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Charge transport in normal metal/s + p-wave superconductor junctions with Rashba type spin–orbit coupling

Y. Sawa[a,b,*], T. Yokoyama[a,b], Y. Tanaka[a,b], C. Iniotakis[c], N. Hayashi[c], M. Sigrist[c]

[a] *Department of Applied Physics, Nagoya University, Nagoya 464-8603, Japan*
[b] *CREST, Japan Science and Technology Corporation (JST) Nagoya 464-8603, Japan*
[c] *Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland*

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Abstract

We study charge transport in normal metal/s + p-wave superconductor (S + P) junctions with Rashba type spin–orbit coupling (RSOC). Applying the Blonder–Tinkham–Klapwijk theory, we calculate a bias (V) dependence of tunneling conductance, changing the strength of RSOC and Δ_p/Δ_s. Here $\Delta_{s(p)}$ is the absolute value of pair potential of S(P) component. For $\Delta_p < \Delta_s$, a gap structure appears ranging from $eV = 0$ to $eV = |\Delta_s - \Delta_p|$, and a coherent peak appears at $eV = |\Delta_s + \Delta_p|$. For $\Delta_p > \Delta_s$, a zero bias conductance peak (ZBCP) is formed, a dip structure appears at $|\Delta_s - \Delta_p|$, and a weak coherent peak appears at $eV = |\Delta_s + \Delta_p|$. For large RSOC, a weak peak appears at $eV = |\Delta_s - \Delta_p|$ because of RSOC. The bias dependence of conductance depends on the ratio Δ_p/Δ_s and changes qualitatively at $\Delta_p/\Delta_s = 1$. For $\Delta_p > \Delta_s$, $|\Delta_s - \Delta_p|$ can be estimated from a width of ZBCP. For $\Delta_s > \Delta_p$, Δ_s and Δ_p can be estimated from the gap structure and the coherent peak. Thus, the magnitude of gaps can be determined from the experiment of scanning tunneling spectroscopy.

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1. Introduction

Tunneling spectroscopy is one of the most powerful methods for studying superconducting state, which reflects the magnitude and pairing symmetry of the pair potential. Theoretically, tunneling spectroscopy can be modeled as normal metal (N)/superconductor (SC) junction.

In N/SC junctions, Andreev reflection (AR) [1] plays an important role in charge transport. This is a process that an electron directed to SC is reflected back to N as a hole. Blonder, Tinkham and Klapwijk (BTK) revealed a charge transport in N/s-wave SC junctions including the effect of AR [2]. The resulting conductance reflects the magnitude of the gap. The BTK theory is generalized in N/SC junctions with spin–orbit coupling [3,4], and also in N/unconventional superconductor (US) junctions where zero energy state [5] (ZES) is induced near the interface because pair potential changes its sign with the direction of wave number vector. ZES affects the charge transport in N/US hybrid junctions strongly, resulting in the emergence of zero bias conductance peak (ZBCP). Therefore, tunneling spectroscopy is an effective way in studying new types of SCs.

In heavy fermion systems without inversion symmetry like $CePt_3Si$ [6], Rashba type spin–orbit coupling [7] (RSOC) is induced because of the broken inversion symmetry. Then anomalous superconductivity can be realized because of coexistence of superconductivity and RSOC. In such situations, different parities; spin–singlet pairing and spin–triplet pairing can be mixed in superconducting state. From a lot of experimental and theoretical studies, it is found that one of the most possible candidates of superconducting state is s + p-wave pairing [8–15]. However, until now, the magnitude of the gaps of the pairings has not been determined.

*Corresponding author. Department of Applied Physics, Nagoya University, Nagoya 464-8603, Japan.
E-mail address: h062211m@mbox.nagoya-u.ac.jp (Y. Sawa).

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In the present paper, we calculate a bias (V) dependence of tunneling conductance in N/s + p-wave SC (S + P) junctions with RSOC. For $\Delta_p < \Delta_s$, a gap structure appears ranging from $eV = 0$ to $eV = |\Delta_s - \Delta_p|$, and a coherent peak appears at $eV = |\Delta_s + \Delta_p|$. For $\Delta_p > \Delta_s$, ZBCP is formed, a dip structure appears at $|\Delta_s - \Delta_p|$, and a weak coherent peak appears at $eV = |\Delta_s + \Delta_p|$. Here, $\Delta_{s(p)}$ is the absolute value of pair potential of S(P) component. For large RSOC, a weak coherent peak appears at $eV = |\Delta_s - \Delta_p|$ because of RSOC. The bias dependence of conductance changes drastically at $\Delta_p/\Delta_s = 1$. For $\Delta_p > \Delta_s$, $|\Delta_s - \Delta_p|$ can be estimated from a width of ZBCP. For $\Delta_s > \Delta_p$, Δ_s and Δ_p can be estimated from the gap structure and the coherent peak. Thus, the magnitude of gaps can be determined from the experiment of scanning tunneling spectroscopy.

2. Formulation

We use a model of two-dimensional N/S + P junction with RSOC. The N/S + P interface located at $x = 0$ has an insulating barrier described by the delta function $U(x) = H\delta(x)$. Hamiltonian in electron–hole–spin space is expressed as

$$\check{H} = \begin{pmatrix} \hat{H}(\mathbf{k}) & \hat{\Delta}^{\dagger}(\mathbf{k}) \\ -\hat{\Delta}^{*}(-\mathbf{k}) & -\hat{H}^{*}(-\mathbf{k}) \end{pmatrix}, \tag{1}$$

with $\hat{H}(\mathbf{k}) = \xi_{\mathbf{k}} + [\mathbf{V}(\mathbf{k}) \cdot \hat{\boldsymbol{\sigma}}]\Theta(x)$, $\xi_{\mathbf{k}} = \hbar^2 k^2/2m_{n(s)} - E_F + U(x)$, $\hat{\Delta} = [\Delta_s + \mathbf{d}(\mathbf{k}) \cdot \hat{\sigma}](i\hat{\sigma}_y)\Theta(x)$, step function $\Theta(x)$, Fermi energy E_F, pauli matrices in spin space $\hat{\sigma}_j$ ($j = x, y, z$), effective mass $m_{n(s)}$ for N(S + P), Fermi wave number k_F, spin–orbit coupling term $\mathbf{V}(\mathbf{k}) \cdot \hat{\boldsymbol{\sigma}}$, absolute value of pair potential for S component Δ_s, and $\mathbf{d}(\mathbf{k})$ is $\mathbf{d}$-vector with $|\mathbf{d}(\mathbf{k})| = \Delta_p$, the absolute value of pair potential for P component. Here, we assume $\mathbf{d} \| \mathbf{V}$ because the transition temperature becomes highest under this condition [8].

The Bogoliubov-de Gennes equation is expressed as

$$\check{H} \begin{pmatrix} \hat{u}_{1(2)} \\ \hat{v}_{1(2)} \end{pmatrix} = E_{1(2)} \begin{pmatrix} \hat{u}_{1(2)} \\ \hat{v}_{1(2)} \end{pmatrix} \tag{2}$$

for electronlike quasiparticles and

$$\check{H} \begin{pmatrix} \hat{\sigma}_y \hat{v}_{1(2)} \hat{\sigma}_y \\ \hat{\sigma}_y \hat{u}_{1(2)} \hat{\sigma}_y \end{pmatrix} = -E_{1(2)} \begin{pmatrix} \hat{\sigma}_y \hat{v}_{1(2)} \hat{\sigma}_y \\ \hat{\sigma}_y \hat{u}_{1(2)} \hat{\sigma}_y \end{pmatrix} \tag{3}$$

for holelike quasiparticles with

$$E_{1(2)} = \sqrt{[\xi_{\mathbf{k}} + (-)V]^2 + |\Delta_{1(2)}|^2},$$
$$\hat{u}_{1(2)} = u_{1(2)}[1 + (-)\hat{\mathbf{V}} \cdot \hat{\boldsymbol{\sigma}}],$$
$$\hat{v}_{1(2)} = v_{1(2)}(-i\hat{\sigma}_y)[1 + (-)\hat{\mathbf{V}} \cdot \hat{\boldsymbol{\sigma}}],$$
$$u_{1(2)} = \sqrt{\frac{1}{2}\left(1 + \frac{\sqrt{E_{1(2)}^2 - |\Delta_{1(2)}|^2}}{E_{1(2)}}\right)},$$
$$v_{1(2)} = \mathrm{sgn}(\Delta_{1(2)})\sqrt{\frac{1}{2}\left(1 - \frac{\sqrt{E_{1(2)}^2 - |\Delta_{1(2)}|^2}}{E_{1(2)}}\right)},$$
$$\Delta_{1(2)} = \Delta_s + (-)\Delta_p, \quad \hat{\mathbf{V}} = \mathbf{V}/V, \quad V = |\mathbf{V}|. \tag{4}$$

Eqs. (4) are quite similar to quasiclassical Green's functions obtained in Ref. [15].

Hereafter, we only consider the case of $\mathbf{V} = \lambda(k_y, -k_x, 0)$ with Rashba coupling constant λ. The eigenfunctions of the Hamiltonian are expressed as

$$^{T}(u_1, -i\alpha_1^{-1}u_1, i\alpha_1^{-1}v_1, v_1), \quad ^{T}(i\alpha_1 v_1, v_1, u_1, -i\alpha_1 u_1),$$
$$^{T}(u_2, i\alpha_2^{-1}u_2, -i\alpha_2^{-1}v_2, v_2), \quad ^{T}(-i\alpha_2 v_2, v_2, u_2, i\alpha_2 u_2), \tag{5}$$

with $\alpha_{1(2)} = k_{1(2)-}/k_{1(2)}$, $k_{1(2)} = -(+)(m_s\lambda/\hbar^2) + \sqrt{(m_s\lambda/\hbar^2)^2 + k_F^2}$, and $k_{1(2)\pm} = k_{1(2)}\,e^{\pm i\phi_{1(2)}}$. Here, $\phi_{1(2)}$ is an angle of the wave number $k_{1(2)}$ with respect to the interface normal.

Wave function $\psi(x)$ for $x \geqslant 0$ is expressed as linear combination of eigenfunctions of the Hamiltonian. Wave function $\psi(x)$ for $x \leqslant 0$ is expressed as

$$\psi(x) = \left[e^{ik_{F_x}x} \begin{pmatrix} 1(0) \\ 0(1) \\ 0 \\ 0 \end{pmatrix} + a e^{ik_{F_x}x} \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} + b e^{ik_{F_x}x} \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} + c e^{-ik_{F_x}x} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} + d e^{-ik_{F_x}x} \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \right] e^{ik_{F_y}y} \tag{6}$$

for up(down)-spin state with $k_{F_x} = k_F \cos\phi$, where ϕ is an angle of the wave number k_F with respect to the interface normal in the N region. a and b are AR coefficients, c and d are normal reflection coefficients.

The wave function follows the boundary conditions [16]:

$$\psi(x)|_{x=+0} = \psi(x)|_{x=-0},$$
$$\check{v}_x\psi(x)|_{x=+0} - \check{v}_x\psi(x)|_{x=-0} = \frac{\hbar}{m_s i}\frac{2m_s H}{\hbar^2}\begin{pmatrix} \hat{1} & \hat{0} \\ \hat{0} & -\hat{1} \end{pmatrix}\psi(0). \tag{7}$$

Extending the BTK theory [2], the dimensionless conductance is expressed as

$$\sigma_S = \sum_{\uparrow,\downarrow} \int_{-\pi/2}^{\pi/2} [1 + |a|^2 + |b|^2 - |c|^2 - |d|^2] \cos\phi \, d\phi. \tag{8}$$

In the following section, we consider the bias (V) dependence of the tunneling conductance normalized by that in the normal state σ_S/σ_N, changing Δ_p/Δ_s and magnitude of the RSOC β. We define parameters $Z = 2m_s H/\hbar^2 k_F$ and $\beta = 2m_s\lambda/\hbar^2 k_F$ in the calculation.