Zero-bias conductance peak in disordered ferromagnetic metal/$d_{x^2-y^2}$ wave superconductor junction

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Abstract

We investigate numerically the spin-polarized tunneling effect in ferromageneic metal / insulator / $d_{x^2-y^2}-$wave superconductor (FM/I/d-wave SC) junctions. It is shown that the height of the zero-bias conductance peak owing to the zero energy states is depending on the magnitude of the exchange potential and the randomness near the junction interface.

Key words: Zero energy states; Zero-bias conductance peak; disorder; spin-polarized tunneling

One of the most remarkable feature of d-wave superconductor junctions is the zero-bias conductance peak (ZBCP) [1–3]. The origin of the ZBCP is the zero-energy states (ZES) formed at interfaces of d-wave superconducting junctions [4]. Spin-dependent transport properties in ferromagnetic metal/d-wave superconductor (FM/I/d-SC) junctions have been received considerable theoretical and experimental attentions because recent nano-technology enables hybrid structures between Mn oxides compound and high-T$_C$ superconductors. It has been revealed by recent theoretical studies [5–7] that the ZBCP in FM/I/d-SC junctions is suppressed by the exchange potential in FM. However, these theoretical studies assume that FM/I/d-SC junctions are in the clean limit. The purpose of this paper is to investigate effects of randomness on the ZBCP in FM/I/d-SC junctions. We consider a FM/I/d-SC junction as shown in inset of Fig. 1. The junction is stacked along the (100) direction of a square lattice. A single-orbital tight-binding model is used to describe the system. The effective mean-field (BCS) Hamiltonian $\mathcal{H} \equiv H + \Delta$ is given by

$$H = -t \sum_{l,m,\sigma} \left(c^{\dagger}_{l+1,m,\sigma} c_{l,m,\sigma} + c^{\dagger}_{l,m+1,\sigma} c_{l,m,\sigma} + \text{H.c.} \right) + \sum_{l,m,\sigma} v_{l,m} c^{\dagger}_{l,m,\sigma} c_{l,m,\sigma} - \mu \hat{n} \,, \qquad (1)$$

$$\Delta = \sum_{l,m,l',m',\sigma} \Delta^{m,m'}_{l,l'} c_{l,m,\sigma} c_{l',m',-\sigma} \,, \qquad (2)$$

where (l,m) are lattice indeces, $\sigma =\uparrow$ or $\downarrow$ denotes the spin of an electron, t is the hopping integral, $v_{l,m}$ is the potential at (l,m), μ is the chemical potential, $\hat{n}$ is the number operator, and $\Delta^{m,m'}_{l,l'}$ is the pair potential. In this paper, the length is measured in units of the lattice constant a and the energy is measured in units of t. We consider junctions where the orientation angle between the (100) direction and the interface normal is $\pi/4$ as depicted in inset of Fig. 1. In these junctions, the pair potential$\Delta^{m,m'}_{l,l'}$ is given by $(-)\Delta_0$ for $l = l' \pm 1, m = m' \pm (\mp)1$ and 0 for otherwise. The exchange poten-

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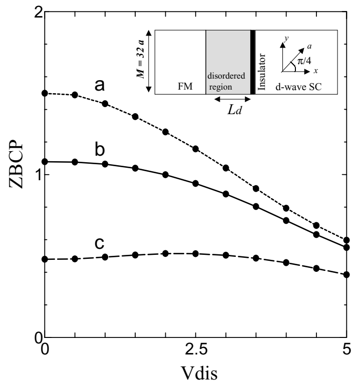

Fig. 1. Random potential V_{dis} dependence of zero-bias conductance. The magnitude of Fermi energy and the length of random region are setted $E_F = -2.5$ and $L_d = 2.0$, respectively. The magnitude of exchange potential is (a) $V_{ex} = 0.0$, (b) $V_{ex} = 0.5$, (c) $V_{ex} = 2.0$.

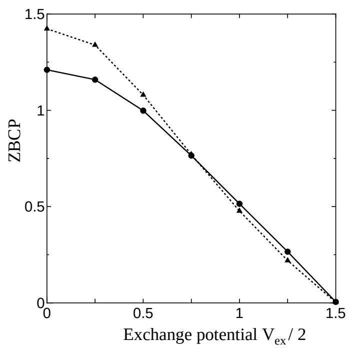

Fig. 2. Exchange potential V_{ex} dependence of zero-bias conductance for $V_{dis} = 2.0$ and $E_F = -2.5$. The dotted line represents the result obtained for clean junction ($V_{dis} = 0.0$).

tial in FM is given by $V_{ex} = (v_\uparrow - v_\downarrow)$ where $v_{\uparrow(\downarrow)}$ is the on-site potential $(-)v_{l,m}$ for $\uparrow$ $(\downarrow)$. The randomness in FM is considered through random on-site potentials $v_{l,m}$. We assume that $v_{l,m}$ takes a random values uniformly distributed within $\pm V_{dis}/2$ at disordered region. We calculate numerically the averaged conductance $< G >$ for various samples which have different random configurations by using the Kubo formula [8,9] and the recursive Green's function method [10–12].

The averaged conductance $< G > /M$ at the zero-bias (ZBCP) are plotted in Figure. 1 as a function of V_{dis}. The curve (a) indicates results of N/I/d-SC. The curve (b) and (c) denote results of FM/I/d-SC junctions, where $V_{ex} = 0.5$ and 2.0 in (b) and (c), respectively. In N/I/d-SC junctions, the height of the ZBCP monotonically decreases with increasing V_{dis} as shown in curve (a). The height of the ZBCP is drastically suppressed owing to the exchange potential and randomness as shown in curve (b) and (c). Furthermore, the height of the ZBCP in FM/I/d-SC junctions has a non-monotonic dependence on V_{dis} for large V_{ex} as shown in the curve (c). In the limit of strong randomness, (i.e.,$V_{dis} \gg 1$), the height of the ZBCP in FM/I/d-SC approaches that in N/I/d-SC because the diffuse reflection by the random potential becomes rather dominant than the effects of the exchange potential.

Figure 2 shows a relation between the averaged ZBCP and V_{ex}, where $V_{dis} = 0$ and 2.0 in a dotted and a solid line, respectively. The height of the ZBCP is monotonically decreases with increasing V_{ex}. For large V_{ex}, ZBCP in disorderd junctions is larger than that in the clean junctions. The retro-reflectivity of the Andreev reflection (AR)[13] is responsible for ZES. In FM/I/d-SC, the retro-reflectivity is seriousely broken by the exchange potential which leads to the suppression of the ZBCP. In disordered junctions, however, the retro-reflectivity is slightly recovered by the disorder near the interface since the momenta parallel to the interface is no longer conserved. Thus the ZBCP in the disordered junction is slightly larger than that in the clean junction.

In summary, we have studied the effects of disorder near the interface of the FM/I/d-SC junctions on the ZBCP. The enhancement of ZBCP originates from the fact that the breakdown of the retro-reflectivity of the AR is recovered due to the random scattering of quasi-particles.

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References

[1] Y. Tanaka and S. Kashiwaya, Phys. Rev. Lett. **74** 3451 (1995).

[2] S. Kashiwaya and Y. Tanaka, Rep. Prog. Phys. **63** 1641 (2000).

[3] I. Iguchi *et al.*, Phys. Rev. B **62** (2000) R6131.

[4] C. R. Hu, Phys. Rev. Lett. **72** 1526 (1994) .

[5] J-X. Zhu, B. Friedman, and C. S. Ting, Phys. Rev. B **59**, 9558 (1999).

[6] S. Kashiwaya *et al.*, Phys. Rev. B **60**, 3527 (1999).

[7] I. Zutic and O. T. Valls, Phys. Rev. B **60**, 6320 (1999).

[8] R. Kubo, J. Phys. Soc. Jpn. **12** 570 (1957).

[9] Y. Takane, H. Ebisawa, J. Phys. Soc. Jpn. **61** 1685 (1992).

[10] P. A. Lee, D. S. Fisher, Phys. Rev. Lett. **47** 882 (1981).

[11] Y. Asano, Phys. Rev. B**63** 052512 (2001).

[12] H. Itoh, Y. Tanaka, J. Inoue, and S. Kashiwaya, Physica C **367** 99 (2002).

[13] A. F. Andreev, Zh. Eksp. Teor. Fiz. **46** 1823 (1964) [Sov. Phys. JETP **19** 1228 (1964)].

[14] H. Itoh, N. Kiraura, Y. Yoshida, Y. Tanaka, J. Inoue, Y. Asano, and S. Kashiwaya, Proceedindg of MS+S2002.