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Spin injection in ferromagnetic single-electron transistor

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We consider the single-electron transistor with ferromagnetic outer electrodes and nonmagnetic island. Tunneling current causes nonequilibrium electron–spin distribution in the island. The dependencies of the magnetoresistance ratio on the bias and gate voltages show the dips which are directly related to the induced separation of Fermi levels for electrons with different spins.

Key words: single-electron transistor, ferromagnetism, magnetoresistance.

The success in fabrication of tunnel structures with large magnetoresistance [1, 2] attracted considerable attention to this topic. For tunnel junctions made of ferromagnetic films, the difference as high as 26% at 4.2 K (up to 18% at room temperature) between the tunnel resistances for parallel and antiparallel film magnetization has been observed [2], which allows their application as magnetic sensors. The low temperature values agree well with the theoretical result [1] $\Delta R/R = 2P_1P_2/(1 + P_1P_2)$ where the spin polarizations P_1 and P_2 of tunneling electrons in the films are measured in a separate experiment [3] (for example, the polarization is about 47% for CoFe, 40% for Fe, and 34% for Co).

With the decrease of the tunnel junction area, the single-electron charging [4] becomes important leading to new effects. The study of tunnel magnetoresistance in this regime is a rapidly growing field [5–10]. For example, the enhancement of the magnetoresistance ratio $\Delta R/R$ due to Coulomb blockade has been discussed in Refs [5, 9]. In Refs [8, 10] the theoretical model of ferromagnetic single-electron transistor (SET-transistor) has been considered, in which the tunnel resistances of junctions are different for parallel and antiparallel magnetizations of electrodes, thus changing the current through the system. The very interesting effect of magneto-Coulomb oscillations in SET-transistor has been observed and explained in Refs [5, 6].

In this paper we consider a SET-transistor which has ferromagnetic outer electrodes and nonmagnetic central island (see inset in Fig. 1A). When the coercive fields of two ferromagnetic electrodes are different, the standard technique of the magnetic field sweeping (see, e.g. Ref. [2]) allows to obtain parallel or antiparallel polarizations of outer electrodes. In the first approximation the current through SET-transistor does not depend on these polarizations because the island is nonmagnetic (Zeeman splitting is negligible). However, if the electron spin relaxation in the island is not too fast, then the tunneling of electrons with preferable spin orientation creates the nonequilibrium spin-polarized state of the island (similar to the effect discussed in

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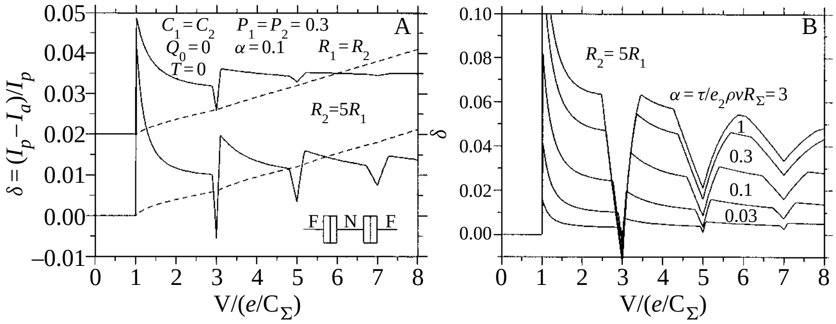

Fig. 1. The dependence of the magnetoresistance ratio δ on the bias voltage V for A, two different ratios R_2/R_1 and B, for several values of the dimensionless spin relaxation time α. Inset in A shows the schematic of the SET-transistor with ferromagnetic (F) outer electrodes and a nonmagnetic (N) island, while the dashed lines show the I_p–V curves (arbitrary units).

Ref. [11] in absence of the Coulomb blockade). This in turn affects the tunneling in each junction and leads to different currents I_p and I_a through the SET-transistor in the parallel and antiparallel configurations.

We calculate the dependence of the relative current change $\delta = (I_p - I_a)/I_p$ on the bias and gate voltages. Nonzero δ is already the evidence of the nonequilibrium spin state in the island. Moreover, the voltage dependence of δ shows the dips, the width of which directly corresponds to the energy separation between Fermi levels of electrons with different spins in the island.

We consider the SET-transistor consisting of two tunnel junctions with capacitances C_1 and C_2. Background charge Q_0 describes the influence of the gate voltage. We assume that the voltage scales related to the polarization of ferromagnetic electrodes and to the barrier suppression, are large in comparison with the single-electron charging energy. Then the polarization of outer electrodes can be taken into account by the difference between the tunnel resistances $R^u_{1,2}$ and $R^d_{1,2}$ for electrons with 'up' and 'down' spins. The total junction resistances $R_1 = (1/R^u_1 + 1/R^d_1)^{-1}$ and $R_2 = (1/R^u_2 + 1/R^d_2)^{-1}$ do not depend on the magnetic polarizations P_1 and P_2 of electrodes, while 'partial' resistances are given by $R^u_i = 2R_i/(1 + P_i)$ and $R^d_i = 2R_i/(1 - P_i)$.

We assume that the energy relaxation of electrons in the island is much faster than the spin relaxation. So, we characterize the nonequilibrium spin state by the difference ΔE_F between Fermi levels for 'up' and 'down' spins while both distributions are determined by the thermostat temperature T (the spin distribution is assumed to be uniform along the island).

The equations of the 'orthodox' theory for single-electron transistor [4] (we assume $R_i \gg R_K = h/e^2$) should be modified in our case. The energy gain $W^{u(d)\pm}_i$ for tunneling to (+) or from (-) the island through ith junction is different for 'up' and 'down' electrons,

$$W^{u\pm}_i(n) = W^{\pm}_i \mp \Delta E_F/2, \qquad W^{d\pm}_i(n) = W^{\pm}_i \pm \Delta E_F/2, \tag{1}$$

where $W^{\pm}_i = (e/C_\Sigma)[\mp(ne + Q_0) \mp (-1)^i V C_1 C_2/C_i - e/2]$, n is the number of extra electrons on the island, $C_\Sigma = C_1 + C_2$, and V is the bias voltage. The corresponding tunneling rates satisfy the usual equation [4] $\Gamma^{s\pm}_i(n) = W^{s\pm}_i(n)/e^2 R^s_i[1 - \exp(-W^{s\pm}_i(n)/T)]$, where $s = u, d$ denotes spin. The average current I through the SET-transistor can be calculated as $I = \sum_{n,s} e[\Gamma^{s+}_1(n) - \Gamma^{s-}_1(n)]\sigma(n)$, where $\sigma(n)$ is the stationary solution of the master equation [4] $d\sigma(n)/dt = \sum_{i,s,\pm}[\sigma(n \pm 1)\Gamma^{s\mp}_i(n \pm 1) - \sigma(n)\Gamma^{s\pm}_i(n)]$. Finally, the Fermi level separation ΔE_F should satisfy the self-consistent equation

$$\Delta E_F \rho v/\tau = \sum_{n,i}[\Gamma^{u+}_i(n) - \Gamma^{d+}_i(n) - \Gamma^{u-}_i(n) + \Gamma^{d-}_i(n)]\sigma(n), \tag{2}$$

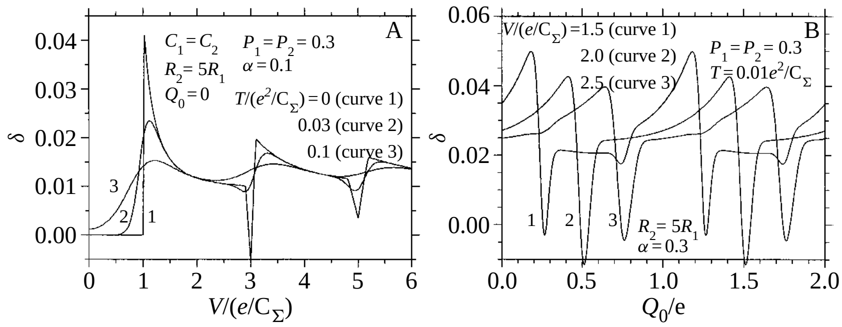

Fig. 2. A, The δ–V dependence for different temperatures T. B, The dependence of δ on the background charge Q_0 for several bias voltages.

where τ is the electron spin relaxation time for the island, ρ is the density of states (per spin), and v is the island's volume. We introduce also the dimensionless spin relaxation time $\alpha = \tau/e^2\rho v(R_1 + R_2)$.

The signs of polarizations P_1 and P_2 can be changed using the external magnetic field, that interchanges resistances R_i^u and R_i^d. So the current I_p for the parallel magnetization ($P_1 P_2 > 0$) is different from the current I_a when one magnetization direction is reversed, $P_2 \to -P_2$. Figure 1A shows the numerically calculated dependence of the magnetoresistance ratio δ (solid line) on the bias voltage V for the SET-transistor with parameters $C_1 = C_2$, $Q_0 = 0$, $T = 0$, $|P_1| = |P_2| = 30\%$, and $\alpha = 0.1$. For the upper curve (shifted up for clarity) we assumed $R_2 = R_1$ while $R_2 = 5R_1$ for the lower curve. The δ–V dependence shows the oscillations with the same period e/C_i as for the Coulomb staircase. The existence of oscillations is a trivial consequence of the charge dynamics in SET-transistor, similar to the effect discussed in Refs [8, 10].

More interesting features seen in Fig. 1a are the triangular-shape dips near the bias voltages

$$V = [e/2 + ne + (-1)^i Q_0]/C_i, \tag{3}$$

at which the derivative of the I–V curve (dashed line in Fig. 1A) abruptly increases. The dips are more pronounced for unequal resistances (better Coulomb staircase). The edges of a dip correspond to the alignment between the Fermi level in an electrode and one of the split Fermi levels for electrons with different spins in the island. Hence, the dip width ΔV is directly related to the Fermi level splitting, $\Delta V = \Delta E_F C_\Sigma / eC_i$. Notice that the magnetoresistance ratio δ can be negative within the dip range (see Fig. 1).

The width of the dips in Fig. 1A increases with voltage because the larger current provides larger ΔE_F (the crude estimate is $\Delta E_F = \alpha I(P_1 - P_2)eR_\Sigma$). In the case $|P_1| = |P_2|$, shown in the figures, $\Delta E_F = 0$ for parallel magnetization. When $|P_1| \neq |P_2|$, the dip shape is determined by two different values of ΔE_F leading to the trapezoid-like shape instead of the triangular one.

The increase of the spin relaxation time τ leads to larger ΔE_F and, hence, increases δ as well as widening the dips, which is illustrated in Fig. 1B ($\delta = 0$ for $\tau = 0$). The change of the polarization amplitudes $|P_1|$ and $|P_2|$ leads to similar effects. In the limit of large bias voltage the current can be found analytically, $IR_\Sigma/V = 1 - (\alpha/2)(P_1 - P_2)^2/\{1 + (\alpha/2)[R_\Sigma^2/R_1R_2 - R_1R_2(P_1/R_1 + P_2/R_2)^2]\}$, leading to $\delta = 2\alpha|P_1P_2|$ for small α and $\delta = 2\alpha|P_1P_2|/[1 + 2\alpha(1 - (|P_1| - |P_2|)^2/4)]$ for $R_1 = R_2$.

The finite temperature smears the features of the δ–V dependence (see Fig. 2A), but obviously does not change δ in the large-bias limit. The dips disappear when T becomes comparable to ΔE_F while the oscillations disappear at higher temperatures determined by the single-electron energy scale e^2/C_Σ.

Notice that two series of dips determined by eqn (3) coincide in Figs 1 and 2A. With the change of the background charge Q_0 by the gate voltage, these two series will move in opposite directions. The dips can be also seen on the δ–Q_0 dependence which is shown in Fig. 2B for different bias voltages V.

To estimate the parameters of a possible experimental realization, let us assume a Co–Cu–Co SET-transistor. The polarization $|P| = 30\%$ used in figures is a conservative value for Co. The spin relaxation rate τ for the nonmagnetic island, which is the most crucial parameter of the effect, depends much on the material quality. In Ref. [12] $\tau \sim 2 \times 10^{-8}$ s has been reported for very pure Cu at $T = 1.4$ K (a similar value has been found in Ref. [12] for Al, while $\tau \sim 10^{-8}$ s has been reported for Al in Ref. [11]). Let us choose $\tau = 10^{-8}$ s. Then using $\rho = 9 \times 10^{21}/\mathrm{eV}/\mathrm{cm}^3$ for Cu, $R_\Sigma = 10^5\ \Omega$, and the island volume $v = 200\mathrm{nm} \times 50\mathrm{nm} \times 20\mathrm{nm}$, we get $\alpha = 0.35$. Hence, the effect of nonequilibrium spin distribution should be rather strong, and we could expect the magnetoresistance ratio δ up to $\sim 10\%$. For $C_\Sigma \sim 3 \times 10^{-16}$ F the dips of the δ–V dependence could be observed at temperatures below ~ 0.2 K while the oscillations could be noticeable up to $T \sim 1$ K. Because of typically small coercive fields, $H \sim 10^2$ Oe [2], the Zeeman splitting corresponds to the energy scale $\Delta E \sim 10^{-6}$ eV $\sim 10^{-2}$ K and can be neglected.

We have discussed the dc case only. In the ac case the dynamic solution of the master equation should be used, and also the left side of eqn (2) should be replaced by $[d(\Delta E_F)/dt + \Delta E_F/\tau]\rho v$. The measurement of the frequency dependence can give the direct experimental way of the spin relaxation time determination. Another way to measure τ is using the 'perpendicular' component of the magnetic field which leads to the suppression of nonequlibrium spin polarization because of the Hanle effect [11]. Let us also mention that experiments using the SET-transistor with the superconducting middle electrode could be very interesting to study the influence of the injected spin polarization on the superconductivity.

In conclusion, we have considered the SET-transistor consisting of ferromagnetic electrodes and a non-magnetic island. The nonequilibrium spin distribution in the island leads to a considerable magnetoresistance which has a specific dependence on the bias and gate voltages. In particular, it shows the dips directly related to the Fermi level splitting.

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