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Torque due to spin-polarized current in ferromagnetic single-electron transistors

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A theoretical analysis of current-induced torque acting on the magnetic moment of the central part (island) of a ferromagnetic single-electron transistor has been carried out in the regime of sequential tunnelling. The island is assumed to be ferromagnetic and attached to two leads (electrodes). One of the leads is ferromagnetic, and the corresponding magnetic moment is oriented arbitrarily. The torque is calculated from the spin current absorbed by the magnetic moment of the island, and calculations are carried out in the limit of fast spin relaxation on the island (no spin accumulation).

Key words: *single electron transistor; spin-polarized transport; current-induced magnetic switching*

1. Introduction

It is well known that spin-polarized current in magnetic multilayers or nanopilars can switch the magnetic configuration from a parallel to antiparallel one and/or *vice versa*. The switching is a result of angular momentum transfer from a conduction electron system to the local magnetization, and takes place when the electric current exceeds a certain critical density [1]. Current-induced magnetic switching is of great importance, mainly because it offers a possibility of manipulating magnetic moment orientation without an external magnetic field. The switching phenomenon in all-metal magnetic structures has already been observed experimentally in various systems [2, 3].

Recently, magnetic switching has also been reported in simple planar tunnel junctions [4], where the current density is much smaller than in metallic devices. In this paper, we consider the possibility of current-induced switching in ferromagnetic double-barrier tunnel junctions with a Coulomb blockade, i.e. in ferromagnetic single-electron transistors (SETs). We calculate the torque exerted on the magnetic moment

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of the central electrode (island) and on the magnetic moment of the external ferromagnetic lead. It is worth noting that a significantly different mechanism of the switching phenomenon due to spin-polarized current in ferromagnetic SETs has been recently predicted by Inoue and Brataas [5]. This mechanism is based on spin accumulation in the nonmagnetic island. In our case, however, we consider the limit of fast spin relaxation, so there is no spin accumulation on the island. Such an approximation is justified, since spin relaxation time in ferromagnetic systems is usually significantly smaller (due to a stronger spin-orbit coupling) than in nonmagnetic ones. Apart from this, we consider the torque acting on both the island and external lead, whereas in Ref. [5] only the torque acting on the magnetic leads was studied.

2. Model and method

We consider a SET whose one external electrode and island are ferromagnetic, whereas the second external electrode is nonmagnetic. The magnetic moments of the lead and island can be oriented arbitrarily, as shown in Fig. 1. The island is assumed to be sufficiently large to neglect level quantisation, but small enough to have a charging energy $e^2/2C$ significantly larger than the thermal energy k_BT, $e^2/2C >> k_BT$, where C is the island capacitance. Moreover, we consider only the case where the charge on the island is well localized, which takes place when the resistances $R_{l(r)}$ of the two barriers separating the island from the external electrodes are much larger than the quantum resistance, $R_{l(r)} >> R_Q = h/e^2$. The indices l and r refer to the left and right barriers, respectively. As a consequence, orthodox tunnelling theory based on second-order perturbation theory (Fermi golden rule) and on the master equation is applicable. This theory describes electronic transport in the sequential tunnelling regime relatively well. Finally, as already stated in the Introduction, we restrict ourselves to the situation with no spin accumulation on the island. Therefore, the energy change associated with the tunnelling process can be entirely determined from the change in the electrostatic energy.

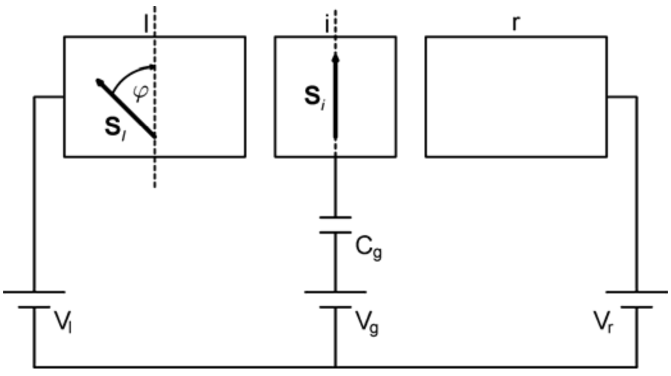

Fig. 1. A schematic diagram of the ferromagnetic single-electron transistor. The vectors $\mathbf{S}_l$ and $\mathbf{S}_i$ indicate the net spin moments of the left external electrode and the island, respectively

A detailed description of the method used to calculate the tunnelling current and transport characteristics is presented elsewhere [6]. This method allows us to calculate the tunnelling current across each barrier. The total charge current I_0 in each ferromagnetic component of the device can be written as $I_0 = I_+ + I_-$, where I_+ and I_- are the currents flowing in the spin-majority and spin-minority channels, respectively. The corresponding spin current I_s may then be defined as $I_s = I_+ - I_-$.

Electrons in the ferromagnetic components of the device have spin orientations either parallel (spin-majority) or antiparallel (spin-minority) to the net local spin polarizations (local spin quantization axis). When the magnetic moments of the island and left electrode are non-collinear, electrons from the spin-majority (or spin minority) channel of the left electrode can tunnel with some probability to the spin-majority (spin-minority) channel of the island and *vice versa.* An electron tunnelling through the barrier between the magnetic electrode and island adjusts its spin orientation in an atomically thin interfacial layer [7, 8]. Thus some angular momentum is transferred to the local magnetization of the island and also to the magnetic moment of the left electrode, giving rise to the corresponding spin transfer torques. The torques can be then calculated as the difference between spin currents incoming and leaving the interfacial region [7].

The angular momentum absorbed by the island is equivalent to the torque. The absolute value of angular momentum carried by a single electron is $\hbar/2$, hence the total angular momentum transferred to the magnetic moment of the island can be calculated by counting the contributions from individual electrons. As a result, the torque τ_i acting on the island due to the tunnelling current flowing through the left barrier is given by

$$\tau_i = \frac{\hbar}{2e}\left[\left(I_{l+} - I_{l-}\right) - \left(I^{<}_{i+} - I^{<}_{i-}\right)\cos\varphi\right]\frac{1}{\sin\varphi} \tag{1}$$

where $I_{l+(-)}$ and $I^{<}_{i+(-)}$ denote currents in the spin-majority (spin-minority) channel of the left electrode and island, respectively, taken at a certain atomic distance from the left barrier. φ is the angle between the spin moments of the left electrode and island, as defined in Fig. 1, whereas e denotes the electron charge ($e > 0$). According to our definition, the torque is positive when it tends to a clockwise rotation of the magnetic moment. A similar formula can be derived for the torque τ_l exerted on the magnetic moment of the left electrode

$$\tau_l = -\frac{\hbar}{2e}\left[\left(I_{l+} - I_{l-}\right)\cos\varphi - \left(I^{<}_{i+} - I^{<}_{i-}\right)\right]\frac{1}{\sin\varphi} \tag{2}$$

The currents $I_{l+(-)}$, flowing when a bias voltage V is applied can be calculated from the formula

$$I_{l\sigma} = -e\sum_{\sigma'=+,-}\sum_{n}\left[\Gamma^{\sigma,\sigma'}_{l\to i}(n,V) - \Gamma^{\sigma',\sigma}_{i\to l}(n,V)\right]P(n,V) \tag{3}$$

where $\Gamma_{l\to i}^{\sigma,\sigma'}(n,V)$ is the electron tunnelling rate from the spin channel σ in the left electrode to the spin channel σ' on the island when there are already n excess electrons on the island. Similarly, $\Gamma_{i\to l}^{\sigma,\sigma'}(n,V)$ is the tunnelling rate from the island back to the left electrode. Apart from this, $P(n,V)$ is the probability of having n excess electrons on the island, which can be calculated from the relevant master equation [6].

3. Numerical results and discussion

The results of numerical calculations of the angular variation of the torque τ_i acting on the magnetic moment of the island are shown in Fig. 2, for two values of spin polarization of the density of states at the Fermi level in the ferromagnetic components of the device (we assume that the ferromagnetic electrode and island are made of the same material). The corresponding spin asymmetry of the resistance of the left barrier is then $R_l^{p,+}/R_l^{p,-} = 1/p^2$, where $R_l^{p,+(-)}$ is the resistance of the left barrier in the parallel configuration for the spin-majority (spin-minority) channel. Similarly, the spin asymmetry of the resistance of the right barrier is $R_r^{+}/R_r^{-} = 1/p$, where $R_r^{+(-)}$ is the resistance of the right barrier for the spin-majority (spin-minority) channel.

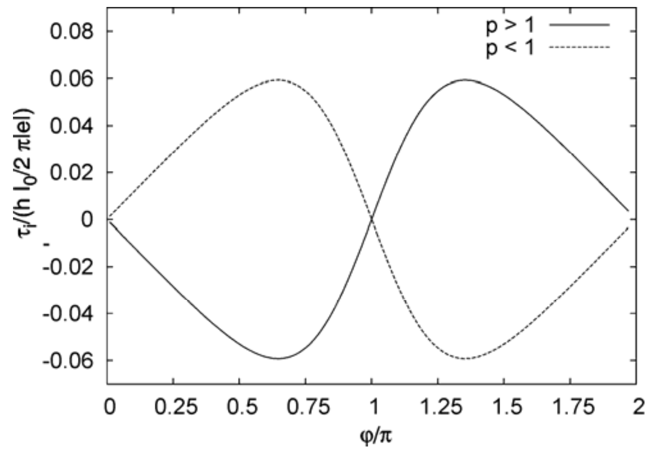

Fig. 2. Normalized torque acting on the island as a function of the angle φ, calculated for $R_l^{p,+}$ = 25 MΩ (1 MΩ), $R_l^{p,-}$ = 1 MΩ (25 MΩ), R_r^{+} = 0.5 MΩ (0.1 MΩ), and R_r^{-} =0.1 MΩ (0.5 MΩ), corresponding to p = 0.2 (p = 5). In the antiparallel configuration we used $R_l^{ap,+} = R_l^{ap,-} = \sqrt{R_l^{p,+}R_l^{p,-}}$. The other parameters were: V_l = 0.043 V, V_r = 0.043 V, V_g = 0, T = 4.3 K and $C_l = C_g = C_r$ = 1 aF

The torque shown in Fig. 2 is normalized to the electric current I_0, and thus changes sign when the current I_0 is reversed. For $p > 1$, the parallel configuration may become unstable for sufficiently large positive currents, $I_0 > 0$, whereas the antiparallel configuration is stable. The situation changes for $p < 1$, for which the parallel configuration is stable for $I_0 > 0$ and the antiparallel configuration becomes unstable. For a negative current, $I_0 < 0$, the torque changes sign and therefore all possible switching phenomena are also reversed. Similar curves also correspond to the torque acting on the magnetic electrode.

The curves presenting the torque normalized to I_0 are universal in the sense that they are independent of the gate and bias voltages. This means that the torque is proportional to the current I_0. Thus, to find the magnitude of the torque one needs to know the magnitude of the current flowing through the system due to the applied bias voltage V. In Figure 3, we show the current as a function of the bias and gate V_g voltages. The curves show typical Coulomb steps and Coulomb oscillations. Thus, the torque τ_i exerted on the magnetic moment of the island reveals similar features as a function of bias and gate voltages.

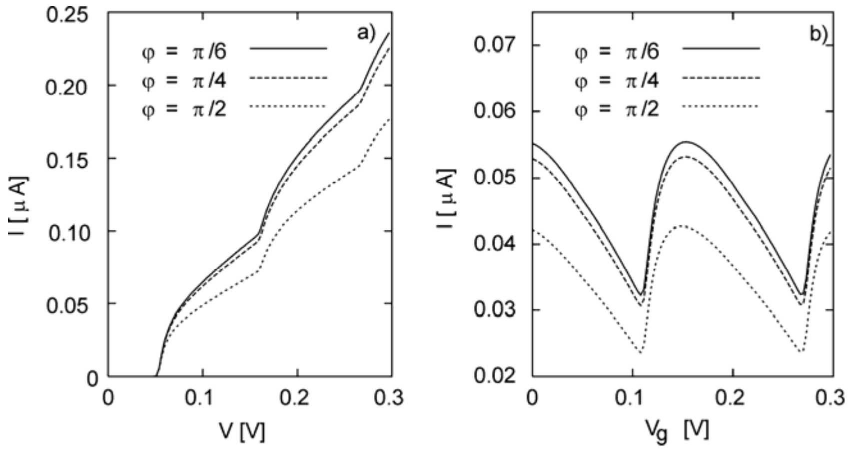

Fig. 3. Electric current as a function of the bias (a) and gate (b) voltages, calculated for $p = 0.2$ and $V_g = 0$ (a), and $V_l = 0.043$ V, $V_r = 0.043$ V (b). The other parameters the same as in Fig. 2

In conclusion, we have calculated the torque exerted by a spin-polarized current on the magnetic moment of the island in a ferromagnetic SET, with the island and one electrode being ferromagnetic. The results of numerical calculations show the possibility of normal and inverse current-induced magnetic switching, similarly as in all-metal layered structures [8]. Numerical calculations have been performed for the situation where the density of states in the ferromagnetic components for one spin orientation is 5 times larger than that for the opposite spin orientation, which is of the order of the corresponding values in ferromagnetic metals. The corresponding ratio may be even significantly larger in half-metallic ferromagnets, where the density of states for one spin orientation is negligibly small.

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