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Spin accumulation, spin currents, and torque, in the problem of motion of a sharp domain wall in magnetic nanowires

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We consider the motion of a sharp domain wall in magnetic nanowires with electric current. The width of the domain wall is much smaller than the electron wavelength, which is typical for magnetic semiconductors. We calculate the distributions of the spin density and the spin current related to different modes of the scattering states. The accumulated transverse components of the spin density and the spin current oscillate in the vicinity of the wall and they essentially affect its dynamics, whereas the longitudinal part of the spin current is responsible for another component of the spin torque creating a force for the current-induced motion of the domain wall along the nanowire. We also analyze the dynamics of the sharp domain wall using the standard Landau–Lifshits–Gilbert formalism and the two-component spin torque calculated for this model.

1 Introduction

Studies on the dynamics of domain walls (DWs) in magnetic nanostructures are motivated by perspective applications in spintronic devices. A contemporary important aspect is the efficient controllability of the motion of DWs by means of external magnetic field or electric current flow, as has been demonstrated by several recent experiments [1–3]. In general, the theoretical formulation of a domain wall motion has long been established [4–6]. These treatments deal with 3D or 2D ferromagnets and are based on a model of classical ferromagnets with separated magnetic and electronic dynamics.

Nowadays research on the DW dynamics is focused on the problem of current-induced magnetic wall motion in nanowires and nanoconstrictions [1, 2, 7]. In the presence of an electric current, the domain wall can move due to the spin torque transmitted to magnetic system from the spin-polarized electron gas, in addition to the linear momentum directly transmitted from electrons to the wall. The question of how to calculate the spin torque is of a prime importance in the theory of domain-wall motion. However, a relatively small number of recent works have addressed this problem [8–10].

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In principle, the DW motion can be described by the Landau–Lifshitz equations, which have a well-known static solution for the DW. However, the search for a corresponding dynamic solution is a nontrivial task, particularly in the presence of an external force. Hence one is obliged to resort to approximate schemes for description of the DW dynamics. Most of these schemes are not strictly mathematically justified but they rely on physically reasonable arguments. The simplest approach assumes an approximate moving-wall solution which has exactly the same shape as dictated by the static solution. The range of validity of this assumption is an open question and it is up to numerical simulations probably [11, 12] to judge its reliability. Most recently, new approaches to this problem have been presented [8, 10], concerning both the calculation of torque and the solution of dynamical equations of motion for the DW.

In this present work we concentrate on the issues of the spin torque and on the wall dynamics in a magnetic nanowire with a DW. Our treatment assumes a small extension of the DW on the scale of the Fermi wave length of the carriers (electrons or holes), and hence the theory is applicable to magnetic semiconductors with a small Fermi momentum.

2 Current-induced spin torque and the domain wall motion

We consider a magnetic wire with a single DW and model it as a 1D system with spin. Furthermore, an electric current is transmitted through the wall. We calculate the torque acting locally on the magnetization considering the DW as a static object. This means we assume that the electrons are scattered from frozen magnetic moments within the wall, transmitting the spin torque from the spin-polarized electrons to the magnetic moments – a process which sets the DW in motion. This treatment is valid when the characteristic velocity of the magnetic moments is much smaller than that of the electrons in the wire.

Our main assumption is that the width of DW is much smaller than the wavelength of electrons at the Fermi level for both majority and minority electrons, $k_{F\uparrow,\downarrow}\delta \ll 1$, where $k_{F\uparrow}$ and $k_{F\downarrow}$ are the Fermi momentum of spin up and down electrons, respectively, and δ is the DW width. We consider a thin nanowire, for which only one size quantization level of electrons is relevant, which requires the condition $k_{F\uparrow,\downarrow}d \ll 1$, where d is the diameter of the wire. These conditions are readily realized in magnetic semiconductor wires.

The corresponding Hamiltonian includes the interaction of electrons with magnetic moments $\boldsymbol{M}_i$ located at the points x_i, $H_{\text{int}} = g \sum_i \sigma \cdot \boldsymbol{M}_i\, \delta(x - x_i)$, where g is the coupling constant. For definiteness, we take the vectors $\boldsymbol{M}_i$ in the x, y-plane, and directed along the x-axis for $x < -\delta/2$ and in the opposite direction for $x > \delta/2$. In view of the imposed condition $k_{F\uparrow,\downarrow}\delta \ll 1$, we can calculate the wave functions (scattering states), as a scattering problem with spin-dependent δ-potential [13]. Then we can find the spin and spin–current profiles

$$\boldsymbol{S}_{\uparrow,\downarrow}(x) = \psi^{\dagger}_{\uparrow,\downarrow}\, \sigma\, \psi_{\uparrow,\downarrow}\,, \qquad \boldsymbol{j}^{s}_{\uparrow,\downarrow}(x) = \frac{i\hbar}{2m}\left[(\nabla_x \psi^{\dagger}_{\uparrow,\downarrow})\, \sigma\, \psi_{\uparrow,\downarrow} - \psi^{\dagger}_{\uparrow,\downarrow}\, \sigma\, \nabla_x \psi_{\uparrow,\downarrow}\right], \tag{1}$$

corresponding to the scattering states with incoming spin up and spin down electrons, respectively.

For the calculation of the spin density and spin currents induced by the electric current in a magnetic nanowire, we utilize the linear response approach to weak perturbation created by the voltage drop. Then the charge and spin currents, as well as the spin density, can be presented as the weighted sums of currents for different spin-polarized scattering states at the Fermi level. The expression for the charge current j_0 has the usual form obtained from the Büttiker–Landauer formula, whereas for the induced spin current and for the accumulated spin we find

$$\boldsymbol{j}^{s}(x) = \frac{e\Delta\phi}{2\pi\hbar}\left(\frac{\boldsymbol{j}^{s}_{\uparrow}(x)}{v_{\uparrow}} + \frac{\boldsymbol{j}^{s}_{\downarrow}(x)}{v_{\downarrow}}\right), \qquad \boldsymbol{S}(x) = \frac{e\Delta\phi}{2\pi\hbar}\left(\frac{\boldsymbol{S}_{\uparrow}(x)}{v_{\uparrow}} + \frac{\boldsymbol{S}_{\downarrow}(x)}{v_{\downarrow}}\right). \tag{2}$$

Here $\Delta\phi$ is the voltage bias. Using (1), (2) and the formulas for scattering states [13], we find that the components of spin current perpendicular to the x-axis, are oscillating functions. The oscillation period is determined by the inverse momentum at the Fermi level. Hence, the oscillation period of the transverse component of spin current is much larger than the domain wall width. We recall that in 3D systems, the transverse component of the spin current decays due to an additional integration over momentum in the DW plane. In metallic ferromagnets, the decay is very fast due to the large Fermi momentum of electrons. However, there is a nonvanishing spin transfer for the transverse component in the 3D case, too.

To calculate the torque acting locally on a magnetic moment inside the DW, we use the formula

$$\boldsymbol{T}_i = -\frac{gM_0}{\hbar}\, \boldsymbol{n}_i \times \boldsymbol{S}(0)\,, \tag{3}$$

which follows from the equation of motion of the magnetic moment, where $\boldsymbol{n}_i$ is the unit vector along the moment $\boldsymbol{M}_i$. Here we can neglect the variation with x of the accumulated spin density $\boldsymbol{S}(x)$ taking it as $\boldsymbol{S}(0)$ because the variation of spin density is smooth on the length scale δ. Here M_0 is the magnitude of moment.

Finally, we find the torque acting on a single localized moment in the domain wall. The result can be presented in the following form

$$\boldsymbol{T}_i = \frac{j_0}{e}\, [\eta\, \boldsymbol{n}_i \times (\boldsymbol{n}_i \times \boldsymbol{s}) + \zeta\, \boldsymbol{n}_i \times \boldsymbol{s}\,]\,, \tag{4}$$

where $\boldsymbol{s}$ is the unit vector along the magnetization $\boldsymbol{M}$ at $x \to -\infty$, and the coefficients η and ζ are constant. The dependence of η/g_0 and ζ/g_0 on the parameters $\tilde{g}_0 = 2mgM_{\text{eff}}/\hbar^2$ and $p = (k_\uparrow - k_\downarrow)/(k_\uparrow + k_\downarrow)$ is presented in Fig. 1a and b, where we denoted $\boldsymbol{M}_{\text{eff}} = \sum_i \boldsymbol{M}_i$, and $g_0 = 2mgM_0/\hbar^2$. As we see, both coefficients strongly depend on the parameters of the ferromagnet and parameters of the wall. In case of small coupling $\tilde{g}_0$, we obtain $\zeta \gg \eta$, i.e., the torque is mostly related to the second component in Eq. (4). In the opposite case of large $\tilde{g}_0$, the first term in (4) dominates.

To study the effect of the torque on the DW motion, we consider the Hamiltonian of magnetic system with two anisotropy constants

$$H_0 = \frac{a}{2}\left(\frac{\partial \boldsymbol{n}}{\partial x}\right)^2 + \frac{\lambda_1}{2}\, n_z^2 + \frac{\lambda_2}{2}\, n_y^2\,, \tag{5}$$

where a is the exchange interaction. We can add the torque (4) to the corresponding Landau–Lifshitz equations of motion for the moments described by magnetic Hamiltonian (5).

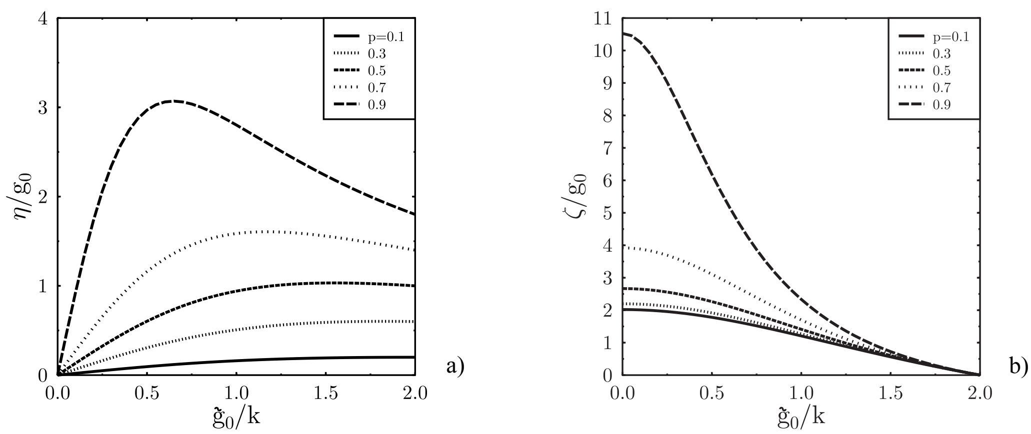

Fig. 1 Dependence of factors η and ζ on the effective coupling $\tilde{g}_0$ for different electron polarization p.

The problem of solving the dynamical equations of motion can be simplified in the limit of $\lambda_1 \gg \lambda_2$. In this case, we find that it has the form of

$$-\frac{1}{\gamma^2 \lambda_1}\frac{\partial^2 \varphi}{\partial t^2} + \frac{j_0^2 \eta^2}{\gamma^2 \lambda_1 e^2} \sin\varphi \, \cos\varphi + a\frac{\partial^2 \varphi}{\partial x^2} - \lambda_2 \sin\varphi \, \cos\varphi + \frac{j_0 \zeta}{\gamma e} \sin\varphi = 0\,, \tag{6}$$

where $\varphi(x, t)$ is the angle between $\boldsymbol{n}(x, t)$ and the x-axis.

If $\zeta \ll \eta$, this equation has a moving kink-like solution $\varphi(x, t) = \varphi(x - vt)$ with a constant velocity. We found that for $j_0 = 0$, the minimum of energy (more exactly, minimum of the quantum mechanical action) corresponds to the static DW. In the limit of small velocity, $v^2 \ll \gamma^2 \lambda_1 a$, the DW behaves like a particle of mass $m_d = \beta_0/\gamma^2 \lambda_1$, where $\beta_0 = (\lambda_2/a)^{1/2}$ is the inverse width of DW, and γ is the gyromagnetic factor. For $j_0 \neq 0$, there is an instability for the current exceeding the critical value of $j_{0\mathrm{cr}} = \gamma e(\lambda_1 \lambda_2/2)^{1/2}/\eta$. It means that the moving DW is energetically more favorable.

The analysis of possible solutions for the case of not too small ζ shows that this component of the torque accelerates the DW but we did not find a simple solution except for the case of very small velocities, because the shape of the DW depends on its velocity v.

3 Conclusions

The considered model of the magnetic nanowire is applicable for semiconducting systems. We calculated the components of spin torque acting on a thin DW in the magnetic nanowire subject to an applied electric current. The different components induce a rotation of the magnetic moments in different directions.

We also considered the dynamics of the domain wall in the presence of applied electric current. We demonstrated that a moving magnetic kink, similar to the static DW, can be a solution of the equations for the magnetic dynamics only under some special conditions. We identified these conditions in the case of a large ratio of magnetic anisotropy constants. In the limit of small velocities, the solution is not a kink since its width decreases with increasing velocity. In the limit of small velocity, the domain wall moves like a particle of a mass determined by the exchange interaction and by the anisotropies. One of the spin torque components ζ, dominating at the small coupling, acts as a driving force for the domain wall, accelerating the wall, provided that there is no pinning to impurities.

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