Multiple-superconducting amplitudes in multi-layer high-T_c cuprates

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Abstract

We study the amplitude of the superconducting (SC) order parameter in each CuO_2 plane in the multi-layer high-T_c cuprates by calculating the tunneling conductance of the superconductor/insulator/superconductor junction. Comparing the tunneling parallel and perpendicular to the CuO_2 plane, we find that the multiple SC amplitude can be detected only in the parallel tunneling.

Key words: multi-layer cuprate; multiple gap; tunneling Hamiltonian; SIS junction

The multi-layer high-T_c cuprates have several CuO_2 planes within a conducting block, in which the doping rate in the outer CuO_2 planes (OPs) is different from that in the inner CuO_2 planes (IPs) [1]. Since the superconducting (SC) amplitude, i.e., the amplitude of the SC order parameter, depends on the doping rate, it is possible that the OP's SC amplitude is different from the IP's SC amplitude [2]. Such multiple SC amplitude has been studied with the nuclear-magnetic-resonance (NMR) measurement and been estimated by the temperature dependence of the Knight shift and the relaxation time [2]. In four-layer compounds, a smaller SC amplitude seems to couple to a larger SC amplitude [2]. The difference between them should be also observed with the tunneling measurement that is a direct probe of the SC amplitudes.

The density of states (DOS) in high-T_c superconductors is obtained by the tunneling measurements with a superconductor/insulator/normal-metal (SIN) junction [3–5]. Most of the SIN experiments are considered to observe the OP's DOS, by which we can obtain the OP's SC amplitude. On the other hand, with the superconductor/insulator/superconductor (SIS) break junction, one can measure the convolutions of the DOS and obtain the SC amplitude [6–8]. The SIS junction can be fabricated in either parallel or perpendicular direction to the CuO_2 plane [6].

In this study, we show the effect of the multiple SC amplitude in tri-layer systems on the tunneling conductance. The SIS junctions both parallel and perpendicular to the CuO_2 plane are examined. We find that the multiple SC amplitude behavior is significant in the parallel direction.

For the conducting block, we adopt the Hamiltonian as,

$$
\begin{aligned}
H &= H_0 + H_\perp + H', \qquad (1)\\
H_0 &= \sum_{k,\sigma,n} \xi(k)\; c^\dagger_{k,\sigma,n} c_{k,\sigma,n},\\
H_\perp &= \sum_{k,\sigma,\langle n,m\rangle} \epsilon_\perp(k)\; c^\dagger_{k,\sigma,n} c_{k,\sigma,m},\\
H' &= \sum_{k,n} \left[\Delta_n(k) c^\dagger_{k,\uparrow,n} c^\dagger_{-k,\downarrow,n} + \Delta^*_n(k) c_{-k,\downarrow,n} c_{k,\uparrow,n}\right],\\
\xi(k) &= a\cdot(k_x^2+k_y^2)-\mu,\\
\epsilon_\perp(k) &= (t_\perp/4)\left\{\cos(k_x)-\cos(k_y)\right\}^2,\\
\Delta_n(k) &= \bar{\Delta}_n \left\{\cos(k_x)-\cos(k_y)\right\},
\end{aligned}
$$

where $c^\dagger_{k,\sigma,n}(c_{k,\sigma,n})$ is the electron creation (annihilation) operator with momentum k, spin σ. The summa-

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tion $\langle n, m \rangle$ runs for adjacent pairs of planes. The CuO_2 planes are indicated by $n, m = 1, 2, 3$. Hereafter, the IP and the OP are assigned to 1 and 2 (3), respectively. Other parameters are chosen as, $a = 1.2$, $\mu = 3.0$, $t_\perp = -1.0$, $\bar{\Delta}_1 = 0.5$, $\bar{\Delta}_2 = \bar{\Delta}_3 = 1.0$. The tunneling Hamiltonian is given as,

$$H_T = \sum_{k,\sigma,n,m} T_{n,m} \left(\tilde{c}^\dagger_{k,\sigma,n} c_{k,\sigma,m} + \text{H.c.} \right), \tag{2}$$

where one superconductor is distinguished from the other by tilde. The tunneling direction is imposed on the tunneling matrix elements. For the perpendicular tunneling,

$$T_{n,m} = T \delta_{n,2} \delta_{m,3}, \tag{3}$$

and for the parallel tunneling,

$$T_{n,m} = T \delta_{n,m}, \tag{4}$$

where $\delta_{n,m}$ is the Kronecker's delta and we choose $T = 1.0$. The tunneling conductance is calculated within the second order of T and the k-summation is carried out on 2000×2000 k-points in the area, $0 \leq k_x, k_y \leq \pi$. The Dirac's delta function that appears in the equation of the DOS and the tunneling conductance is replaced by the Lorentzian with the broadening, $\eta = 0.005$.

In Fig. 1 (a), the IP's and OP's DOS are plotted by dotted and solid lines, respectively. Around $\omega = \pm 1.0$ corresponding to the OP's SC amplitude, the OP's DOS has dominant peaks splitted by the inter-layer coupling. The OP's DOS has another tiny peak around $\omega = 0.5$ corresponding to the IP's SC amplitude, although almost weight is contained in the IP's DOS. Each SC amplitude can be observed in the DOS in each CuO_2 plane. If it is difficult to measure the IP's DOS, the multiple SC amplitude is not sufficiently visible.

In Fig. 1 (b), the tunneling conductances, $\mathrm{d}I/\mathrm{d}V$, parallel and perpendicular to the CuO_2 plane are plotted as functions of the voltage, V, by solid and broken lines, respectively. In the perpendicular direction, $\mathrm{d}I/\mathrm{d}V$ increases toward V=2.0 and begins to decrease around V=2.0. This voltage corresponds to $2\Delta_2 = 2\Delta_3 \sim 2.0$ on the Fermi energy, while we can not find a peak around $2\Delta_1 \sim 1.0$. On the other hand, in the parallel direction, we can find a clear peak around $2\Delta_1$ in addition to the peak around $2\Delta_2$. Therefore, the SIS break junction parallel to the CuO_2 plane can show the multiple SC amplitude behavior.

In summary, we calculated the tunneling conductance of SIS junction parallel and perpendicular to the CuO_2 plane. We found that the multiple SC amplitude behavior is visible in the parallel direction.

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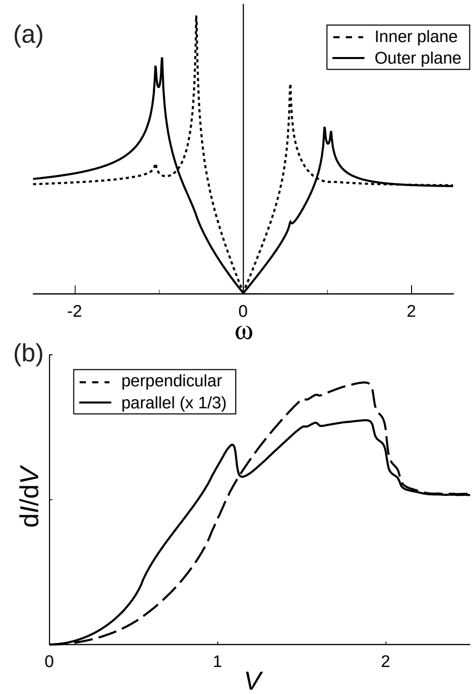

Fig. 1. (a) The DOS in the OP (solid line) and the IP (dotted line) are plotted as functions of the energy, ω. Two OPs are identical. (b) The tunneling conductance, $\mathrm{d}I/\mathrm{d}V$, is plotted as a function of the applied voltage, V. The tunneling perpendicular and parallel to the CuO_2 plane are drawn by broken and solid lines, respectively. The value of the conductance in the parallel direction is reduced to 1/3 for the graphical convenience.

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