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Andreev reflection in metal- and ferromagnet-d-wave superconductor tunnel Junction

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Abstract

We report on the influence of d-wave pairing symmetry in high-T_c superconductor by tunneling spectroscopy. The zero-bias conductance peak(ZBCP) which is produced by tunneling through the *ab*-plane is observed on both of metal Au/$YBa_2Cu_3O_y$(N/S) tunnel junctions and ferromagnet Co/Au/ $YBa_2Cu_3O_y$(F/N/S) tunnel junctions. The effects of Andreev reflection on the differential conductance of each junctions are dependent on the tunnel direction. For the S/N/F junction, it appears the suppression of the ZBCP due to the suppression of Andreev reflection at the interface between a ferromagnetic material and a d-wave superconductor. By comparing these experimental results with recent theoretical works on Andreev reflection, the existence of Andreev bound state is verified in high-T_c superconductor, due to the d-wave symmetry of the pair potential.

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

I. Introduction

Recently, it has been widely accepted that the high T_c-superconductor has a d_{x2-y2}-wave pairing symmetry [1] throughout much experimental and theoretical works. 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 conventional BCS s-wave superconductors that have a finite energy gap over the entire Fermi surface.

For this sign change, Hu [2] predicted that the midgap surface exist on a (110) surface of d_{x2-y2}-wave symmetry superconductor, they can give rise to a zero-bias conductance peak(ZBCP). Tanaka [3] and Kashiwaya [4] discussed it 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 midgap states like a ZBCP occur by means of a scattering process known as Andreev reflection [5,6]. An electron in the normal metal is retroreflected at the NS interface as a hole, and a Cooper pair is carried away in the superconductor. For the spin-polarized quasiparticle injection from ferromagnet, however, there can cause novel features due to spin effect of energy band.

In this paper, the conductance anomaly related interference effect in d-wave superconductor is investigated based on the tunneling spectroscopy by observations of metal Au/$YBa_2Cu_3O_y$ (N/S) junctions and ferromagnet Co/Au/ $YBa_2Cu_3O_y$(F/N/S) junctions. To explain the ZBCP of tunneling spectrum we will use the process of Andreev reflection [5] at a normal metal-superconductor(N/S)

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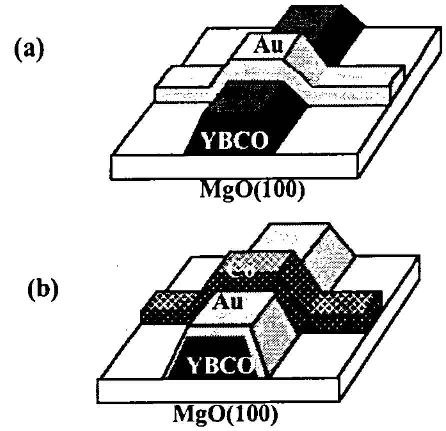

Fig. 1. The sample geometries of (a)N/S junction and (b)F/N/S junction

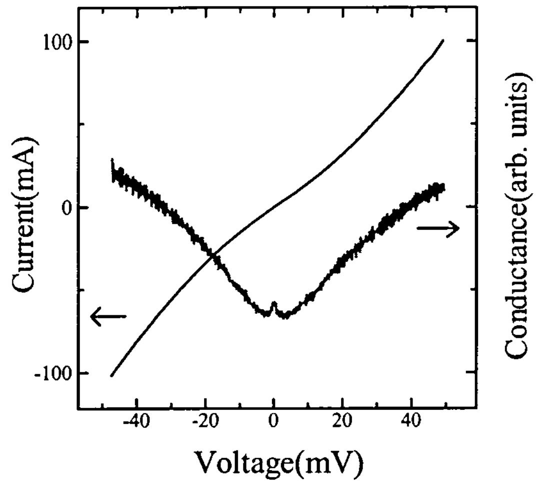

Fig. 2. The *I-V* characteristic and conductance spectrum of metal Au/$YBa_2Cu_3O_y$ / junction at 4.2K.

interface.

In addition we will discuss the influence of Andreev reflection at a ferromagnet/normal metal/superconductor (F/N/S) interface. For the study of spin polarized quasiparticle injection into HTSC superconductor related to the current gain, it plays an important role for the applications of supercoducting devices.

II. Experimental

The *c*-axis oriented $YBa_2Cu_3O_y$(YBCO) films were prepared by a pulsed-laser deposition technique on MgO (100) substrates. They have thickness of about 50-60 nm and patterned into a stripline 50 μm. The Au layer of 100 *nm* thickness was evaporated by an electron- beam technique. This forms N/S structure tilted against the *a*-axis of YBCO film. For F/N/S junctions, we deposited the Au barrier 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 intercept some degradation of superconductivity of YBCO film due to direct sputtering deposition on the surface of YBCO film. The geometry of the fabricated tunnel junctions is shown in figure 1.

The current-voltage (*I-V*) characteristics are taken by sweeping bias current, measuring the voltage on *ab*-plane of tunnel junction. The measurements of tunneling spectra were performed by a standard four-terminal method using a lock-in amplifier. For temperature dependence of tunneling spectra, it was measured at the temperature 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* characteristic and a curve of conductance versus voltage of N/S junction at 4.2 *K*. For conductance spectrum, it exhibits a ZBCP at zero bias voltage.

Note that, electrons in a metal cannot penetrate into a superconductor if their excitation energy with respect to the Fermi level is below the superconducting gap Δ. However, the current flows to N/S junction in response to a small applied voltage $V<\Delta/e$ including zero bias voltage, by means of a scattering process known as Andreev reflection. When an excitation reflects elastically off a (110) surface, its momentum exchanges, $k_{+F} \rightarrow k_{-F}$. Incident and reflected wave packets propagate through different order parameter field, $\Delta(k_{+F}, r)$ vs. $\Delta(k_{-F}, r)$, which leads to Andreev scattering. A zero energy bound states(so-called midgap states) occur at

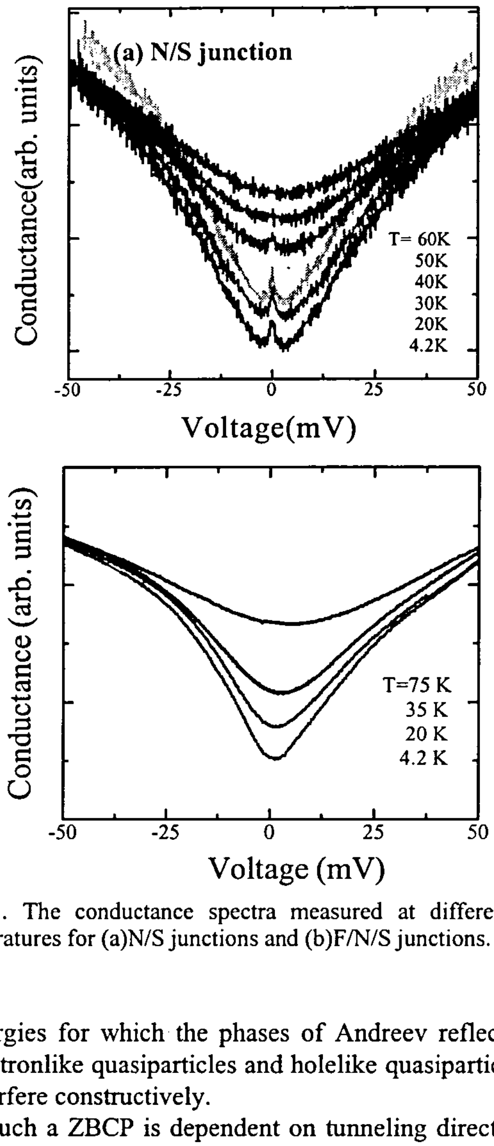

Fig. 3. The conductance spectra measured at different temperatures for (a)N/S junctions and (b)F/N/S junctions.

energies for which the phases of Andreev reflected electronlike quasiparticles and holelike quasiparticles interfere constructively.

Such a ZBCP is dependent on tunneling direction of quasiparticles. Recently it was reported by W. Wang [14] that for d_{x2-y2}-wave superconductor, a maximum of ZBCP was observed at the tilted orientation angle of 45° from the *a*-axis of YBCO film(it is (110) direction) and that a dip structure around zero bias was mostly observed at the tilted angle of 0°. In our experiments the tilted orientation angle of tunneling junction is between 45° and 0°. Our results are coincident with theoretical results of conductance spectra well [3,4]. The orientation dependence of ZBCP doesn't appear at the s-wave superconductors. Therefore, the appearance of ZBCP implies that the anisotropic high-T_c superconductors have d_{x2-y2}-wave pairing symmetry for their pair potential.

Figure 3 shows the temperature dependence of the tunneling conductance spectra for N/S junctions and F/N/S junctions. In N/S junction the ZBCP took a maximum value at 4.2*K* and disappeared above 50*K*. It increased nonlinearly as measuring temperature was reduced. While, in F/N/S junction, it didn't have a ZBCP. This can be explained due to the suppression of Andreev reflection related with spin-polarized quasiparticles [16]. When the current is fed into normal metal, the electrons in normal metal are spin polarized and the spin-polarized quasiparticles are injected into superconductor. The spin-polarized currents are not equal numbers of "*up*" and "*down*" spin 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 arise to a suppression of ZBCP values [18,19].

Note that, the Au layer in our experiment plays role as the barrier which can avoid spin glass effect and degradation for surface of superconductor, as well as spin accumulation layer [15]. Thickness of an Au layer is able to affect on current gain that is important in application of superconductor like three terminal device [17].

In summery we have reported a conductance anomaly when the quaiparticles are transported on (110) surface of superconductor using the metal Au/$YBa_2Cu_3O_y$ (N/S) and ferromagnet Co/Au/ $YBa_2Cu_3O_y$(F/N/S) tunnel junctions. 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 ferromagnet, we discussed reduction of ZBCP due to suppression of Andreev reflection under the influence of spin-polarized quasiparticls.

Acknowledgments

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