Theory of spin effect on Coulomb blockade of single-electron tunneling in ferromagnetic system

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Abstract. Spin dependent single electron tunneling in a ferromagnetic double junction is investigated theoretically in the limit of incoherent sequential tunneling. The junction consists of a small nonmagnetic metallic grain with discrete energy levels, which is connected to two ferromagnetic electrodes. We have developed a new theoretical model taking into account charge as well as spin degrees of freedom. The model allows us to investigate new phenomena such as spin accumulation and spin fluctuations.

Keywords: Coulomb blockade, single electron tunneling, ferromagnetic nanojunctions

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1 Introduction

Single-electron tunneling in mesoscopic double-junctions has been extensively studied in the last decade both experimentally and theoretically [1]. When the central electrode (grain) is small enough, then discrete charging of this electrode leads to Coulomb blockade of electric current below a certain threshold voltage and to characteristic ‘Coulomb staircase’ at higher voltages. The interplay of ferromagnetism and discrete charging was studied only very recently [2]. It was shown that spin accumulation in the grain, together with discrete charging, is responsible for oscillations in the tunnel magnetoresistance (TMR), i.e., in the change of junction resistance when the magnetic configuration is varied from antiparallel to parallel alignment. In this paper we study the influence of discrete energy levels of the grain on single-electron tunneling phenomena in ferromagnetic junctions. The studies are performed within an approach, which is a generalization of the orthodox method [1] for the case with many electron channels including spins.

2 Description of the model

We consider spin dependent transport in a double ferromagnetic nanojunction in the limit of incoherent sequential tunneling, where the orthodox tunneling theory is appli-
cable. Accordingly, the resistances of the left, \( R_2 \), and right, \( R_1 \), barriers for both spin directions (\( \sigma = \uparrow, \downarrow \)) are assumed to be much larger than the quantum resistance \( R_Q = h/2e^2 \).

In the stationary state the electric current \( I \) is given by

\[
I = e \sum_{N_\uparrow, N_\downarrow} \sum_{r = \pm} \left[ r \Gamma_\uparrow(N_\uparrow, N_\downarrow) + r \Gamma_\downarrow(N_\uparrow, N_\downarrow) \right] P(N_\uparrow, N_\downarrow),
\]

where the probability \( P(N_\uparrow, N_\downarrow) \) to find in the grain \( N_\uparrow \) and \( N_\downarrow \) excess electrons with spin \( \sigma = \uparrow \) and \( \sigma = \downarrow \), respectively, is calculated from the relevant master equation \([4]\).

In the present model we operate in the two-dimensional space of states \((N_\uparrow, N_\downarrow)\), in contrast to the spinless orthodox method \([1]\) which was confined to the one-dimensional space. The spin dependent rates of electron tunneling to \((r = +)\) and off \((r = -)\) the grain through the \( j \)-th junction \((j = 1, 2)\) are given by \([4]\)

\[
\Gamma_{j\sigma}^{\pm}(N_\uparrow, N_\downarrow) = \Delta E \sum_i \left[ 1 + \exp \left( \mp \frac{E_i - \Delta E N_\sigma - E_F}{2k_B T} \right) \right]^{-1} \left[ 1 + \exp \left( \pm \frac{E_i + eV_j(N_\uparrow, N_\downarrow) - E_c}{k_B T} \right) \right]^{-1},
\]

where \( E_F \) denotes the Fermi energy and the summation runs over discrete energy levels \( E_i \) of the grain, which are assumed to be equally separated with the level spacing \( \Delta E \). The formula (2) is obtained for \( k_B T \approx \Delta E \), when the distribution function of \( N_\sigma \) among the levels of the island differs appreciably from the Fermi-Dirac distribution function \([3]\). The voltage drop \( V_j(N_\uparrow, N_\downarrow) \) on the \( j \)-th junction is given by

\[
V_j(N_\uparrow, N_\downarrow) = (-1)^j V \frac{C_1 C_2}{C_j C} + eN, \tag{3}
\]

where \( N = N_\uparrow + N_\downarrow \) is the total number of excess electrons on the grain, \( C_j \) is the capacitance of the \( j \)-th junction, \( C \) denotes the total capacitance of the grain \( C = C_1 + C_2 \), while \( V, e \) and \( T \) stand for the bias voltage, electron charge and temperature, respectively. Finally, \( E_c \) is the charging energy, \( E_c = e^2/2C \). We have also assumed that the energy relaxation time is much shorter than the time between successive tunneling events and shorter than the spin relaxation time. Magnetic configuration of the junction can be varied by an external magnetic field and the rotation from antiparallel to parallel alignment is accompanied by a change in the junction resistance (in our case \( R_{1\downarrow} \rightarrow R_{1\uparrow}, R_{1\uparrow} \rightarrow R_{1\downarrow} \)).

3 Results and discussion

We have calculated numerically the bias voltage dependence of the current \( I_{\uparrow\uparrow} \) and \( I_{\uparrow\downarrow} \) flowing through the junction with parallel and antiparallel alignment of the electrode magnetic moments, \( TMR = (I_{\uparrow\uparrow} - I_{\uparrow\downarrow})/I_{\uparrow\downarrow} \), spin accumulation \( < M > \equiv < N_\uparrow - N_\downarrow > \) and spin fluctuations \( \text{rms}(M) = \sqrt{<M^2>} - <M>^2 \). The results are presented in Fig.1 and Fig.2 for various temperatures. For \( T = 2.3 \text{ K} \) each curve in Fig.1 has
Additional steps which result from opening additional electron channels corresponding to discrete energy levels. These steps are clearly seen only for $T \ll \Delta E/k_B$, while for higher $T$ they are smeared out. Spin asymmetry in the tunneling rates leads to imbalance of incoming and outgoing currents, which causes a change in the local chemical potential and in the number of electrons of a particular spin orientation. This, in turn, gives rise to spin accumulation (Fig. 1c). One can note that in the first stage the average $< M >$ increases with increasing bias voltage, which is due to increasing number of active magnetic channels with increasing $V$ (see also spin fluctuations presented in Fig. 1d). This process continues until $V \approx 20$ mV, when it is more favorable to open a new charge channel. This, in turn, results in a reduction of the spin accumulation and spin fluctuations. At low $T$ the shape of the spin accumulation curve for even number of electrons accumulated in the grain is different from the shape corresponding to an odd number of electrons (this is due to a difference in the $(N_\uparrow, N_\downarrow)$ - space of states for the cases of even and odd numbers). The effect of spin accumulation has a direct influence on the character of TMR (see Fig. 1b, where the small steps correspond to discrete energy levels while the large-scale oscillations correspond to single electron charging).

The situation analysed above corresponds to a system with a large difference in the junction resistances. In the case of a symmetrical double junction, on the other hand, the I-V steps are not seen in the parallel configuration as shown in Fig. 2a (apart from small steps seen at low temperatures, which result from the discreteness of electronic structure). However, the value of TMR in the ohmic limit (for high $T$)
Fig. 2 Voltage characteristics of the current (a) and TMR (b) for the device with symmetric tunneling resistances $R_{1\uparrow} = R_{2\uparrow} = 102 \, \text{M\Omega}$, $R_{1\downarrow} = R_{2\downarrow} = 51 \, \text{M\Omega}$ in the parallel configuration. The other parameters are the same as in Fig.1.

can be larger (compare Figs 1b and 2b). In the antiparallel configuration, on the other hand, the junction ceases to be symmetrical, which leads to the oscillations in TMR with increasing $V$, seen in Fig.2b. However, amplitude of these oscillations is quickly damped.

4 Summary

We presented in this paper calculations of electric current in ferromagnetic double nanojunctions with discrete electronic structure of the central electrode. The discreteness leads to additional structure in the $I$-$V$ curves and in the voltage dependence of spin accumulation, spin fluctuations and TMR. This fine structure is clearly seen only for small $T$, while for higher $T$ it is smeared out. When the spin-flip relaxation time is much longer than the time between successive tunneling events, the effect of spin accumulation leads to TMR which oscillates with increasing $V$ (clearly seen for asymmetrical junctions).

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