Physics Letters A 382 (2018) 351–356

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Asymmetric d-wave superconducting topological insulator in proximity with a magnetic order

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ARTICLE INFO

Article history:
Received 16 September 2017
Received in revised form 29 November 2017
Accepted 30 November 2017
Available online 5 December 2017
Communicated by L. Ghivelder

Keywords:
Topological insulator
d-wave superconductivity
Andreev reflection
Majorana mode
Tunneling conductance

ABSTRACT

In the framework of the Dirac–Bogoliubov–de Gennes formalism, we investigate the transport properties in the surface of a 3-dimensional topological insulator-based hybrid structure, where the ferromagnetic and superconducting orders are simultaneously induced to the surface states via the proximity effect. The superconductor gap is taken to be spin-singlet d-wave symmetry. The asymmetric role of this gap respect to the electron–hole exchange, in one hand, affects the topological insulator superconducting binding excitations and, on the other hand, gives rise to forming distinct Majorana bound states at the ferromagnet/superconductor interface. We propose a topological insulator N/F/FS junction and proceed to clarify the role of d-wave asymmetry pairing in the resulting subgap and overgap tunneling conductance. The perpendicular component of magnetizations in F and FS regions can be at the parallel and antiparallel configurations leading to capture the experimentally important magnetoresistance (MR) of junction. It is found that the zero-bias conductance is strongly sensitive to the magnitude of magnetization in FS region m_{zfs} and orbital rotated angle α of superconductor gap. The negative MR only occurs in zero orbital rotated angle. This result can pave the way to distinguish the unconventional superconducting state in the relating topological insulator hybrid structures.

1. Introduction

The surface states of a three-dimensional topological insulator (3DTI) is considered an intriguing aspect of topological phase of matter. The charge carriers, which are protected by time-reversal symmetry obey from the spin-polarized massless Dirac fermions [1–3]. Unlike exotic two-dimensional monolayer atomic structures as graphene or molybdenum disulfide, there is no spin and valley degeneracies in single Dirac cone of 3DTI. Among the peculiar properties of topologically conserved surface states one can be addressed: i) theoretically proposed by Fu and Kane [4], and experimentally observed [5,6] p-wave-like superconducting correlations emerged via proximity coupling 3DTI to a conventional s-type superconductor ii) the emergence of chiral Majorana mode [7] at the ferromagnet/superconductor (F/S) interface, which is of experimentally importance to detect the Majorana fermions [8,9]. However, chiral Majorana mode, which corresponds to the zero-energy bound state has a significant impact on the low-energy electron–hole excitations, leading to modifying Andreev reflection (AR) at the F/S interface [10] and thermal transport [11,12]. On the other hand, anisotropic d-wave asymmetry pairing due to including nodal points in its superconducting gap can give rise to potentially forming the zero-energy Andreev bound state and, of course, zero-bias conductance [13,14]. Actually, angular-resolved AR process and resulting energy bound states at the F/S interface can be influenced by the orbital rotation angle $0 \leq \alpha \leq \pi/4$ of d-wave pair potential. However, Bi-based cuprate Bi_{2212} is found to be a candidate for anisotropic spin-singlet d-wave superconducting gap [15–19].

Very recently, the coexistence of proximity-induced a conventional superconducting pair potential and a ferromagnetic order at the same time in the surface of 3DTI has been theoretically investigated [20–22]. The superconducting topological insulator quasiparticle excitations are found to present a new renormalized effective gap by means of a magnetic order. The authors have used spin-singlet s-wave order parameter. Due to the spin symmetry of cooper pair, it makes the components to be even in momentum, when the spatial coordinates of two electrons are exchanged. Hence, the exchange of time coordinates has to result in even in frequency. In singlet d-wave pairing, the asymmetric pair potential, which is provided by the rotation angle α can be odd in momentum. Therefore, it may be odd under the exchange of

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https://doi.org/10.1016/j.physleta.2017.11.035
0375-9601/

time coordinates [23,24]. Specifically, for maximum orbital rotation angle $\alpha = \pi/4$, the pair potential changes its sign under inversion of angle of incidence $\Delta_d(\pi - \theta_s) = -\Delta_d(\theta_s)$. This causes to create the nodal points in gap. Regarding these aspects, in this paper, we proceed to demonstrate the ferromagnetic order contribution to the asymmetric superconducting effective gap in 3DTI. In conventional superconductor-ferromagnet hybrid (without topological insulator), the interplay between exchange field $\mathbf{M}$ posed by a magnetic order and superconducting gap gives rise to strongly limiting the magnitude of $|\mathbf{M}|$, so-called Clogston–Chandrasekhar limitation [25,26]. While, in 3DTI similar hybrid systems, the out-of-plan component of magnetic order m_z opens a gap at Dirac point (no inducing any finite center of mass momentum to the Cooper pair), and odd-frequency triplet component of spin-singlet pair potential creates a gap at Fermi level. The Fermi level is tuned by chemical potential μ_{fs}, that is much larger than superconducting gap. Hence, as an important point, there is no limitation for magnitude of magnetization, and it can take a value up to chemical potential $m_{zfs} \leq \mu_{FS}$ in 3DTI hybrid structures. Very recently, spin-polarized scanning tunneling spectroscopy of ultrathin $FeTe_{1-x}Se_x$ ($x = 0, 0.5$) films on bulk topological insulators has been experimentally presented [27]. The authors indicate that the superconducting gap spatially coexists with bi-collinear antiferromagnetic order. In Ref. [28], simultaneous manifestations of superconductivity and weak ferromagnetism has been reported in the case of applying the disorder at the interfaces of twisting bicrystals of 3DTI $Bi_{1-x}Sb_x$ ($0.07 < x < 0.22$). Particularly, EuS has been experimentally deposited on top of the topological insulator Bi_2Se_3, see Ref. [29], and ferromagnetic order induction to the 3DTI estimated to be around 60–400 meV/nm^2 per applied Tesla.

Regarding the inversion symmetry breaking at the normal/superconductor interface, the above mentioned superconducting gap may significantly affect the electron–hole conversion, featuring AR process at the interface. This can obviously provide strong changes in charge and spin-polarized transport of ferromagnet/ferromagnetic-superconductor (F/FS) junction. However, the search for transport properties of different hybrid structures including Majorana fermions has led to publish impressive number of guiding theoretical studies for experimental measurements [7,30–35]. Particularly, as an interesting feature of topological insulator F/FS interface, we pay attention to the formation of Majorana mode energy with dependency on the induced magnetization. We present, in section 2, the explicit signature of magnetic order in low-energy effective 3DTI d-wave superconductor Hamiltonian. The electron(hole) quasiparticle dispersion energy is analytically calculated, which seems to exhibit qualitatively distinct behavior in hole excitations ($|k_{fs}| < K_F$) by varying the magnitudes of magnetization and orbital rotated angle. By considering the magnetization is ever less than chemical potential in FS region, the superconducting wavevector and corresponding eigenstates are derived analytically. Section 3 is devoted to unveil the above key point of FS energy excitation, Majorana mode energy, Andreev process and resulting tunneling conductance and respective discussions. In the last section, the main characteristics of proposed structure are summarized.

2. Theoretical formalism

2.1. 3DTI superconducting effective gap

We employ the relativistic generalization of Bogolioubov–de Gennes approach to obtain the electron–hole quasiparticle excitations in the surface state of the 3DTI. These excitations are influenced by magnetic order from a ferromagnet with magnetization $\mathbf{M}$ on top of the surface of topological insulator. This effect is considered by the perpendicular component of magnetization (m_{zfs}) contribution to the Dirac–Bogoliubov–de Gennes (DBdG) Hamiltonian. For finite magnetization, the odd-frequently triplet components, which occur in topological insulator with proximity in a singlet pairing symmetry can become dominant, resulting in a noticeable superconductor subgap structure with emerging low-energy peaks (see, for example Ref. [20–22]). In Nambu (particle-hole) and spin space, with basis $\psi_{FS}^{e(h)} = \left[\psi_\uparrow(k), \psi_\downarrow(k), \psi_\uparrow^\dagger(-k), \psi_\downarrow^\dagger(-k)\right]^T$, the interplay between ferromagnetic and d-wave symmetry superconductor orders in the surface state of the 3DTI is described by the equation

$$\begin{pmatrix} \hat{h}_F^{TI}(k) & \Delta_d(k) \\ -\Delta_d^*(-k) & -\hat{h}_F^{*TI}(-k) \end{pmatrix} \psi_{FS}^{e(h)} = \varepsilon_{FS}^{e(h)} \psi_{FS}^{e(h)}, \tag{1}$$

where $\hat{h}_F^{TI}(k)$ denotes the two-dimensional Dirac Hamiltonian of the 3DTI under the influence of a magnetization $\mathbf{M}$

$$\hat{h}_F^{TI}(k) = \hbar v_F(\hat{\boldsymbol{\sigma}} \cdot \mathbf{k}) - \mu_{FS}\hat{\sigma}_0 + \mathbf{M} \cdot \hat{\boldsymbol{\sigma}}.$$

Here, v_F indicates the surface Fermi velocity, and μ_{FS} is the chemical potential and the ferromagnetic contribution corresponds to an exchange field $\mathbf{M} \equiv (m_x, m_y, m_z)$. Pauli matrices $\hat{\sigma}_0$ and $\hat{\boldsymbol{\sigma}}$ act on spin space. It is worth to point out that the Fermi energy of Bi-based 3DTI can be estimated as $\mu_{FS} \geq 50$ meV. A comparable magnetization can be obtained by proximity from a ferromagnetic insulator. Recently, EuS was experimentally deposited on top of the topological insulator Bi_2Se_3 [29], and ferromagnetic order induction to the 3DTI estimated to be around 60–400 meV/nm^2 per applied Tesla. $\Delta_d(k)$ is superconducting order parameter, which depends on both the orbital and spin-symmetry of the Cooper pair. The gap matrix for spin-singlet d-wave asymmetry can be given as

$$\Delta_d^{\pm}(k) = \Delta_0 i\hat{\sigma}_y \cos(2\theta_{fs} \mp 2\alpha)e^{i\varphi}, \tag{2}$$

where Δ_0 is the uniform amplitude of the superconducting gap, and φ is the phase of superconducting order parameter. The $+$ $(-)$ sign is denoted for the case of quasi-electron (quasi-hole), θ_{fs} is the angle of incidence in superconductor region, and α indicates orbital orientation angular. By diagonalizing the Eq. (1), we arrive at an energy–momentum quartic equation. We suppose the component of magnetization vector along x and y-directions to be zero. In this work, we are interesting to induce perpendicular to the surface component of magnetization at the two parallel and antiparallel configurations respective to a ferromagnetic topological insulator, which will be considered in a F/FS junction in the next section.

The dispersion relation resulted from Eq. (1) for electron–hole excitations is found to be of the form:

$$\varepsilon_{FS}^{e(h)} = \zeta\sqrt{\left(-\tau\mu_{FS} + \sqrt{m_{zfs}^2 + v_F^2\left|k_{fs}\right|^2 + \left|\Delta_d^{+(-)}\right|^2(\frac{m_{zfs}}{\mu_{FS}})^2}\right)^2 + \left|\Delta_d^{+(-)}\right|^2\left(1 - (\frac{m_{zfs}}{\mu_{FS}})^2\right)}, \tag{3}$$

where the parameter $\zeta = \pm$ denotes the electron-like and hole-like excitations, while $\tau = \pm$ distinguishes the conduction and valence bands. Of course, equation (3) is clearly reduced to the standard eigenvalues for superconductor topological insulator in the absence of magnetic order $m_{zfs} = 0$ (see, Ref. [30]). The above energy excitation relation is enough complicated. As regards, it is deduced that the effective superconductor subgap is renormalized by magnetization with a factor $\eta = \sqrt{1 - (m_{zfs}/\mu_{FS})^2}$. Indeed,