QUANTUM-INTERFERENCE SEMICONDUCTOR DEVICES REVISITED*

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First, a simple semiclassical approach has been applied to the problem of a quantum phase acquired by an electron carrying both the charge and spin, which travels in an electromagnetic field. Basic hypothetical devices whose operation relies on the quantum interference, including spin-related interference, are discussed in the following. Finally, experimental results demonstrating two-beam interference in a planar quantum dot are presented.

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1. Introduction

The concept of quantum interference transistor (QUIT) has been considered in the literature since more than one decade [1–4]. In conventional field effect transistor (FET) an applied gate voltage modulates the source–drain current by varying the carrier concentration in the conduction channel. Instead, in the original version of QUIT the current is modulated owing to the interference of electron waves passing through two continuous channels by the application of a gate voltage that differentiates the quantum phases in the channels. The necessary condition of the interference is preservation of quantum phase coherence along alternative electron trajectories up to the point of their recombination. Inelastic scattering destroys the phase coherence and this limits the coherence length of electrons in semiconductors usually to several hundreds of nanometers at liquid helium temperatures.

QUITs have been expected to exhibit several advantages, such as very little power dissipation and a high speed of operation. Unfortunately, a little fault tolerance excludes QUIT as a candidate for a successor to FET. Nevertheless, one observes now a reviving interest in the quantum-interference devices [5, 6] mainly

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in the context of the electron's spin that could be used, in addition to electron's charge, in future nanoelectronics. This paper presents a brief survey of the subject, which includes a few novel results and pays an attention to the spin-related interference devices.

2. Quantum-mechanical phase

Probability amplitude in quantum mechanics is given by a complex number that can be written in an exponential form whose argument, φ, is called the quantum-mechanical phase. In semiclassical approximation the phase φ acquired by an electron traveling along a given trajectory expresses itself through the classical action S, and the Planck constant $\hbar = h/2\pi$, as

$$\varphi = \frac{S}{\hbar} \equiv \frac{1}{\hbar}\int L\mathrm{d}t, \tag{1}$$

where L is the Lagrangian of the electron (being an explicit function of the electron's position and velocity), and the integration is performed over traveling time. It should be emphasized that the semiclassical approximation gives exact results in regions where the electron is subject to the effect of a constant potential, and only such cases will be considered in this paper.

In classical mechanics the Lagrangian equals kinetic minus potential energy, $L = T - U$, whereas in electrodynamics it contains an additional term, $-e\boldsymbol{A}\boldsymbol{v}$, that is due to the interaction of a traveling electron with the vector potential $\boldsymbol{A}$ of a magnetic field. Therefore the Lagrangian can be written as

$$L = T - U - e\boldsymbol{A}\boldsymbol{v} = \frac{mv^2}{2} + eV - e\boldsymbol{A}\boldsymbol{v}, \tag{2}$$

where m, $-e$, and $\boldsymbol{v}$ denote respectively the electron's effective mass, charge, and velocity. Here, $-eV$ is the electrostatic potential energy, where V stands for the scalar potential of an electric field.

We can also take into account the spin of the electron, in a phenomenological approach, by including into the potential energy additional terms $-\boldsymbol{\mu}\boldsymbol{B} + \boldsymbol{\mu}(v \times \boldsymbol{E})/2c^2 \equiv -\boldsymbol{\mu}\boldsymbol{B}_{\mathrm{eff}}$, where c is the velocity of light. Here, $-\boldsymbol{\mu}\boldsymbol{B}$ is the energy of interaction of the magnetic moment $\boldsymbol{\mu}$ with the magnetic field of the induction $\boldsymbol{B}$, and $\boldsymbol{\mu}(\boldsymbol{v}\times \boldsymbol{E})/2c^2$ is the energy of relativistic interaction of a traveling magnetic moment $\boldsymbol{\mu}$ with the electric field $\boldsymbol{E}$ (including the so-called Thomas precession), which is called the spin–orbit interaction. Within this approximation the generalized Lagrangian of an electron traveling in an electromagnetic field takes the following form:

$$L = \frac{mv^2}{2} + eV - e\boldsymbol{A}\boldsymbol{v} + \boldsymbol{\mu}\boldsymbol{B} - \frac{\boldsymbol{\mu}(\boldsymbol{v} \times \boldsymbol{E})}{2c^2}. \tag{3}$$

It is frequently convenient to introduce into this expression the total energy of an electron $W = T+U$. In a system being very close to equilibrium the total energy of an electron at the Fermi energy may be assumed to be constant throughout the system. Then, integrals of the type $\int W dt$ are identical for all alternative trajectories and thus their contribution to the resulting phase difference cancel.

When a traveling electron is subject to an effective magnetic field $\boldsymbol{B}_{\mathrm{eff}}$, which is not uniform, and the electron's spin follows adiabatically direction of the magnetic field, then the electron acquires an additional geometrical Berry phase [7]. Upon returning the vector $\boldsymbol{B}_{\mathrm{eff}}$ to its original direction during electron traveling, the electron acquires a geometrical phase given by half the solid angle subtended by $\boldsymbol{B}_{\mathrm{eff}}$ with a sign depending on the spin sense.

3. Aharonov–Bohm interferometer

A prototype of quantum-interference transistor is the so-called Aharonov–Bohm (AB) interferometer. It represents a conducting ring of mesoscopic size, which is supplied with two current leads at opposite points of ring periphery. This is a doubly connected conductor that contains two separate branches linking a source of electrons to their drain (Fig. 1). It is assumed in the following that each branch represents a quasi-one-dimensional conductor (quantum wire) with only single transversal mode propagating in it. Moreover, it is assumed that the conduction is due to electrons at the Fermi level, and that the electrons travel ballistically.

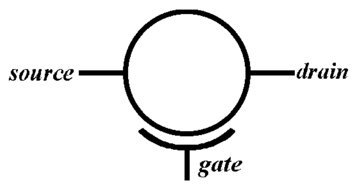

Fig. 1. Aharonov–Bohm ring with a gate attached capacitively to one of its branch.

An electron emanating from the source has two alternative trajectories to reach the drain. When the two branches of the ring are identical then the interference at the drain is constructive. Differentiation of the quantum-mechanical phases in these branches can be achieved by either magnetic field or electrostatic potential. Having in mind device applications it is preferred to control the interference by an electrostatic potential. Therefore, the famous magnetostatic Aharonov–Bohm effect [8] will be excluded from the present considerations. Instead, we will refer to the electrostatic AB effect in which the quantum phase can be controlled by a scalar potential. Such a device, in which an external voltage is applied to a gate that is capacitively coupled to one branch of the AB ring, has been indeed proposed in the literature [1, 3]. We have shown, however, that operation of such device would be rather doubtful because of a quantum-mechanical limitation [9].

In fact, when a moderate voltage is applied to the gate, its primary result is the field effect owing to which the ring segment underneath the gate becomes charged. When the gate potential is positive, this charge is carried by incoming electrons that occupy empty quantum states of the wire. This charge defines, through the density of states in the wire, a change in the potential of the segment whose length is l. The resulting phase difference at the drain can be written as

$\Delta\varphi = \Delta k_{\rm F} l$, where $\Delta k_{\rm F}$ denotes a change of the Fermi wave number in the segment underneath the gate caused by the induced charge. One may write a formal relation

$$\Delta\varphi = \Delta k_{\rm F} l = \left(\frac{{\rm d}E(k)}{{\rm d}k}\frac{{\rm d}n(E)}{{\rm d}E}\right)^{-1} N, \tag{4}$$

where $E(k)$ is the electron energy as a function of its wave number, and N is an average number of the electrons induced in one branch of the ring. The second factor in the parenthesis represents the one-dimensional density of states that is just proportional to the reciprocal of the first factor

$$\frac{{\rm d}n(E)}{{\rm d}E} = \frac{2}{\pi}\left(\frac{{\rm d}E(k)}{{\rm d}k}\right)^{-1}. \tag{5}$$

Inserting Eq. (5) into Eq. (4), one gets

$$\Delta\varphi = \frac{\pi}{2} N. \tag{6}$$

It is seen that already a single electron charge induced results in an essential phase difference, $\Delta\varphi = \pi/2$. Variation of the charge by a quantity $-2e$ alters the constructive interference into the destructive one and vice versa. It means that the electrostatic AB interferometer belongs in fact to the category of single-electron devices.

Such a device will suffer from charge fluctuations that appear on the gate–wire capacitor. Those fluctuations, well known in the physics of single-electron phenomena in solids, can be of either thermal or quantum-mechanical origin. In order for the electric charge on the capacitance C to be defined with an accuracy better than e, against a background of thermal and quantum fluctuations, the following inequalities had to be fulfilled, respectively:

$$\frac{e^2}{2C} \gg k_{\rm B}T, \quad R \gg \frac{h}{e^2}. \tag{7}$$

Here, T is the temperature, $k_{\rm B}$ is the Boltzmann constant, and R is the resistance through which the capacitance C is charged. In principle, the thermal fluctuations can always be reduced below an arbitrary level by lowering the temperature. Instead, the quantum fluctuations cannot be avoided because the second inequality in Eq. (7) can hardly be fulfilled in the considered case.

4. T-shaped structure

Instead of the AB ring, one can use a T-shaped structure (being an analog of the microwave T-junction) that has been first proposed by Sols et al. [2] and Datta [3]. It is a mesoscopic structure that consists of a conducting longitudinal arm linking the source of electrons to their drain, which is coupled to a transverse arm of a length l (Fig. 2). The transverse arm is terminated with the Schottky gate and thus a voltage applied to the gate can control its length. Variation of this length tunes the quantum-mechanical transmission between the source and drain.

The reason is that amplitudes of the electron wave functions in the transverse and longitudinal arms must fit at the junction. There are incident and reflected

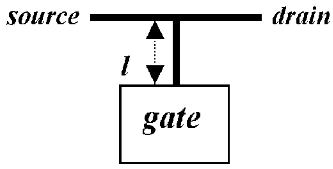

Fig. 2. T-shaped structure with gate-controlled length of the transverse arm.

waves running in the transverse arm, which combine into a standing wave whose one node is located at the arm's terminal. When the second node is located at the junction, i.e. when $kl = \pi n$ $(n = 1, 2, 3\ldots)$, the amplitude of a running wave in the longitudinal arm must be zero and then, the device conductance also is zero. Instead, the conductance reaches a maximum when an arrow of the standing wave appears at the junction, i.e. when $kl = \pi(n - 1/2)$.

Such a device could be electrostatically defined in a two-dimensional electron gas (2DEG) of a GaAs-based heterostructure using the split-gate technique. If the arms represent quasi-one-dimensional conductors, the switching between conducting and blocking states of the device requires a change in the length of the transverse arm by a quarter of the Fermi wavelength that is typically 40 nm. We have estimated the gate voltage required to switch the device, taking into account the experimentally found magnitude of the lateral shift of the depletion-layer boundary per unit gate voltage (see Sec. 8), to be about 100 mV.

5. Spin-related interference

The spin of electron brings into Lagrangian the term $\boldsymbol{\mu}\boldsymbol{B}_{\text{eff}}$, where the effective magnetic field $\boldsymbol{B}_{\text{eff}}$ includes both an external magnetic field and an apparent magnetic field experienced by the traveling electron in the presence of a transverse electric field. Each of these two contributions results differently in the energy splitting between spin-up and spin-down states (for which projection of the spin angular momentum is respectively parallel and antiparallel to $\boldsymbol{B}_{\text{eff}}$) (Fig. 3). Semiclassically, a spin-related phase is connected with the Larmor precession of

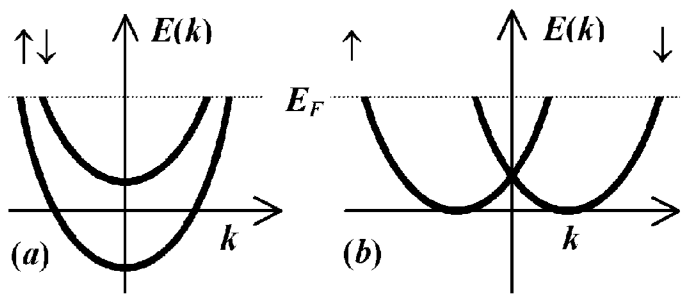

Fig. 3. (a) Zeeman splitting in an external magnetic field, (b) Rashba's spin–orbit splitting.

spin magnetic moment around the effective magnetic field direction. The Larmor frequency, $\omega_L = g\mu_B B_{eff}/2\hbar$, where g is the Lande g-factor, and μ_B is the Bohr magneton, defines the resulting splitting energy, $2\hbar\omega_L$. In order for the interference to be dominated by a spin contribution, the splitting energy should exceed the Fermi energy, which usually requires applying very strong magnetic fields.

The situation would become more plausible if to exploit diluted magnetic semiconductors (DMS) that exhibit a giant Zeeman splitting. Unfortunately, DMSs contain a high density of magnetic ions, whose presence could dramatically reduce the electron phase-coherence length due to the inelastic spin-flip scattering.

An alternative way to obtain a large Zeeman splitting in a 2DEG is to use hybrid ferromagnet–semiconductor structures in which micromagnets are deposited on the top of a semiconductor heterostructure and whose stray field penetrates the active region of the device.

Finally and fortunately, one can also exploit the spin–orbit coupling, which will be discussed in Sec. 7.

6. Spin filter

Consider now the Zeeman splitting due to external magnetic field. It results in a differentiation of the wave numbers of conduction electrons with opposite spin orientations. The new wave numbers of electrons at the Fermi level, $k_\uparrow$, $k_\downarrow$, are given by the relation

$$E_F = \frac{\hbar^2 k^2_{\uparrow,\downarrow}}{2m} \pm \frac{g\mu_B B}{2}, \tag{8}$$

where E_F is the Fermi energy in zero magnetic field, and the signs $\pm$ correspond to the spin-up and spin-down states. This effect allowed us to propose a novel quantum-interference device that might be called the spin filter, which is based on the T-shaped structure.

Namely, because electrons with opposite spin polarizations have different Fermi wavelengths, one can so adjust the magnetic induction, B, and the transverse-arm length, l, that the device will only transmit electrons with one definite spin orientation. To reach this goal one should assure at the junction simultaneously a node for one wavelength and an arrow for the other, i.e. $k_\uparrow l = \pi n$ and $k_\downarrow l = \pi(n-1/2)$. This requirement leads to the following relations:

$$gBl^2 = \pi\left(\frac{n}{4}-1\right)\frac{h}{e}, \quad k_F l = \pi\left(n^2 - \frac{n}{2} + \frac{1}{8}\right), \tag{9}$$

where k_F is the Fermi wave number in zero magnetic field. From Eq. (9) we find, for instance, that for $2\pi/k_F = 40$ nm, $g = 2$, and $n = 3$ a 100% spin filtering would be reached at $l = 0.7$ μm and $B = 2.5\times10^{-3}$ T.

7. Device with spin–orbit coupling

Recently, an attractive possibility of manipulating the spin–orbit interaction, in order to control the quantum-mechanical phase, has been revealed. It has been established that in 2DEG appearing in narrow-gap semiconductors a considerable energy splitting between spin-up and spin-down states occurs even in zero magnetic field [10–12]. This effect, known as the Rashba spin–orbit splitting [13, 14], arises from interaction of a traveling spin magnetic moment with a perpendicular electric field that exists at heterostructure interface. The splitting energy is commonly written as $2k_F\alpha$, where the coefficient α is proportional to the expectation value of the electric field at the interface. In several narrow-gap semiconductor systems containing quantum well α has been found to be of the order of 10^{-11} eV m. Moreover, it has been shown that a gate voltage can effectively control this coefficient [12]. In particular, Nitta et al. [10] have shown that in an inverted $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum well a change of the gate voltage from +1.5 V to –1 V enhances the spin–orbit coupling coefficient α from 0.65 to 1.05×10^{-11} eV m.

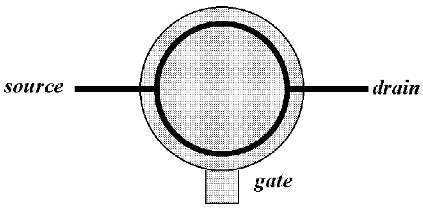

Fig. 4. Aharonov–Bohm ring in which a uniform spin–orbit splitting is controlled by a gate voltage.

Basing on this finding, Nitta et al. [5] have proposed a spin device that would work without any external magnetic field. It represents an AB ring in which a gate electrode covers the whole ring area (Fig. 4). A voltage applied to the gate varies the spin–orbit splitting uniformly in the ring. Electron waves, which follow alternative trajectories in upper and lower branch of the ring, recombine at the drain with opposite wave vectors. Therefore, they contribute to the Lagrangian with different signs and thus give rise to a phase difference

$$\Delta\varphi = \pm\frac{\pi R g \mu_B E}{c^2\hbar} \equiv \pm\frac{2\pi R\alpha m}{\hbar^2}, \tag{10}$$

where R is the ring radius, and the signs $\pm$ correspond to opposite spin orientations. Taking into account the experimental values of α, one finds by Eq. (10) that in AB ring with $R = 0.3$ μm a gate voltage of the order of 1 V would assure 100% conductance modulation.

It is worth noting that the phase difference is here independent of the electron wave number, which means that contributions from different propagating modes in a multimode interferometer would sum to a net interference effect. It should be also added that because an apparent magnetic field has here the radial orientation an electron would acquire a geometrical Berry phase, which however does not enter into the resulting phase difference.

8. Two-beam interference in a planar quantum dot

The above considerations are to be completed with presentation of some of our experimental results, which — although do not concern directly the systems discussed before — are very instructive. Our experiment was performed using an open quantum dot defined electrostatically in a 2DEG accumulated at the interface

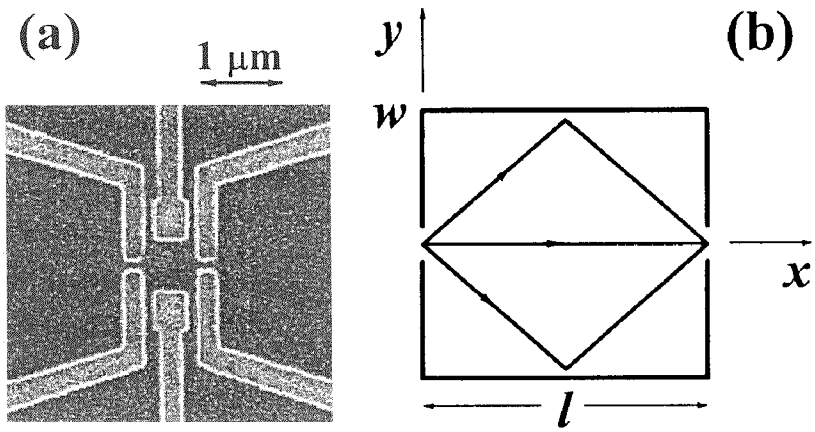

Fig. 5. (a) Secondary-electron image of the quantum dot, (b) main trajectories of ballistic electrons.

of an $Al_{0.3}Ga_{0.7}As/GaAs$ modulation-doped heterostructure [15]. Metal Schottky gates deposited on the top of the heterostructure defined a square quantum dot of a lithographic size 0.8×0.8 μm^2 (Fig. 5a). Small openings in front and back gates of the dot acted as the entry and exit ports for electrons.

We measured the conductance through the dot as a function of the potential difference between opposite side gates, keeping the sum of these potentials constant. Typical result obtained at the temperature 4.2 K is shown in Fig. 6 where five oscillation cycles of the conductance are seen. After applying a weak magnetic field normal to the 2DEG sheet, positions of the oscillation cycles displace themselves along the voltage scale.

These results are explained as follows. Some of the electrons entering the dot follow the straight-line trajectory that links directly the entry with the exit (Fig. 5b). This trajectory contributes dominantly to the conductance. Other entering electrons are diffracted to directions considerably away from this trajectory and undergo specular reflections at dot boundaries. Among them one can distinguish two symmetric trajectories, which undergo a single reflection at opposite side walls before recombination at the exit. They subsequently contribute to the conductance. Interference between partial waves following these trajectories is tuned by the potential difference applied to the side-wall gates, which differentiates the lengths of these trajectories. Magnetic field applied normal to the dot plane changes the interference pattern owing to the magnetostatic AB effect.

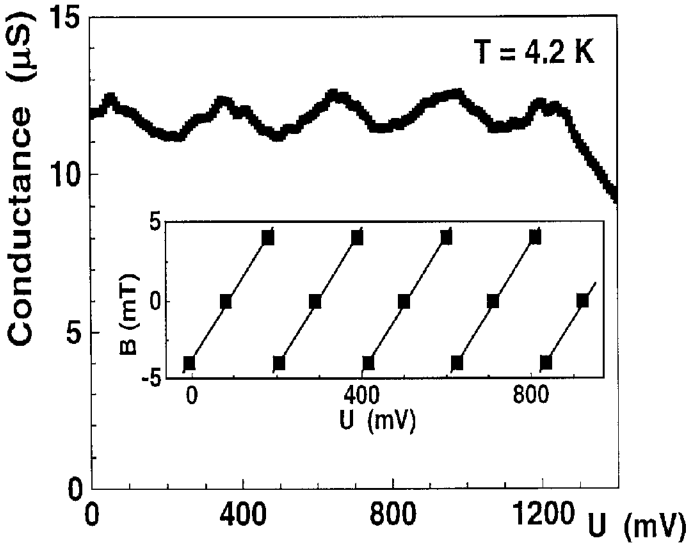

Fig. 6. Conductance oscillations in the dot as a function of the potential difference applied to the side gates. In the inset: displacement of conductance maxima with magnetic field.

This experiment shows that a gate voltage can indeed control the electron interference in a planar structure. From the period of the conductance oscillations we have found the lateral shift of the depletion area boundary per unit gate voltage to be ≈ 0.1 μm/V.

9. Conclusions

To operate at reasonable temperatures the dimensions of quantum-interference devices should be reduced down to the quantum length scale, which is determined by the Fermi wavelength (typically 40 nm for a 2DEG in GaAs). Structures with this length scale could be fabricated using the present time epitaxy and lithography. Unfortunately, a little fault tolerance seems to constitute an insuperable barrier for a wide application of such devices.

However, spin-related interference devices might find a niche in the emerging branch of electronics that is called spintronics. Those devices would have an advantage over other spin-related devices, which have been considered by now, since they do not need injection of spin-polarized electrons. New ideas concerning spin-related interference devices are still expected.

Acknowledgments

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