Canted Magnetization Texture in Ferromagnetic Tunnel Junctions

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We study the formation of inhomogeneous magnetization texture in the vicinity of a tunnel junction between two ferromagnetic wires nominally in the antiparallel configuration and its influence on the magnetoresistance of such a device. The texture, dependent on magnetization rigidity and crystalline anisotropy energy in the ferromagnet, appears upon an increase of ferromagnetic interwire coupling above a critical value and it varies with an external magnetic field.

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Spin polarized transport in multilayer ferromagnet-metal-ferromagnet system and magnetic tunnel junction is a subject of intense theoretical and experimental studies. The majority of such studies addresses the investigation of the tunneling magneto-resistance (MR) and giant MR effects, which consist of a switch from lower to higher conductivity when polarization of leads in a MR device change from an antiparallel to parallel configuration. In tunnel junctions, the MR effect is the result of a difference between rates of tunneling of the magnetization near the interface (where tunneling electrons majority and minority bands on the opposite sides of a junctions, and it’s the strongest when magnetization switching by an external magnetic field changes from an ideally antiparallel magnetization state in the two wires to a parallel one). Any deviations of the magnetization near the interface (where tunneling characteristics of the device are formed) from perfectly parallel/antiparallel orientation would reduce the size of the effect.

In this paper we investigate a possibility of formation of inhomogeneous magnetization texture in the vicinity of a highly transparent tunnel junction caused by ferromagnetic coupling of magnetic moments on the opposite sides carried by tunneling electrons. We find that a canted magnetization state can form if such ferromagnetic tunneling coupling, \( t' \), exceeds some critical value \( t_c \) determined by the interplay between crystalline anisotropy and magnetization rigidity in the ferromagnet. This means that a tunnel junction with \( t' < t_c \) can be viewed as an atomically sharp magnetic domain wall, whereas the increase of the junction transparency above \( t_c \) gradually transforms it into a broad texture typical for bulk ferromagnetic material. For \( t' > t_c \), we study the evolution of the texture upon application of an external magnetic field and construct a parametric diagram for distinct magnetization regimes. As an example, we consider a device consisting of a tunnel junction between two easy-axis ferromagnetic wires magnetically biased at the ends as illustrated in Fig.1. We show that when the magnetic field exceeds some critical value, \( B_c \), the barrier between the states with polarization parallel/antiparallel to the field disappears. As a result, both wires will be polarized parallel to the magnetic field and the domain wall will be pushed away toward the end of the wire. When a magnetic field is swept back (to \( B < B_c \)) and its sign changes, the domain wall returns back to the tunnel junction. The resulting hysteresis in the magnetization state of the device leads to a hysteresis loop in its MR, which we analyze taking into account the formation of the texture near the tunnel junction with \( t' > t_c \).

A quasi-1D magnetization texture, \( S(z) \), near the tunnel junction between two wires of length \( L \), which changes slowly on the scale of the lattice constant \( a \) can be described using the energy functional,

\[
E = \frac{J}{2} \left( \int_{-L}^{0} dz \left( \partial_z S(z) \right)^2 - \int_{-L}^{L} dz \left[ \xi_1 \left( S^x(z) \right)^2 + \xi_2 \left( S^y(z) \right)^2 \right] + \frac{g_d w^3}{2 a^3} \int_{-L}^{L} dz dz' V(z-z') \left( S^x(z) S^x(z') + S^y(z) S^y(z') - 2 S^z(z) S^z(z') \right) - \frac{\mu_B w^2}{a^3} \int_{-L}^{L} dz S^z(z) + E' \right). \tag{1}
\]

Here \( J \sim tw^2/a \) is the magnetization rigidity (where \( t \) is the exchange coupling between the neighboring atoms, \( w \) is the wire thickness). The crystalline anisotropy parameters are \( \xi_1 > \xi_2 > 0 \), whereas \( g_d = \gamma^2/a^3 \) parameterizes dipole-dipole interaction of magnetic moments, with

\[
V(z) = \frac{1}{2w} \int d^2 \rho d^2 \rho' \frac{2z^2 - (x-x')^2 - (y-y')^2}{((x-x')^2 + (y-y')^2 + z^2)^{5/2}},
\]

where the integration is carried out over the cross-section of the wire, \( d^2 \rho = dx dy, d^2 \rho' = dx' dy' \). For \( |z| > w, V(z) \)
For a smooth magnetization texture varying at a length scale longer than the wire thickness, we approximate the non-local dipole-dipole interaction as \( V(z) \approx V_0 \delta(z) \), where \( V_0 = \int \frac{dV}{dz} V(z) \). Finally, \( \mu \) is the magnetic moment per atom, and \( \mathbf{B} = B \mathbf{e}_z \) is an external magnetic field.

The energy of the interacting wires takes the form

\[
E = \frac{J}{2} \left[ \int_{-L}^{0} \right] dz \left\{ (\theta'(z))^2 + \alpha^2 \sin^2(\theta(z)) + 2\alpha^2 \lambda_B \left[ 1 - \cos(\theta(z)) \right] \right\} - t' \cos(\theta_0),
\]

where \( \theta'(z) = d\theta(z)/dz \), \( \theta_0 = \theta(-0) - \theta(+0) \). Relevant parameters present in Eq. (3) are

\[
\alpha = \sqrt{\left( \frac{2\xi - 3 \xi_0}{a^3} \right) + 3 \delta V_0}, \quad \lambda_B = \frac{2\mu_B w^2}{J a^3 \alpha^2},
\]

where

\[
B_c = \frac{J a^3 \alpha^2}{2 \mu_B w^2}.
\]

The meaning of the parameter \( B_c \) is the following. When \( B = B_c \), the energy barrier between the states of noninteracting wires \( (t' = 0) \) with polarizations parallel/antiparallel to the external magnetic field disappears and the polarization antiparallel to the magnetic field becomes absolutely unstable, leading to a jump of the magnetic domain wall from the junction toward the magnetically biased end of the wires. Below we assume that \( B_c \) is much less than the field required to switch the polarization of the left/right hand side leads. The parameters \( \alpha \) and \( \lambda_B \) characterize a typical domain wall width in an infinite wire. For example, \( \alpha^{-1} \) is the domain wall width for \( B = 0 \) for a long wire with \( L a \gg 1 \). An external magnetic field \( \mathbf{B} = B \mathbf{e}_z \) makes the domain wall asymmetric. It compresses the domain wall width on the side where magnetization is aligned with \( \mathbf{B} \) to \( \alpha_+^{-1} \), \( \alpha_+ = \alpha \sqrt{1 + \lambda_B} \), and it stretches the domain wall width on the side where \( \mathbf{S} \) is antiparallel to \( \mathbf{B} \) to \( \alpha_-^{-1} \), \( \alpha_- = \alpha \sqrt{1 - \lambda_B} \).

To minimize the energy in Eq. (3), we employ the following procedure. First, we fix the boundary values \( \theta(z) \) and find the optimal form of \( \theta(z) \) for given \( \theta(\pm 0) \). Then we minimize \( E(\theta(+0), \theta(-0)) \) versus the canting angles \( \theta(\pm 0) \). The first step of such a procedure requires solving the optimum equation

\[
\theta''(z) = \frac{\alpha^2}{2} \left[ \sin(2\theta(z)) + 2\lambda_B \sin(\theta(z)) \right].
\]

The latter shows that that \( \theta(z > 0) \left[ \pi - \theta(z < 0) \right] \) takes its maximal value \( \theta(+0) \left[ \pi - \theta(-0) \right] \) at \( z = 0 \), and that it decreases as \( \exp(-\alpha z) \) [\( \exp(\alpha z) \)] for \( |z| \gg \alpha^{-1} \). Also the differential equation (4) has the first integral \( v_{\pm}(\theta) = \theta'(z) \),

\[
v_{\pm}(\theta) = \alpha \sqrt{\left[ 1 + \lambda_B \right]^2 - (\cos(\theta) + \lambda_B)^2},
\]

where the sign \( \pm \) corresponds to positive/negative \( z \). Substituting \( v_{\pm} \) into energy in Eq. (3) and changing the integration variable from \( z \) to \( \theta \) we arrive at

\[
E = J \left( \frac{\theta(+0)}{0} v_{+}(\theta) d\theta + \frac{\pi}{\theta(-0)} v_{-}(\theta) d\theta \right) - t' \cos(\theta_0),
\]
which represents the explicit dependence of energy $E(\theta(+0), \theta(-0))$ on the canting angles on each side of the junction. Minimizing the energy with respect to these angles, we identify possible regimes for the magnetization texture.

First, we consider the magnetization texture in the absence of an external magnetic field, $B = 0$. In this case the texture is symmetric, $\theta(-z) = \pi - \theta(z)$, so that $v_+(\theta) = v_-(\theta) = \sin(\theta)$ and

$$E = 2J_0(1 - \cos(\theta(+0))) + t' \cos(2\theta(+0)).$$

The latter result indicates the existence of a critical value $t_c = J_0/2$ of the coupling constant $t'$, such that for $t' < t_c$ the energy reaches its minimum when $\theta(+0) = \pi - \theta(-0) = 0$ and magnetization is homogeneous in each of two wires, whereas for $t' > t_c$ the energy minimum corresponds to the magnetization texture in the vicinity of the tunnel junction, with

$$\theta(+0) = \pi - \theta(-0) = \arccos(t_c/t').$$

In the presence of external magnetic field, the magnetization texture becomes asymmetric. In this case, we determine canting angles $\theta(\pm 0)$ numerically from the set of two equations,

$$\partial \theta(\pm 0) E = Jv_\pm(\theta(\pm 0)) - t' \sin(\theta(-0) - \theta(+0)) = 0.$$  \hspace{1cm} \text{(7)}$$

The results of numerical analysis of Eqs. (7) are gathered in the parametric diagram in Fig. 2 where we indicate the six parametric intervals separated by lines $B_1$, $B_1'$, $t_1$, and the axis $B = 0$ corresponding to different regimes of magnetization texture. Below, we describe the evolution of the magnetization state of the junction upon sweeping the magnetic field from $-B_c$ to $+B_c$ (in comparison to an inverse sweep from $+B_c$ to $-B_c$). When the exchange coupling constant $t'$ and the magnetic field $B$ are not strong enough (parametric interval $I$ ($I'$) in Fig. 2), the energy functional has two minima. The first of them corresponds to $\theta(+0) = \pi - \theta(-0) = 0$ and the magnetization is homogeneous in each of two wires. The second corresponds to the state with both wires polarized parallel to the external magnetic field and the domain wall pushed away towards the end $z = -L$ ($z = L$) of the wire. As a result, the polarization in the vicinity of the tunnel junction is homogeneous, i.e., $\theta(-0) = \theta(+0) = 0$ ($\theta(-0) = \theta(+0) = \pi$).

![FIG. 2: Parametric diagram $t' - B$. There are four lines, $B_1$, $B_1'$, $t_1$, and the axis $B = 0$ separating phases one from another (see the text for details). The lines $B_1$ and $t_1$ ($B_1' = -B_1$ and $t_1$) touch one another at the point $X$ ($X'$). The boundary values $\theta(\pm 0)$ as a function of the external magnetic field are calculated for $t' = 0.5t_c$, $0.95t_c$ and $1.2t_c$ (dashed lines).](image)

Typical dependencies of $\theta(+0)$ on a magnetic field $B$ are illustrated in Fig. 3 for $t' = 0.5t_c$, $t' = 0.95t_c$, and $t' = 1.2t_c$, respectively. The dependencies of $\theta(-0)$ on $B$ can be obtained from Fig. 3 by the transformation

$$\theta(-0, B) = \pi - \theta(+0, -B).$$

The formation of canted magnetization in the vicinity of a tunnel junction with high transparency would affect the magnetoresistance characteristic of such a junction. The latter can be modelled using the tunnel Hamiltonian approach. When the domain wall width $\alpha^{-1}$ is sufficiently larger then the elastic mean free path, the tunneling Hamiltonian can be written as

$$H = H_0 + H_T, \hspace{1cm} H_0 = \sum_{\nu = \pm} \sum_{\mathbf{k}, \sigma} \epsilon_\sigma(\mathbf{k}) c_{\nu \mathbf{k} \sigma}^\dagger c_{\nu \mathbf{k} \sigma},$$

where $\epsilon_\sigma(\mathbf{k}) = \epsilon(\mathbf{k}) - \sigma \Delta$. Here $H_0$ is the Hamiltonian of the isolated ferromagnetic wires, $H_T$ is the tunneling Hamiltonian, $c_{\nu \mathbf{k} \sigma}$ and $c_{\nu \mathbf{k} \sigma}^\dagger$ are annihilation and creation operators of electron propagating in the left ($\nu = L$) or right ($\nu = R$) wire with wave vector $\mathbf{k}$ and spin parallel ($\sigma = 1/2$ or $|\rangle$) or antiparallel ($\sigma = -1/2$ or $\rangle$) to the wire polarization $\mathbf{S}(\pm 0)$ (2). In the following we will assume that the Fermi momenta for the majority and minority
bands are sufficiently larger than \( \alpha \pm \) and therefore treat conduction band electrons as three dimensional.

\[
H_T = \sum_{\sigma, \sigma'} \sum_{\mathbf{k}, \mathbf{k}'} t_{\sigma' \sigma}^{\mathbf{k}' \mathbf{k}} c_{\mathbf{k}'}^{\dagger} c_{\mathbf{k}} + \text{h.c.},
\]

where the tunneling matrix elements \( t_{\sigma' \sigma}^{\mathbf{k}' \mathbf{k}} \) describe the transfer of an electron with wave vector \( \mathbf{k} \) and spin state \( \sigma \) from the left wire to the state with \( \mathbf{k}' \) and \( \sigma' \) in the right wire and the quantization axes for the conduction band electrons are directed along the magnetization vectors \( \mathbf{S}(\pm L) \) which are not necessarily collinear so that the transitions between the majority/minority bands of one wire and majority/minority bands of the other are possible even for the nominally antiparallel configuration of \( \mathbf{S}(\pm L) \). We consider the model in which electrons tunnel from one wire to another without spin flipping. In this case the spin dependence of \( t_{\sigma' \sigma}^{\mathbf{k}' \mathbf{k}} \) is determined by a single parameter, the angle \( \theta_0 = \theta(-0) - \theta(+0) \) between the vectors \( \mathbf{S}(\pm 0) \),

\[
t_{\sigma' \sigma}^{\mathbf{k}' \mathbf{k}} = \frac{|2\pi^2 L^2 v_z^2(k) v_z^2(k')|^{1/2}}{L^2} \times \left[ \cos(\theta_0/2) \delta_{\sigma \sigma'} + i \sin(\theta_0/2) \tau_3^{\sigma \sigma'} \right],
\]

where \( \tau^x \) is the Pauli matrix, and \( v_z^2(k) \) is a component of electron velocity \( \mathbf{v}(\mathbf{k}) = \nabla_k E_{\sigma}(\mathbf{k})/\hbar \) perpendicular to the interface.

When vectors \( \mathbf{S}(+0) \) and \( \mathbf{S}(-0) \) are antiparallel (parametric intervals \( I \) and \( I' \) in Fig. 2), electrons can tunnel only from the majority band of one wire to the minority band of the other so that conductance of such a junction is

\[
G_{\parallel} = \frac{2\pi e^2 \hbar^2}{h} \left( \frac{2\pi \hbar}{L} \right)^2 N_1 v_z^2 (N_1 v_z^2)^2 + (N_1 v_z^2)^2 \frac{2}{2},
\]

where \( N_1 \) and \( N_\parallel \) are the densities of states in the majority and minority bands at the Fermi level, and \( v_z^2 \) are the average value of \( |v_z(k)| \) over the majority/minority Fermi surface,

\[
v_z^2 = \frac{1}{N \sigma} \sum_{\mathbf{k}} |v_z(k)| \delta(\epsilon - \epsilon(k)).
\]

When the ends \( z = \pm 0 \) of the wires have parallel magnetization, i.e., \( \theta(\pm 0) = 0 \) or \( \pi \), the conductance is

\[
G_{\parallel} = \frac{2\pi e^2 \hbar^2}{h} \left( \frac{2\pi \hbar}{L} \right)^2 (N_1 v_z^2)^2 + (N_1 v_z^2)^2 \frac{2}{2},
\]

which determines the magneto-resistance (MR) ratio

\[
\delta = \frac{G_{\parallel} - G_{\parallel}}{G_{\parallel}}.
\]
produces conductance $G(\theta_0)$ and the reduced observable MR ratio, $\delta$,

$$G(\theta_0) = G_{\uparrow\uparrow} \cos^2(\theta_0/2) + G_{\uparrow\downarrow} \sin^2(\theta_0/2),$$

$$\delta = \frac{G_{\uparrow\uparrow} - G(\theta_0)}{G_{\uparrow\uparrow}} = \delta_0 \sin^2(\theta_0/2). \quad (8)$$

The results of calculations for the conductance in MR devices with various junction transparencies (and positive and negative magnetic field sweep in the magnetoresistance) are gathered in Fig.4. The conductance dip at small magnetic fields indicates the regime when a ferromagnetic domain wall in the device in Fig.1 is pinned to the tunnel junction. The detailed structure of the hysteresis loop depends on whether the magnetization texture is formed near the junction or not which of course depends on the value of the ferromagnetic interwire coupling. For small inter-wire coupling, in Fig.4(a), the jump between parallel and antiparallel polarizations in the vicinity of the tunnel junction give rise to jumps in the conductance between $G_{\uparrow\uparrow}$ and flat conductance minimum equal to $G_{\uparrow\downarrow}$. With increasing the inter-wire coupling towards the critical value $t_c$ (determined by the interplay between crystalline anisotropy and magnetization rigidity in ferromagnet), an interval of magnetic fields appears where the conductance increases continuously, due to the formation of the canted magnetization texture and its change by a magnetic field, Fig.4(b). For inter-wire coupling above a critical value $t_c$, Fig.4(c), the minimum of the conductance exceeds $G_{\uparrow\downarrow}$ even in the absence of a magnetic field, indicating the formation of a broad texture, which also suggests a reduction of MR ratio in a high-transparency junction.

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