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Majorana fermions, Andreev reflection and magnetoresistance effect in three-dimensional topological insulators

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ABSTRACT

We study the transport properties of ferromagnet/ferromagnet/s-wave superconductor junctions formed on the surface of a three-dimensional topological insulator in an experimentally relevant regime. It is found that the total Andreev reflection happens at zero bias and the zero-bias conductance in the junctions is not dependent on the magnetizations. We show that the features are strongly related to the formation of Majorana fermions in the middle ferromagnet. However, for finite bias, the conductance is very sensitively controlled by the relative orientation of the magnetizations and this leads to a controllable magnetoresistance effect in the system. These results provide guidance for searching the Majorana fermion and possess potential applications in superconducting spintronics.

1. Introduction

Majorana fermions (MFs) are a class of excitations which are their own antiparticles [1]. It is suggested that the MF is a promising candidate for topological quantum computation owing to its non-Abelian character [2–4]. Realization and controlling of MFs are hot research issues in condensed matter physics [5–7]. There are several systems [8–18] which are predicted to host MFs. Topological insulators (TIs) [19–22], among others, have attracted active studies on the properties of the MF recently [23–32]. It has been shown [23,24,26–29] that MFs exist as surface states in the junction between a superconductor (S) and a ferromagnet (F) deposited on a TI with Fermi level at or close to the Dirac point. Especially in Ref. [27], the transport properties associated with MFs and the Andreev reflection (AR) in topological normal metal (N)/F/S junctions have been studied. It is found the chiral Majorana model generated in the junctions can be controlled by the direction of the magnetization in F. However, as pointed in Ref. [31], the TI materials with finite chemical potential are more easy to realize in experiments and the authors studied the experimentally relevant S/F/S Josephson junctions on a three dimensional (3D) TI. The 4π periodic Andreev bound state (ABS) as a feature of the presence of MFs is predicted. Yet this characteristic is a single-channel effect and no 4π periodicity of the ABS can be obtained for all incident angles in experiments.

To our knowledge, the research on the MF and its relation with transport properties in topological F/S junction with finite chemical potential is still lack. Here, we theoretically study the charge transport in F/F/s-wave S junctions formed on the surface of a 3D TI with the chemical potential μ far away from the Dirac point. The magnetizations are chosen as $|\mathbf{m}_{1,2}| < \mu$, which is also different from that in Refs. [23,24,26–29]. It is found that the MF still exists in our system and it is an all-channel effect which may be observable in experiments. The formation of MFs shows strong associations with the AR and hence the conductance. We find at zero bias, there is no backscattering for the electron incidence and the total AR ($|a|=1$) comes into being, which are related to the formation of the MF as the superposition of electrons and the reflected holes in the middle F. The zero-bias conductance (ZBC) is irrespective of the magnetizations. However, for the non-zero bias case, the backscattering is finite due to the presence of the effective barriers and the conductance is sensitively dependent on the orientation of the two magnetizations. We define the magnetoresistance (MR) for finite bias and giant values can be obtained in a large range of bias. The oscillatory behaviors of the conductance and the MR with the width of the middle ferromagnet are also investigated.

2. Formalism

We consider F1/F2/s-wave S junctions formed on the surface of a 3D TI with F1($x<0$), F2($0<x<L$) and S($x>L$) as shown in Fig. 1.

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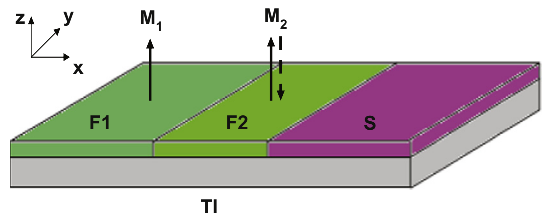

Fig. 1. Schematic illustration of ferromagnet (F1)/ferromagnet (F2)/superconductor (S) junctions formed on the surface of a 3D topological insulator (TI). The current is flowing along the x-axis on the surface of the TI.

The interfaces F1/F2 and F2/S are located at $x=0$ and $x=L$, respectively.

In the Nambu basis, the Hamiltonian of the surface state on the TIs is given by

$$\check{H} = \begin{pmatrix} \hat{H}(\mathbf{k})+\hat{M} & \hat{\Delta} \\ -\hat{\Delta}^* & -\hat{H}^*(-\mathbf{k})-\hat{M}^* \end{pmatrix}, \tag{1}$$

with $\hat{H}(\mathbf{k})=v_F(\hat{\sigma}_x k_x+\hat{\sigma}_y k_y)-\mu$, $\hat{M}=\mathbf{m}_1\cdot\hat{\boldsymbol{\sigma}}\Theta(-x)+\mathbf{m}_2\cdot\hat{\boldsymbol{\sigma}}\Theta(x)\Theta(x-L)$ and $\hat{\Delta}=i\hat{\sigma}_y\Delta\Theta(x-L)$. Here, μ, $\hat{\boldsymbol{\sigma}}$, v_F, $m_{1(2)}$ and Δ denote the chemical potential, Pauli matrices, Fermi velocity, magnetizations and s-wave pairing amplitude, respectively. We have assumed the same chemical potential in Fs and S. In our calculations, the magnetizations are taken perpendicular to the surface of the TI, i.e. $\mathbf{m}_{1(2)}=(0,0,m_{1(2)})$. Furthermore, we only consider the case of $m_1>0(\mathbf{m}_1\parallel\hat{z})$ due to the reflection symmetry of the junctions about xy-plane. The direction of $\mathbf{m}_2$ may be easily controlled by an external field and it is parallel (antiparallel) to $\mathbf{m}_1$ for $m_2>(<)0$.

Assuming an electron being injected from F1 with an injection angle θ_1, the wave functions $\Psi_{F1}(x)$, $\Psi_{F2}(x)$ and $\Psi_S(x)$ are given by

$$\Psi_{F1}(x)=[\Psi^e_{in}e^{ik_{1x}x}+a\Psi^h_r e^{ik_{1x}x}+b\Psi^e_r e^{-ik_{1x}x}]e^{ik_y y}, \tag{2}$$

$$\Psi_{F2}(x)=[f_1\Psi^e_R e^{ik_{2x}x}+f_2\Psi^e_L e^{-ik_{2x}x}+f_3\Psi^h_L e^{ik_{2x}x}+f_4\Psi^h_R e^{-ik_{2x}x}]e^{ik_y y}, \tag{3}$$

$$\Psi_S(x)=[c\Psi^e_S e^{ik_S x}+d\Psi^h_S e^{-ik_S x}]e^{ik_y y}, \tag{4}$$

with $k_{1(2)x}=(\sqrt{\mu^2-m^2_{1(2)}}/v_F)\cos\theta_{1(2)}$ and $k_S=k_F\cos\theta_s$. Conservation of k_y (due to translation invariance) can give the relations between $\theta_{1(2)}$, θ_s and θ_1. The four component wave vectors $\Psi^e_{in(r)}$, Ψ^h_r, $\Psi^e_{L(R)}$, $\Psi^h_{L(R)}$ and $\Psi^{e(h)}_S$ are given respectively by $\Psi^e_{in(r)}=(u_{1+},+(-)u_{1-}e^{+(-)i\theta_1},0,0)^T$, $\Psi^h_r=(0,0,v_{1+},-v_{1-}e^{-i\theta_1})^T$, $\Psi^e_{L(R)}=(u_{2+},+(-)u_{2-}e^{+(-)i\theta_2},0,0)^T$, $\Psi^h_{L(R)}=(0,0,v_{2+},-(+)v_{2-}\ e^{-(+)i\theta_2})^T$, $\Psi^e_S=(u,ue^{i\theta_s},-ve^{i\theta_s},v)^T$ and $\Psi^h_S=(v,-ve^{-i\theta_s},\ ue^{-i\theta_s},u)^T$ with $u_{\alpha+(-)}=\sqrt{(\mu+E+(-)m_\alpha)/(\mu+E)}$, $v_{\alpha+(-)}=\sqrt{(\mu-E+(-)m_\alpha)/(\mu-E)}$ $(\alpha=1,2)$ and u, v being the superconducting coherent factors. Throughout our paper, we are concerned with the situation $\mu\le\Delta,|E|$. In this case, we have only normal Andreev reflection at F2/S interface and no specular Andreev reflection [33].

The coefficients of the Andreev reflection a and normal reflection b are obtained by imposing the boundary condition $\Psi_{F1}(0)=\Psi_{F2}(0)$ and $\Psi_{F2}(L)=\Psi_S(L)$. With BTK formalism, the angle-averaged normalized tunneling conductance of the junctions is given by

$$\sigma_0=\frac{\sqrt{\mu^2-m_1^2}}{2\mu}\int\sigma(\theta_1)\cos\theta_1\,d\theta_1, \tag{5}$$

with the angle-resolved tunneling conductance $\sigma(\theta_1)=1+|a|^2-|b|^2$.

3. Results and discussion

First, we present the numerical results for the angle-resolved tunneling conductance. In our calculations, we have set $k_F L=5$. Fig. 2(a) gives the conductance spectra for different m_2 at $\theta_1=0$. There are two remarkable characteristics in the spectra: (i) The conductance for each m_2 has a zero-bias peak and the peak is of the same value. This value is equal to 2 which implies $|a|=1$. (ii) The finite-bias conductance is splitting for different m_2. The conductance spectra for different θ_1 at $m_2/\mu=0.6$ is shown in Fig. 2(b). They also possess the characteristics stated above for θ_1.

Here, we give physical explanations for the novel angle-resolved conductance spectra. For the Hamiltonian in both Fs and s-wave S, we have a particle–hole symmetry $\Pi\check{H}(\mathbf{k})\Pi^{-1}=-\check{H}^*(-\mathbf{k})$ [16,28]. The operator Π is defined as $\Pi=\hat{\tau}_x\otimes\hat{I}$, where $\hat{\tau}_x$ is the Pauli matrix in the particle–hole space and $\hat{I}$ is the unit matrix in the spin space. After this transformation, the electron-like quasiparticles are related to the hole-like quasiparticles in Fs by $\Pi\Psi^e_{\mathbf{k}}(E)=\Psi^h_{-\mathbf{k}}(-E)^*$.

The scattering matrix S which describes the scattering at energy E from incident quasiparticles to outgoing quasiparticles in F1 can be written as

$$S=\begin{pmatrix} b & a' \\ a & b' \end{pmatrix}, \tag{6}$$

where coefficients $a(a')$ and $b(b')$ indicate the AR and the normal reflection for an incident electron(hole) respectively. The transformation Π on the scattering matrix will give $\hat{\tau}_x S\hat{\tau}_x^{-1}=S^*$. Taking into account the unitarity of the S matrix, we get $a^*b=0$ at the Fermi level $(E=0)$. In the absence of Fermi energy mismatch here, the choice of $b=0$ and $|a|=1$ is reasonable which is the different situation from that in Ref. [34]. In our system at $E=0$, there is no backscattering for the electron incidence and the total AR happens. Actually, this is strongly related to the formation of the Majorana fermion [27].

In the middle F, the superposition of the right-going electron Ψ^e_R and the left-going hole Ψ^h_L forms a new state with the wave

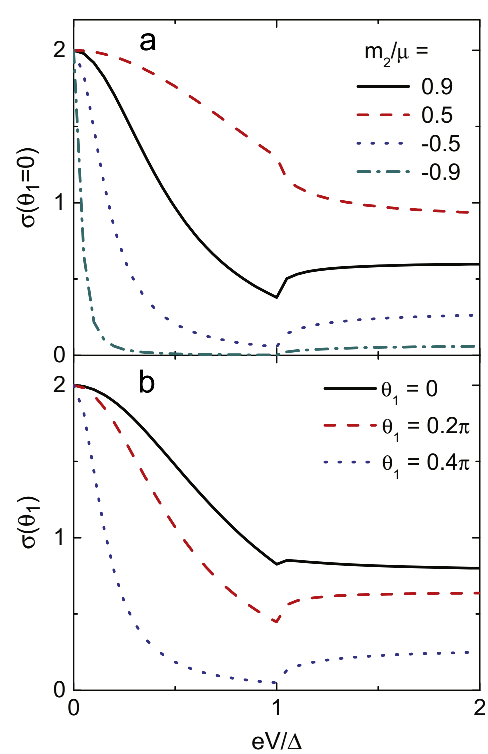

Fig. 2. Plot of the angle-resolved conductance spectra $\sigma(\theta_1)$ at $m_1/\mu=0.9$. (a) $\theta_1=0$: $m_2/\mu=0.9$, 0.5, -0.5 and -0.9. (b) $m_2/\mu=0.6$: $\theta_1=0$, 0.2π and 0.4π.