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Effects of Rashba spin–orbit coupling interface on the orientation-dependent conductance in ferromagnet/spin-triplet superconductor junction

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ABSTRACT

We study theoretically the tunneling charge conductance in ferromagnet/spin-triplet superconductor junction with the spin–orbit coupling interface. It is shown the symmetry of the conductance about the relative angle between the magnetization in ferromagnet and the **d**-vector in superconductor is broken due to the presence of the interfacial Rashba spin–orbit coupling. We present the conductance for various cases of the angle. For each angle, the spin-active mechanism provided by the interface is investigated. The interface effects for different spin polarization in the ferromagnet is also considered.

1. Introduction

Tunneling spectroscopy is a direct and effective probe of the interplay between ferromagnetism and superconductivity in ferromagnet (F)/superconductor (S) heterostructures [1–7]. The low-energy tunneling conductance of the structures is governed by the Andreev reflection (AR) process [8], in which an electron injected from F is reflected back as a hole while a cooper pair propagates inside S. For F/s-wave S junction, the hole reflected into F occupies the band with the spin opposite to that of the electron. As a result, the spin polarization in F will suppress the AR and hence the subgap conductance. If F is in the half-metallic state with full spin polarization, the AR process is forbidden owing to the absence of one of the spin bands; the subgap conductance vanishes at zero temperature. For F/spin-triplet S (TS) junction, the interplay between ferromagnetism and superconductivity become more complex and interesting [9,10]. In this case, the tunneling conductance depends not only on the degree of the spin polarization but also sensitively on the relative angle between the magnetic moment in F and the **d**-vector in TS. This will give some symmetries of the spectra about the orientation of the magnetic moment when $\mathbf{d} \parallel c$-axis [11].

However, if the interface of F/S junctions can provide some type of spin-flip mechanism, the above effect of the spin polarization on the conductance will be changed. For example, the ferromagnetic interface between the half-metallic F and s-wave S will bring V-shape conductance within the energy gap at zero temperature. In addition to the magnetic interface, the spin–orbit coupling is another mechanism for the spin-active interface [12–17], which maintains the time-reversal symmetry. In Ref. [14], the author studies the conductance spectra in F/spin-singlet S junction in the presence of the interfacial Rashba spin–orbit coupling (RSOC). The equal-spin AR is generated in the junction and results in novel conductance properties. The effects of the interfacial RSOC in normal metal/p-wave S junction are also investigated in Ref. [17]. However, how the RSOC affects the charge transport in F/TS junction is another question to be answered.

Our motivation in this paper is to clarify the effects of the RSOC interface on the orientation-dependent conductance in F/TS junction with $\mathbf{d} \parallel c$-axis. We find the RSOC interface can provide spin-flip, spin-mixing or spin-filtering mechanism depending on the orientation of the magnetic moment. The symmetry of the spectra about the polar angle in F/TS junction without RSOC is broken here. As a result, we calculate the conductance for various values of the angle and they are compared with that in the same junction without RSOC. For each angle, we analyze the spin-active mechanism provided by the RSOC interface employing the interfacial potential matrix expressed in the coordinate of the spin space

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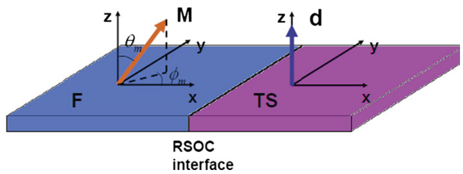

Fig. 1. Schematic illustration of ferromagnet (F)/spin-triplet superconductor (TS) junction with the Rashba spin–orbit coupling (RSOC) interface. The **d**-vector in TS is assumed to be along the z-axis. The direction of the magnetization in F is denoted by the polar angle θ_m and the azimuthal angle ϕ_m. The current in the junction is flowing along the x-axis.

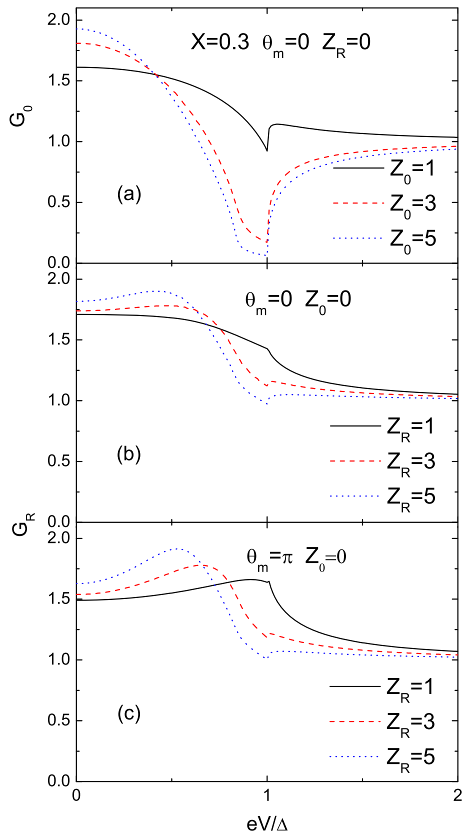

Fig. 2. The conductance spectra for $\theta_m = 0$ and π at $X = 0.3$. (a): G_0 with $Z_0 = 1, 3$ and 5. (b)–(c): G_R with $Z_R = 1, 3$ and 5.

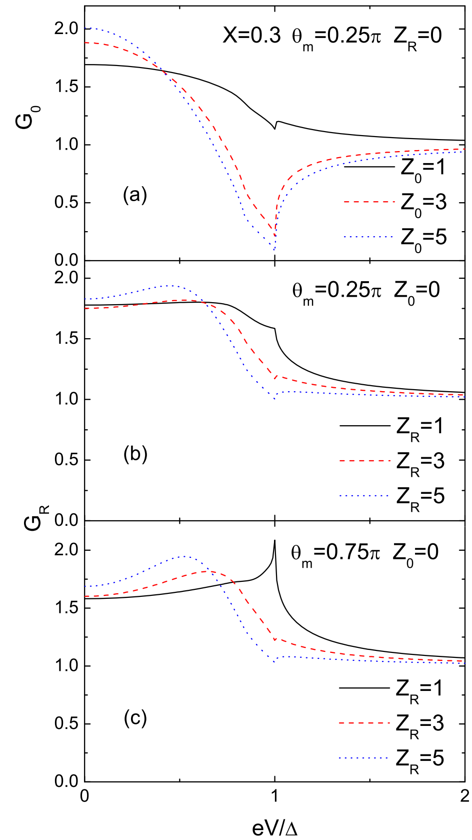

Fig. 3. The conductance spectra for $\theta_m = 0.25\pi$ and 0.75π at $X = 0.3$. Z_0 and Z_R are taken the same as that in Fig. 2.

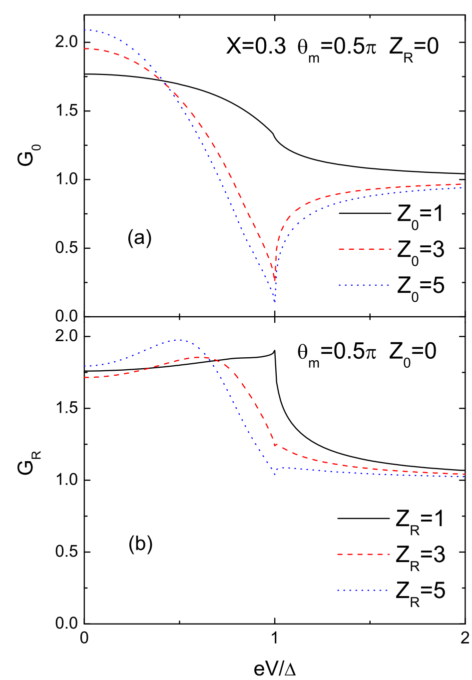

Fig. 4. The conductance spectra for $\theta_m = 0.5\pi$ at $X = 0.3$. Z_0 and Z_R are taken the same as that in Fig. 2.

in F. The influence of the spin polarization on the conductance in the presence of the RSOC is also considered.

2. Model and formalism

We consider a two-dimensional F/TS junction with semi-infinite electrodes in the clean limit as shown in Fig. 1. The direction of the magnetization $\mathbf{M} = M\mathbf{m}(\theta_m, \phi_m)$ in F is specified by the unit vector $\mathbf{m}(\theta_m, \phi_m)$ with the polar angle θ_m and the azimuthal angle ϕ_m (see Fig. 1). The interface barrier, located at $x = 0$ and along y axis, is modeled by a delta function $\hat{U}(\mathbf{k})\delta(x) = [U_0\hat{\mathbf{1}} + U_R\mathbf{e}_x \cdot (\hat{\sigma} \times \mathbf{k})]\delta(x)$ [16,17] with $\mathbf{e}_x$ the unit vector along the interface normal, where U_0 and U_R denote the strength of the spin-independent potential and the RSOC potential, respectively and $\hat{\sigma}$ are the Pauli matrices.

The gap matrix of the TS is generally given by

$$\hat{\Delta}(\mathbf{k}) = \big(\mathbf{d}(\mathbf{k}) \cdot \hat{\sigma}\big) i\hat{\sigma}_2, \tag{1}$$

where $\mathbf{d}(\mathbf{k})$ is the **d**-vector in the TS. In this work, we deal with a TS with the **d**-vector given by

$$\mathbf{d}(\mathbf{k}) = \Delta f(\mathbf{k})\hat{\mathbf{z}}, \tag{2}$$

with $f(\mathbf{k}) = (k_x + ik_y)$. This chiral p-wave paring state is considered as a strong candidate for the ground state of Sr_2RuO_4 [1,18].