Anomalous magnetoresistance on the topological surface

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Abstract. We report theoretical study of charge transport in two-dimensional ferromagnet/ferromagnet junction on a topological insulator. The conductance across the interface shows anomalous dependence on the directions of the magnetizations of the two ferromagnets. This stems from the way how the wavefunctions connect between both sides. It is found that the conductance depends strongly on the in-plane direction of the magnetization. Moreover, in stark contrast to the conventional magnetoresistance effect, the conductance at the parallel configuration can be much smaller than that at the antiparallel configuration.

1. Introduction

Recently, topological insulator has received much attention both theoretically and experimentally [1, 2, 3, 4, 5] because it belongs to a new state of matter in the time-reversal symmetric systems. 3D topological insulators are characterized by two-dimensional metallic states on the surface of the sample. These surface states are protected by the time-reversal symmetry and the topology of the bulk gap, and are robust against the disorder scattering and electron-electron interactions.

On the surface of 3D topological insulator, the electrons obey the 2D Dirac equations. This corresponds to the infinite mass Rashba model [6]. This has been observed by the spin- and angle-resolved photoemission spectroscopy [7, 8]. Therefore, the next step in this field is to unveil unique property of the surface state of the topological insulators, in particular that relevant to magnetism [9, 10, 11, 12, 13, 14, 15, 16]. One remarkable feature of the Dirac fermions is that the Zeeman field acts like vector potential: the Dirac Hamiltonian is transformed as \( \mathbf{k} \cdot \sigma \rightarrow (\mathbf{k} + \mathbf{m}) \cdot \sigma \) by the Zeeman field \( \mathbf{m} \). Therefore, we can expect unusual spin related phenomena by the magnetic field in topological insulator.

In this paper, we study charge transport in 2D topological ferromagnet/ferromagnet junction. The ferromagnet is made of the topological surface with a ferromagnetic insulator on the top. We find anomalous magnetoresistance in this spin-valve: The conductance strongly depends on the in-plane rotation of the magnetization. In stark contrast to the conventional magnetoresistance effect, the conductance may have its minimum at the parallel configuration, while it may take a maximum near antiparallel configuration. This is attributed to the connectivity of the wavefunction across the junction. [13]
2. Formulation

We consider 2D ferromagnet/ferromagnet junctions which is abbreviated as F1/F2 below. We focus on charge transport at the Fermi level inside the bulk gap of the topological insulator, which is described by the 2D Dirac Hamiltonian

\[ H = \begin{pmatrix} m_z & k_x + m_x - i(k_y + m_y) \\ k_x + m_x + i(k_y + m_y) & -m_z \end{pmatrix} \]

(1)

where \( m_x, m_y \) and \( m_z \) are exchange field and we set \( \hbar = 1 \). The ferromagnetism is induced due to the proximity effect by the ferromagnetic insulators deposited on the top. The interface is parallel to \( y \)-axis and located at \( x = 0 \). We choose the exchange field in the F1 side as \( m_1 = (m_x, m_y, m_z) = m_1(\sin \theta \cos \varphi, \sin \theta \sin \varphi, \cos \theta) \) while in the F2 side, we set \( m_x = m_y = 0 \) and \( m_z = m_2 \).

We consider the junction between different ferromagnets. This type of interface should contain a built-in electric field. Thus, we take into account the potential drop in F2 which represents the difference of the Fermi energies in the two ferromagnets. Then, with the above Hamiltonian, we have the wave function in the F1 side:

\[ \psi(x \leq 0) = \frac{1}{\sqrt{2E(E - m_z)}} e^{ik_x x} \left( \frac{\tilde{k}_x - ik_y}{E - m_z} \right) + \frac{r}{\sqrt{2E(E - m_z)}} e^{-ik_x x} \left( \frac{-\tilde{k}_x - ik_y}{E - m_z} \right) \]

(2)

with \( \tilde{k}_x = k_x + m_x \) and \( \tilde{k}_y = k_y + m_y \), and also that in the F2 side reads

\[ \psi(x \geq 0) = \frac{t}{\sqrt{2E'(E' - m_2)}} e^{ik'_x x} \left( \frac{k'_x - ik_y}{E' - m_2} \right) \]

(3)

with \( E' = E - V \), where \( E = \sqrt{m_x^2 + (k_x + m_x)^2 + (k_y + m_y)^2} = \pm \sqrt{m_x^2 + m_y^2 + k_y^2} \). Here, the sign corresponds to the upper and lower bands. Below, "n" and "p" mean that the Fermi level crosses the upper and lower bands, respectively. Also, \( r \) and \( t \) are reflection and transmission coefficients, respectively. It should be noticed that the Fermi surface in the F1 is shifted by \((-m_x, -m_y)\) from the origin. Due to the translational invariance along the y-axis, the momentum \( k_y \) is conserved. Hence, the common factor \( e^{ik_y y} \) is omitted above.

By matching the wavefunctions at the interface \( x = 0 \), we obtain the transmission coefficient \( t \). Here, we omit the expression of \( t \) because it is rather complicated.

We parametrize \( k_x + m_x = k_F \cos \phi \), and \( k_y + m_y = k_F \sin \phi \). Then, we have \( E = \sqrt{m_x^2 + (k_x + m_x)^2 + (k_y + m_y)^2} = \sqrt{m_x^2 + k_y^2} \).

Finally, we obtain the normalized tunneling conductance as

\[ \sigma = \int_{-\pi/2}^{\pi/2} d\phi \text{Re} \left[ \psi^\dagger(x \geq 0)v_x \psi(x \geq 0) \right] = \frac{1}{2} \int_{-\pi/2}^{\pi/2} d\phi |t|^2 \text{Re} \left[ \frac{k'_x}{E} \right] \]

(4)

where \( v_x = \frac{\partial H}{\partial k_x} = \sigma_x \).

3. Results

In the following, we will fix \( m_1 = \sqrt{0.9}E \). In Fig. 1, the normalized tunneling conductance \( \sigma \) in n-n junction is shown for (a) \( m_2 = 0 \) and (b) \( m_2 = \sqrt{0.9}E \). In Fig. 1 (a), the F2 is no longer ferromagnetic. However, the conductance strongly depends on the direction of the magnetization in the F1. At \( \theta = 0 \) or \( \pi \), the mismatch of the wavefunctions between the two sides and that of the sizes of Fermi surfaces suppress \( \sigma \). At \( \theta = \pi/2 \), on the other hand, the wavefunctions and the sizes of the Fermi surfaces are the same on both sides except the shift of Fermi surface
Figure 1. (Color online) tunneling conductance $\sigma$ for $m_2 = 0$ ((a) and (c)), and $m_2 = \sqrt{0.9}E$ ((b) and (d)). n-n junction at $V = 0$ in (a) and (b). p-n junction at $V = 2E$ in (c) and (d).

in the momentum space due to the in-plane component of the magnetization as shown in the upper panel of Fig. 2. However, this difference of the in-plane momentum between the two sides provides a strong dependence of $\sigma$ on the in-plane rotation angle $\varphi$, which is not seen in the conventional magnetoresistance effect. Since $k_y$ is conserved, the positions of the Fermi surfaces strongly influence the charge transport: if exchange field points to $x$-axis, there is no evanescent wave. On the other hand, when exchange field is in $y$-direction, the Fermi surface moves to the $k_y$ direction and hence the overlap region of $k_y$'s between F1 and F2 is reduced. Therefore, the number of the evanescent modes increases and hence the conductance is strongly suppressed. Thus, we can obtain giant magnetoresistance in this system.

In Fig. 1 (b), the conductance is large at the parallel configuration ($\theta = 0$) while it is small for antiparallel configuration ($\theta = \pi$). This $\theta$ dependence, similar to the conventional magnetoresistance effect, can be explained by the overlap integral of the wavefunctions on both sides, as discussed later.

We show tunneling conductance in p-n junction with $V = 2E$ for $m_2 = 0$ in Fig. 1 (c) and $m_2 = \sqrt{0.9}E$ in Fig. 1 (d). In Fig. 1 (c), a similar tendency to Figure 1(a) is seen. In Fig. 1 (d), in contrast to the conventional magnetoresistance effect, the conductance takes minimum at the parallel configuration ($\theta = 0$) while it takes maximum near antiparallel configuration ($\theta = \pi$).

To understand these results intuitively, we describe the underlying physics in Fig. 2 where the arrows indicate the spin directions in the limiting case of $|m_z| \to \infty$, showing the connection of the wavefunctions on both sides. In the n-n junctions, the tunneling amplitude is determined by the overlap of the same eigenfunctions for parallel configuration ($\theta = 0$), while for antiparallel configuration ($\theta = \pi$) it is given by the overlap of the different eigenfunctions, as shown in Figs. 2 (a) and (b). Thus, the tunneling amplitude takes its maximum at $\theta = 0$, and this explains the $\theta$ dependence of the conductance in Fig. 1 (b). In a similar way, in p-n junctions, we find that the tunneling amplitude at $\theta = \pi$ becomes larger than that at $\theta = 0$ as indicated in Figs. 2 (c) and (d). This is the origin of the anomalous $\theta$ dependence of the conductance in Fig. 1 (d).
Figure 2. (Color online) (upper) Positions of Fermi surfaces. On the F1, the Fermi surface moves as illustrated, as \( \mathbf{m}_1 \) rotates around z-axis. (lower) Connectivity of the wavefunction across the n-n junction ((a) and (b)), and p-n junction ((c) and (d)). The magnetizations are parallel \( (\theta = 0) \) in (a) and (c), while they are antiparallel \( (\theta = \pi) \) in (b) and (d). The arrows represent the electron’s spin.

4. Summary
We investigated charge transport in 2D topological ferromagnet/ferromagnet junction. The ferromagnet is made of the topological surface with a ferromagnetic insulator on the top. We found anomalous magnetoresistance in this system.

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