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Andreev reflection and bound states in topological insulator based planar and step Josephson junctions

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HIGHLIGHTS

- Junction angle dependency of Andreev reflection (AR) and bound states is studied.
- Potential barrier induced spin rotation causes junction angle dependent AR.
- Step and planar normal-superconductor junction shows distinct conductive behavior.
- Dirac cone ellipticity affects Andreev bound state in step Josephson junction.
- Josephson current can be tuned using potential barrier at the junction.

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ABSTRACT

A superconductor-topological insulator-superconductor (S/TI/S) junction having normal region at angle θ is studied theoretically to investigate the junction angle dependency of the Andreev reflection and the formation of the Andreev bound states in the step and planar S/TI/S structures. It is found that the Andreev reflection becomes θ dependent only in the presence of the potential barrier at the TI/S interface. In particular, the step and planar TI/S junction have totally different conductive behavior with bias voltage and potential barrier in the regime of retro and specular Andreev reflection. Interestingly, we find that the elliptical cross section of Dirac cone, an important feature of topological insulator with step surface defect, affects the Fabry-Perot resonance of the Andreev reflection induced Andreev bound states (which become Majorana zero energy states at low chemical potential) in the step S/TI/S structure. Unlike the usual planar S/TI/S structures, we find these ellipticity affected Andreev bound states lead to non-monotonic Josephson super-current in the step S/TI/S structure whose non-monotonicity can be controlled with the use of the potential barrier, which may find applications in nanoelectronics.

1. Introduction

The topological insulator (TI) is a novel quantum material which is an insulator in the bulk but possess gap-less helical edge and surface states in 2D and 3D respectively [1,2]. The presence of time reversal symmetry in topological insulators makes these edge and surface states robust against the presence of non magnetic impurity [3–5]. Due to the high spin orbit coupling, TI possesses strong spin current and can carry this spin current to long lengths even at room temperature [6,7](in case of graphene). These properties makes TI a potential candidate for spintronics devices and quantum computer applications.

Further, recent STM observations show the presence of naturally occurring step defects on the surface of topological insulators [8,9] which has raised interest in the nano step junctions of the topological insulator. The remarkable localization of the surface states of the Dirac electron near the step edge due to absence of backscattering in TI [9,10] and the presence of elliptical cross-sectioned Dirac cone at the surface parallel to the crystal growth axis in TI suppress the conductance of the TI surface with step defect as compared to planar TI surface [11]. This ellipticity of Dirac cone also acts like the scaling factor for the Josephson current which has been studied recently in normal and ferromagnetic step and edge Josephson junctions [12]. These studies reveal that the geometry of the junction considerably affects the transport of the Dirac electron in topological insulator based structures.

Keeping in mind this geometrical aspect of TI nano-structures, in the past decade, a lot of study has been made on the helical Andreev bound states (ABS) and the Josephson effect occurring in

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the topological insulator based Josephson junction. The ABS in Josephson junctions, are the result of Fabry-Perot interference of the electron and hole states [13–15] induced by Andreev reflection (AR) [16,17]. The AR is an electron scattering process where the electron gets converted into a hole when it is incident on the normal-superconductor (NS) interface. But in contrast to the usual metal based Josephson junction, the unusual spin momentum locking present in topological insulators makes these ABS helical and unique in TI based Josephson junctions. Helical ABS leads to fractional [18,19], anomalous Josephson current [20–23] and facilitates Josephson junction to host zero energy Majorana fermion states [15,14,24–29] (a suggested candidates for topological quantum computational applications [30,31]). The helical nature of ABS also causes non trivial superconducting Klein tunneling of copper pair in the TI based Josephson junction in the presence of potential barrier [32,33], integer [21] and even-odd magnetic flux effect [34,35] in the Fraunhofer oscillation of the Josephson current in the presence of magnetic field.

Motivated from the fact that both the geometry of TI nanostructure and non trivial superconducting Klein tunneling in the presence of potential barrier [32,33] in TI based planar Josephson junction affect the electronic transport, we study a general superconductor-topological insulator-superconductor (S/TI/S) junction (as shown in Fig. 1) involving the TI region at an angle in the presence of junction barrier potential. This will enable us to probe the junction angle dependency of the Andreev reflection and Andreev bound states mediated Josephson current in the presence of barrier potential.

Here we show the Andreev reflection (AR) depends on the junction angle (θ) only in the presence of non zero barrier potential at the TI/S interface. Despite the junction angle independency of AR in the absence of barrier potential the conductance across TI/S interface shows variation with θ due to θ dependent ellipticity of the Dirac cone present in TI. This stimulates distinct barrier potential and bias voltage controllable conductive behavior in the step and planar TI/S junction in the regime of specular and retro Andreev reflection. It is further shown, that the Andreev reflection induced Fabry-Perot resonance of the electron and hole states in the step S/TI/S structure depends on ellipticity, which leads to the barrier potential controllable Andreev bound states mediated non-monotonic Josephson current in the step S/TI/S structure. Josephson current for the planar S/TI/S structure has also been found which is monotonic unlike the step S/TI/S junction.

This paper is organized as follow: in Section 2, we introduce the model for the S/TI/S structure. In Section 3, the Andreev reflection and conductive behavior of the step and planar TI/S junction have been described. In Section 4, we calculated the ABS in the step and planar S/TI/S structure and described the effect of the potential barrier and ellipticity on the Josephson current induced by these helical ABS. In Section 5 the results are summarized and concluded.

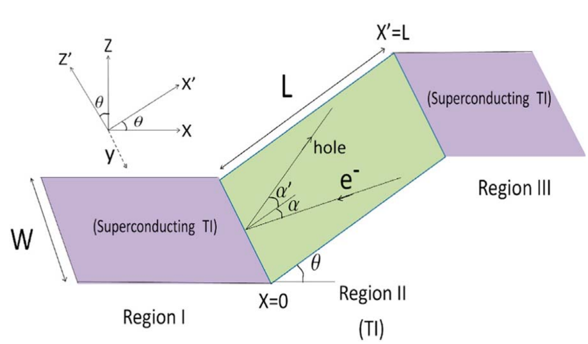

Fig. 1. Schematic of a topological insulator (TI) based superconductor-TI-superconductor (S/TI/S) structure involving TI region at angle θ. The region-I and III is TI surface in proximity with s-wave superconductor and region-II is a normal TI.

2. Model

Fig. 1 shows the geometry of the considered topological insulator based angled S/TI/S junction. It consists of two surfaces in the xy plane (region-I, III) and one surface in the x′y plane at an angle θ with respect to the xy plane, denoted as region-II. In the region-I ($x<0$) and III ($x>L\cos\theta$), the topological insulator surfaces are in contact with the S-wave superconductor having pairing potential, $\Delta=\Delta_o e^{i\phi}$ and $\Delta=\Delta_o e^{-i\phi}$ respectively, where Δ_o is superconducting gap and ϕ is the phase, this is done to induce superconductivity in the region-I, III by the proximity effect. The region-II ($0<x<L\cos\theta$) is a normal topological insulator of length 'L' and width 'W'. Since in the superconductor the electron and hole excitations are coupled through the pairing potential so this S/TI/S hetero-junction is described by the Bogoliubov-de Gennes Hamiltonian given by

$$H_S=\begin{bmatrix} H-\mu+U(x) & \Delta(x)\sigma_o \\ \Delta(x)^*\sigma_o & -T^{\dagger}(H-\mu+U(x))T \end{bmatrix}. \tag{1}$$

For which the quasi-particle (coupled electron and hole excitations) states are defined by the Nambu basis, $\psi=(\psi_\uparrow,\psi_\downarrow,\psi_\downarrow^*,-\psi_\uparrow^*)^T$. Where in Eq. (1), μ is the chemical potential, σ_o is a 2×2 unit matrix, T is the time reversal operator and U is the electrostatic potential defined as $U(x)=-U_0[\Theta(-x)+\Theta(x-L\cos\theta)]$, the role of which is to tune the Fermi wave vector mismatch between the normal topological insulator (region II) and superconducting region I and III, here Θ is the Heaviside step function. The Δ is the superconducting pairing potential given by, $\Delta(x)=\Delta_0[e^{i\phi}\Theta(-x)+e^{-i\phi}\Theta(x-L\cos\theta)]$. The 'H' in Eq. (1) is given by,

$$H=H_1\Theta(-x)+H_2\Theta(x)\Theta(L\cos\theta-x)+H_3\Theta(x-L\cos\theta).$$

Here H_1, H_2 and H_3 are the low energy electron Hamiltonian in the region-I, II and III respectively. We shall consider the topological insulator in which the electron obeys the Rashba like Dirac Hamiltonian [36] at low energy which is given by, $H=\hbar\nu_i\hat{n}.(\vec{\sigma}\times\vec{k})$, where $\hat{n}$ is the unit vector perpendicular to the surface of the topological insulator, $\vec{\sigma}=(\sigma_x,\sigma_y,\sigma_z)$ are Pauli matrices for the spin space, $\vec{k}=k_x,k_y,k_z$ are the wave vector, ν_i is the Fermi velocity and $\hbar$ is the Plank constant. So the Hamiltonian H_1 and H_3 [36] of the region I and III are given by

$$H_1=H_3=\hbar\nu_1(\sigma_x k_y-\sigma_y k_x) \tag{2}$$

with basis $\psi=(\psi_\uparrow,\psi_\downarrow)^T$, where the ν_1 is the Fermi velocity of the electron in region I and III. In the topological insulator like Bi_2Se_3, both the Dirac cone cross section and Fermi velocities differ on the two perpendicular surfaces of 3D topological insulator, the top surface which is perpendicular the crystal growth axes, has the circular cross sectioned Dirac cone and the surface perpendicular to the top surface, has elliptical cross sectioned Dirac cone [11,37]. Further, a general topological insulator surface which is at an angle with the crystal growth axes also has elliptical cross sectioned Dirac cone whose ellipticity depends upon the angle of this surface with the crystal growth axes [37]. As in the region-II of the S/TI/S structure considered by us, the topological insulator surface is at angle θ with the xy plane, so to find the surface states in the region II we used the low energy electron Hamiltonian derived in Ref. [37] for an arbitrary topological insulator surface at an angle with the crystal growth axes. The low energy electron Hamiltonian, H_2