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Spin-dependent transport in ferromagnetic single-electron transistors with non-collinear magnetizations

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Electronic transport in a ferromagnetic single-electron transistor is analysed theoretically in the sequential tunnelling regime. One of the external electrodes and the central part (island) of the device are assumed to be ferromagnetic, with the corresponding magnetizations being non-collinear. The analysis is based on the master equation method, and the respective transition rates are determined from the Fermi golden rule. It is shown that the electric current and corresponding tunnel magnetoresistance (TMR) strongly depend on the angle between the magnetizations. For an arbitrary magnetic configuration, TMR is modulated by charging effects, which give rise to characteristic dips (cusps) at the bias voltages corresponding to the Coulomb steps in the current–voltage characteristics.

Key words: *single electron transistor; spin-polarized transport; tunnel magnetoresistance*

1. Introduction

Electronic transport in single electron transistors (SETs) with nonmagnetic islands has already been the subject of extensive experimental and theoretical studies [1–3]. The problem of spin-polarized transport in SETs based on quantum dots or metallic particles, however, has been addressed only recently [4–6]. The transport properties of such devices have mainly been investigated in situations where magnetic moments are aligned either in parallel or antiparallel. Nevertheless, in real systems the magnetic moments of the leads can form an arbitrary angle and such a non-collinear configuration may strongly affect transport characteristics.

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In this paper, we present the results of our theoretical analysis of spin-polarized electronic transport in a ferromagnetic single-electron transistor (FM SET), whose one external electrode and the central part (referred to as the island) are ferromagnetic, while the second external electrode is nonmagnetic. The angle β between the spin polarizations of the ferromagnetic lead and the island is arbitrary. Our main objective is to analyse the dependence of electric current and tunnel magnetoresistance (TMR) on the angle β. It is shown that the transport characteristics of an FM SET strongly depend on its magnetic configuration. Such a dependence stems from the spin asymmetry of tunnelling rates for spin-majority and spin-minority electrons.

In order to analyse transport in FM SETs, we have employed the lowest-order perturbation theory. The corresponding transition rates are then given by the Fermi golden rule, whereas the relevant probabilities that the island is in respective charge states are determined from the appropriate master equation. We have analysed numerically the electric current flowing through the system and the corresponding TMR in various magnetic configurations. It is shown that both current and TMR exhibit a nontrivial dependence on the angle between magnetic moments of the ferromagnetic lead and island. In addition, discrete charging has been shown to modulate TMR, with characteristic dips (or cusps) at the bias voltages corresponding to the Coulomb steps.

The consecutive sections of this paper deal with the following. In Section 2 we present the model and theoretical description, numerical results are shown and discussed in Section 3, and conclusions are given in Section 4.

2. Model and theoretical description

A scheme of the single-electron transistor under consideration is shown in Fig. 1. The first lead as well as the island is made of a ferromagnetic material, whereas the second lead is nonmagnetic. There is a nonzero angle β between the spin moments of the left electrode and island. Further, a gate voltage is attached capacitively to the island, enabling a tuning of system operation.

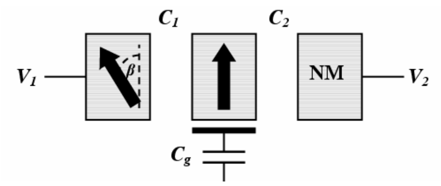

Fig. 1. Schematic diagram of the ferromagnetic single-electron transistor. The arrows indicate the net spin moments of the island and left electrode, forming an angle β. The electrode on the right is nonmagnetic

If thermal energy is smaller than the charging energy, then the energy needed to transfer an extra electron onto the island becomes dominant and establishes a new relevant energy scale. Discrete charging effects then become observable and the current flowing through the system displays current–voltage characteristics with typical Coulomb steps. Apart from this, Coulomb oscillations of electric current occur with increasing gate voltage. We show that these effects lead to characteristic dips (cusps) in TMR with increasing bias voltage.

When the applied voltage does not exceed a certain threshold voltage, sequential tunnelling is exponentially suppressed and the system is in the Coulomb blockade regime. Although first-order tunnelling is then prohibited by the energy conservation rule in the Coulomb blockade, the current can still be mediated by higher-order tunnelling processes (like co-tunnelling) which take place through the virtual states of the island.

In our considerations, however, we take into account only sequential tunnelling processes and assume that the contribution coming from higher-order processes is small compared to the first-order. This is justifiable when the barrier resistances significantly exceed the quantum resistance, $R_j >> R_q = h/e^2$ (j = 1, 2), which implies that the island is in a well defined charge state and the orthodox tunnelling theory is applicable. Electrical resistance of the first (left) tunnel barrier depends on the tunnelling matrix elements between the corresponding states in the left lead and the island, which in turn depend on the relative angle between their magnetizations. The resistance of the second barrier is independent of the magnetic configuration. We further take into account only spin-conserving tunnelling processes and assume that spin relaxation time on the island is shorter than the time between two successive tunnelling events, which means that there is no spin accumulation. Moreover, the island is assumed to be relatively large, so that the quantization of the corresponding energy levels can be neglected.

Electric current flows through the system due to successive tunnelling events. The tunnelling rate of a spin-majority (+) electron from the first lead to the spin-minority (–) electron band in the island can be expressed in terms of the Fermi golden rule as:

$$\Gamma_{1\to i}^{+-} = \frac{2\pi}{\hbar}\left|\left\langle \Psi_{1+}\right| H_T \left|\Psi_{i-}\right\rangle\right|^2 \delta(\varepsilon_f - \varepsilon_i) \tag{1}$$

where $\left|\Psi_{1+}\right\rangle$ and $\left|\Psi_{i-}\right\rangle$ are the wave functions for majority electrons in the first electrode and minority electrons in the island, respectively, ε_i (ε_f) is the energy of the initial (final) state of the system, whereas H_T is the tunnelling Hamiltonian. The wave functions are written in local reference systems (with local quantization axes determined by the local spin moments). As the global reference system, we assume the local one in the island. When a bias voltage V is applied to the system, the tunnelling rates from the first (ferromagnetic) lead to the island, which is already occupied by N excess electrons, can be written in the form:

$$\Gamma_{1\to i}^{++}\left(N,V\right) = \cos^2\frac{\beta}{2}\Gamma_{1\to i}^{p+}\left(N,V\right) \tag{2a}$$

$$\Gamma_{1\to i}^{--}\left(N,V\right) = \cos^2\frac{\beta}{2}\Gamma_{1\to i}^{p-}\left(N,V\right) \tag{2b}$$

$$\Gamma_{1\to i}^{+-}\left(N,V\right)=\sin^2\frac{\beta}{2}\Gamma_{1\to i}^{ap}\left(N,V\right) \tag{2c}$$

$$\Gamma_{1\to i}^{-+}\left(N,V\right)=\sin^2\frac{\beta}{2}\Gamma_{1\to i}^{ap}\left(N,V\right) \tag{2d}$$

with $\Gamma_{1\to i}^{p+(-)}\left(N,V\right)$ denoting the tunnelling rate of spin majority (+) and spin minority (–) electrons in the parallel configuration, whereas $\Gamma_{1\to i}^{ap}\left(N,V\right)$ is the tunnelling rate for both spin orientations in the antiparallel configuration. The tunnelling rates $\Gamma_{1\to i}^{p+(-)}\left(N,V\right)$ are defined as:

$$\Gamma_{1\to i}^{p+(-)}\left(N,V\right)=\frac{1}{e^2R_1^{p+(-)}}\frac{\Delta E_1\left(N,V\right)}{\exp[\Delta E_1\left(N,V\right)/k_BT]-1} \tag{3}$$

where $-e$ is the electron charge ($e > 0$), $R_1^{p+(-)}$ denotes the spin-dependent resistance of the left junction in the parallel configuration, k_B is the Boltzmann constant, and T stands for temperature. Here, $\Delta E_1(N,V)$ describes a change in the electrostatic energy of the system caused by the respective tunnelling event. A similar expression also holds for $\Gamma_{1\to i}^{ap}\left(N,V\right)$, but with $R_1^{p+(-)}$ replaced by R_1^{ap}. Since both ferromagnetic electrodes are assumed to be made of the same material, R_1^{ap} is independent of the electron spin. In a similar way one can derive the tunnelling rates from the island back to the first electrode.

The rates for tunnelling through the second junction are also spin-dependent, but they are independent of the angle β. For any magnetic configuration, they are given by formula (3) with $R_1^{p+(-)}$ replaced by $R_2^{+(-)}$ and $\Delta E_1(N,V)$ replaced by $\Delta E_2(N,V)$.

The electrostatic energy of the system is given by:

$$E\left(N,Q\right)=\frac{\left(Ne-Q\right)^2}{2C} \tag{4}$$

where $C = C_1 + C_2 + C_g$ is the total capacitance of the island, C_1 and C_2 are the capacitances of the first and second junctions, C_g is the gate capacitance, whereas $Q = C_1V_1 + C_2V_2 + C_gV_g$ represents the charge on the island induced by the applied voltages.

In order to calculate the electric current flowing through the system in a stationary state, we take into account the fact that the net transition rate between charge states with N and $N + 1$ excess electrons on the island is equal to zero in a steady state [7]. The corresponding master equation then determines the probability $P(N,V)$ of finding the island in a state with N excess electrons when a bias voltage V is applied to the system. The steady-state master equation reads:

$$
\begin{aligned}
&-\sum_{\sigma,\sigma'=+,-}\left[\Gamma^{\sigma\sigma'}_{1\to i}(N,V)+\Gamma^{\sigma\sigma'}_{i\to 1}(N,V)+\Gamma^{\sigma}_{2\to i}(N,V)+\Gamma^{\sigma}_{i\to 2}(N,V)\right]P(N,V)\\
&+\left[\sum_{\sigma,\sigma'=+,-}\Gamma^{\sigma\sigma'}_{1\to i}(N-1,V)+\sum_{\sigma=\uparrow,\downarrow}\Gamma^{\sigma}_{2\to i}(N-1,V)\right]P(N-1,V)\\
&+\left[\sum_{\sigma,\sigma'=+,-}\Gamma^{\sigma\sigma'}_{i\to 1}(N+1,V)+\sum_{\sigma=\uparrow,\downarrow}\Gamma^{\sigma}_{i\to 2}(N+1,V)\right]P(N+1,V)=0
\end{aligned}
\tag{5}
$$

Finally, the electric current flowing through the system can be calculated from the formula:

$$
I(V)=-e\sum_{\sigma,\sigma'=+,-}\sum_{N=-\infty}^{\infty}\left[\Gamma^{\sigma,\sigma'}_{1\to i}(N,V)-\Gamma^{\sigma,\sigma'}_{i\to 1}(N,V)\right]P(N,V)
\tag{6}
$$

Equation (6) corresponds to the current flowing through the first junction, which in the stationary limit is equal to the current flowing through the second junction.

3. Numerical results and discussion

Equation (6) can be used to calculate the tunnelling current for any magnetic configuration. For a given bias voltage V, the tunnel magnetoresistance is quantitatively described by the ratio

$$
TMR=\frac{I(\beta=0)-I(\beta)}{I(\beta)}
\tag{7}
$$

where $I(\beta)$ is the current flowing when the angle between spin moments of the lead and island is equal to β (β = 0 corresponds to the parallel configuration). Below we present the results of our numerical calculations of electric current flowing through the system and the corresponding *TMR* as a function of the bias voltage (Fig. 2) and the angle β (Fig. 3).

For all magnetic configurations, the dependence of electric current on the bias voltage is non-linear and exhibits characteristic Coulomb steps, as shown explicitly in Fig. 2a for a few values of the angle β. The electric current decreases with increasing angle over the whole bias range. This dependence of electric current on magnetic configuration leads to a non-zero TMR effect, as shown in Fig. 2b. Two local minima (dips) in TMR, visible in Fig. 2b, occur at bias voltages corresponding to the positions of Coulomb steps in the current–voltage characteristics of Fig. 2a. It is worth noting that this is not a general behaviour and that for some other parameters one finds maxima (cusps) instead of minima in TMR at the current steps [5]. It also follows from Fig. 2b that the magnitude of TMR increases monotonously with an increasing angle between magnetizations.

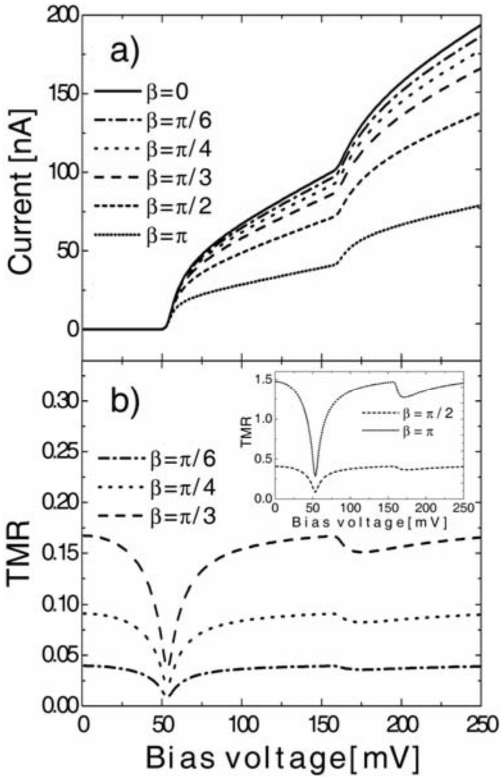

Fig. 2. The bias dependence of electric current (a) and TMR (b) in a symmetrically biased ($V_1 = V/2$, $V_2 = -V/2$) FM SET with non-collinear magnetizations for several values of the angle between magnetic moments. The parameters used in the numerical calculations are: $C_1 = C_2 = C_g$ 1 aF, V_g 0, $R_1^{p+} = 25$ MΩ, $R_1^{p-} = 1$ MΩ, $R_2^{+} = 0.5$ MΩ, $R_2^{-} = 0.1$ MΩ, and $R_1^{ap+} = R_1^{ap-} = \sqrt{R_1^{p+} R_1^{p-}}$

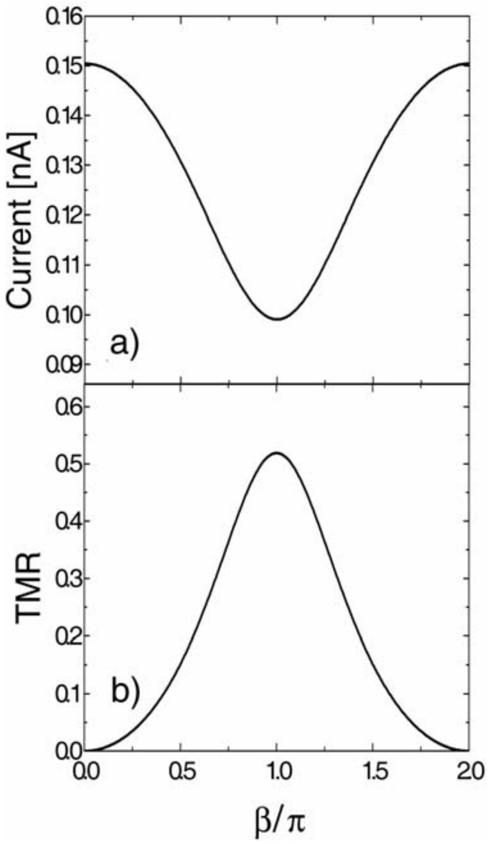

Fig. 3. Electric current (a) and the corresponding tunnel magnetoresistance (b) as a function of the angle between spin moments of the left lead and island. The bias voltage is $V = 50$ mV ($V_1 = 25$ mV, $V_2 = -25$ mV), while the other parameters are the same as in Fig. 2

The dependence of electric current flowing through the system on the angle β, and the corresponding TMR, are shown explicitly in Fig. 3a and b, respectively, for a particular bias voltage. The minimum in electric current occurs in the antiparallel magnetic configuration, which corresponds to a maximum in TMR. This behaviour is qualitatively similar to the normal spin valve effect observed in magnetic layered structures.

4. Conclusions

In this paper, we have calculated and analysed in detail the current flowing through a ferromagnetic single-electron transistor with non-collinear magnetizations and the corresponding tunnel magnetoresistance. The FM SET device consists of a ferromagnetic island and one ferromagnetic electrode, whereas the second external electrode is nonmagnetic. The bias dependence of electric current reveals a characteristic Coulomb staircase. Furthermore, the current flowing through the system, as well as the tunnel magnetoresistance, strongly depend on the angle between magnetizations.

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