INSTITUTE OF PHYSICS PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY

Supercond. Sci. Technol. **14** (2001) 1014–1017 PII: S0953-2048(01)27365-5

Spin-injection properties and conductance spectra of Co/Au/YBaCuO and Co/Au/BiSrCaCuO tunnel junctions

Takayuki Ishibashi[1], Kazushige Sato[1], Koutarou Yonemitsu[1], Katsuaki Sato[1], Kiejin Lee[2] and Sunmi Kim[2]

[1] Faculty of Technology, Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei, Tokyo 184-8588, Japan

[2] Department of Physics, Sogang University, CPO Box 1142, Seoul 121-742, Korea

Received 25 July 2001, in final form 17 October 2001

Published 21 November 2001

Online at stacks.iop.org/SUST/14/1014

Abstract

Tunnelling spectra of Co/Au/$YBa_2Cu_3O_y$ (YBaCuO) and Co/Au/$Bi_2Sr_2CaCu_2O_x$ (BiSrCaCuO) tunnel junctions have been studied in order to understand the electrical properties of ferromagnet/high-T_c superconductor junctions, and to study the difference between YBaCuO and BiSrCaCuO. The energy gap structures and a zero-bias conductance peak (ZBCP) are clearly observed in conductance spectra for both Co/Au/YBaCuO and Co/Au/BiSrCaCuO junctions. This result can be compared with that of Au/YBaCO and Au/BiSrCaCuO junctions, a normal metal/superconductor (S/N) junction. In the case of Co/Au/YBaCuO and Co/Au/BiSrCaCuO junctions, the amplitude of the ZBCP is smaller than that of the S/N junctions. This result indicates that the tunnelling properties are strongly affected by a spin polarization of electrons flowing through the junctions. Furthermore, the amplitude of the ZBCP observed in the Co/Au/YBaCuO junction is smaller than that of the Co/Au/BiSrCaCuO junction. The difference is attributed to the difference in anisotropy of the two superconductors.

1. Introduction

A tunnel junction consisting of a ferromagnetic material and a superconductor, F/S junction, has been known to be a good probe to analyse the physical properties of both ferromagnetic and superconducting materials [1]. Recently, theoretical studies in terms of the Andreev reflection in d-wave superconductors revealed that F/S junctions provide information on the pairing symmetry and the spin polarization of quasi-particles (QPs) injected into the high-T_c superconductors, which are expected to appear as a peculiarity in the zero bias conductance peak (ZBCP) of the junctions [2]. Experimental confirmation of the theory requires a number of conductance spectra in different F/S junctions with various kinds of superconductors, since individual high-T_c superconductors have different types of crystal structures, critical temperatures, anisotropy parameters, etc, which should strongly affect electrical properties of F/S junctions.

In F/S junctions, a substantial suppression of superconductivity by the injection of spin-polarized current has been theoretically predicted [3–5]. Therefore, conductance spectra should be investigated in F/S junctions to understand the transport properties of spin-polarized electrons. Nevertheless, only a few experimental studies have been performed on the conductance spectra.

In this paper, we report on the electrical properties of ferromagnetic material/normal-metal/high-T_c superconductor (F/N/S) tunnel junctions. As a spin injector electrode, we used a Co ferromagnetic metal, which is known to have a spin polarization as large as 35% [1]. We selected this metal because it is more stable than any other ferromagnetic 3D transition metals and its physical properties are well known. In this experiment, a thin Au layer is used to prevent a reaction between the Co and the superconductor. As high-T_c superconductors, we adopted $YBa_2Cu_3O_y$ (YBaCuO) and $Bi_2Sr_2CaCu_2O_x$ (BiSrCaCuO) films. Although these materials have a

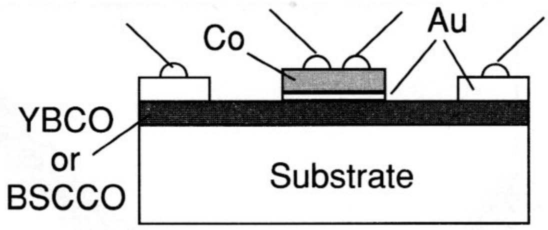

Figure 1. A schematic illustration of the F/N/S junction.

similar critical temperature (T_c) (YBaCuO: 90 K, BiSrCaCuO: 80 K), they show quite different anisotropy in the electrical transport properties. Generally speaking, YBaCuO has an anisotropy parameter $\gamma = 5$, while BiSrCaCuO has γ larger than 100, although the parameter depends on the carrier concentration in superconductors. Such a difference in anisotropy is considered to have a strong influence on the transport properties of the F/N/S junctions. To elucidate the effect of spin-polarized QPs on the transport properties in F/S junctions, normal-metal/superconductor (N/S) tunnel junctions, Au/YBaCuO and Au/BiSrCaCuO tunnel junctions, were prepared for comparison.

2. Experiment

Figure 1 shows a schematic illustration of the Co/Au/YBaCuO or Co/Au/BiSrCaCuO junctions. The junctions were prepared on epitaxially grown YBaCuO and BiSrCaCuO thin films with a *c* axis orientation. The YBCO films of 50–60 nm in thickness were prepared by a pulsed-laser deposition technique on MgO (001) substrates or off-axis $SrTiO_3$ (001) substrates with a tilt angle of 20° towards the [110] direction. The YBCO films were patterned into a strip line with a width of 20 μm using a conventional photolithography technique with a wet etching process. The effective junction area was $100 \times 20\ \mu m^2$ for both junctions. The BiSrCaCuO films with a thickness of 150 nm were grown by the molecular beam epitaxy (MBE) technique on MgO (001) substrates. The junction area of $1 \times 1\ mm^2$ was patterned using a metal mask. For F/N/S junctions, Au layers were deposited on the superconducting films to reduce the junction resistance and to avoid the formation of a spin glass phase at the S/F interface [3, 6]. The Co metal of 50–300 nm thickness was deposited by an RF magnetron sputtering method on the Au layer. The superconducting properties of the films have been found to suffer severe degradation when the Co layer was directly sputtered onto the high-T_c film. The isolation effect of the Au barrier at the F/S interface provided a noticeable improvement in superconducting properties. Using this sandwich structure, the tunnel junction resistance showed a nearly exponential increase of about two orders of magnitude, with an increase in the thickness of the Au interlayer. A thickness of at least 10 nm was necessary for the Au barrier layer to prevent degradation of superconducting properties.

The Au layer of 50–200 nm thickness was also deposited for the fabrication of the Au/YBaCuO and the Au/BiSrCaCuO tunnel junctions. The current–voltage characteristics of the junctions were measured using a dc four-probe method and the conductance spectra were measured using a lock-in amplifier.

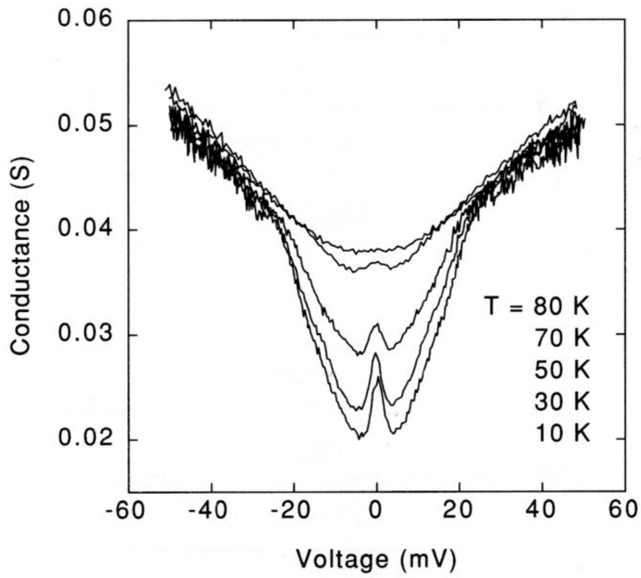

Figure 2. Conductance spectra of a Au/BiSrCaCuO junction measured between 10 and 80 K.

3. Results and discussion

Figure 2 shows the conductance spectra of the Au/BiSrCaCuO N/S junction measured at temperatures between 10 and 80 K. A V-shaped gap structure is clearly observed from which the energy gap value is determined to be 25 meV at 10 K. The observed gap structure is consistent with that measured by using the scanning tunnel spectroscopy (STS) [7, 8]. In our conductance spectra, a ZBCP structure is clearly observed in addition to the gap structure. The ZBCP amplitude decreases with increasing temperature until it disappears at T_c of the BiSrCaCuO film. The ZBCP structure is attributed to an Andreev reflection at the S/N interface and is strongly dependent on the crystal orientation of the superconductors. Taking into account the d-wave nature of high-T_c superconductors, Kashiwaya *et al* have theoretically derived an angle dependence of the ZBCP, which appears only when electrons flow along the *ab*-plane and should not appear along the *c*-axis. Observation of ZBCP indicates that in our N/S junction, a current flows along the *ab*-plane as well as along the *c*-axis direction. In other word, the surface of our BiSrCaCuO thin films is not atomically flat but subjected to many steps, as schematically illustrated in figure 3(*a*). In the case of the BiSrCaCuO thin films grown on the MgO substrate, several kinds of *c*-axis-oriented grains with different in-plane orientations are grown due to a large lattice mismatch between the BiSrCaCuO and the MgO. It means that there are many defects in the junction area. However, we can neglect those defects in the electrical measurement because they do not contribute to the ZBCP.

In the case of YBaCuO, we have to be careful in the preparation of the junctions, since YBaCuO is less stable than BiSrCaCuO. Therefore, reproducible observations of ZBCP are difficult in Au/YBaCuO junctions fabricated by an *ex situ* process due to the deterioration of the surface by exposure to air. To solve the problem, the Au inter-layer has been deposited *in situ* to fabricate the Co/Au/YBaCuO junction. In order to enhance the ZBCP, off-axis substrates have been used. It is known that an off-axis substrate is effective in avoiding

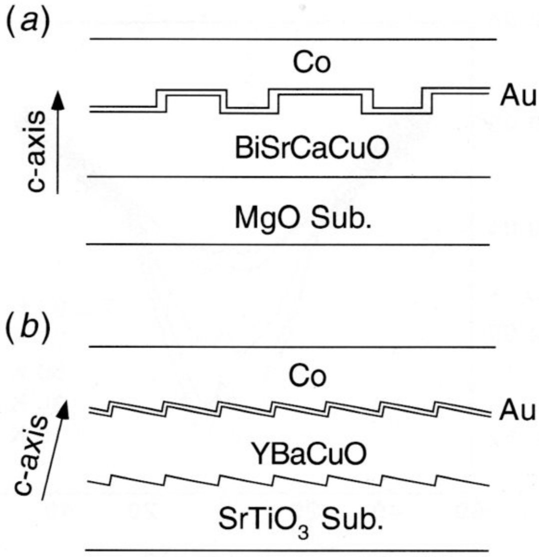

Figure 3. A schematic illustration of an interface of the F/N/S junction.

spiral growth and obtaining twin-free thin films, although it makes step structures on the surface of thin films as shown in figure 3(*b*). This structure is suitable for our purpose, since those steps should contribute to the ZBCP.

Figure 4 shows conductance spectra of the Co/Au/YBaCuO tunnel junction measured at temperatures between 10 and 65 K. This junction was fabricated on the off-axis substrates with a Au barrier layer of 30 nm in thickness. The gap structure and the ZBCP are clearly observed. The existence of the ZBCP is well explained by the tunnelling theory for anisotropic superconductors by assuming the tunnelling current is governed by the [110] surface [2]. It is considered that the differential conductance characteristics for the Co/Au/YBaCuO tunnel junction may be affected by the effective interface boundary and degree of spin polarization of the tunnel injector. For Co/Au/YBaCuO tunnel junctions along the [110] direction, the interface volume of the [110] surface can be estimated from the tilted angle along [11 sin 20°]. The [110] tunnel surface exists at the tunnelling boundary as well as on the *c*-axis-oriented surface. Therefore, the observed ZBCP due to the conductivity in the [110] surface is qualitatively consistent with the theory of the Andreev reflection [2].

In the case of the Co/Au/BiSrCaCuO junction, the ZBCP is clearly observed up to T_c of the film (~80 K) as shown in figure 5, this feature being the same as that of the Au/BiSrCaCuO junction. However, it is found that the amplitude of the ZBCP is smaller than that of Au/BiSrCaCuO junctions. This result indicates that the ZBCP is suppressed by spin polarization of QPs. Suppression of the ZBCP has been predicted theoretically by Kashiwaya *et al* [2]. Compared with the Co/Au/YBaCuO junction, the temperature dependence of the ZBCP in the Co/Au/BiSrCaCuO junction is quite different. The ZBCP in the Co/Au/BiSrCaCuO junction can be observed up to T_c for both F/N/S and N/S tunnel junctions, whereas it disappears around 40 K in the YBaCuO junctions. The difference may be attributed to the difference in anisotropy of the two superconductors. Since the ZBCP is caused by an anisotropy in the high-T_c superconductors, it can

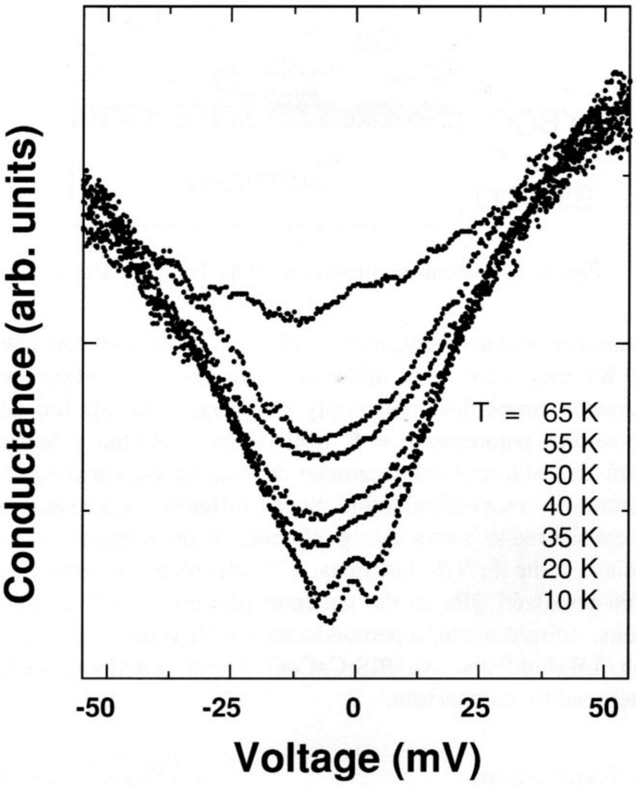

Figure 4. Conductance spectra of a Co/Au/YBaCuO junction measured between 10 and 65 K.

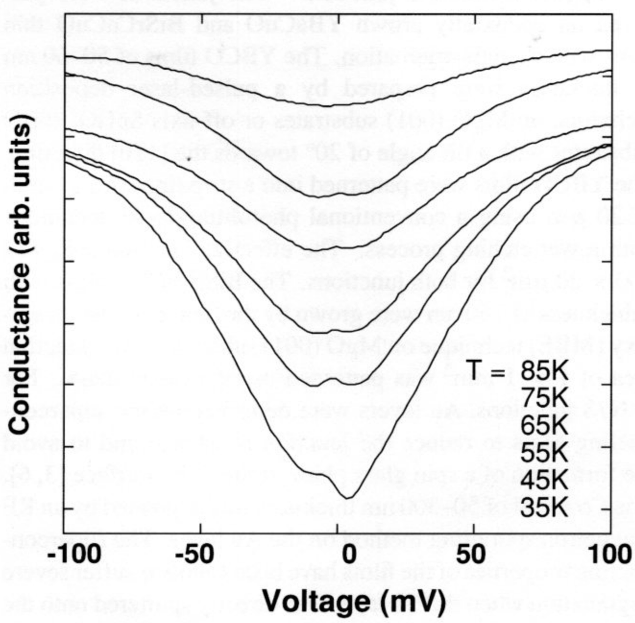

Figure 5. Conductance spectra of a Co/Au/BiSrCaCuO junction measured between 35 and 85 K.

be concluded that a large anisotropy causes a large amplitude of the ZBCP. Therefore, the BiSrCaCuO, which has a large anisotropy parameter $\gamma > 100$, shows larger ZBCP than the YBaCuO in which γ is nearly equal to 5.

Finally, the dependence of transport properties of Co/Au/BiSrCaCuO junctions for different thicknesses of Au interlayers is discussed. Figure 6 shows conductance spectra of Co/Au/BiSrCaCuO junctions fabricated on the same BiSrCaCuO thin film with different Au thickness of 20, 30

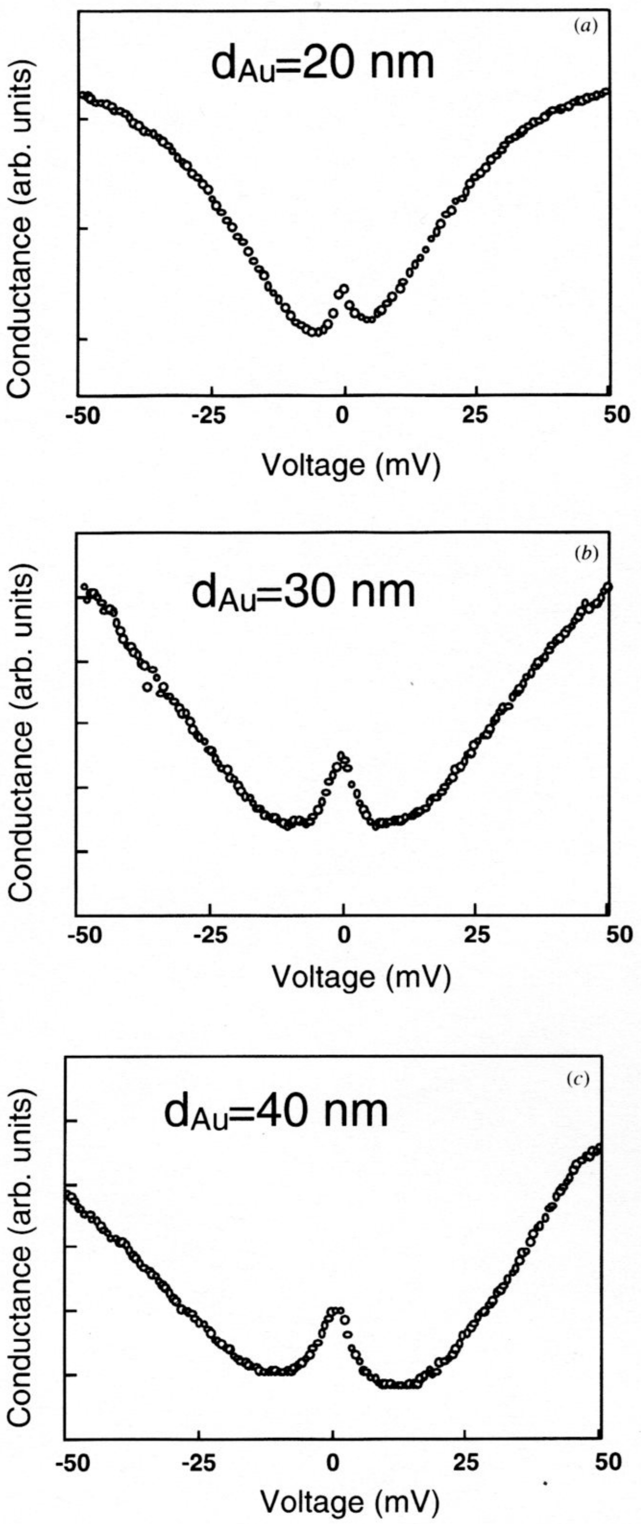

Figure 6. Conductance spectra of Co/Au/BiSrCaCuO junctions with different Au thicknesses: (*a*) 20 nm, (*b*) 40 nm and (*c*) 50 nm.

and 40 nm. These conductance spectra have been normalized at 50 mV. The amplitude of the ZBCP decreases with increasing thickness of the Au layer. The Au inter-layer plays the role of a protection layer for preventing a reaction between the magnetic materials and high-T_c superconductors.

On the other hand, however, the spins are scattered by the Au layer. Therefore, the degree of spin polarization of the QPs decreases with increasing thickness of the Au layer. This indicates that the ZBCP increases with the decreasing degree of the spin polarization of QPs injected into the superconductors. Such a suppression of the ZBCP depending on the Au thickness agrees with Kashiwaya's calculation. The Au thickness dependence of the degree of the spin polarization in the F/N/S junctions has been confirmed by the suppression of the critical current in Co/Au/YBaCuO junctions. In that case, the current gain for the suppression of the critical current decreases with increasing Au thickness. This result also corresponds to the change of the degree of the spin polarization of QPs.

Finally we should mention the thickness of the Au. Taking into account the diffusion length of the spins, the Au layer should be less than 1 nm. However, the effect of the spin polarization was confirmed only in the Au layer several nm in thickness. The result can be interpreted as follows: effective thickness is smaller than the thickness indicated in this paper because the surfaces of the superconductor thin films have a roughness of several nanometres.

4. Summary

In summary, conductance spectra of the Co/Au/YBCO and the Co/Au/BSCCO tunnel junctions were studied. These junctions showed gap structures with the ZBCP. It was confirmed that the ZBCP was strongly dependent on the direction, the anisotropy of the superconductors and the degree of the spin polarization of the QPs injected into the superconductors.

Acknowledgment

This work has been supported by the Joint Research Project between Japan and Korea by Japan Society for the Promotion of Science (2000-6-114-01-2).

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