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Spin Dynamics in Magnetic Heterostructures Driven by Current-Induced Spin–Orbit Torques

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In this work it is shown that in magnetic heterostructure with the structural inversion symmetry due to the presence of the Rashba effective field responsible for the effects of spin–orbit scattering, the spin dynamics in the magnetic layer is described by a modified system of coupled equations for the exchange-coupled localized spins and spin accumulation. As a result, this system is reduced to an effective Landau–Lifshitz equation for the total magnetization with the additional torques which act similarly to the spin transfer torque in magnetic tunnel junction. Based on these equations, we calculated numerically the field dependences of the switching current density for the different magnetization geometries, in particular for that was used in work of Miron et al., which are in a good agreement with the experimental results for the reasonable fitting parameters.

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1. Introduction

The current-induced transfer of spin angular momentum in magnetic heterostructures is now one of the most promising effects for the technological progress of high-dense and non-volatile memory elements towards the size scalability close to the 45 nm node and below. Spin–orbit torque effects in heterostructure with the structural inversion symmetry are considered as a good alternative to mechanisms of the spin-transfer torque generated in the current-perpendicular-to-plane spin-valve structure [1], so their study is of great practical interest. In this paper we analyze the features of the spin–orbit switching induced by current in the magnetic film for various geometries of its magnetization based on generalized Landau–Lifshitz–Gilbert equations.

2. Landau–Lifshitz–Gilbert equation with the Rashba effective field

Consider the action of the nonequilibrium spin accumulation on the magnetic state of the ferromagnetic ultrathin film in heterostructure with nonuniform transverse crystal field $\mathrm{d}V(z)/\mathrm{d}z$ along the z axis perpendicular to the film plane when the current $\boldsymbol{J}$ flows in the x–direction. For the paramagnetic carrier system in a conducting layer, the Rashba field $\boldsymbol{H}_\mathrm{R} = c[\boldsymbol{J}\times\boldsymbol{z}] = cJ[\boldsymbol{j}\times\boldsymbol{z}]$ creates the spin accumulation $\boldsymbol{m}_\mathrm{R} = \chi_\mathrm{P}\boldsymbol{H}_\mathrm{R}$, to which nonequilibrium spin system of this layer eventually should relax. Here $c = \alpha_\mathrm{R} m/en\mu_B\hbar$, $\boldsymbol{j} = \boldsymbol{J}/J$, $\chi_\mathrm{P} = \mu_\mathrm{B}^2 g_\mathrm{F}$ is the Pauli paramagnetic susceptibility, α_R is the effective Rashba spin–orbit coupling constant, m is the electron effective mass, e is the electron charge, n is the electron density, μ_B is the Bohr magneton, $\hbar$ is the reduced Planck constant, g_F is the density of states at the Fermi level. This effect can be taken into account in the spin dynamics by adding to the kinetic equation for spin accumulation, suggested, for example, in [2], additional terms related to the presence of quasi-equilibrium state of spin accumulation $\boldsymbol{m}_\mathrm{R}$ and the effect of the spin rotation in the field $\boldsymbol{H}_\mathrm{R}$. For the macrospin magnetization geometry in the case of uniform current injection we can write the next system of equations:

$$\frac{\partial \boldsymbol{m}}{\partial t} + \frac{\boldsymbol{m} - \chi_\mathrm{P} cJ\boldsymbol{s}_\mathrm{R}}{\tau} + \gamma\lambda\boldsymbol{m} \times\boldsymbol{M}_0 + \gamma cJ\boldsymbol{m}\times\boldsymbol{s}_\mathrm{R} = 0, \quad (1)$$

$$\frac{\partial \boldsymbol{M}_0}{\partial t} = -\gamma\boldsymbol{M}_0 \times \left(\boldsymbol{H}_\mathrm{eff} + \lambda\boldsymbol{m} - \frac{\alpha}{\gamma M}\frac{\partial \boldsymbol{M}_0}{\partial t}\right), \quad (2)$$

where $\boldsymbol{s}_\mathrm{R} = \boldsymbol{H}_\mathrm{R}/H_\mathrm{R}$, α is the damping parameter, γ is gyromagnetic ratio, τ is spin relaxation time, λ is exchange interaction parameter.

To perform an analysis of the magnetization equilibrium states, we suggest for the simplicity that the spin accumulation rearranges itself with time much faster than the local magnetization, i.e. $\tau \ll 1/\alpha\gamma M_0$, so it can be supposed that $\partial\boldsymbol{m}/\partial t = 0$. In this approximation the system of Eqs. (1), (2) reduces to the modified equation of magnetodynamics

$$\frac{\partial \boldsymbol{M}_0}{\partial t} = -\gamma\boldsymbol{M}_0 \times \left(\boldsymbol{H}_\mathrm{eff} + A_\mathrm{R}J\boldsymbol{s}_\mathrm{R} + B_\mathrm{R}J\boldsymbol{M}_0\times\boldsymbol{s}_\mathrm{R} - \frac{\alpha}{\gamma M}\frac{\partial \boldsymbol{M}_0}{\partial t}\right), \quad (3)$$

where the coefficients of the spin-transfer efficiency A_R and B_R are as follows:

$$A_\mathrm{R} = \lambda pc\left[1 + \tilde{J}\lambda\tilde{\tau}^2\boldsymbol{s}_\mathrm{R}\boldsymbol{e}_\mathrm{M} + \left(\tilde{J}\tilde{\tau}\right)^2\boldsymbol{s}_\mathrm{R}\boldsymbol{s}_\mathrm{R}\right] \Big/ \left[1 + (\lambda\tilde{\tau})^2 + \left(\tilde{J}\tilde{\tau}\right)^2\boldsymbol{s}_\mathrm{R}\boldsymbol{s}_\mathrm{R} + 2\tilde{J}\lambda\tilde{\tau}^2\boldsymbol{e}_\mathrm{M}\boldsymbol{s}_\mathrm{R}\right], \quad (4)$$

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$$B_{\mathrm{R}} = \gamma p \lambda^2 c\tau \Big/ \left[1 + (\lambda\tilde{\tau})^2 + \left(\tilde{J}\tilde{\tau}\right)^2 \boldsymbol{s}_{\mathrm{R}}\boldsymbol{s}_{\mathrm{R}} + 2\tilde{J}\tilde{\tau}\lambda\tilde{\tau}\boldsymbol{e}_{\mathrm{M}}\boldsymbol{s}_{\mathrm{R}}\right], \quad (5)$$

where $\tilde{J} = Jc/M$, $\tilde{\tau} = \tau\gamma M$.

The effective field has the next form

$$\boldsymbol{H}_{\mathrm{eff}} = \left(\frac{2K_x}{M^2}M_x + H\right)\boldsymbol{e}_x + \left(\frac{2K_z}{M^2} - 2\pi M^2\right)M_z\boldsymbol{e}_z, \quad (6)$$

where $\boldsymbol{e}_i$ are the unit vectors along the axes $i = x, z$, K_x, K_z are the uniaxial anisotropy constants.

The obtained equation of magnetodynamics is similar to the generalized Landau–Lifshitz–Gilbert (LLG) equation within the Slonczewski–Berger model used for the description of the spin-transfer torque in the free magnetic layer of spin-valve heterostructure [3]. In our case, however, the current dependence of the coefficients of the spin-transfer efficiency preserves the symmetry by changing the current sign.

3. Steady states and magnetization switching under applied magnetic field and current

The stationary points of the dynamic system (3) are determined from the condition of its solvability when $\partial\boldsymbol{M}_0/\partial t = 0$. Stability of the obtained stationary points is defined after linearization of Eqs. (3) near the equilibrium states for small magnetization deviations $\delta M/M_0 \sim \exp(\lambda t) \ll 1$ by analysis of the roots λ_i of the characteristic equation. Bifurcation change of the type of stationary point takes place at the critical current density $J = J_{\mathrm{c}}(H)$ depending on the applied magnetic field.

In the case when the Rashba field and the initial magnetization vector are collinear with the applied magnetic field $\boldsymbol{H}$ acting along the x axis the most relevant equilibrium magnetization states are the directions $\pm\boldsymbol{M}_0||\boldsymbol{e}_x$ ($m_{x0} = \pm 1$) that correspond to the stable focus-type fixed point at zero magnetic field. For small magnetic field $|H| < 2K_x/M$, the critical current density at which the loss of stability of one of the equilibrium states occurs is given by the relation

$$J_{\mathrm{c}} = -m_{x0}\frac{\alpha\,(H + 2K_x m_{x0}/M + 2\pi M)}{B_{\mathrm{R}}M + \alpha A_{\mathrm{R}}}. \quad (7)$$

Figure 1 illustrates the field dependence of the critical currents for the case when the current-induced Rashba field is oriented parallel to the easy axis of magnetic layer. At low magnetic fields $H < H_{\mathrm{c}} \sim 2K_x/M$, the both equilibrium states are stable between the obtained values of the threshold current density and the hysteresis loop of the spin switching occurs. With the magnetic field increasing, we have an intersection region for the curves $J_{c\pm}(H)$ in which the only steady-state spin precession is possible. The above example of the magnetization behaviour in the magnetic thin film with the effect of spin–orbit transfer of current-induced torques is similar to the same one in the magnetic free layer of spin-valve structures when the spin-polarized current is flowing through it.

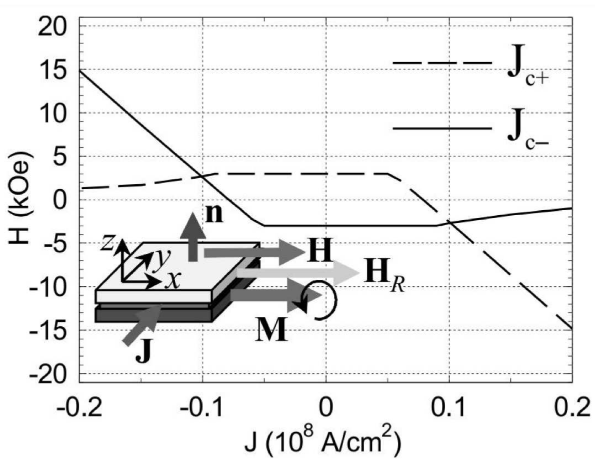

Fig. 1. Critical current densities $J_{c\pm}(H)$ (dashed and solid lines) of spin-orbit switching of magnetization states $m_{x0} = \pm 1$ for the case $\boldsymbol{H}_{\mathrm{R}}||\boldsymbol{H}$. The inset shows the considered magnetization geometry. Parameters of calculations: $M \sim 10^3$ G, $K_x = 1.5\times10^6$ erg/cm^3, $K_z = 0$, $\gamma = 2\times10^7$ s^{-1} Oe^{-1}, $\alpha \sim 0.01$, $\alpha_{\mathrm{R}} \sim 3\times10^{-9}$ eV m, $n \sim 10^{22}$ cm^{-3}, $\chi_{\mathrm{P}} = 4\times10^{-5}$, $\lambda \sim 10^4$, $\tau \sim 5\times10^{-14}$ s.

Now we consider the case, which is close to the experiment in [4]. We assume that the easy magnetization axis and the external magnetic field are directed along the x axis, and the demagnetization energy is compensated by an induced magnetic anisotropy along the z axis perpendicular to the film plane. The current direction $\boldsymbol{j}$ is parallel to the x axis so that the Rashba field is perpendicular to the applied magnetic field. In the absence of current, for $K_z \le 2\pi M^2$ the spin switching is carried out by the magnetic field exceeding the critical value $H_{\mathrm{c}-} = 2K_x/M$. The applied current $J \ne 0$ leads to the reduction of the first critical magnetic field $H_{\mathrm{c}-}(J)$ as it is shown in Fig. 2. At the first critical field $H_{\mathrm{c}-}(J)$ the initial antiparallel magnetization state $m_{z0} = -1$ loses its stability and magnetization changes its direction to the new equilibrium state which is close to the initial magnetization direction. Disruption of the last state in favour of the opposite direction along the easy magnetization axis (global switching) occurs at the second critical field $H_{\mathrm{c}+}(J)$.

The current dependences of critical magnetic fields $H_{\mathrm{c}+}(J)$ and $H_{\mathrm{c}-}(J)$ found by numerical calculations based on magnetodynamic Eqs. (1), (2) are shown in Fig. 2.

The values of the chosen parameters allow us to achieve a very good agreement between the theoretical values of critical magnetic field and the experimental one (see closed triangles in Fig. 2). Note that if the exchange constant, the spin relaxation time, and the Rashba parameter are chosen corresponding to the literature data indicated in a variety of works [5–8], then necessary Pauli susceptibility parameter $\chi_{\mathrm{P}} = 4 \times 10^{-4}$ significantly exceeds the typical values of the Pauli susceptibility in metals. It means that the given parameter should be considered as an adjustable parameter for the considered model.

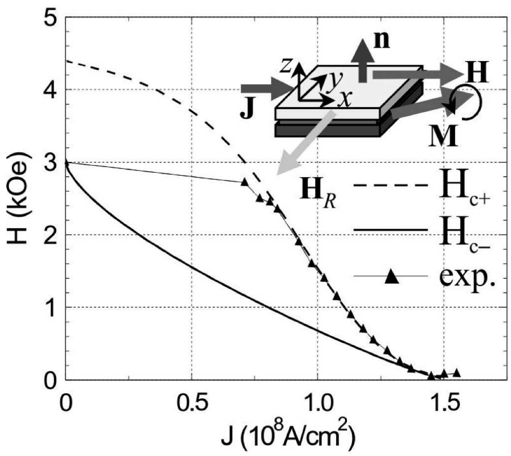

Fig. 2. Critical magnetic fields $H_{c-}(J)$ and $H_{c+}(J)$ (solid and dashed lines) of current-induced spin switching for the case $\boldsymbol{H}_R \perp \boldsymbol{H}$, which is close to the experiment of Ref. [4]. Closed triangles correspond to the experimental points. The inset shows the magnetization geometry of the spin switching. Parameters of calculations: $M \sim 10^3$ G, $K_x = 2.2 \times 10^6$ erg/cm^3, $K_z = 6.98 \times 10^6$ erg/cm^3, $\gamma = 2 \times 10^7$ s^{-1} Oe^{-1}, $\alpha \sim 0.01$, $\alpha_R \sim 3 \times 10^{-10}$ eV m, $n \sim 10^{22}$ cm^{-3}, $\chi_P = 4 \times 10^{-4}$, $\lambda \sim 2 \times 10^4$, $\tau \sim 5 \times 10^{-14}$ s.

In this connection it should be noted that there may be additional important mechanisms for the transfer of spin angular momentum in magnetic heterostructures, associated, for example, with the spin Hall effect [9].

4. Summary

Thus, the basic principles underlying spin–orbit transfer mechanism of the current-induced torques are close to the exchange mechanism of spin-transfer torques from current perpendicular to the plane (CPP) in a spin-valve heterostructure. Comparison with the observed values of critical magnetic field and threshold current densities required for spin switching show that for the consistency of theory and experiment the increased values of the Rashba constant and Pauli susceptibility are needed. It indicates that the parameters used in generalized magnetodynamic equations are determined not only by the bulk Rashba effect but also by the other mechanisms, such as the spin Hall effect, arising from the scattering of spin carriers at the interfaces of the structure.

Acknowledgments

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