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Orientation-dependent conductance in 2DEG/spin-triplet superconductor junctions with Rashba spin–orbit coupling

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ABSTRACT

We study the conductance of two-dimensional electron gas/spin-triplet superconductor junctions in the presence of Rashba spin–orbit coupling. The conductance shows anisotropic dependence on the orientation of the **d**-vector in the superconductor and is simultaneously symmetric about the vector reversal. The properties are distinct from those for ferromagnet/spin-triplet superconductor or/and two-dimensional electron gas/spin-singlet superconductor junctions. The effects of the strength of the spin–orbit coupling and the height of the interfacial barrier are also investigated.

1. Introduction

The layered perovskite oxide Sr_2RuO_4 is believed to be a rare example of spin-triplet superconductor (TS) [1,2]. Its Cooper pair wave function possesses an antisymmetric spatial part and a symmetric spin part which can be described with the three-component complex **d**-vector [3,4]. For Sr_2RuO_4 with a tetragonal crystal, there are various types of allowed states, some of which are unitary with $\mathbf{d}\times\mathbf{d}^*=0$. The direction of the **d**-vector for a unitary state is perpendicular to the plane in which the electrons are equal spin paired. Due to the presence of the **d**-vector, the physics in structures including TS is very rich [5–10]. One important point is the presence of the surface Andreev bound states [11,12] which have been observed in the experiment of tunneling spectroscopy of Sr_2RuO_4 [13]. Recently, the origin of the states is understood from the view point of topological superconductivity [14–16].

The studies on the transport properties in ferromagnet (F)/TS heterostructures have also been an important aspect in condensed matter physics. It is found in [17] that the conductance of F/TS junction with $\mathbf{d}\parallel\hat{\mathbf{z}}$ strongly depends on the direction of the magnetization and the paring symmetry of TS. The information about the direction of the **d**-vector is obtained. Spin current and $0-\pi$ transition in F/TS and TS/F/TS structures are also studied by Brydon et al. [18–20]. In these structures, the physical mechanism is the interplay between the magnetization and the **d**-vector.

In recent years, the heterostructures including two-dimensional electron gas with Rashba spin–orbit coupling (R2DEG) and superconductor (S) have become a new field to study superconductivity and its future applications [21–24]. Besides F, R2DEG is another spin-split electron system which can be realized experimentally in heterostructures such as InAs and HgTe [25–27]. However, different from F, R2DEG keeps the time-reversal symmetry. The electrons in R2DEG have momentum-locked spins due to the Rashba spin–orbit coupling (RSOC). The control of the strength of RSOC with an electronic field has also been reported [28]. Many investigations have devoted themselves to the effects of RSOC on the transport properties in R2DEG/S junctions. The authors in [29] calculate the conductance of R2DEG/s-wave S junction. The RSOC shows different influences on the conductance depending on the interfacial barrier height of the junction. The specular Andreev reflection [30] in R2DEG/d-wave S junction is revealed by Lv et al. [31] as the interaction of RSOC and superconductivity. The transport properties in R2DEG/s-wave S/R2DEG and F/R2DEG/d-wave double junctions are also investigated in [32,33]. Although important results have been achieved in the above investigations, the involved superconductor is limited to the spin-singlet case. How RSOC interacts with the spin-triplet superconductivity is another question to be answered.

Our motivation in this paper is to clarify the conductance properties in R2DEG/TS junction which is the simplest structure containing both RSOC and spin-triplet superconductivity. The TS is assumed in a unitary state which is considered as a candidate for

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Sr_2RuO_4. We find that the conductance is anisotropic when changing the orientation of the **d**-vector and simultaneously symmetric about the vector reversal owing to the existence of RSOC. The results are distinct from those in F/TS junctions where the conductance is a cosine function of the relative angle between the magnetization and the **d**-vector [34]. We discuss in detail the zero-bias conductance (ZBC) as a function of the polar angle and the azimuthal angle of **d**-vector. The effects of the RSOC strength and the interfacial barrier on the conductance are also investigated.

2. Formalism

We consider a R2DEG/TS junction as shown in Fig. 1. The interface barrier, located at $x=0$ and along the y-axis, is modeled by a delta function $U(x) = U\delta(x)$. In this work, we deal with a TS with the **d**-vector given by

$$\mathbf{d}(\mathbf{k}) = \Delta f(\mathbf{k})\hat{\mathbf{n}}(\theta_n, \phi_n), \tag{1}$$

where the unit vector $\hat{\mathbf{n}}(\theta_n, \phi_n)$ specifies the direction of the **d**-vector with the polar angle θ_n and the azimuthal angle ϕ_n. The orbital part is taken as $f(\mathbf{k}) = (k_x + ik_y)$. This chiral p-wave paring state is considered as a strong candidate for Sr_2RuO_4 [35,36]. The gap matrix of the TS can be given by

$$\hat{\Delta}(\mathbf{k}) = (\mathbf{d}(\mathbf{k})\cdot\hat{\sigma})i\hat{\sigma}_2. \tag{2}$$

The effective Hamiltonian $\check{H}$ of the junction for the Bogoliubov–de Gennes (BdG) equation is expressed as

$$\check{H} = \begin{pmatrix} \hat{H}(\mathbf{k}) & \hat{\Delta}(\mathbf{k})\Theta(x) \\ -\hat{\Delta}^*(-\mathbf{k})\Theta(x) & -\hat{H}^*(-\mathbf{k}) \end{pmatrix}, \tag{3}$$

where $\hat{H}(\mathbf{k}) = \xi_k + U(x) + \hat{H}_R\Theta(-x)$ with $\xi_k = \hbar^2k^2/2m - E_F$. The RSOC term $\hat{H}_R = \alpha(\hat{\sigma}\times\mathbf{k})\cdot\hat{e}_z$ with α being the coupling strength.

Through solving the BdG equation, the energy of the electrons in R2DEG can be given by $E_{1(2)} = \xi_k + (-)\alpha k$. The corresponding wave number is $k_{1(2)} = -(+)m\alpha/\hbar^2 + \sqrt{(m\alpha/\hbar^2)^2 + k_F^2}$. Let us consider an electron with the wave number k_1 is injected from R2DEG. Upon defining $\check{e}_1 = (1, 0, 0, 0)^T$, $\check{e}_2 = (0, 1, 0, 0)^T$, $\check{e}_3 = (0, 0, 1, 0)^T$ and $\check{e}_4 = (0, 0, 0, 1)^T$, the wave function in R2DEG can be expressed as

$$\begin{aligned}\Psi_1 = \frac{1}{\sqrt{2}}\Bigg[&\left(\frac{ik_{1-}}{k_1}e^{ik_{1x}x} - b_{11}\frac{ik_{1+}}{k_1}e^{-ik_{1x}x} + b_{12}\frac{ik_{2+}}{k_2}e^{-ik_{2x}x}\right)\check{e}_1 \\ &+ (e^{ik_{1x}x} + b_{11}e^{-ik_{1x}x} + b_{12}e^{-ik_{2x}x})\check{e}_2 + \left(a_{11}\frac{ik_{1+}}{k_1}e^{ik_{1x}x}\right. \\ &\left.-a_{12}\frac{ik_{2+}}{k_2}e^{ik_{2x}x}\right)\check{e}_3 + (a_{11}e^{ik_{1x}x} + a_{12}e^{ik_{2x}x})\check{e}_4\Bigg],\end{aligned} \tag{4}$$

where $k_{1(2)\pm} = k_{1(2)x} \pm ik_y$ with $k_{1(2)x} = k_{1(2)}\cos\theta_{1(2)}$. $\theta_{1(2)}$ represents the incidence angle or the reflection angle of electrons and holes with wave number $k_{1(2)}$. The coefficients $b_{11}(b_{12})$ and $a_{11}(a_{12})$ represent the normal reflection and Andreev reflection to $E_{1(2)}$ band, respectively.

The wave function in TS is given by

$$\begin{aligned}\Psi_{TS} = &(c_{11}u\chi_1e^{ik_xx} - c_{12}u\chi_2^*e^{ik_xx} - d_{11}v\chi_1g^*e^{-ik_xx} + d_{12}vg^*\chi_2^*e^{-ik_xx})\check{e}_1 \\ &+ (c_{11}u\chi_2e^{ik_xx} + c_{12}u\chi_1e^{ik_xx} - d_{11}v\chi_2g^*e^{-ik_xx} - d_{12}vg^*\chi_1e^{-ik_xx})\check{e}_2 \\ &+ (c_{12}vg^*e^{ik_xx} + d_{12}ue^{-ik_xx})\check{e}_3 + (c_{11}vg^*e^{ik_xx} + d_{11}ue^{-ik_xx})\check{e}_4,\end{aligned} \tag{5}$$

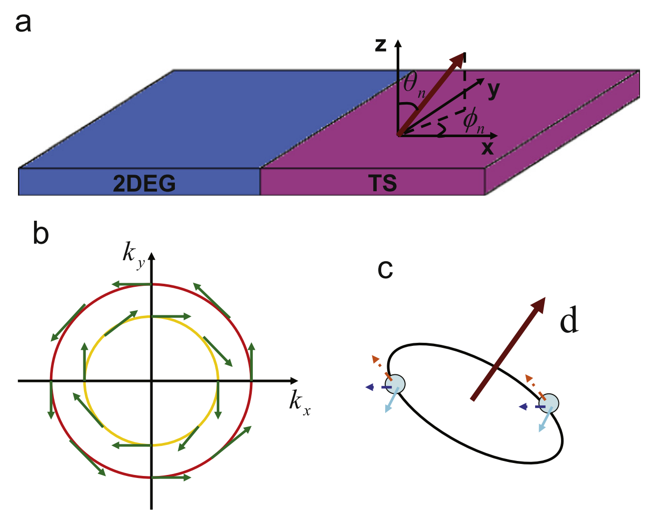

Fig. 1. (a) Schematic illustration of R2DEG/TS junctions. The current is flowing along the x-axis. The direction of the **d**-vector in TS is specified by the polar angle θ_n and the azimuthal angle ϕ_n. (b) The spin structure of electrons in R2DEG. The green arrows indicate the spin quantization axis of the E_1 band (golden circle) and the E_2 band (red circle). (c) The direction of the **d**-vector for the unitary states is perpendicular to the plane in which the electrons are equal spin paired. The small arrows depict the spins of electrons in a pair. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

where the coherent factors $u(v) = \sqrt{E + (-)\sqrt{E^2 - \Delta^2}/2E}$, $\chi_1 = \cos\theta_n$, $\chi_2 = \sin\theta_n e^{i\phi_n}$, $g = e^{i\theta}$ and $k_x = k_F\cos\theta$ with θ being the transition angle of the quasiparticles. The conservation of k_y (due to translation invariance) can give the relations between $\theta_{1(2)}$ and θ. c_{11}, c_{12} and d_{11}, d_{12} are the transition coefficients of the electron-like quasiparticles and the hole-like quasiparticles, respectively.

All the coefficients in the wave functions Ψ_1 and Ψ_{TS} can be determined under the boundary conditions:

$$\begin{aligned}&\Psi_{TS}(x)|_{x=0^+} = \Psi_1(x)|_{x=0^-}, \\ &\check{v}_x\Psi_{TS}|_{x=0^+} - \check{v}_x\Psi_1(x)|_{x=0^-} = \frac{\hbar}{im}\frac{2mU}{\hbar^2}\check{\tau}_3\Psi(0),\end{aligned} \tag{6}$$

where $\check{v}_x$ is the velocity operator in the x direction and $\check{\tau} = \sigma_x \otimes \hat{1}$.

For the electron injection with the wave number k_2, the wave function in R2DEG is designated by Ψ_2, in which we use $b_{21}(b_{22})$ and $a_{21}(a_{22})$ to represent the normal reflection and the Andreev reflection to $E_{2(1)}$, respectively. The coefficients can be solved through replacing Ψ_1 with Ψ_2 in Eq. (6).

The normalized tunneling conductance can be written as

$$\begin{aligned}G = &\int_{-\theta_c}^{\theta_c}\left(1 + |a_{11}|^2 + |a_{12}|^2\frac{\cos\theta_2}{\cos\theta_1} - |b_{11}|^2 - |b_{12}|\frac{\cos\theta_2}{\cos\theta_1}\right)\cos\theta d\theta \\ &+ \int_{-\pi/2}^{\pi/2}\left(1 + |a_{21}|^2 + |a_{22}|^2\frac{\cos\theta_1}{\cos\theta_2} - |b_{21}|^2 - |b_{22}|^2\frac{\cos\theta_1}{\cos\theta_2}\right)\cos\theta d\theta,\end{aligned} \tag{7}$$

with the critical angle $\theta_c = \arcsin(k_1/k_F)$. The conductance G is a function of the polar angle θ_n, the azimuthal angle ϕ_n and the normalized parameters $\lambda = 2m\alpha/\hbar^2k_F$ and $Z = 2mU/\hbar^2k_F$.

3. Results and discussion

For our junction, we find that the conductance is invariant about the **d**-vector reversal, i.e. $G(\theta_n, \phi_n) = G(\pi - \theta_n, \pi + \phi_n)$, which can be indicated by the equation system satisfied by coefficients (see Appendix). This type of symmetry of the conductance can also be found in F/R2DEG junctions where the conductance is invariant upon the magnetization reversal [37]. As a result, in our numerical results, we