Progress in Superconductivity Vol.2 No.1 pp 43-46 1.October 2000

Andreev Reflection in Metal- and Ferromagnet-*d*-wave Superconductor Tunnel Junctions

Sunmi Kim [a], Kiejin Lee*[a], Yunseok Hwang [b], Deokjoon Cha [c], Takayuki Ishibashi[d]
[a] *Sogang University, Seoul, Korea*
[b] *Korea Research Institute for Standards and Science (KRISS), Daejeon, Korea*
[c] *Kunsan National University, Kunsan, Korea*
[d] *Tokyou University of Agriculture and Technology, Tokyo, Japan*
Received 06 November 2000

Abstract

We report on the tunneling spectroscopy of tunnel junctions using d-wave superconductor in relation to Andreev reflection. The zero bias conductance peak (ZBCP) which has maximum on [110] direction of *ab*-plane is observed on metal Au/$YBa_2Cu_3O_y$ tunnel junctions while it is suppressed on the ferromagnetic Co/Au/$YBa_2Cu_3O_y$ tunnel junctions. The effects of Andreev reflection on the differential conductance of each junction are dependent on the tunnel direction. For the Co/Au/$YBa_2Cu_3O_y$ junction, the suppression of Andreev reflection takes place by spin-polarized quasiparticles tunneling from a ferromagnetic material to a *d*-wave superconductor. By comparing these experimental results with recent theoretical works on Andreev reflection, the existence of Andreev bound state due to the *d*-wave symmetry of the pair potential is verified in high-T_c superconductor.

Keywords : $YBa_2Cu_3O_y$, Andreev reflection , zero-bias conductance peak (ZBCP), ferromagnet, *d*-wave superconductor.

I. Introduction

Recently, it has been widely accepted through much experimental and theoretical works that high-T_c superconductors have a *d*-wave pairing symmetry [1] - [6]. Such a pairing state gives rise to an anisotropic energy gap which reduces to zero along nodes according to the sign change of the pair potential (e.g., from Δ_- to Δ_+ where Δ is pair potential) with Fermi wavevector. This is very different from the conventional BCS *s*-wave superconductors that have a finite energy gap over the entire Fermi surface.

For the sign change, Hu predicted that the midgap surface exists on a (110) surface of *d*-wave symmetry superconductor, so that they can give rise to a zero bias conductance peak (ZBCP) [2]. Tanaka [3] and Kashiwaya [4] discussed the existence of the ZBCP by the tunneling spectra of *d*-wave superconductors and showed the appearance of ZBCP when the *a*-axis of the *d*-wave superconductors is tilted from the surface normal. Recently, much theoretical works [7] - [11] have reported that a ZBCP occur by means of a scattering process known as Andreev reflection. The process of Andreev reflection [5] is that an electron in the normal metal is retroreflected at interface between the normal metal and superconductor like a hole and a Cooper pair is carried away in the superconductor. However for the spin-polarized quasiparticles tunneling from ferromagnet, novel features can arise due to spin effect of energy band.

In this paper, the conductance anomaly related to the interference effect in *d*-wave superconductor is investigated based on the tunneling spectroscopy of

* Corresponding author. Fax: +82 2 705 8429
e-mail: klee@ccs.sogang.ac.kr

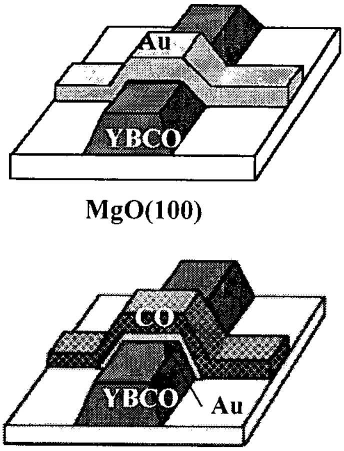


Fig. 1. The sample geometries of (a) a N/S junction and (b) a F/N/S junction

normal metal / superconductor (N/S) and ferromagnet / normal metal / superconductor (F/N/S) junctions. To explain the ZBCP of tunneling spectrum we will use the process of Andreev reflection at a N/S interface. In addition, we will discuss the influence of Andreev reflection at a F/N/S interface. For the application of superconducting three terminal device, we discuss the current gain in terms of the boundary conditions.

II. Experimental

The *c*-axis oriented the $YBa_2Cu_3O_y$ (YBCO) films were prepared by a pulsed-laser deposition technique on MgO (100) substrates. The thickness was about 50-60 nm and it patterned into a stripline of 50 *μm* in width. The Au layer of 100 *nm* in thickness was evaporated by an electron-beam technique. This forms N/S tunnel structure tilted against the *a*-axis of YBCO film. For F/N/S junctions, we deposited the Au barrier (*20 nm*) film on the YBCO film. The Au barrier is necessary to avoid the formation of a spin-glass phase at the N/S interface [13] and can prevent degradation of superconductivity of YBCO film due to direct sputtering deposition on the surface of YBCO film. The geometris of the fabricated tunnel junctions are shown in Fig. 1. The electric

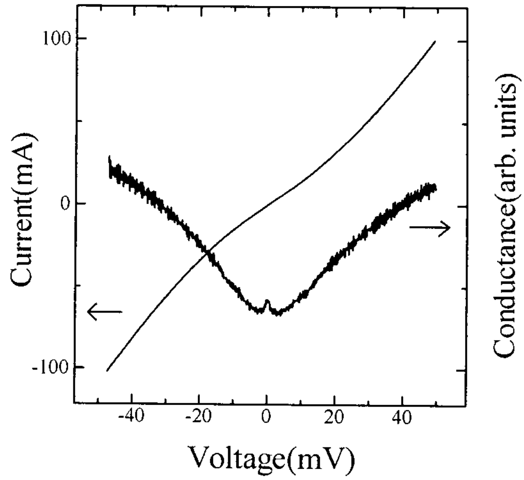


Fig. 2. *I-V* characteristic and conductance spectrum of a N/S junction at 4.2K.

tunneling direction for a N/S junction and a F/N/S junction includes *ab*-plane as well as *c*-axis.

Current-voltage (*I-V*) characteristics are taken by sweeping bias current. The measurements of tunneling spectra were made by a standard four-terminal method using a lock-in amplifier. Temperature dependence of tunneling spectra was measured in the temperatures range from 4.2 *K* to 75 *K*.

III. Results and discussion

The measured critical temperature of the YBCO film is about 85 *K*. Figure 2 shows the *I-V* characteristics and the curve of conductance versus voltage of N/S junction at 4.2 *K*. Conductance spectrum exhibits a ZBCP at zero bias voltage. For the tunneling of *c*-axis, it could not observe ZBCP [2] – [4], [14]. Note that, electrons in a metal can not penetrate into a superconductor if their excitation energy with respect to the Fermi level is below the superconducting energy gap Δ. However, the current flows at low bias voltage $V<\Delta/e$ by means of an Andreev scattering process. When quasiparticles is injected from normal metal with angle φ, in the case of an anisotropic superconductor, the transmitted hole like quasiparticles (ELQ) and electron like quasiparticles (HLQ) have different effective pair potentials Δ_+ and Δ_-,

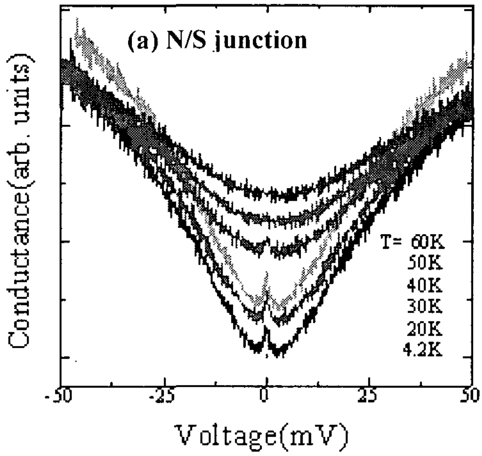
$$\Delta_{\pm} = \Delta(k_{\pm}) \equiv |\Delta_{\pm}| e^{i\theta_{\pm}}, \qquad (1)$$

where $\theta_{\pm}$ are the phases of the effective pair potentials.

Such a ZBCP is dependent on tunneling direction of quasiparticles. Recently it was reported by W. Wang [14] that for a *d*-wave superconductor, a maximum of ZBCP was observed at the tilted orientation angle of 45° from the *a*-axis of YBCO film and that a dip structure around zero bias was mostly observed at the tilted angle of 0°. In our experiments the observed ZBCP is related with tunneling angles between 45° and 0°. The orientation dependence of ZBCP does not appear at the *s*-wave superconductors. Therefore, the appearance of the ZBCP implies that the anisotropic high-T_c superconductors have *d*-wave pairing symmetry for their pair potential.

Figure 3 shows the temperature dependence of the tunneling conductance spectra for a N/S junction and a F/N/S junction. In N/S junction, the ZBCP shows a maximum value at 4.2 *K* and disappeared above 50 *K*. It increased nonlinearly as the measuring temperature was reduced. However, for F/N/S junction, it did not show a ZBCP. This can be explained by the suppression of Andreev reflection related to spin-polarized quasiparticles [16]. When the current is fed into normal metal, the electrons in normal metal are spin polarized. The spin-polarized currents do not have equal numbers of "*up*" and "*down*" spins and therefore, the energy states for electrons and holes are different from unpolarized quasiparticles. In this case, the absence of a hole available for Andreev reflection prohibits supercurrent flow at low voltages and conductance is drastically reduced. Thus, the spin-polarized quasiparticles can result in a suppression of ZBCP values [18] - [19]. It means that Andreev bound state is reduced by spin-polarized quasiparticle effect. For the same tunneling direction, it was found that the F/N/S junction has higher current gain than the N/S junction in Ref. [17]. Spin effect suppressed Andreev bound state may be considered to be a factor to increase the current gain. In addition, the Au layer in our experiment plays a role of spin accumulation layer [15], [17].

In summery we have reported a conductance anomaly when the quaiparticles are transported on



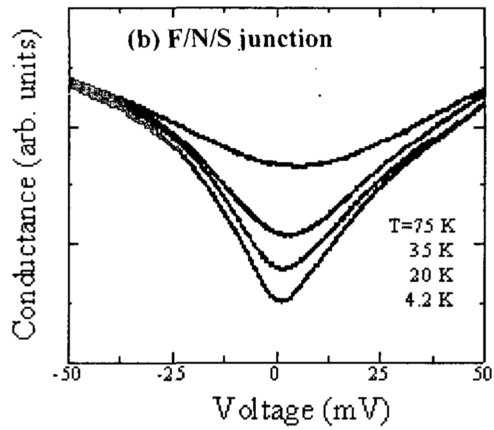


Fig. 3. Conductance spectra measured at defferent temperatures for (a) a N/S junction and (b) a F/N/S junction

(110) surface of superconductor using a Au/YBCO junction for N/S structure and a Co/Au/YBCO junction for F/N/S structure. The appearance of ZBCP due to Andreev reflection is a definite evidence that high-T_c superconductor has *d*-wave pairing symmetry. On *ab*-plane tunneling from a ferromagnet, we discussed reduction of ZBCP due to suppression of Andreev reflection under the influence of spin-polarized quasiparticles.

Acknowledgments

We would like to thank I. Iguchi for valuable discussion. This work was support by KOSEF Joint

Research Project under The Korea-Japan Basic Scientific Promotion Program (2000-6-114-01-2).

References

[1] D. J. van Harliugen, Rev. Mod. Phys. **67**, 515 (1995).
[2] C. R. Hu, Phys. Rev. Lett. **72**, 1526 (1994); C. Yang and C. R. Hu, Phys. Rev. B **50**, 16 766 (1994).
[3] Y. Tanaka and S. Kashiwaya, Phys. Rev. Lett. **74**, 3451 (1995).
[4] S. Kashiwaya, Y. Tanaka, M. Koyanagi, H. Takashima, and K. Kajimura, Phys. Rev. B **51**, 1350 (1995).
[5] A. F. Andreev, Zh. Dksp. Teor. Fiz. 46, 1823(1964)[Sov. Phys.-ZEPT 19, 1228 (1964)].
[6] G. E. Blonder, M. Tinkham, and T. M. Klapwijk, Phys. Rev. B**25** 4515 (1982).
[7] C. Bruder, Phys. Rev. B**41**, 4017 (1990).
[8] J. H. Xu, J. K. Miller, Jr., and C. S. Ting, Phys. Rev. B**53**, 3604 (1996).
[9] Y. Koyama, Y. Takane and K. Ebjsawa, J. Phys. Soc. Jpn. **65**, 683 (1996).
[10] D. Rainer, H. Burkgardt, M. Fogelstrom and J. A. Sauls, J. Phys, Chem Solids, Vol **59**, No.10-12; pp. 2040-2044 (1998).
[11] L. Alff, Kleefisch, U. Schoop, M. Zittartz, T. Kemen, T. Bauch, A. Marx, and R. Gross, Eur. Phys. J. B**5**, 423-438 (1998).
[12] M. Hurd, T. Lofwander, G. Johansson and G. Wendin, Phys. Rev. B. **59**, 4412 (1999).
[13] M. Rubinstein, P. Lubitz, W. E. Carolos, P. R. Broussard, D. B. Chrisey, J. Horwitz, and J. J. Krebs, Phys. Rev. B. **47**, 15350 (1993).
[14] W. Wang. M. Yamazaki, K. Lee and I. Iguchi, Phys. Rev. B, **60**, 4272 (1999).
[15] Mark Johnson, Phys. Rev. Lett. **70**, 2142 (1993).
[16] K. Lee and B. Friedman, Supercond. Sci. Technol. **12**, 741-744 (1999).
[17] K. Lee, W. Wang, and I. Iguchi, Appl. Phys. Lett, **75**, 1149 (1999).
[18] R.J. Soulen, Jr, M. S. Osofsky, B. Nadgorny, T. mbrose, P. R. Broussard, M. Rubinstein, IEEE Trans. Appl. Super. **9**, 3636 (1999).
[19] M. J. M. de Jong and C. W. J. Beenakker, Phys. Rev. Lett. **74** 1657 (1995).