Conductance and electron spin polarization in resonant tunneling

I. L. Aleĭner and Yu. B. Lyanda-Geller
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, 194021, Leningrad

(Submitted 21 December 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 2, 89–92 (25 January 1991)

In the resonant tunneling of ballistic electrons in a magnetic field, the transmission coefficient depends on the electron spin. The curve of the conductance and the spin polarization of the transmitted electrons versus the magnetic field has a series of resonance peaks.

A resonant tunneling of electrons is an effect seen clearly in ballistic transport.[1]

How is the resonant tunneling of the spin splitting of electron levels altered in a magnetic field?

The transmission coefficient T for one-dimensional electrons of a structure consisting of two potential barriers (Fig. 1) is given by

 0021-3640/91/020091-05$01.00

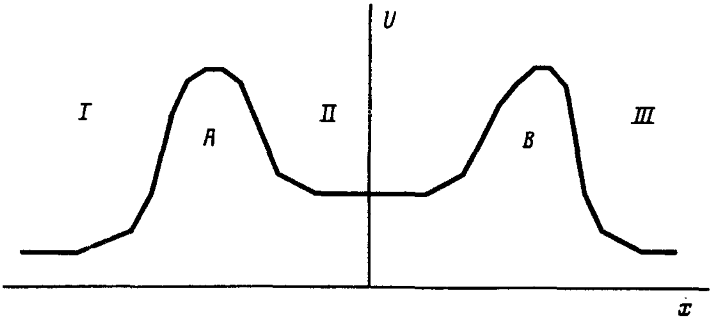

FIG. 1. Schematic diagram of the potential relief in the resonant tunneling.

$$T = \frac{T_A T_B}{|1 - \sqrt{R_A R_B}\exp(i\theta)|^2}, \tag{1}$$

where $T_{A(B)}(\epsilon)$ are the transmission coefficients of barriers A and B, respectively, $R_{A(B)} = 1 - T_{A(B)}$ are the reflection coefficients, $\theta(\epsilon)$ is the total phase shift acquired by the electron over a cycle of motion in region II between the barriers, and ϵ is the energy of the electrons. The coefficient T becomes one under the condition

$$\theta = 2\pi n, \text{ where } n \text{ is an integer}, \tag{2}$$

and $T_A = T_B$. We assume that barriers A and B are identical.

Condition (2) determines the positions of the quasidiscrete levels in the region between the two barriers. If the transmission coefficients satisfy $T_{A(B)} \ll 1$, the width of these levels is small in comparison with the distance between them. An agreement of the energy of the tunneling electron with the energy of a quasidiscrete level corresponds to a resonant transmission.

In a magnetic field H, the effective potential energy of the electron is

$$U(x) = U_0(x) + g\mu\bar{\sigma}\bar{H}, \tag{3}$$

where $U_0(x)$ is the two-barrier potential, g is the electron g-factor, which we assume for simplicity to be independent of the coordinate, μ is the Bohr magneton, and σ_i are the Pauli matrices. It follows from (3) that the resonant-tunneling levels for electrons with different spin projections onto the magnetic field are different:

$$U_\uparrow - U_\downarrow = 2g\mu H. \tag{4}$$

Let us consider the tunneling of electrons with an energy $\epsilon = \epsilon_F$. The curve of the transmission coefficient versus the magnetic field consists of a series of resonance peaks for each of the spin projections. For electrons with opposite spins, the peaks occur at different values of the magnetic field.

Let us consider the quasi-one-dimensional system which was studied experimentally in Ref. 2.

This structure (Fig. 2) is formed by two adiabatic contractions in a two-dimensional GaAs electron gas. The Fermi levels to the left and right of the barriers differ by an amount equal to the applied potential eV, so a small current I flows through the constrictions (in the experiments of Ref. 2, $I < 1$ nA). The length of a one-dimensional channel was 1.5 μm at a mean free path of 9 μm.

The conductance of the system, $G = dI/dV|_{V=0}$, is determined by the transmission coefficients for the electrons passing along different trajectories (channels) through the barriers. There is no entanglement of the channels under the conditions of an adiabatic passage of the constrictions. The conductance is given under these conditions by[3]

$$G = \frac{e^2}{h}\sum_j (T_{j\downarrow} + T_{j\uparrow}), \tag{5}$$

where T_j is the transmission coefficient for the electrons along trajectory j.

The motion along these trajectories for $H = 0$ is determined by the one-dimensional Schrödinger equation

$$\left(-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + U_0^{(j)}(x)\right)\psi(x) = \epsilon\psi(x), \tag{6}$$

where $U_0^{(j)}(x) = [h^2\pi^2/2md^2(x)]j^2$, the x axis is directed along the direction in which the electrons are moving, and d is the width of the constriction. For trajectories j such that

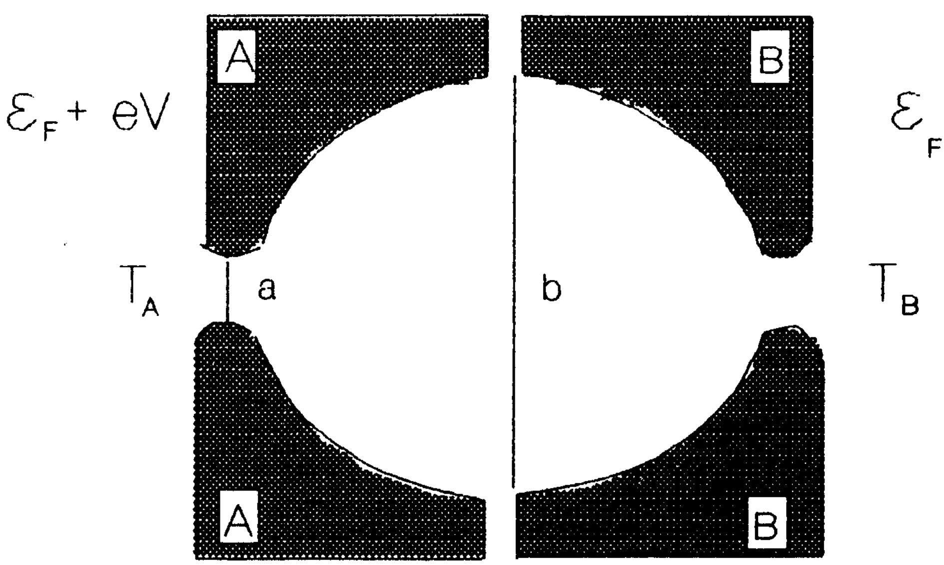

FIG. 2. Adiabatic contractions set up in a 2D GaAs gas by a potential applied to contacts A and B (Ref. 2).

$$\epsilon_1 \equiv \frac{\hbar^2\pi^2}{2ma^2}j^2 < \epsilon_F, \tag{7}$$

where a is the smallest width of the constriction (Fig. 2), the electron transmission coefficient is one, if the above-barrier reflection of the electrons is ignored. In the case

$$\epsilon_2 \equiv \frac{\hbar^2\pi^2}{2mb^2}j^2 > \epsilon_F \tag{8}$$

(b is the largest dimension of the region between the constrictions), the transmission of electrons is exponentially small. Finally, in the interval

$$\epsilon_2 < \epsilon_F < \epsilon_1 \tag{9}$$

there can be a resonant tunneling.

In the experiments of Ref. 2, the magnetic field was directed perpendicular to the plane of the 2D gas. In this case the oscillations of the conductance are due primarily to a motion of the Fermi level of the 2D gas in the quantizing magnetic field. If the magnetic field is directed parallel to the direction in which the electrons are moving, the Fermi level is immobile up to magnetic fields at which the magnetic length λ_H becomes comparable to the thickness of the 2D layer.

The conductance in this case is given by

$$G = \frac{e^2}{h}\sum_j [T_j(\epsilon_F + g\mu H) + T_j(\epsilon_F - g\mu H)]. \tag{10}$$

Under conditions (7) and (9), if the number of trajectories is not too large, the conductance, like the transmission coefficient, is described by a clearly defined sequence of resonance peaks. The imposition of a magnetic field along the direction in which the electrons are moving thus makes it possible to distinguish the oscillations in the conductance which are of a spin nature.

If the dimensions of the region between the barriers are on the order of 10^{-4} cm, the distance between the quasidiscrete levels is $\simeq 10^{-5}$ eV, and the corresponding oscillation period is $\simeq 1$ kOe. The temperature in Ref. 2 is 10 mK, which is much smaller than the distance between quasidiscrete levels. Consequently, it is valid to analyze the situation with a stepped Fermi distribution of electrons. If the thickness of the 2D layer is on the order of 100 Å, the position of the Fermi level will be independent of the magnetic field in fields below 50 kOe.

In the case in which ϵ_F (a) coincides with a quasidiscrete level in the region between the barriers for electrons with a common spin projection and (b) simultaneously lies between the two levels of the resonant tunneling for particles with opposite spin projections, the flux of transmitted electrons is partially polarized. The degree of electron polarization, P, is given by

$$P = \frac{T(\epsilon_F + g\mu H) - T(\epsilon_F - g\mu H)}{T(\epsilon_F + g\mu H) + T(\epsilon_F - g\mu H)}. \tag{11}$$

The maximum value of the polarization is

$$P = \frac{2R_A}{R_A^2 + 1} \qquad (12)$$

For absolutely opaque barriers, the polarization (12) becomes unity.

If there is a nonequilibrium spin polarization of the electrons (two different Fermi levels for the electrons with opposite spins), the resonant tunneling leads to a change in the degree of polarization and to a dependence of the conductance on the polarization, even in the absence of a magnetic field.

We also note that a spin dependence of the electron transmission coefficient is possible in the case of tunneling through an isolated barrier and in the case of above-barrier reflection, although the effects in these cases will be less obvious than in the case of resonant tunneling.

We wish to thank V. I. Perel' and G. E. Pikus for a discussion of the results.

[1]L. L. Chang, L. Esaki, and R. Tsu, Appl. Phys. Lett. **24**, 593 (1974).
[2]L. P. Kouwenhoven, in *Abstracts of Twentieth International Conference on Physics of Semiconductors*, Thessaloniki, Greece, 1990.
[3]Y. Imry, in *Directions in Condensed Matter Physics* (ed. G. Grinstein and G. Mazenko), World Scientific Publ., Singapore, 1986, p. 101.

Translated by D. Parsons