Current-induced magnetic dynamics in an asymmetric ferromagnetic single-electron devices

M. Kowalik

Department of Physics
Adam Mickiewicz University,
Poznań, Poland

Mesoscopic Physics Division
Adam Mickiewicz University,
Poznań, Poland

Abstract

The theoretical calculations of possible dynamics for a localized magnetic moment of the central electrode in a ferromagnetic single-electron devices are presented. The spin-transfer torque from spin current absorbed by the central electrode is calculated. Thereafter, an in-plane component of spin torque is regarded during the integration of Landau-Lifsitz-Gilbert equation and the time evolution of the localized magnetic moment of the central electrode is obtained. The necessary conditions for switching of the magnetic moment is discussed.

Model

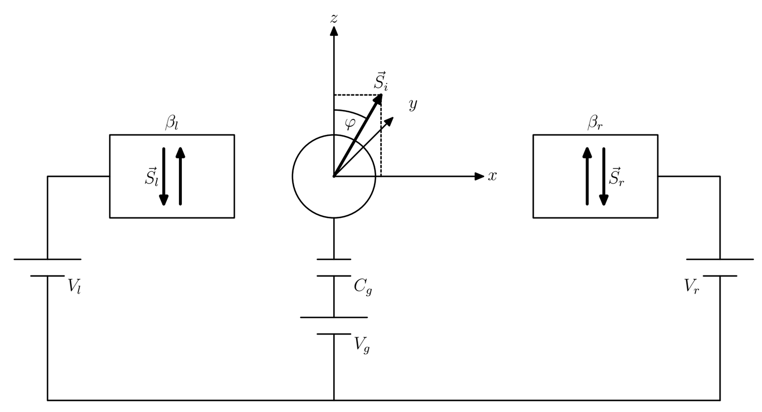

Fig. 1. An asymmetric ferromagnetic SET.

A schematic diagram of the asymmetric ferromagnetic SET. The vectors $\vec{S}_l$, $\vec{S}_r$ and $\vec{S}_i$ are the unit vectors along the classical net spin moments of the left and right electrodes and of the island, respectively. Potential applied to the left and right electrode are V_l and V_r, where the island is connected capacitively to the gate voltage V_g.

Assumptions

- The central electrode i a sphere, big enough to neglect the quantization of an energy levels, however small enough to have the charging energy significantly larger than the thermal energy.
- The charge on the island is well localized (the resistances $R_{l(r)}$ of the two tunnel barriers are much larger than the quantum resistance).
- Only the sequential tunneling processes are considered.
- Fermi golden rule is used to calculate the possible tunneling rates.
- The probabilities that there is a given number of the additional electrons on the island are calculated with the aid of the master equation.
- The energy relaxation time is much smaller than the time between two successive tunneling events.
- The spin relaxation time can be arbitrary.
- Only in-plane component of the spin torque are taken into account.
- The dynamic is given by the generalized Landau-Lifshitz-Gilbert equation.

Formulas

The shift of the Fermi level on the island due to spin accumulation is calculated in a self-consistent way from the following spin balance condition:

$$\frac{1}{e}(I_l^\sigma - I_r^\sigma) - \frac{D_i\Omega_i}{\tau_{sf}}\Delta E^\sigma = 0$$

where $\sigma = +, -$ refers to the spin-majority and spin-minority electrons, respectively. I_l^σ (I_r^σ) is the current flowing in the σ channel through the left (right) junction. D_i denotes the density of states of the island, Ω_i is the island's volume, while τ_{sf} is the spin relaxation time.

The in-plane torque $\vec{\tau_i}$ acting on the net spin moment of the island due to the spin-polarized current is given by:

$$\vec{\tau_i} = \vec{\tau_{il}} + \vec{\tau_{ir}}.$$

Here $\vec{\tau_{il}}$ and $\vec{\tau_{ir}}$ is the spin-transfer torque exerted on the island by the left and right electrode, respectively.

The value of $\vec{\tau_{ij}}$, for $j = l, r$, is obtained as

$$\tau_{ij} = \frac{\hbar}{2e}\left[(I_{j+} - I_{j-}) - (I_{ij+} - I_{ij-})\cos\varphi_j\right]\frac{1}{\sin\varphi_j}.$$

I_{j+} and I_{j-} are the currents flowing in the spin-majority and spin-minority channels in the j-th electrode taken at an atomic distance from the barrier. I_{ij+} and I_{ij-} are the currents in the spin-majority and spin-minority channels in the island close to the barrier between the island and j-th electrode. φ_l and φ_r denote the angles between the net spin moment of the left, right electrode and the net spin moment of the island, respectively. e is the electron charge.

The generalized Landau-Lifshitz-Gilbert equation taken into account is:

$$\frac{d\vec{s}}{dt} = -\gamma_g\mu_0\vec{s}\times\vec{H}_{eff} - \alpha\vec{s}\times\frac{d\vec{s}}{dt} + \frac{\gamma_g}{M_sV}\vec{\tau_i}$$

where $\vec{s}$ is the unit vector along the net spin moment of the island, γ_g a value of the giromagnetic ratio, μ_0 is the magnetic vacuum permeability, $\vec{H}_{eff}$is an effective magnetic field acting on the net spin moment of the central electrode, M_s is the saturation magnetization and V is the volume of the island.

The effective field is given as:

$$\vec{H}_{eff} = \vec{H}_{ext} - H_a(\vec{s}\cdot\vec{z})\vec{z} + \vec{H}_d.$$

$\vec{H}_{ext}$ is the external field, H_a is the magnetic anisotropy field $\vec{H}_d$ stands for the demagnetization field and $\vec{z}$ is a unit vector along the z direction.

Numerical results

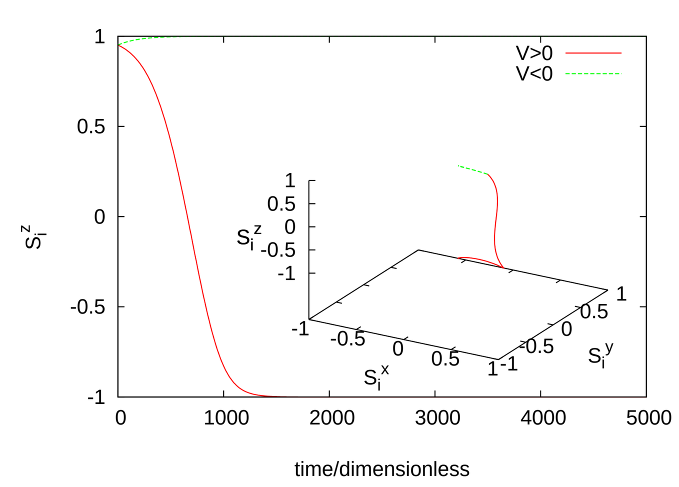

Fig. 2. The time dependence of the z-th component of the net spin moment of the island for charge current flow from the left electrode to right one ($V_l > V_r$) and for the charge current flow from right electrode to the left one ($V_l < V_r$). The net spin moment of the left electrode is assumed to point along to the positive z-th direction whereas the net spin moment of the right electrode in the opposite direction. The other parameters used for calculations are as follow. The initial position of the net spin moment of the island is given by $\phi = \pi/10$ and $\eta = 0$. We assumed the symmetrical applied voltage, so $|V_l = |V_r| = 0.16$ V. For the presented data we assume that all the electrodes are made of the same ferromagnetic material, given by $\beta_l = \beta_i = \beta_r = 4$. The tunnel junctions are characterized by $C_l = C_r = 1$ aF and $R_l^{P,+} = 1$ MΩ, $R_r^{P,+} = 0.1$ MΩ. For the island we assumed: $M_s = 8\cdot 10^5$ A/m, $H_a = 0.002\cdot 10^5$ A/m, $\alpha = 0.05$, $r = 2$ nm, $D_i\Omega_i = 10001$/eV and $\tau_{sf} = 10^{-6}s$ s. The temperature is $T = 4.2$ K. For the gate we chosen $V_g = 0$ V and $C_g = 1$aF. The external field is assumed to be $M_{ext} = 0$ A/m.

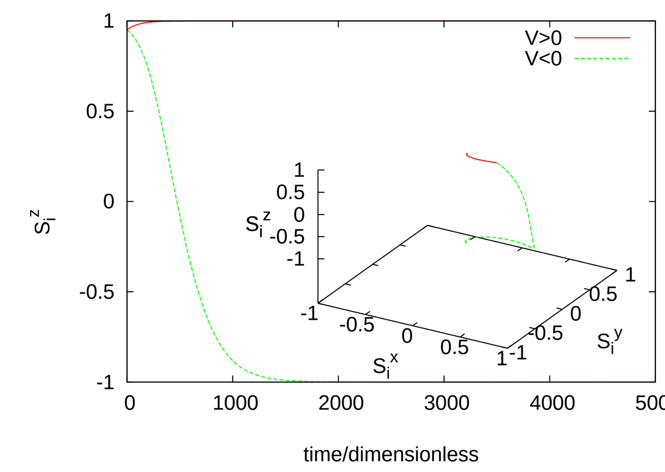

Fig. 3. The time dependence of the z-th component of the net spin moment of the island for charge current flow from the left electrode to right one ($V_l > V_r$) and for the charge current flow from right electrode to the left one ($V_l < V_r$). The net spin moment of the left electrode is assumed to point along to the negative z-th direction whereas the net spin moment of the right electrode in the opposite direction. The others parameters are the same as in Fig. 2.

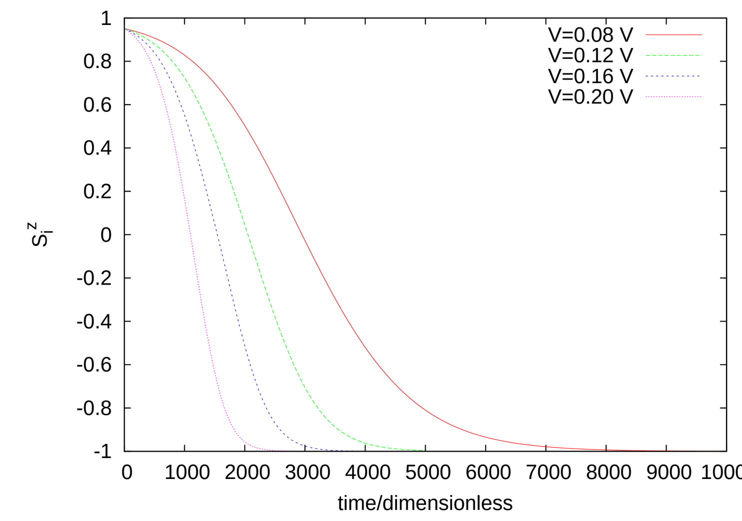

Fig. 4. The time dependence of the z-th component of the net spin moment of the island for different absolute value of the applied voltage ($V = 0.8, 0.12, 0.16, 0.20$ V). In all cases $|V_l| = |V_r| = V$ and $V_l > V_r$. The other parameters used for calculationsare are the same as in Fig. 2.

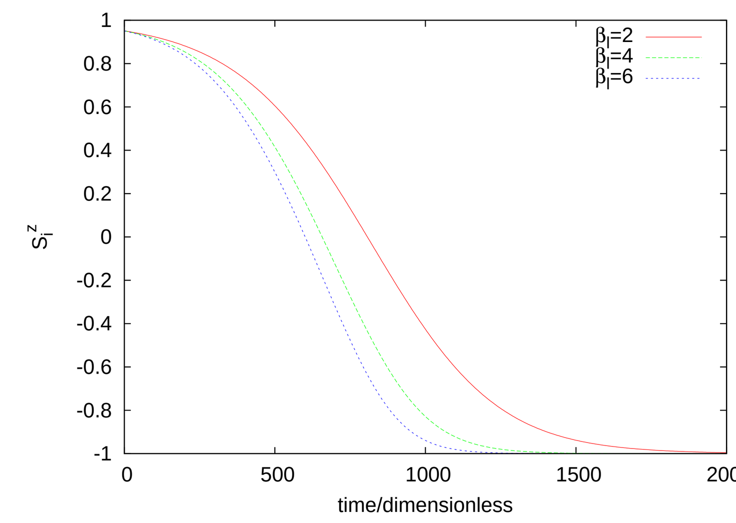

Fig. 5. The time dependence of the z-th component of the net spin moment of the island in the case where the left electrode is made of different ferromagnetic material ($\beta_l = 2, 4, 6$). In all cases $|V_l| = |V_r| = 0.16$ V and $V_l > V_r$. The other parameters are the same as in Fig. 2.

References

[1] J.C. Slonczewski, J. Magn. Mater. 159, L1 (1996).
[2] L. Berger, Phys. Rev. B 54, 9353 (1996).
[3] Y. Huai, F. Albert, P. Nguyen, M. Pakala, and T. Valet, Appl. Phys. Lett. 84, 3118 (2004).
[4] H. Meng, J. Wang, and J.-P. Wang, Appl. Phys. Lett. 88, 082504 (2006).
[5] M. Kowalik, I. Weymann, and J. Barnaś, Materials Science (PL) 25, No 2, 453 (2007)
[6] H. Grabert, M. H. Devoret (Eds.), *Single Charge Tunnelling* NATO Advanced Study Institute, Series B, Vol. 294, Plenum Press, New York (1992). Appl. Phys. Lett. 88, 082504 (2006).
[7] J. Barnaś and A. Fert, J. Mag. Mag. Mat. 192, 391 (1999).
[8] A. N. Korotkov and V. I. Safarov, Phys. Rev. B 59, 89 (1999).
[9] J. C. Slonczewski, Phys. Rev. B 71, 24411 (2005).
[10] M. Gmitra and J. Barnaś, Phys. Rev. Lett. 96, 207205 (2006).
[11] I. Theodonis, N. Kioussis, A. Kalitsov, M. Chshiev, and W. H. Butler, Phys. Rev. Lett. 97, 297205 (2006).