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Macroscopic description of spin transfer torque

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Abstract

A macroscopic description of the current-induced torque due to spin transfer has been developed for layered systems consisting of ferromagnetic films, separated by nonmagnetic layers. The description is based on the classical spin diffusion equations for the distribution functions used in the theory of current-perpendicular-to-plane giant magnetoresistance (CPP-GMR), and the relevant boundary conditions for the longitudinal and transverse components of the spin current and spin accumulation. The torque is expressed as a function of the usual parameters derived from CPP-GMR experiments and two additional parameters involved in the transverse boundary conditions. The model describes qualitatively the normal and inverse switching phenomena studied in recent experiments. We also discuss a structure for which the spin torque disappears at a noncollinear magnetic configuration.

Keywords: Spin transfer; Magnetic switching; Spin currents

1. Introduction

The spin polarized current transferred through a magnetic body can switch its magnetic moment without applying an external magnetic field. The theoretical concept was introduced independently by Slonczewski [1] and Berger [2]. Current-induced magnetic switching (CIMS) has been clearly demonstrated by experiments on structures F1/N/F2, consisting of two ferromagnetic layers F1 and F2 of different thicknesses, separated by a nonmagnetic layer N [3]. Starting from a parallel configuration of the magnetizations in F1 and F2, a current exceeding a certain critical value can reverse the magnetic moment of the thinner magnetic layer to set up an antiparallel configuration. In turn, a current in the opposite direction can switch back the structure to the parallel configuration. Such a back and forth magnetic switching is of great importance for spintronics.

Both current-perpendicular-to-plane giant magnetoresistance (CPP-GMR) and CIMS depend on spin accumulation effects. This is well known for CPP-GMR. For CIMS, this has been shown by experiments in which the spin accumulation profile is manipulated by introducing spin-flip scattering at different places in the structure [4]. It turns out that both the GMR effect and the spin transfer torque can be enhanced by introducing spin-flip scattering outside a F1/N/F2 trilayer (in the leads) or reduced by spin-flip scattering in the nonmagnetic layer N. This calls for a unified theory of CPP-GMR and spin transfer torque, taking into account spin accumulation, spin relaxation, and both interface and bulk spin dependent scattering.

The model used in this paper to calculate angular dependence of the torque due to spin transfer fits directly with the interpretation of CPP-GMR data in the model of Valet and Fert [5]. Most of the necessary parameters can be derived directly from the analysis of CPP-GMR experimental data. The additional parameters, namely the real and imaginary parts of the mixing conductance can be derived from quantum-mechanical calculations [6,7] of the transmission of spin currents at the interface under consideration.

The calculations of our model are based on the macroscopic transport equations derived from the Boltzmann equation by Valet and Fert [5] for the CPP-GMR of multilayers with collinear magnetizations. We assume that the absorption of transverse component of the spin currents is quasi-interfacial, as this has been justified by a quantum description of the transmission of transverse spin current into a ferromagnetic

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layer [7]. The calculations are based on the boundary conditions for the spin currents and spin accumulation at the interfaces involved, derived by Brataas et al. [8].

2. Theoretical description

The structure F1/N/F2 under consideration consists of two left F1 (thick) and right F2 (thin) magnetic films, separated by a nonmagnetic layer N [9]. Thickness of the nonmagnetic spacer layer is d_N, whereas of the thick and thin magnetic films is d_{F1} and d_{F2}, respectively. The structure is shown schematically at the top of Fig. 1, where also left L and right R leads are indicated. Both ferromagnetic films are magnetized in their planes, and magnetization of the thin layer is rotated by an angle φ around the axis x normal to the films. Axis z of the coordinate system is along the net spin of the thick (F1) ferromagnetic film (opposite to the corresponding magnetization). In both ferromagnetic films, the local quantization axes are along the local net spin, while as the global quantization axis we choose the local one in the thick ferromagnetic film. According to our definition, charge current I_0 is positive when it flows along the axis x from left to right, i.e., from the thick towards thin magnetic films (electrons flow then from right to left).

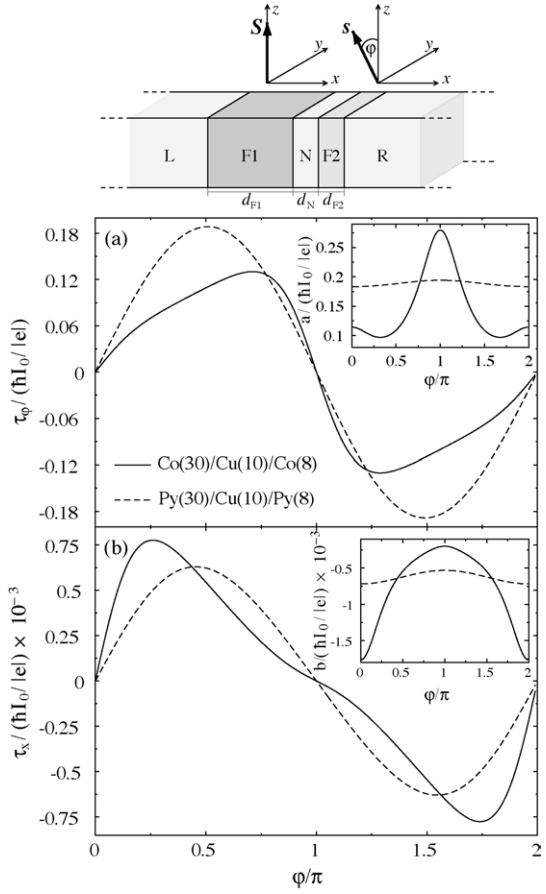

Fig. 1. Top: schematic structure of a trilayer system. Arrows indicate orientation of the net spin of the magnetic films. (a) Normalized in-plane torque τ_φ acting on the thin ferromagnetic film due to spin transfer, calculated as a function of the angle φ for Co/Cu/Co and Py/Cu/Py stacks. The values in brackets indicate the thicknesses in nanometer. (b) Normalized out-of-plane torque, calculated as a function of the angle φ for the same systems as in (a). The insets indicate angular dependence of the corresponding parameters a and b, respectively.

We assume the electric current in the multilayer is carried by free-like conduction electrons of equal concentrations in all the layers and without spin polarization in equilibrium. The distribution function inside the films is a 2×2 matrix in the spin space, and its spatial variation can be described by the diffusion equation. We assume the distribution functions are uniform in the plane of the films, and vary only along the axis x normal to the films. We also assume that the internal exchange field inside ferromagnetic metals is strong enough so that the component of the distribution function perpendicular to the local magnetization vanishes. Thus, the distribution function is diagonal when the spin quantization axis is parallel to the local spin polarization of the ferromagnetic system.

Electron distribution function is a 2×2 matrix in the spin space. Owing to strong exchange field in ferromagnetic layers, it is diagonal in the local reference frame (quantization axis along the local spin polarization). The diffusion equation for the distribution function leads then to the following equations for the electro-chemical potentials $\bar{\mu}_\uparrow$ and $\bar{\mu}_\downarrow$ for spin-majority and spin-minority electrons [10],

$$\frac{\partial^2(\bar{\mu}_\uparrow - \bar{\mu}_\downarrow)}{\partial x^2} = \frac{1}{l_{sf}^2}(\bar{\mu}_\uparrow - \bar{\mu}_\downarrow), \tag{1}$$

$$\frac{\partial^2(\bar{\mu}_\uparrow + \bar{\mu}_\downarrow)}{\partial x^2} = \eta \frac{\partial^2(\bar{\mu}_\uparrow - \bar{\mu}_\downarrow)}{\partial x^2}, \tag{2}$$

where the spin diffusion length l_{sf} is defined as $1/l_{sf}^2 = (1/l_\uparrow^2 + 1/l_\downarrow^2)/2$ with $l_\uparrow^2 = D_\uparrow \tau_{sf}$, $l_\downarrow^2 = D_\downarrow \tau_{sf}$, and $\eta = (D_\downarrow - D_\uparrow)/(D_\downarrow + D_\uparrow)$. Here, τ_{sf} is the spin-flip relaxation time and $D_\uparrow$ ($D_\downarrow$) denotes the spin diffusion constant for spin-majority (spin-minority) electrons. The above equations are equivalent to the equations derived from the Boltzmann equation approach by Valet and Fert [5].

Solutions of Eqs. (1) and (2) for the electro-chemical potentials can be written in the general form as $\breve{\bar{\mu}} = \bar{\mu}_0 \breve{1} + g\breve{\sigma}_z$ with $\bar{\mu}_0 = (\bar{\mu}_\uparrow + \bar{\mu}_\downarrow)/2$, $g = (\bar{\mu}_\uparrow - \bar{\mu}_\downarrow)/2$ being the spin accumulation, and $\breve{1}$ denoting the 2×2 unit matrix. Explicit solutions for $\bar{\mu}_0$ and g are:

$$\bar{\mu}_0 = \eta \left[A \exp\left(\frac{x}{l_{sf}}\right) + B \exp\left(\frac{-x}{l_{sf}}\right) \right] + Cx + G, \tag{3}$$

$$g = A \exp\left(\frac{x}{l_{sf}}\right) + B \exp\left(\frac{-x}{l_{sf}}\right), \tag{4}$$

with A, B, C and G being constants to be determined from appropriate boundary conditions.

Diffusive spin and charge currents can be written in the form $\breve{j} = (j_0 \breve{1} + j_z \breve{\sigma}_z)/2$, with $j_0 = j_\uparrow + j_\downarrow$ being the particle current (charge current I_0 is $I_0 = e j_0$ with e being the electron charge, $e < 0$) and $j_z = j_\uparrow - j_\downarrow$ denoting the z-component of the spin current. Explicit forms of j_0 and j_z are:

$$j_0 = -\rho_F C (D_\uparrow + D_\downarrow), \tag{5}$$