

Spin torque characteristics for the asymmetric non-collinearly polarized ferromagnetic single-electron devices

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Spin-transfer torque due to spin polarized current, acting on the magnetic moment of a central electrode (island) of a single-electron ferromagnetic transistor has been theoretically calculated. The magnetic moments of the external electrodes are oriented non-collinearly with respect to the magnetic moment of the island. In an asymmetric situation under consideration, all the electrodes are made of various magnetic materials. The torque is calculated from the spin current absorbed by the island, and electric current flowing through the system is calculated in the sequential transport regime. The asymmetry in tunnelling processes leads to spin accumulation when the spin relaxation time is sufficiently long, which is also taken into account when calculating the spin torque.

Key words: *spin-transfer torque; spin-polarized current; single-electron transistor*

1. Introduction

Possibility of switching the direction of magnetization by a spin-polarized current in nanoscale devices has recently drawn a considerable attention, mainly due to its potential application in a new kind of memory devices [1, 2]. As has been predicted theoretically by Berger [3] as well as by Slonczewski [4], spin-transfer torque is exerted on the local magnetization if the spin-polarized current is flowing through a magnetic device. In the case of a nanoscale system, like a single-electron transistor (SET), the density of the spin-polarized current flowing through the system is small compared to that flowing in thin films. Therefore it may be not sufficient to switch the local magnetization or to induce precession. It was suggested [5] that in such a case an important source of the instability of the magnetization may be spin accumulation.

The calculations for the asymmetric ferromagnetic SET, where the spin accumulation processes are taken into account, have been presented in this paper. Different

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conducting ferromagnetic materials can be used to prepare each of the SET electrodes, so the SET is asymmetric. Apart from this, magnetic moments of the electrodes are assumed to be oriented arbitrarily in one plane.

2. Model and method

The presented calculations were carried out for the asymmetric ferromagnetic SET shown in the Fig. 1. Each of the electrodes, left (l), the island (i) and the right (r) one, are made of different conducting ferromagnetic materials, which is included via different values of β_l , β_i , and β_r . The spin asymmetry coefficient β is defined as $\beta = D^+/D^-$, where D^+ and D^- denote the densities of states for the majority, and minority electrons, respectively. The vectors \mathbf{S}_l , \mathbf{S}_i , and \mathbf{S}_r indicate the net spin moments of the electrodes, which are oriented arbitrarily. φ_l denotes the angle between the net spin moment of the left electrode and the net spin moment of the island, and φ_r is the angle between the net spin moment of the island and that of the right electrode. The potentials V_l and V_r are applied to the external electrodes, left and right, respectively. Moreover, the island is connected capacitively to the gate voltage V_g . The island is assumed to be big enough to treat the energy spectrum as a continuum. Nevertheless, it is small enough to have the charging energy $e^2/2C$, C being the island capacitance, significantly larger than the thermal energy $k_B T$.

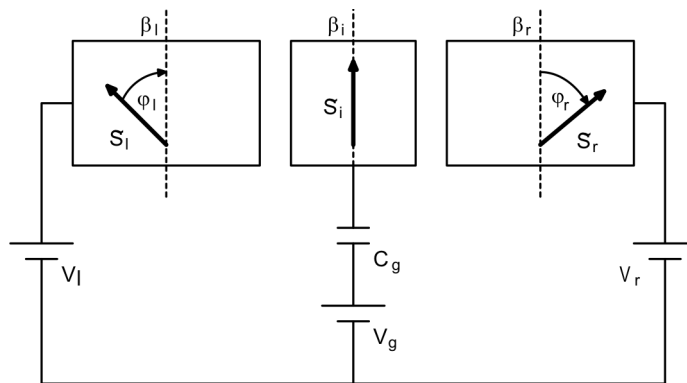


Fig. 1. A schematic diagram of the asymmetric ferromagnetic SET with all the electrodes made of various ferromagnetic materials. The vectors \mathbf{S}_l , \mathbf{S}_i and \mathbf{S}_r indicate the net spin moments of the left external electrode, the island and the right external electrode, respectively. The angle between the net spins of the left (right) electrode and of the island is denoted by φ_l and φ_r . A bias voltage is applied to the left and right electrodes V_l and V_r , while the island is capacitively connected to the gate voltage V_g

Different resistances for the majority and minority electrons in a parallel and anti-parallel configuration are introduced for the left and right tunnel junctions. All introduced resistances are assumed to be considerable larger than the quantum resistance.

The current flowing through the system is calculated in the sequential transport regime in the same way as presented in [6].

The torque acting on the net spin moment of the island is obtained from the spin-current absorbed by the island and it can be written as:

$$\tau_i = \sum_{j=l,r} (\Delta I_j - \Delta I_{i(j)} \cos \varphi_j) \sin \varphi_j$$

where $\Delta I_j = I_j^+ - I_j^-$ and $\Delta I_{i(j)} = I_{i(j)}^\uparrow - I_{i(j)}^\downarrow$ for $j = l, r$. I_j^+ , I_j^- are the currents in the spin-majority and spin-minority channels taken at the atomic distance of the given electrode j from the barrier, and $I_{i(j)}^+$, $I_{i(j)}^-$ are the currents in the spin-majority and spin-minority channels on the island close to the barrier between the island and a j -th electrode [7].

The intrinsic spin-flip processes on the island may be arbitrary, thus the shift of the Fermi levels for the spin-majority and spin-minority electrons should be taken into account. Therefore the balance equation

$$(I_r^\sigma - I_l^\sigma) - \frac{D_i \Omega_i}{\tau_{sf}} \Delta E^\sigma = 0$$

should be solved self-consistently [8, 9]. I_r^σ , I_l^σ are the currents flowing through the right and left junctions, respectively for the spin-majority ($\sigma = \uparrow$) or spin-minority ($\sigma = \downarrow$) electrons. D_i indicates the density of states of the island, Ω_i is the volume of the island. Fermi level shift for spin-majority or spin-minority electrons is ΔE^σ and τ_{sf} is the spin relaxation time on the island.

3. Numerical results and discussion

In Figure 2, the normalized torque acting on the central electrode in function of φ_r (for $\varphi_l = 0$) is presented. The left and the central electrodes are made of different ferromagnetic materials, characterized by the spin asymmetry coefficient $\beta_l = 0.2$, $\beta_i = 0.3$, and β_r is different for each curve. Therefore, each curve represents the situation where the right electrode is made from different ferromagnetic material. In the case of $\beta_r < 1$, the maximum value of the normalized torque is getting smaller as β_r approaches unity. For $\beta_r = 1$, the left electrode becomes non-ferromagnetic. In that case, there is only one source of the torque acting on the island which comes from the left electrode. For $\beta_r > 1$, it is clearly visible that for the increasing values of β_r , the maximum value of the normalized torque also increases.

In Figure 3, also the normalized torque acting on the central electrode as a function of φ_r (for $\varphi_l = 0$), is presented for various spin relaxation times τ_{sf} . All electrodes are made of different ferromagnetic materials ($\beta_l = 0.2$, $\beta_i = 0.3$, $\beta_r = 6.0$). For such

an asymmetric ferromagnetic SET it can be seen that the normalized torque acting on the net spin moment of the island is affected by the spin relaxation time, opposite to the case where all electrodes are made of the same material [7]. Nevertheless this increase of the normalized torque is rather small and may be not sufficient to produce the instability of the net spin moment.

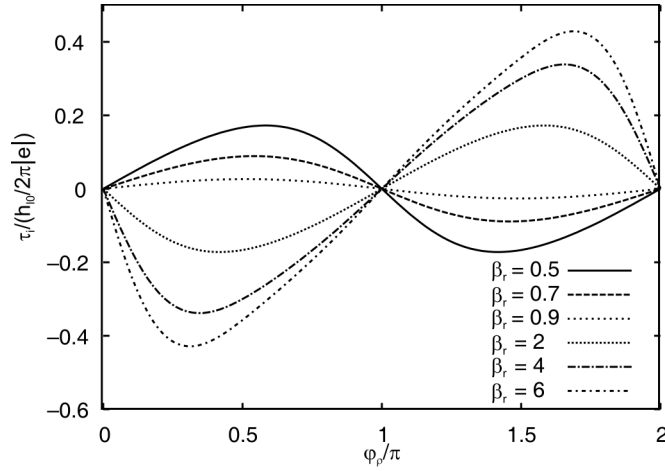


Fig. 2. The normalized torque acting on the island due to the spin-polarized current in function of φ_i , $\varphi_l = 0$. The spin asymmetry coefficients of the left and the central electrode are 0.2 and 0.3, respectively.

Other parameters are: $\tau_{sf} = 10^{-6}$ s, $R_l^{\uparrow p} = 0.1$ M Ω , $R_r^{\uparrow p} = 1.0$ M Ω , $R_j^{\uparrow ap} = R_j^{\downarrow ap} = \sqrt{R_j^{\uparrow p} R_j^{\downarrow p}}$ for $j = l, r$,

$$C_l = C_r = C_g = 1 \text{ aF}, V_l = 0.8 \text{ V}, V_r = 0 \text{ V}, V_g = 0 \text{ V}, D_p \Omega_l 1000 \text{ eV}^{-1}, \text{ and } T = 4.2 \text{ K}$$

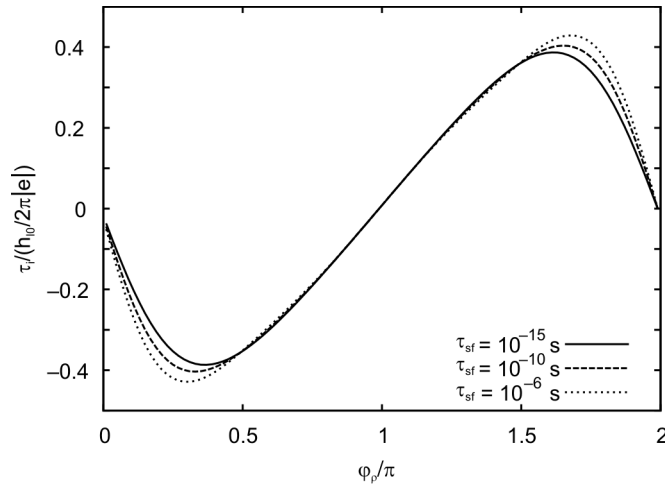


Fig. 3. Normalized torque acting on the island due to the spin-polarized current in function of φ_i , $\varphi_l = 0$ for various spin relaxation times. The spin asymmetry coefficients of the left, central and right electrodes are 0.2, 0.3 and 6.0, respectively. Other parameters are the same as in Fig. 2

Acknowledgements

This work was supported by funds from the Polish Ministry of Science and Higher Education as a research project in years 2006–2009.

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Received 7 May 2007

Revised 5 November 2007