Tunneling Anisotropic Magnetoresistance of Helimagnet Tunnel Junctions

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We theoretically investigate the angular and spin dependent transport in normal-metal/helical-multiferroic/ferromagnetic heterojunctions. We find a tunneling anisotropic magnetoresistance (TAMR) effect due to the spiral magnetic order in the tunnel junction and to an effective spin-orbit coupling induced by the topology of the localized magnetic moments in the multiferroic spacer. The predicted TAMR effect is efficiently controllable by an external electric field due to the magnetoelectric coupling.

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Introduction.- Transport across two ferromagnetic layers separated by a tunnel barrier depends in general on the relative orientation of the layers magnetizations giving rise to the tunnel magnetoresistance (TMR) effect. In the presence of spin-orbit interactions TMR becomes spatially anisotropic. Tunnel anisotropic magnetoresistance TAMR is observed not only in magnetic tunnel junctions with two ferromagnetic electrodes but also in ferromagnetic/insulator/normal-metal systems such as Fe/GaAs/Au. Here we show that TAMR is a distinctive feature of normal-metal/multiferroic/ferromagnetic heterojunctions with the particular advantage of being electrically controllable. The coexistence of coupled electric and magnetic order parameters in multiferroics holds the promise of new opportunities for device fabrications. Our interest is focused on helimagnetic multiferroics. The topology of the local helimagnetic moments in these materials induces a resonant, momentum-dependent spin-orbit interaction. The non-collinear magnetic order together with the induced spin-orbit coupling result in uniaxial TAMR with a C$_2$ symmetry. These two factors and their interplay determine the size and the sign of TAMR. In particular, a linear dependence on the spiral helicity results in an electrically tunable spin-orbit interaction by means of the magnetoelectric coupling, and thus TAMR is electrically controllable accordingly.

Device proposition.- The proposed multiferroic tunnel junction is sketched in Fig. 1. It consists of an ultrathin helical multiferroic barrier sandwiched between a normal metallic (NM) layer and a ferromagnetic conductor (FM). The ferroelectric polarization $P$ in the multiferroic barrier creates in general surface charge densities $\pm|P|$ which are screened by the induced charge at the two metal electrodes. A depolarizing field emerges in the barrier. Taking the spontaneous electric polarization as $P_z = 700 \mu C/m^2$ and the dielectric constant to be $\epsilon = 30$ in the ferroelectric phase of TbMnO$_3$, the potential drop generated by the depolarizing field in the multiferroic barrier is estimated to be on the energy scale of $meV$, which is much smaller than any other relevant energy scale in the system. In the present study, we neglect this potential modification, and assume that the barrier potential has a rectangular shape with the height $V_0$. All energies are given with respect to the NM Fermi energy $E_F$. Based on this approximation, the Hamiltonians governing the carrier dynamics in the two electrodes and the oxide insulator have the following form,

$$
\begin{align*}
H_{NM} &= -\frac{\hbar^2}{2m_e} \nabla^2, \quad \text{for } z < 0, \\
H_{MF} &= -\frac{\hbar^2}{2m^*} \nabla^2 + Jn_r \cdot \sigma + V_0, \quad \text{for } 0 \leq z \leq d, \\
H_{FM} &= -\frac{\hbar^2}{2m_e} \nabla^2 - \Delta \mathbf{m} \cdot \sigma, \quad \text{for } z > d, \quad (1)
\end{align*}
$$

where $V_0$ and $d$ are the height and the width of the potential barrier (see Fig. 1(c)), $m_e$ is the free-electron mass, $m^*$ is the effective electron mass of the oxide ($m^*/m_e \approx 10$), and $\sigma$ is the vector of Pauli matrices. $\mathbf{m} = [\cos \phi, \sin \phi, 0]$ is a unit vector defining the in-plane magnetization direction in the ferromagnet with respect $z$.

FIG. 1. (Color online) (a) Schematic diagram of the helical multiferroic tunnel junctions consisting of a normal metallic layer as the bottom electrode and a ferromagnetic layer for the top one. The vector $\mathbf{m}$ indicates the magnetization orientation specified by the angle $\phi$ in $xy$ (FM) plane. The $zx$ plane refers to the spiral plane of a multiferroic oxide. (b) The arrows show the induced resonant spin-orbit coupling, $qk_x \sigma_y$ in the multiferroic barrier. (c) The tunnel barrier potential profile.
to the [100] crystallographic direction. \( \Delta \) is the half-width of the Zeeman splitting in the ferromagnetic electrode. \( Jn_r \) is the exchange field, where \( n_r \) is given by the multiferroic oxide local magnetization at each spiral layer (labelled by a integer number \( l \)) along the z-axis, i.e., \( n_r = (-1)^l [\sin \theta_r, 0, \cos \theta_r] \) with \( \theta_r = \bar{q}_m \cdot r \) and \( \bar{q}_m = [\bar{q}, 0, 0] \) being the spiral spin-wave vector. The physical picture behind the term \( H_{MF} \) in eq. (11) is that a tunneling electron experiences an exchange coupling at the sites of the localized, non-collinear magnetic moments within the barrier. In effect this acts on the electron as a non-homogenous magnetic field. Performing a local unitary transformation within the barrier, one can also view the influence of the barrier as consisting of a local unitary transformation within the barrier. The expansion coefficients, \( a_{ij}^l(k) \) (or even less). To get more insight in TAMR we consider the anisotropic spin-orbit coupling contributions and \( g = c^2/8 \pi^3 \hbar \). \( A \) and \( M(\phi) \) are matrices whose elements are given respectively by

\[
A_{ij} = \langle a_{ij}^l(k) \rangle \quad M_{ij}(\phi) = m_im_j \quad (i, j = x, y, z).
\]

The notation \( \langle \ldots \rangle \) stands for the integration over \( \theta_r \) and \( k_\parallel \). Introducing \( \mathbf{w}(\theta_r, \mathbf{k}) \) and \( \mathbf{m} \) into \( G_{\text{aniso}}(\phi) \), Eq. (11), the anisotropic conductance can be rewritten as

\[
G_{\text{aniso}}(\phi) = \alpha \cos^2 \phi + \beta \sin^2 \phi.
\]

Considering the symmetry of the expansion coefficient \( a_{ij}^l(k) \) we obtain for the above expression, \( \alpha = g(a_{ij}^l(k)J^2 \sin^2 \theta_r) \) and \( \beta = g(a_{ij}^l(k)q^2k_z^2) \). Hence, the TAMR coefficient is given by

\[
\text{TAMR} = \frac{G(0) - G(\phi)}{G(\phi)} \approx \gamma (1 - \cos 2\phi), \quad \gamma = \frac{\alpha - \beta}{2G_0}
\]

The above angular dependence of TAMR is quite general. The helical magnetic order and the induced spin-orbit interaction give rise to the anisotropy in the magnetoconductance. However, as evident from Eq. (11), the TAMR coefficient \( \gamma \) depends on \((\alpha - \beta)\), i.e. contributions from the exchange interaction and the spin-orbit coupling term have opposite effects, which is confirmed by the following model calculations.

**Ultrathin barriers.** Experimental observations\(^7\) indicate that thin film multiferroics can retain both magnetic and ferroelectric properties down to a thickness of 2 nm (or even less). To get more insight in TAMR we consider ultrathin tunneling barriers that can be approximated by a Dirac-delta function\(^8\). The effective spin-orbit interaction \( H_{SO}^{\parallel} \) throughout the multiferroic barrier reduces then to the plane of the barrier, \( H_{SO}^{\parallel} = \mathbf{w}(\theta_r, \mathbf{k}) \cdot \mathbf{\sigma} \bar{q}(\mathbf{z}) \) with \( \mathbf{w}(\theta_r, \mathbf{k}) = [J \sin \theta_r, qk_z, J \cos \theta_r] \). \( \bar{q} \) and \( \bar{q} \) are renormalized exchange and resonant spin-orbit coupling parameters, \( \bar{q} \approx \bar{q}_{\text{Vd}} \) and \( J \approx \langle J(z) \rangle \) referring to space and momentum averages with respect to the unperturbed states at the Fermi energy. In the following, we treat \( J \) and \( \bar{q} \) as adjustable parameters. Obviously, the electron momentum parallel to the junction interfaces \( k_\parallel \) is conserved. Then the transverse electron wave functions in NM \((z < 0)\) and FM \((z > 0)\) regions can be written as

\[
G(\phi) = \frac{\alpha^2}{2\pi} \int d^2k_{||} \frac{d\theta_r}{(2\pi)^2} T(k, \mathbf{m}) = G_0 + G_{\text{aniso}}(\phi)
\]
\[
\Psi_{NM}^\sigma(z) = e^{i\kappa z}\chi_\sigma + r_{\sigma,\sigma} e^{-i\kappa z} \chi_\sigma + r_{\sigma,\bar{\sigma}} e^{-i\kappa z} \chi_{\bar{\sigma}}, \quad (11)
\]
\[
\Psi_{FM}^\sigma(z) = t_{\bar{\sigma},\sigma} e^{i\kappa z} \chi_\sigma + t_{\bar{\sigma},\bar{\sigma}} e^{i\kappa z} \chi_{\bar{\sigma}}, \quad (12)
\]

with
\[
\kappa = \sqrt{\frac{E}{2m_e} - k^2}, \quad (13)
\]
\[
k_\sigma = \sqrt{\frac{(E + \sigma \Delta)}{2m_e} - k^2}, \quad (14)
\]

and the spinors introduced as
\[
\chi_\sigma = \frac{1}{\sqrt{2}} \left( \begin{array}{c} 1 \\ \sigma e^{i\phi} \end{array} \right), \quad (15)
\]

and correspond to an electron spin parallel (\(\sigma = 1\)) or antiparallel (\(\sigma = -1\)) to the magnetization direction in the ferromagnetic electrode. The reflection (\(r_{\sigma,\sigma}\) and \(r_{\sigma,\bar{\sigma}}\)) and transmission (\(t_{\bar{\sigma},\sigma}\) and \(t_{\bar{\sigma},\bar{\sigma}}\)) coefficients can be analytically obtained from the continuity conditions for \(\Psi(z)\) and \(\Psi'(z)/m\) at \(z = 0\).\]

\[
\Psi_{NM}^\sigma(0^-) = \Psi_{FM}^\sigma(0^+), \quad (16)
\]
\[
\frac{\hbar^2}{2m_e} \frac{d\Psi_{NM}^\sigma(z)}{dz} \bigg|_{z=0^-} + (V_0 d + \hat{\omega}(\theta, r) \cdot \sigma) \Psi_{NM}^\sigma(0^-) = \frac{\hbar^2}{2m_e} \frac{d\Psi_{FM}^\sigma(z)}{dz} \bigg|_{z=0^+.} \quad (17)
\]

The transmissivity of a spin-\(\sigma\) electron through the multiferroic tunnel junctions reads
\[
T_\sigma(E, k_||, \theta) = \Re \left[ \frac{k_\sigma}{\kappa} |t_{\sigma,\sigma}|^2 + \frac{k_{\bar{\sigma}}}{\kappa} |t_{\bar{\sigma},\bar{\sigma}}|^2 \right]. \quad (18)
\]

For a small applied bias voltages, the conductance \(G\) is determined by the states at the Fermi energy \(E_F\),
\[
G_\sigma = \frac{e^2}{\hbar} \int \frac{d^2k_\parallel}{(2\pi)^2} \frac{d\theta}{2\pi} T_\sigma(E_F, k_||, \theta_r). \quad (19)
\]

Fig. 2(top) shows the TAMR angular dependence ~ (1 − \(\cos 2\phi\)), at \(E_F = 5.5 eV, \Delta = 2 eV, V_0 = 0.5 eV\), and \(d = 2 nm\). It is clear that TAMR has \(C_{2v}\) symmetry. For small \(J\) the spin-orbit interaction dominates the tunneling properties, we have positive TAMR. As \(J\) increases, the size of TAMR is influenced by the interplay between the exchange field and the induced spin-orbit interaction. The TAMR is typically ~0.1%, which is on the same order as in the Fe/GaAs/Au tunnel junctions have been recently realized experimentally\(^{15}\). A transition from positive to negative TAMR is observed, which is consistent with the previous finding, i.e. Eq.\(^{10}\) within the phenomenological model. On the other hand, the helicity of the spiral magnetic order \(\hat{q}\) in helimagnetic multiferroics is experimentally controllable by a small (~1kV/cm) transverse electric field\(^{11}\). Consequently,

\[
\begin{array}{c}
\text{FIG. 2. The angular-dependence of TAMR on different strengths of the exchange field } J(eV) \text{ and on the coefficient } \gamma \text{ that enters the TAMR due to the competition between the exchange field and the induced spin-orbit interaction. The used numerical values are } E_F = 5.5 eV, \Delta = 2 eV, V_0 = 0.5 eV, \text{ and } d = 2 mm. \text{ Top: } \hat{q} = 0.28. \text{ Bottom: } J = 0.1 eV. \\
\end{array}
\]

Conclusions.- We studied the electron tunneling properties through helical multiferroic junctions. The spiral magnetic ordering and the induced spin-orbit interaction in the multiferroic barrier lead to the TAMR effect. Due to the magnetoelectric coupling, the strength of the induced spin-orbit coupling is electrically controllable which reders a tunable TAMR by an external electric field.

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