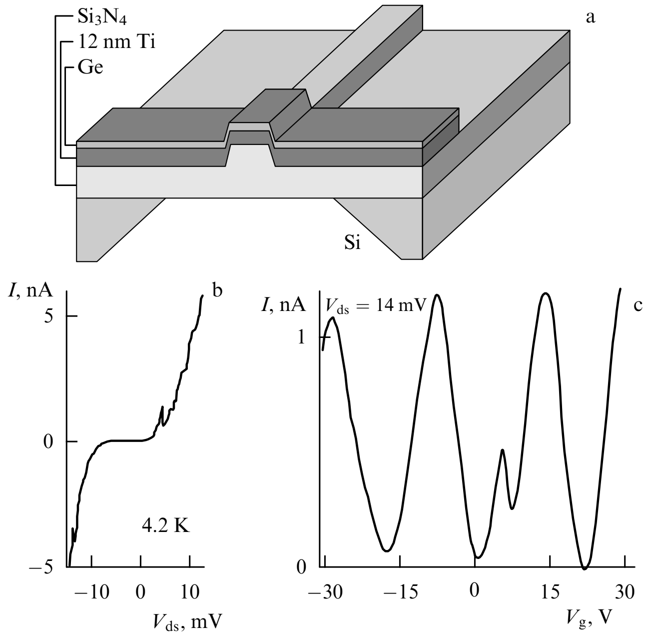

Figure 1. (a) Scheme and (b, c) measured parameters of a one-electron transistor manufactured by the method of rupture of a nanowire by a step.

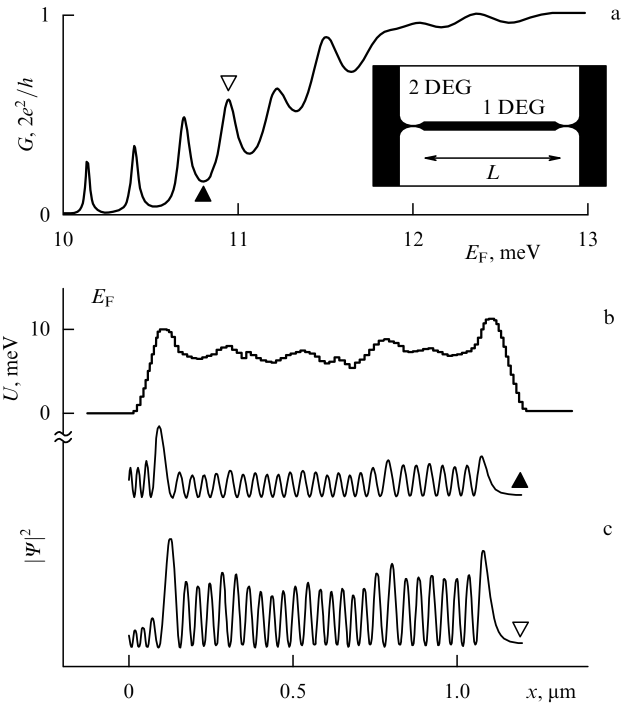

Figure 2. Results of modeling a one-electron Fabry-Perot interferometer [a single-mode quantum wire separated from reservoirs by semi-transparent electronic mirrors (insert)].

electrons in the wire by unity results in the corresponding change in k_F by $\pi/2L$. This property of a one-dimensional electron gas leads to important results for interference transistors based on single-mode electron waveguides.

A variety of types of interference transistors have been suggested, which are mainly based on ring interferometers [3–6]. Below we consider the simplest example of such a device: a quantum wire with two semitransparent barriers separated by a distance L and with a metal gate deposited atop. In a real situation, such barriers may be narrowing at the ends of the wire (insert in Fig. 2). It is obvious that such a device represents an electron analog of the Fabry–Perot interferometer, whose transparency is varied not by moving 'mirror-barriers' but by a small variation of the wavelength of electrons. For example, to transfer the interferometer from the state with high conductance G to the state with low conductance G, or vice versa, the value of $k_F L$ should be change by $\pi/2$, i.e., according to Eqn (1), the number of electrons should be changed by unity.

Figure 2a shows the result of modeling the conductance of a single-mode wire using the Landauer formula:

$$G = \frac{2e^2}{h} T(E_F) ,$$

where T is the coefficient of propagation of an electron between reservoirs and E_F is the Fermi energy. The calculation neglects insignificant effects of coupling between modes of transverse motion at the entrance and exit of the waveguide but takes into account the fluctuation potential with an amplitude about of 1 meV. The wire without mirrors is represented by a one-dimensional barrier of height of about 7 meV and width about 1 μm. A similar situation is realized in experimental structures at characteristic concentrations of two- and one-dimensional gases equal to 3×10^{11} cm^{-2} and 5×10^5 cm^{-1}, respectively, for which the screening of the charged impurities becomes substantial. In the solution of the one-particle Schrödinger equation, the smooth profile of the barrier potential was replaced by a step function (Fig. 2b) as in Ref. [7]. The calculation showed that for characteristic electron energies 10–12 meV, an interferometer with mirror-barriers of height of about 11 meV and width about 0.1μm yields 50% interference modulation. A decrease in the modulation level compared to that in the ideal case occurs due to lowering of one of the barriers from 11 to 10 meV. Thus, despite the displacement of quasi-levels to the region of the continuous spectrum, which corresponds to the classically allowed motion, the resonances remain strong in the case of realistic smearing of barrier edges. Figure 2c shows the dependences of the probability densities on the coordinate for the energies corresponding to 25.5 and 26 de Broglie half waves in the interferometer and to 51 and 52 electrons, respectively, in a one-dimensional electron gas in the quantum wire. The triangles in Fig. 2a indicate the corresponding peaks and the valley between them. The form of the dependence $G(E_F)$, taking into account the region of small values of E_F not shown in Fig. 2a (this region corresponds to one-electron resonance tunneling, which is usually not observed due to the Coulomb blockade), can be readily explained. When $E_F \ll V$ (V is the barrier height), the transparency and, hence, the conductance are close to zero. For E_F close to V, oscillations with the largest amplitudes are observed, when the values of G in the *on* and *off* states differ by an order of magnitude. Finally, for $E_F \gg V$, high conductance modulated by oscillations with very small amplitudes is observed. It is obvious that the existence of a regime of strong modulation of the conductance in the interferometer is of practical and fundamental importance for manufacturing a one-electron transistor.

Observation of interference oscillations

We have found recently that a ring quasi-ballistic continuous gate interferometer can operate as a Fabry – Perot interferometer. In this case, branching points at the entrance and exit of the ring interferometer and the barriers of the fluctuation potential at its arms play the role of the electronic mirrors. To solve the problem of the electron motion in an ideal single-mode ring interferometer, the simple conditions of continuity of the wave function ($\Psi_1 = \Psi_2 = \Psi_6$) and conservation of the flow ($\Psi'_1 = \Psi'_2 + \Psi'_6$) at the branching points are sufficient (Fig. 3a). In the case of equal interferometer arms, these conditions take the form $\Psi_1 = \Psi_2$, $\Psi'_1 = 2\Psi'_2$, and the problem is reduced to a one-dimensional problem with the electronic mirrors located at points $x = 0, L$ (Fig. 3b). The situation corresponds to an ideal Fabry – Perot interferometer with energy-independent mirror transparency. In this case, the interferometer transparency is determined by the expression $T = |t|^2 = 1/(1 + 9\sin^2 k_{\mathrm{F}}L/16)$. Taking into account Eqn (1), we obtain that the oscillation period of the conductance will correspond to a change in the number of electrons in the arm by two (in the ring, by four).

To verify the above concept, we manufactured the ring structures based on a highly mobile two-dimensional electron gas in the AlGaAs/GaAs heterotransition using electron lithography with subsequent plasmochemical anisotropic etching (Fig. 3c). Then, a metal AuTi gate was deposited onto them. The effective diameter of a single-mode ring was 0.7 μm. One can see that a change in the gate voltage causes quasi-regular oscillations of the resistance. The Fourier spectrum exhibits two periods equal to 10 and 40 meV. The shortest period corresponds to the addition of four electrons to the ring. The low-frequency oscillations are most likely caused by the formation of the Fabry – Perot interferometer inside one of the arms of the ring. The small amplitude of high-frequency oscillations suggests the significant role of scattering. The single-mode and quasi-ballistic nature of the electron transport in the ring is confirmed by the observation of phase inversion of the Aharonov-Bohm oscillations (Figs 4b and 5). Thus, the results reported show the possibility of fabrication of one-electron interference transistors. However, to obtain one-electron large-amplitude oscillations in the Fabry-Perot interferometer with a controllable length, it is necessary to refine the technology of manufacturing single-mode quantum wires and to perform further experiments.

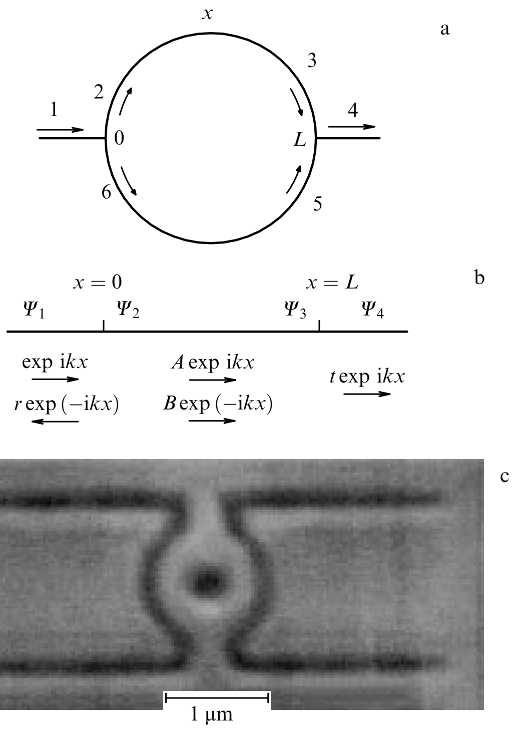

Figure 3. (a) Schematic image and (c) photograph of a ring interferometer; (b) a one-dimensional model of propagation of an electron through an ideal ring in zero magnetic field.

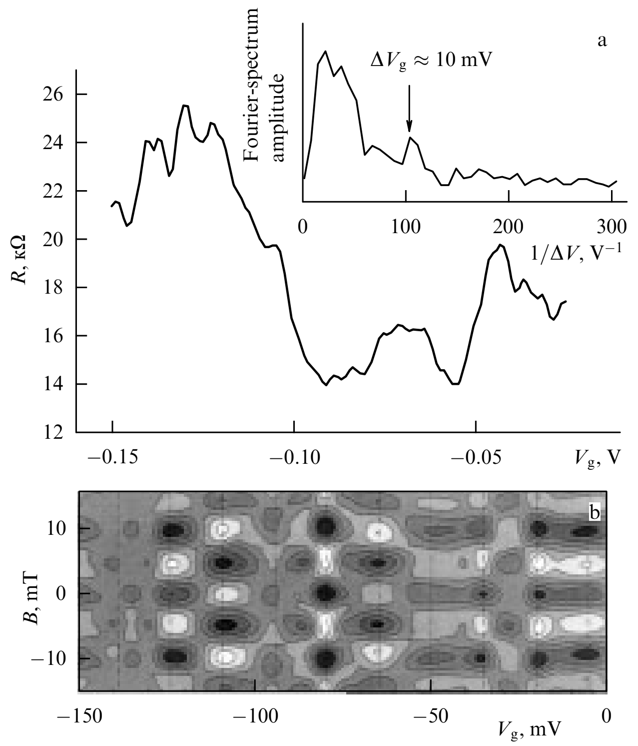

Figure 4. (a) Dependence of the resistance of a ring interferometer on the gate voltage; insert: the amplitude $R(V_g)$ of the Fourier spectrum; (b) the contour map of the conductance oscillations $G - \langle G(B) \rangle$ in coordinates of the gate voltage and magnetic field.

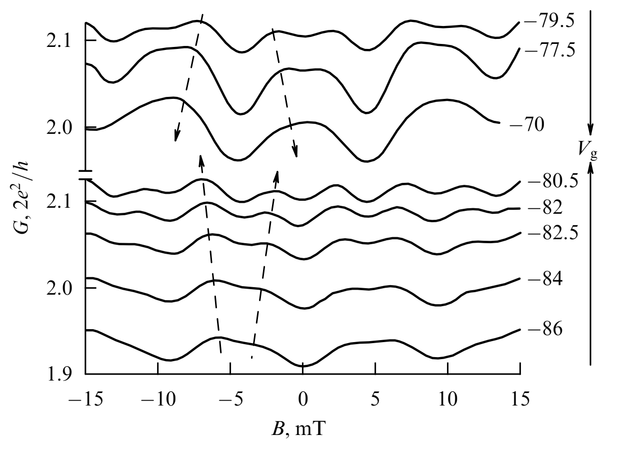

Figure 5. Experimental observation of the phase inversion of the Aharonov-Bohm oscillations upon changing V_g near the conductance peak of a ring interferometer.

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