Spin-dependent electron grating effect from helical magnetization in multiferroic tunnel junctions

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Abstract

In multiferroic oxides with a transverse helical magnetic order, the magnetization exchange coupling is sinusoidally space-dependent. We theoretically investigate the spin-dependent electron grating effect in normal-metal/helical-multiferroic/ferromagnetic heterojunctions. The spin wave vector of the spiral can be added or subtracted from the electron spacial wave vector inducing spin-conserved and spin-flipped diffracted transmission and reflection. The predicted grating effect can be controlled by magnetization exchange coupling strength, the helicity spatial period, and the magnetization of the ferromagnetic layer.

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I. INTRODUCTION

In optics, a diffraction grating is an optical component with a periodic structure, which splits and diffracts light into several beams traveling in different directions. The directions of these beams depend on the spacing of the grating and the wavelength of the light. Similar effect can be found in electron transport as an effect of particle-wave duality. Electron diffraction is most frequently used in high-energy transmission electron microscope to study the crystal structure of solids. In mesoscopic tunnel junctions, the electron energy is determined by the Fermi energy of the reservoirs, which could be in the order of meV. In this energy scale, the electron wave length can be as large as several nanometers. Transport diffraction can be observed in nano-scale gratings. Recently, optical transient spin-grating spectroscopy was used to measure the lifetime of spin polarization waves in spin-orbit-coupled semiconductor quantum wells. Diffraction by transient helical spin wave generated by exciting a 2DEG with two non-collinear beams from a femtosecond laser can be detected by a probe pulse. Preceding experimental realization, spin propagation theories in semiconductor 2DEG with Rashba spin-orbital coupling are intensively discussed.

The coexistence of coupled electric and magnetic order parameters in multiferroics (MF) holds the promise of new opportunities for device fabrications. Our interest is focused on the helimagnetic MF, in which the magnetization exchange coupling is sinusoidally space-dependent. In real space, the eigen spinor of the helimagnet is a static spin wave pointing along the helical magnetization. Using a space-dependent gauge transformation, it is shown that the topology of the local helical magnetic moments in these materials induces a resonant, momentum-dependent spin-orbit interaction (SOI). Jia et al. found that the momentum dependence of the SOI is analogous to semiconductor-based 2DEG with the Rashba and Dresselhaus spin-orbit interaction being equal. When the strength of the two dominant SOI are equal, SU(2) symmetry is restored, giving rise to a persistent helical spin density wave confirmed by transient spin-grating spectroscopy. This analogy suggests the existence of similar effect in MF helimagnets. Recently, electron spin resonance in chiral helimagnet was proposed. In this work, we investigate the spin-resolved transmission properties in normal-metal (NM)/helical-MF/ferromagnetic (FM) heterojunctions. Spin-flipped grating effect is found in electron transmission as a result of the sinusoidally-space-dependent magnetization in the MF layer.
II. THEORETICAL FORMULATION

The MF tunnel junction we consider follows that proposed by Jia et al.\textsuperscript{6}. It consists of an ultrathin helical-MF barrier sandwiched between a NM layer and a FM conductor. The ferroelectric polarization $\mathbf{P}$ in the MF barrier creates, in general, surface charge densities $\pm |\mathbf{P}|$ which are screened by the induced charge at the two metal electrodes\textsuperscript{9,10}. Potential drop in the ferroelectric phase of TbMnO$_3$ generated by the depolarizing field in the thin-film MF barrier is estimated to be on the energy scale of millielectron volt, which is much smaller than any other relevant energy scale in the system\textsuperscript{6,11}. In the present study, we neglect this potential modification and assume that the barrier potential has a rectangular shape with the height $V_0$. Based on this approximation, the Hamiltonians governing the carrier dynamics in the two electrodes and the oxide insulator have the following form:

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

(1)

where $V_0$ and $d$ are the height and width of the potential barrier, and $m_e$ is the free-electron mass. $m^*$ is the effective electron mass of the oxide ($m^*/m_e \approx 10$) and $\sigma$ is the Pauli vector. $\mathbf{m} = [\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta]$ is a unit vector defining the magnetization direction in the FM with respect to the [100] crystallographic direction. $\Delta$ is the half width of the Zeeman splitting in the FM electrode. $J\mathbf{n}_r$ is the exchange field, where $\mathbf{n}_r$ is given by the MF oxide local magnetization at each spiral layer (labeled by an integer $l$) along the $z$ axis\textsuperscript{12}, i.e., $\mathbf{n}_r = (-1)^l [\sin \theta_r, 0, \cos \theta_r]$ with $\theta_r = \bar{q}_m \cdot \mathbf{r}$ and $\bar{q}_m = [\bar{q}, 0, 0]$ being the spiral spin-wave vector. The physical picture behind the term $H_{MF}$ in Eq. (1) is that a tunneling electron experiences an exchange coupling at the sites of the localized noncollinear magnetic moments within the barrier. In effect this acts on the electron as a nonhomogenous magnetic field.

Experimental observations\textsuperscript{13–15} indicate that thin-film MF can retain both magnetic and ferroelectric properties down to a thickness of 2 nm (or even less). We consider ultrathin tunneling barriers that can be approximated by a Dirac-delta function\textsuperscript{16}. The helical MF barrier reduces to a plane barrier. Hamiltonian in the MF layer can be rewritten as

$$
H_{MF} = -\frac{\hbar^2}{2m^*}\nabla^2 + \left(\tilde{J}\mathbf{n}_r \cdot \sigma + V_0 d\right) \delta(z),
$$

(2)

where we assume a single spiral layer with $l = 0$. $\tilde{J} = \langle J(z) \rangle d$ refers to space and momentum
The reflection ($r_{n\sigma}^\sigma$) and transmission ($t_{n\sigma}^\sigma$) amplitude in the $n$th diffraction order can be numerically obtained from the continuity conditions\textsuperscript{6,16} for $\Psi(x, y, z)$ at $z = 0$.

$$
\Psi_{NM}^\sigma(x, y, 0^-) = \Psi_{FM}^\sigma(x, y, 0^+),
$$

$$
\left. \frac{\hbar^2}{2m_e} \frac{\partial \Psi_{NM}^\sigma(x, y, z)}{\partial z} \right|_{z=0^-} + \left[ V_0d + \tilde{\bf w}(\theta_r) \right] \Psi_{NM}^\sigma(x, y, 0^-) = \left. \frac{\hbar^2}{2m_e} \frac{\partial \Psi_{FM}^\sigma(x, y, z)}{\partial z} \right|_{z=0^+},
$$

with

$$
\tilde{\bf w}(\theta_r) = j \begin{bmatrix} \cos \theta_r & \sin \theta_r \\ \sin \theta_r & -\cos \theta_r \end{bmatrix}.
$$

The continuity equation can be expressed in the equations of each diffracted order. Transmissivity of a spin-$\sigma$ electron through the MF tunnel junction with the incident wave vector $[k_x, k_y, k_z]$ to the $n$-th diffracted order and spin-$\sigma'$ channel with the outgoing wave vector $[k_n^x, k_y, k_n^{z\sigma'}]$ reads

$$
T_{n\sigma'}(E, k_y, \theta_{xz}) = \frac{|k_n^z|^2}{k_z} |t_{n\sigma'}|^2.
$$
III. NUMERICAL RESULTS AND INTERPRETATIONS

We consider the diffracted transmission properties of the NM/helical MF/FM junctions. In numerical calculations, the NM Fermi energy $E_F$ is chosen to be 5.5 eV. The spatial average of the helimagnetic exchange coupling strength $\bar{J} = 0.2$ eV·nm, which is reasonable compared to the Fermi energy. Period of short-period helimagnets$^{17}$ is 3-6 nm and of long-period helimagnets is 18-90 nm. In our model we consider the period to be 10 nm and hence $\bar{q} = 2\pi/10$ nm$^{-1}$. The magnetization direction in the FM is fixed to be $\theta = 1$ and $\phi = 0.5$ in radian. Zeeman splitting in the FM electrode $\Delta = 2$ eV. Barrier height of the MF oxide plane $V_0 = 0.5$ eV and width $d = 2$ nm. We consider 5 diffraction orders, which is sufficient as higher orders decrease exponentially.

During transmission, the incident electron with wave vector $[k_x, k_z]$ would absorb or emit $n\bar{q}$ from the helimagnet and be diffracted into tunnels with wave vector $[k^{\sigma n}_x, k^{\sigma n}_z]$. The diffraction level can be defined by the number $n$ being sequel positive and negative integers following the definition in optical gratings. $n = 0$ labels the zero-order transmission channel with the transmission direction the same to the incidence. $n = \pm 1$ labels the $\pm 1$-order transmission channel with the transmission direction shift an angle to $[k_x \pm \bar{q}, k^{\pm 1\sigma}_z]$, and etc. The diffraction tunnel number correspondence is illuminated in Fig. 1. The incident wave vector is set to be $k_x = \bar{q}$ to make figure scale brief and the diffraction phenomenon is analogous for all incident $k_x$.

Numerical results of the transmission diffraction effect are shown in Fig. 2. The incident wave vector is set to be $k_x = \bar{q}$ and analogous diffraction effect can be found for continuously all $k_x$. From the transmissivity $T^{\sigma\sigma'} [T^{\sigma\sigma'}_{\sigma'} \text{ in Eq. (7)}]$ plotted in Fig. 2, it can be seen that the spin-conserved transmission is a direct grating effect with the transmission amplitude exponentially decreasing as the diffraction order is increased (see also insets of Fig. 2). The transmission of one-way incident light through sinusoidal gratings is delta-function-like strict lines. Analogously, direction of transmission of one-way incident electron through sinusoidal helimagnet is discrete strict lines of different grating orders and the spin is conserved or flipped. The spin-flipped transmission is an effect of the electron-helimagnet coupling. As a result, $\pm 1$ order magnifies in spin-flipped transmissivity. For arbitrary $m$ relative to the chirality of the helimagnet, $+1$ and $-1$ order transmission may not be symmetric. Physically, an electron with spin polarization along the FM magnetization is transmitted in different
direction with its spin rotating an angle as the cartoon Fig. 3 shows.

Results of an arbitrary FM magnetization is shown in Fig. 2. We also considered some special FM configurations. Numerically calculation demonstrates that for \( \mathbf{m} \) pointing to the \( z \)-direction (\( \theta = 0 \)), an incident spin-down electron would be completely transmitted to ±1 order with all the spin flipped and transmission in the other channels is several orders smaller. Reversely, for \( \mathbf{m} \) pointing to the \( -z \)-direction (\( \theta = \pi \)), an incident spin-up electron would be completely transmitted to ±1 order with all the spin flipped and transmission in the other channels is several orders smaller. Opposite channel priority can also be found when the chirality of the helimagnet is turned over. Along this physical track, for \( \mathbf{m} \) lying in the \( x \)-direction (\( \theta = \pi/2, \phi = 0 \)), ±1 order transmission magnifies in spin-flipped channels with +1 and −1 orders symmetric. For \( \mathbf{m} \) lying in the \( y \)-direction (\( \theta = \pi/2, \phi = \pi/2 \)), spin-conserved grating is extremely suppressed and spin-flipped transmission would only occur in +1 order for spin-up incidence and in −1 order for spin-down incidence. These results can be interpreted by the effect of the exchange coupling in the helimagnet. When the spin polarization is along the helimagnet spiral axis (\( z \)-direction in our structure), the grating “seen” by the incident spin-up electron and that “seen” by the spin-down electron is in opposite modulation, hence spin-flipped grating effect is enhanced. When the spin polarization is perpendicular to the helimagnet spiral plane (\( x-z \) plane in our structure) spin grating effect is extremely suppressed.

In the NM/helical-MF/FM junction setup, all adjustable parameters can induce difference phenomenons in the electron diffracted transmission. In above discussions a short-period helimagnet (with period 10 nm) is considered. For long-period helimagnet (18-90 nm), grating effect would be extremely diminished. Above we considered a small exchange coupling strength in the helical MF oxide. For strong coupling strength comparable to the Fermi energy, spin grating effect would dominate direct transmission making the diffraction pattern more prominent.

**IV. CONCLUSIONS**

We theoretically investigate the spin-dependent electron grating effect induced by scattering from a sinusoidal helimagnet thin film sandwiched between NM and FM electrodes. An incident electron with spin polarization parallel or antiparallel to the FM magnetization...
is diffracted into different direction with its spin rotating an angle resembling an optical grating effect. The diffraction phenomenon can be tuned by external parameters such as the magnetization exchange coupling strength, the helicity spatial period, and the magnetization of the ferromagnetic layer.

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FIG. 1: Different tunnels in the wave vector space. The incident beam travels with wave vector \((k_x = \vec{q}, k_z)\). The transmitted beam traveling in the same direction of the incident beam is indexed as tunnel 0. The transmitted beam with wave vector \((k'_x = k_x + n\vec{q}, k'_z)\) are indexed as tunnel \(n\) with \(n\) being sequel positive and negative integers following the definition in optical grating effect.
FIG. 2: Spin-conserved and spin-flipped transmission in different tunnels ($k^n_x = k_x + n\bar{q}, k^n_z$) of an incident spin-up electron with wave vector ($k_x = \bar{q}, k_z$). Numbers label the tunnel indexes $n$. Four panels indicate transmission $T^{uu}$ ($T^{uu}$), $T^{ud}$ ($T^{ud}$), $T^{du}$ ($T^{du}$), and $T^{dd}$ ($T^{dd}$), respectively. Insets are logarithms of the transmission to show the slight effect of high diffraction orders. The used numerical values are $E_F = 5.5$ eV, $V_0 = 0.5$ eV, $d = 2$ nm, $\bar{q} = 2\pi/10$ nm$^{-1}$, $\phi = 0.5$ radian, $\theta = 1$ radian, $k_x = \bar{q}$, $k_y = 2\bar{q}$, and $\tilde{J} = 0.2$ eV $\cdot$ nm.
FIG. 3: A cartoon sketching a spin-dependent electron grating effect from helical magnetization in multiferroic tunnel junctions. The helical spin structure in a helimagnet diffracts a spin-polarized electron beam into several beams traveling in different directions with all beams containing spin-flipped components. The green arrows indicate the transmitted spin polarization. Helicity of the multiferroic oxide is in white arrows.