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Coherent conductance and magnetoresistance in a topological insulator ferromagnet/superconductor/ferromagnet junction

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ABSTRACT

We investigate theoretically the coherent conductance and magnetoresistance in a topological insulator ferromagnet/superconductor/ferromagnet (F/SC/F) junction with perpendicular magnetization. It is shown that there exists a large difference between the coherent conductance of the parallel and antiparallel magnetization configurations, which leads to a large magnetoresistance. The superconductor layer thickness dependence of the magnetoresistance is discussed in terms of the contributions of the local Andreev reflection, electron elastic cotunneling and crossed Andreev reflection to the parallel and antiparallel conductances.

1. Introduction

In the past years, the magnetoresistance in conventional ferromagnet/superconductor/ferromagnet (F/SC/F) junctions have been studied extensively with the aim of designing devices with large magnetoresistance [1–4]. With the invention of graphene these studies extended to the graphene based F/SC/F junctions [5–7]. The graphene based hybrid structures show some different properties in comparison with their conventional metallic counterparts since, the charge carriers in graphene are massless Dirac fermions which obey Dirac's equation instead of usual Schrodinger's equation. Yang et al. have investigated the crossed Andreev reflection and magnetoresistance in graphene based F/SC/F junction [5]. They found that the magnetoresistance in this system can be improved largely in comparison with that in the conventional F/SC/F junction.

Recently, the transport properties of the topological insulator based ferromagnet/superconductor hybrid structures have attracted much attention [8–13]. Like graphene, the electrons on the surface of the three dimensional topological insulator obey the two dimensional Dirac equation. However, there are some differences between topological insulator and graphene. For example, in contrast to graphene, the conductance properties of the topological insulator surface depend sensitively on the direction of magnetization [8]. Recently, the crossed Andreev reflection of a topological insulator F/SC/F junction with in-plane magnetization has been studied in Ref. [14]. It has been found that the electron elastic cotunneling and crossed Andreev reflection depend sensitively on the relative directions of the in-plane magnetizations of the two ferromagnets. The mechanism behind this is that the in-plane magnetization shifts the position of quasiparticle Fermi surface in a direction parallel to the magnetization.

In this paper we investigate the coherent conductance and magnetoresistance of a topological insulator F/SC/F junction with perpendicular magnetization. The perpendicular magnetization m has no effect on the position of the quasiparticle Fermi surface while it causes that the spin of the eigenstate in the ferromagnet region changes from $(k_x, k_y, 0)^t$ direction to the $(k_x, k_y, m)^t$ direction [15]. Such that, in parallel (antiparallel) magnetization configuration the wave functions of the two ferromagnets are the same (different). Thus, the connection of wave functions between two ferromagnets in parallel magnetization configuration is different from that in antiparallel magnetization configuration. We investigate the effect of this on the conductance and magnetoresistance of a topological insulator F/SC/F junction. We find that when the thickness of the superconductor layer is of the order of or less than the superconductor coherence length the topological insulator F/SC/F junction exhibits a large magnetoresistance which oscillates between positive and negative values as a function of superconductor layer thickness. We discuss the superconductor layer thickness dependence of the magnetoresistance in terms of the contributions of the local Andreev Reflection, electron elastic cotunneling and crossed Andreev reflection to the parallel and antiparallel conductances. We also investigate the effects of a gate voltage exerted on the superconductor layer. We find that both the parallel and antiparallel conductances and the magnetoresistance oscillate as the gate voltage changes.

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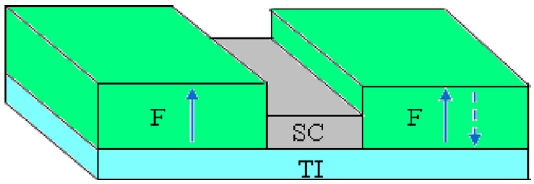

Fig. 1. Schematic illustration of a topological insulator (TI) based F/SC/F junction. The magnetizations in *F* layers are oriented along the *z*-direction.

2. Theoretical model

We consider an F/SC/F junction on the surface of a three dimensional topological insulator in the *x*-*y* plane, as shown in Fig. 1. The ferromagnetism is assumed to be induced in $x<0$ and $x>d$ regions via the proximity effect to a ferromagnetic material, while superconductivity is induced in $0<x<d$ region via the proximity effect to a superconductor.

We assume that the two ferromagnets have the same magnetization described by $\vec{m}=m\hat{z}[\Theta(-x)\pm\Theta(x-d)]$, where the plus and minus signs, respectively, correspond to the parallel and antiparallel magnetization configurations and $\Theta(x)$ is the Heaviside step function. The superconducting pair potential $\Delta(x)$ is assumed to be in the form $\Delta(x)=\Delta_0 e^{i\phi}\Theta(x)\Theta(d-x)$, where Δ_0 and φ are amplitude and phase of the pair potential. The quasiparticles in the topological insulator based F/SC/F junction can be described by the following Dirac–Bogoliubov de Gennes equation [16]

$$\begin{pmatrix} H(v_F\vec{p}+e\vec{A}_{eff}) & \Delta(x) \\ -\Delta^{\blacklozenge}(x) & -H^{*}(-v_F\vec{p}+e\vec{A}_{eff}) \end{pmatrix}\psi(x)e^{ip_y y/\hbar v_F}=E\psi(x)e^{ip_y y/\hbar v_F} \tag{1}$$

where $H=v_F\vec{p}.\vec{\sigma}+e\vec{A}_{eff}.\vec{\sigma}-E_F+V(x)$. The vector potential $e\vec{A}_{eff}$ is proportional to the magnetization $\vec{m}$. Here v_F denotes the Fermi velocity of the quasiparticles in the topological insulator and σ denote the usual Pauli matrices. The potential $V(x)$ is taken as $V(x)=-U_0\Theta(x)\Theta(d-x)$ in the superconductor region.

For an electron with energy E incident on the F/SC/F junction from the left ferromagnet, taking into account the possible processes: (1) local Andreev reflection, (2) normal reflection, (3) direct transmission to the right ferromagnetic layer via elastic cotunneling and (4) formation of a Cooper pair with another electron from right ferromagnetic layer via crossed Andreev reflection; the wave functions in the three regions can be written as

$$\psi_{F1}=\begin{pmatrix}1\\A_1e^{i\theta}\\0\\0\end{pmatrix}e^{ik_1x}+a\begin{pmatrix}0\\0\\1\\-A_1'e^{-i\theta'}\end{pmatrix}e^{-ik_1'x}+b\begin{pmatrix}1\\-A_1e^{-i\theta}\\0\\0\end{pmatrix}e^{-ik_1x},$$

$$\psi_{SC}=c\begin{pmatrix}1\\e^{i\theta_{Se}}\\e^{-i\beta}e^{-i\varphi}\\e^{i\theta_{Se}}e^{-i\beta}e^{-i\varphi}\end{pmatrix}e^{ik_{Se}}+d\begin{pmatrix}1\\-e^{-i\theta_{Se}}\\e^{-i\beta}e^{-i\varphi}\\-e^{-i\theta_{Se}}e^{-i\beta}e^{-i\varphi}\end{pmatrix}e^{-ik_{Se}x}+e\begin{pmatrix}1\\-e^{-i\theta_{Sh}}\\e^{i\beta}e^{-i\varphi}\\-e^{-i\theta_{Sh}}e^{i\beta}e^{-i\varphi}\end{pmatrix}e^{-ik_{Sh}x}+f\begin{pmatrix}1\\e^{i\theta_{Sh}}\\e^{i\beta}e^{-i\varphi}\\e^{i\theta_{Sh}}e^{i\beta}e^{-i\varphi}\end{pmatrix}e^{ik_{Sh}},$$

$$\psi_{F2}=t\begin{pmatrix}1\\A_2e^{i\alpha}\\0\\0\end{pmatrix}e^{ik_2x}+t'\begin{pmatrix}0\\0\\1\\A_2'e^{i\alpha'}\end{pmatrix}e^{ik_2'x} \tag{2}$$

where a and b are the amplitudes of the Andreev and normal reflections in the left ferromagnetic region, respectively, c,d,e and f are the amplitudes of the electron-like and hole-like quasiparticles in the SC region and t and t' are the amplitudes of the electron elastic cotunneling and crossed Andreev reflection processes in the right ferromagnetic region, respectively. Here, we have

$$\begin{aligned}
&A_1(A_1')=\frac{E+(-)E_F-m}{\sqrt{(E+(-)E_F)^2-m^2}},\\
&k_1(k_1')=\sqrt{(E+(-)E_F)^2-m^2}\ \cos\ \theta(\cos\ \theta')/\hbar v_F,\\
&k_2(k_2')=k_1(k_1')\\
&k_{Se(h)}=(E_F+U_0+(-)\sqrt{E^2-\Delta^2})\cos\ \theta_{Se}(\cos\ \theta_{Sh})/\hbar v_F\\
&\beta=\begin{cases}\arccos(E/\Delta_0) & E<\Delta_0\\ -iar\ csh(E/\Delta_0) & E>\Delta_0\end{cases}
\end{aligned} \tag{3}$$

From the conservation of the y-component of the wave vector, which is held due to translational symmetry invariant along y axis, we have $\alpha=\theta,\ \alpha'=\theta'$, and

$$\begin{aligned}
&\theta'=\arcsin\left(\frac{\sqrt{(E+E_F)^2-m^2}}{\sqrt{(E-E_F)^2-m^2}}\sin\ \theta\right),\\
&\theta_{Se(h)}=\arcsin\left(\frac{\sqrt{(E+E_F)^2-m^2}}{(E_F+U_0+(-)\sqrt{E^2-\Delta^2}}\sin\ \theta\right).
\end{aligned} \tag{4}$$

In the right ferromagnetic region, there are two choices, corresponding to parallel and antiparallel magnetization alignments. For parallel alignment $A_2(A_2')=(E+(-)E_F-m)/(\sqrt{(E+(-)E_F)^2-m^2})$ while, for antiparallel alignment $(A_2(A_2')=E+(-)E_F+m)/(\sqrt{(E+(-)E_F)^2-m^2})$.

All of the coefficients in Eq. (2) can be determined by matching the wave functions at the interfaces. Then, the conductance can be calculated. The Blonder–Tinkham–Klapwijk (BTK) approach [17] has been widely used to calculate the conductance of normal metal/superconductor and ferromagnet/superconductor junctions. Bozovic et al. [18] have extended this approach to the coherent tunneling conductance of the conventional F/SC/F junction, which according to it, the conductance of the topological insulator F/SC/F junction with perpendicular magnetization can be expressed as

$$G_P(G_{AP})=G_0\int_{-\pi/2}^{+\pi/2}d\theta\frac{\sqrt{(E+E_F)^2-m^2}}{2|E+E_F|}\left\{1+|a_P(a_{AP})|^2\frac{\cos\ \theta'}{\cos\ \theta}-|b_P(b_{AP})|^2\right\}\cos\ \theta \tag{5}$$

where P and AP indices denote the parallel and antiparallel magnetization configurations, respectively, $G_0=2e^2N(E+E_F)/h$ with the density of state $N(E+E_F)=|E+E_F|W/(\pi\hbar v_F)$ and W is