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CURRENT-INDUCED SPIN TORQUE ON A DOMAIN WALL IN A MAGNETIC NANOWIRE

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We develop a theory applicable in the regime, where the wavelength of spin up and down electrons, $\lambda_{\uparrow,\downarrow}$, is smaller than the DW width L (smooth DW). This regime is appropriate for strongly doped magnetic semiconductors and metallic ferromagnets. We develop an approach related to a weak (adiabatic) perturbation arising after a local transformation to the uniform magnetization. In the limit of $L \gg \lambda_{\uparrow,\downarrow}$ we find an exponentially small reflection and spin-flip transition amplitudes. The theory is useful in the regime, where the DW width is not so large, and the perturbation corrections to the wave functions are quite essential. We calculate the current-induced spin density and the spin torque acting locally on the magnetic moments within the DW. The spatially-distributed torque acts as a force pushing the DW in one direction as a response to the external current, and also as an internal force, which can distort the static ordering of magnetic moments in the DW.

Keywords: Spin torque; spintronics; domain walls.

1. Introduction

The current-induced spin torque in inhomogeneous ferromagnets has been predicted theoretically 10 years ago by Slonczewski and Berger[1,2]. Since then many experiments confirmed the existence of the spin torque. One of possible experiments is related to the current-induced motion of a domain wall in a magnetic wire[3,4,5,6]. In this case the spin torque rotating a magnetic moment within the wall results in

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appearance of an effective force which sets the DW into motion. This was demonstrated by several experiments and also proposed as a method to manipulate the DW position by an electric current. It is expected that the realization of this idea can have various application in spintronic devices[7]. Even though the basic theoretical concepts of the the spin torque transfer are commonly recognized, some important details concerning the DW motion are not completely understood so far[8,9,10,11].

Here we consider the problem of spin torque when the DW width L is not too large as compared to the wavelength of electrons λ at the Fermi surface. It corresponds to the DW in a constriction for a ferromagnetic metal and also to a nanowire of the magnetic semiconductor. If the electron wavelength is much larger than the DW width, the problem of reflection of electrons from the DW can be solved exactly by using the scattering states[10]. The scattering from the DW in this case is strong and leads to a relatively large resistance of the DW. The current-induced spin accumulation at the wall results in a torque acting on the moments. However, even in the case of magnetic semiconductors, the condition of $\lambda >> L$ is not always well justified. The reason is that the density of electrons (holes for GaMnAs) can be rather high, $n > 10^{21}$ cm^{-3}, which makes $\lambda < L$. In the limit of $\lambda << L$, the problem has a well-known semiclassical solution which shows that the electrons are moving adiabatically so that the spin of an electron transmitted through the DW follows the magnetization orientation[12,13,14,15]. In this case the reflection of electrons from the DW is exponentially small.

2. Model and Calculation of the Torque

Here we reconsider the case of $\lambda \gg L$ using the perturbation theory. We consider a model with the Hamiltonian of 1D electrons in a varying magnetization profile (we use units with $\hbar = 1$)

$$H = -\frac{1}{2m}\frac{d^2}{dz^2} - \boldsymbol{\sigma}\cdot\mathbf{M}(z), \tag{1}$$

where $\mathbf{M}(z) = [M\sin\varphi(z),\, 0,\, M\cos\varphi(z)]$ and $\varphi(z) = \pi - \arccos\tan(z/L)$. This form of the magnetization profile correspond to the domain wall in the $z-x$ plane, so that for $z = -\infty$ the magnetization is directed along the z axis, and for $z = +\infty$ in the opposite direction. The magnitude of M describes spin splitting of the electron bands.

Using the local unitary transformation $T(z)$ to a local frame, in which the vector $\mathbf{M}(z)$ is directed along the axis z[16] we obtain[14] a transformed Hamiltonian, $\tilde{H} = T(z)\,H\,T^{\dagger}(z)$,

$$\tilde{H} = -\frac{1}{2m}\frac{d^2}{dz^2} - M\sigma_z + \frac{m\beta^2(z)}{2} + i\sigma_y\beta(z)\,\frac{d}{dz}\,, \tag{2}$$

where $\beta(z) = \varphi'(z)/2m$ and we used the condition $k_{\uparrow,\downarrow}L \gg 1$.

Now we assume that the variation of magnetization is small so that the last two terms in Eq. (2) can be considered as a small perturbation. The perturbation correction to the eigenfunction of the unperturbed Hamiltonian $\tilde{H}_0$ is

$$\delta\tilde{\psi}(z) = \int_{-\infty}^{\infty} dz'\, G_\varepsilon(z,z')\, V(z')\, \tilde{\psi}_0(z') \tag{3}$$

where the Green function $G_\varepsilon(z,z')$ obeys the equation

$$\left(\varepsilon + \frac{1}{2m}\frac{d^2}{dz^2} + M\sigma_z + \mu\right) G_\varepsilon(z,z') = \delta(z-z'), \tag{4}$$

μ is the chemical potential and $V(z)$ is the perturbation matrix. Using (4) we find that $G_\varepsilon(z,z')$ is a diagonal matrix with elements

$$G_{\varepsilon\,\uparrow,\downarrow}(z,z') = -\frac{im\, e^{i|z-z'|\,k_{\uparrow,\downarrow}}}{k_{\uparrow,\downarrow}}\,, \tag{5}$$

where $k_{\uparrow,\downarrow} = \left[2m\,(\mu - M + \varepsilon)\right]^{1/2}$, and we consider the retarded Green function, $\varepsilon > 0$. We remind that the real wave function can be calculated using the inverse transformation, $\psi_\varepsilon = T^\dagger \tilde{\psi}_\varepsilon$.

We can take the function $\psi_0(z)$ corresponding to the incoming from $z = -\infty$ wave with electron spin up or down. Using Eqs. (3) to (5) we find

$$\delta\psi_{\varepsilon\uparrow}(z) = \int_{-\infty}^{\infty} dz'\, e^{ik_\uparrow z'} \begin{pmatrix} -im^2\beta^2(z')\, e^{ik_\uparrow|z-z'|}/2k_\uparrow \\ -m\beta(z')\, k_\uparrow\, e^{ik_\downarrow|z-z'|}/k_\downarrow \end{pmatrix}, \tag{6}$$

$$\delta\psi_{\varepsilon\downarrow}(z) = \int_{-\infty}^{\infty} dz'\, e^{ik_\downarrow z'} \begin{pmatrix} m\beta(z')\, k_\downarrow\, e^{ik_\uparrow|z-z'|}/k_\uparrow \\ -im^2\beta^2(z')\, e^{ik_\downarrow|z-z'|}/2k_\downarrow \end{pmatrix}. \tag{7}$$

For $z < 0$ and $|z| \gg L$, the correction $\delta\psi_{\varepsilon\uparrow}(z)$ contains both reflected spin up and down waves corresponding to the reflection with and without spin flips. Calculating the reflection amplitudes $r_{\uparrow,\downarrow}$ and $r^f_{\uparrow,\downarrow}$ of non-spin-flip and spin-flip reflections, we find

$$r_{\uparrow,\downarrow} = -\frac{i\pi\, e^{-\pi k_{\uparrow,\downarrow} L}}{2\,(1 - e^{-2\pi k_{\uparrow,\downarrow} L})}\,, \tag{8}$$

$$r^f_{\uparrow,\downarrow} = \mp\frac{i\pi k_{\uparrow,\downarrow}\, e^{-\pi k_+ L}}{k_{\downarrow,\uparrow}\,(1 + e^{-2\pi k_+ L})}\,, \tag{9}$$

where $k_+ = (k_\uparrow + k_\downarrow)/2$. The reflected waves have an exponentially small amplitudes for $k_{\uparrow,\downarrow} L >> 1$. However, the condition of applicability of the perturbation theory is that the correction $\delta\psi(z)$ to $\psi_0(z)$ should be small, and this condition is satisfied even for $k_{\uparrow,\downarrow} L$ slightly larger than 1.

Similarly, for $z > 0$ and $|z| \gg L$, using (6) and (7) one can find the nonadiabatic correction to the wave function describing the transmitted waves. Note that the correction to the transmitted waves is larger as it contains slowly oscillating functions in integrals (6) and (7).

The spin density associated with a single transmitted wave $\psi_{\varepsilon\uparrow,\downarrow}(z) = \psi_{0\,\varepsilon\,\uparrow,\downarrow}(z) + \delta\psi_{\varepsilon\,\uparrow,\downarrow}(z)$ can be calculated from

$$\mathbf{S}_{\uparrow,\downarrow}(z) = \psi^\dagger_{\varepsilon\,\uparrow,\downarrow}(z)\, \boldsymbol{\sigma} \psi_{\varepsilon\,\uparrow,\downarrow}(z) = \tilde{\psi}^\dagger_{\varepsilon\,\uparrow,\downarrow}(z)\, \tilde{\boldsymbol{\sigma}}(z)\, \tilde{\psi}_{\varepsilon\,\uparrow,\downarrow}(z) \tag{10}$$

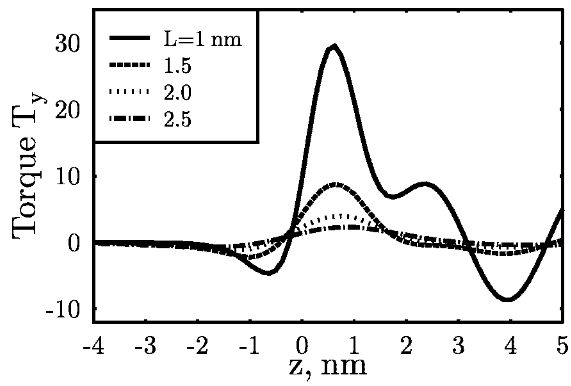

Fig. 1. The out-of-plane component of torque for different values of the domain-wall width.

where $\tilde{\boldsymbol{\sigma}}(z) = T(z)\,\boldsymbol{\sigma}\,T^\dagger(z)$. In a wire with a weak current, the current-induced spin density can be found using the partial spin-density contributions from the up and down waves with the energy at the Fermi level[10]

$$\mathbf{S}(z) = \frac{e\Delta\phi}{2\pi}\left(\frac{\mathbf{S}_\uparrow(z)}{v_\uparrow} + \frac{\mathbf{S}_\downarrow(z)}{v_\downarrow}\right), \tag{11}$$

where $\Delta\phi$ is the voltage related to the current. Here $v_{\uparrow,\downarrow}$ are the velocities of spin up and down electrons at the Fermi level, which correspond to the density of up and down states in the 1D model. In the adiabatic regime, we take the transmission coefficients $|t_\uparrow|^2 \simeq |t_\downarrow|^2 \simeq 1$ and neglect the transmission with spin flips. Then the relation between the current j_0 and voltage $\Delta\phi$ reads as

$$j_0 \simeq \frac{e^2\Delta\phi}{2\pi}\left(\frac{v_\downarrow}{v_\uparrow} + \frac{v_\uparrow}{v_\downarrow}\right). \tag{12}$$

The accumulated spin density of electrons induces a the torque acting on a moment $\mathbf{M}_0(z)$ in the domain wall

$$\mathbf{T}(z) = -\frac{1}{\hbar}\mathbf{M}_0(z) \times \mathbf{S}(z). \tag{13}$$

The unperturbed wave function $\tilde{\psi}_{0\,\varepsilon\,\uparrow,\downarrow}$ gives the electron spin density $\mathbf{S}_0(z)$, which does not affect the magnetic moments. It corresponds to the adiabatic motion of electrons in the smoothly varying magnetization profile. The non-adiabatic correction leading to the appearance of torque is related to the corrections (6) and (7).

Using Eqs. (6),(7),(10)-(13) we calculated numerically the torque density $\mathbf{T}(z)$. It contains nonzero x and z components rotating the moments in the plane, and the y component, rotating the moments in the out-of-plane direction. The out-of-plane component of the torque is presented in Fig. 1. For this calculation we used the parameters: $k_{F\uparrow} = 5 \times 10^7$ cm^{-1}, $k_{F\downarrow} = 3 \times 10^7$ cm^{-1} and $m = m_0$. In the region far from the domain wall, the current-induced torque has an oscillating component related to the non-damped spin-density oscillations (analogue of the Friedel oscillations). This is a specific property of 1D system.

3. Conclusions

In a semiclassical regime, we calculated the nonadiabatic correction to the spin-density created by electrons transmitted through the domain wall in a 1D magnetic nanowire. This model corresponds to the case of magnetic semiconductors with one channel for the transverse motion of electrons, when $k_{F\uparrow,\downarrow}d < 1$, where d is the diameter of the wire. In the case of several channels, the spin-density and the torque are a sum over channels, so that the spin-density oscillations far from the DW are effectively damped, and the torque is decaying outside the DW. However, as we see from the one-channel calculation (Fig. 1), the torque within the DW has a complex profile.

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