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Naoki Koshizuka
Shibaura Institute of Technology

Katsuaki Sato
Tokyo University of Agriculture an...

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Tunneling Spectra of Co/I/BiSrCaCuO Tunnel Junctions

Takayuki ISHIBASHI*, Kazushige SATO, Genda GU[1], Naoki KOSHIZUKA[2] and Katsuaki SATO
Faculty of Technology, Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei, Tokyo 184-8588, Japan
[1]*School of Physics, University of New South Wales, Sydney, NSW 2052, Australia*
[2]*Superconductivity Research Laboratory, ISTEC, 1-10-13 Shinonome, Koto-ku, Tokyo 135-0062, Japan*

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Ferromagnet/insulator/superconductor (F/I/S) tunnel junctions consisting of Co and $Bi_2Sr_2CaCu_2O_x$ (BSCCO) have been fabricated in order to study whether the superconducting properties are affected by the spin-polarized current. Co is a ferromagnetic metal with a spin polarization of approximately 35%, and BSCCO is a high-T_c superconductor with critical temperature (T_c) of 80–90 K. The junctions with $100 \times 100\,\mu m^2$ have been fabricated using photolithography on the cleaved BSCCO single crystal. As a reference, Au/I/BSCCO tunnel junctions have also been fabricated in the same manner. In both junctions, gap structures were clearly observed in dI/dV spectra. However, the gap energy of 28 mV obtained at 30 K for the Co/I/BSCCO junction was smaller than that obtained for the Au/I/BSCCO junction. The zero-bias conductance peak (ZBCP) was observed clearly for the Au/I/BSCCO junction. It is considered that these differences between the Co/I/BSCCO and the Au/I/BSCCO junctions are due to the spin-polarized current flowing through the junctions.

KEYWORDS: spin-polarized current, tunnel junction, Co, BSCCO, zero-bias conductance peak, energy gap

1. Introduction

The studies of ferromagnet/insulator/superconductor (F/I/S) tunnel junctions are expected to provide an understanding of the superconductivity and development of new functional devices. The first experiment on F/I/M junctions was, to our knowledge, demonstrated by Tedrow and Meservey for ferromagnet/Al-O/Al junctions, although Al is a low-T_c material.[1)] They showed that the conductance spectrum is composed of two different quasi-particle density of states (DOS) having up- and down-spins, and they determined the spin polarization for several ferromagnetic metals. For high-T_c superconductors, substantial suppression of superconductivity by the injection of spin-polarized current has been observed.[2–4)] From a theoretical viewpoint, the conductance spectra of the F/I/S junctions have been calculated in terms of the Andreev reflection to the d-wave superconductor.[5,6)] We therefore expect that the study of F/I/S junctions can reveal useful information such as the spin polarization of the electrons, the nonequilibrium superconductivity and the symmetry of the electrons.

In this paper, effects induced by spin-polarized current are investigated using $Co/I/Bi_2Sr_2CaCu_2O_x$ (Co/I/BSCCO) tunnel junctions. The Co metal is chosen as a spin injector, because it is a ferromagnetic material having a spin polarization of 35%, and its physical properties are well known. The BSCCO is a high-T_c superconductor having a critical temperature of 80–90 K (for 2212 phase) and is one of the most stable high-T_c superconductors.

2. Experimental

Figure 1 shows a schematic diagram of the Co/I/BSCCO tunnel junction used in this experiment. The junction is prepared on the cleaved surface, which is the $a-b$ plane, of a BSCCO single crystal grown by the traveling solvent floating zone (TSFZ) method.[7)] The chemical composition of Bi : Sr : Ca : Cu is determined as 2.1 : 1.9 : 1.0 : 2.0. The junction area of $100 \times 100\,\mu m^2$ was patterned by the conventional photolithography method. The junction area was formed by using a lift-off technique with a 500-nm-thick CaF_2 film. A Co metal of 50 nm thickness was deposited on the lift-off area by an RF magnetron-sputtering technique at room temperature. A Au layer of 200 nm thickness was deposited on the Co and the BSCCO as the electrodes. As a reference, Au/I/BSCCO tunnel junctions were also fabricated using the same lift-off process on a single crystal BSCCO cleaved from the same crystal as used for the Co/I/BSCCO junctions.

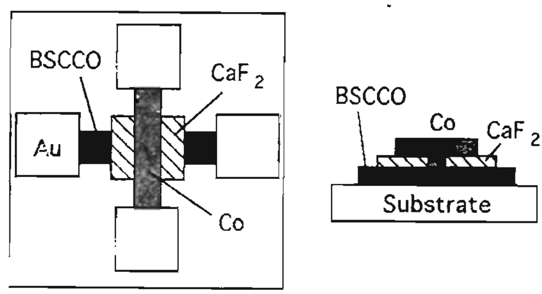

Fig. 1 Schematic drawing of the Co/I/BSCCO junctions. (a) top view, (b) cross section.

Transport properties were measured using the conventional four probe method in a refrigerator-type cryostat between 30 K and room temperature. Spectra of dI/dV were obtained by numerically calculation from $I-V$ curves.

3. Results and Discussion

Figure 2 shows dI/dV spectra of several Co/I/BSCCO junctions measured at 30 K. The junction resistances of these junctions are (a) 0.59, (b) 0.67 and (c) 2.3 Ω. Clear V-shaped gap structures are observed in all samples, with gap energies of (a) 28, (b) 42 and (c) 58 mV. The superconducting gap 2Δ of BSCCO has been determined to be 50–100 meV by scanning tunneling spectroscopy (STS). The gap energy values determined using the Co/I/BSCCO junctions are almost half of these values. The shapes of our gap structures are almost similar to the gap structures measured by STS and various devices;[8–11)] however, no peaks of DOS immediately above the gap are observed in our junctions. In order to confirm whether this difference is related to spin polarization of the Co metal, we studied the $I-V$ characteristics of Au/I/BSCCO

*E-mail address: bashi@cc.tuat.ac.jp

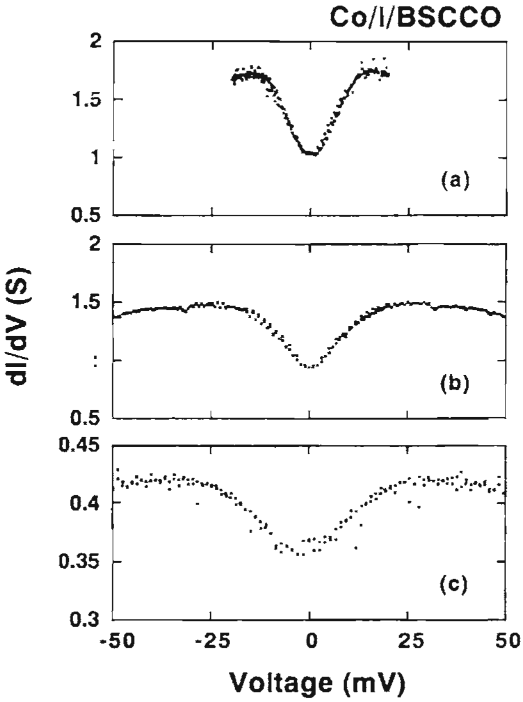

Fig. 2. V-dI/dV of the Co/I/BSCCO junctions at 30 K. The junction resistance are (a) 0.59, (b) 0.67 and (c) 2.3 Ω.

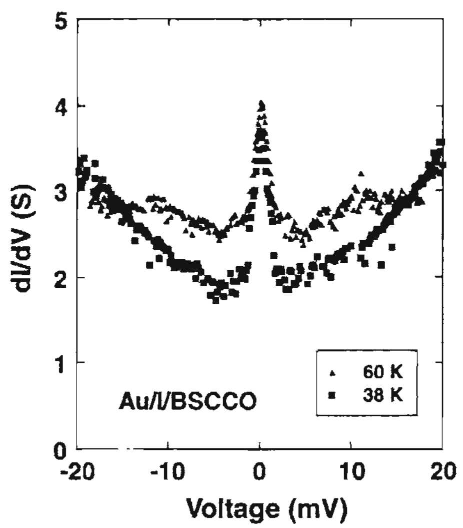

Fig. 3. V-dI/dV of the Au/I/BSCCO junction at 30 and 60 K.

junctions, because the Au is a normal metal without spin polarization. Conductance spectra of the Au/I/BSCCO tunnel junction measured at 38 and 60 K are shown in Fig. 3. We can compare this result with the dI/dV spectrum of the Co/I/BSCCO junction shown in Fig. 2(a), since single crystals used for both junctions are cleaved from the same single crystals and the junction resistance and the measuring temperature are almost the same. As shown in Fig. 3, the gap structure with zero-bias conductance peak (ZBCP) is clearly observed in the Au/I/BSCCO junction. The existence of the gap can be confirmed by the temperature dependence, as shown in Fig. 3. The size of the gap is determined to be larger than 40 mV at 30 K, although the entire gap could not be measured due to the existence of a critical current of BSCCO. Due to the low resistivity (~1 Ω) of these junctions, the current easily reaches the critical current of BSCCO in the c-axis direction.

The energy gap of the Co/I/BSCCO junction is about half of that of the Au/I/BSCCO junction, although the junctions were made from the same single crystal. This result suggests that the superconductivity of the BSCCO is suppressed by the spin-polarized current flowing through the junction. The suppression of the critical current by the injection of the spin-polarized current has been reported by several groups.[2–4] If this is also the case in our junction, the superconducting gap observed in the F/I/S junctions may also be subjected to the suppression.

Theoretical approaches taking into account the d-wave superconductor have shown that the ZBCP can only be observed for the current flowing in the [110] direction and not for the current along the c-axis.[12] Here the [110] direction is equivalent to the [100] or [010] directions of BSCCO, but we describe, in this paper, the directions as in ref. 12. The theoretical calculation indicates that our Au/BSCCO junction has a current flow component in the [110] direction in addition to the [001] direction expected from the structure. The existence of the steps on the cleaved BSCCO surfaces may be the cause of this phenomenon. On the other hand, however, no reproducible ZBCP has been observed in the Co/I/BSCCO junctions. This result indicates that the ZBCP is strongly suppressed by the spin-polarized current. This is qualitatively consistent with the result of a theoretical calculation for the spin polarization dependence of the conductance in the ferromagnet/insulator/superconductor tunnel junction by Kashiwaya *et al.*[5]

Finally, we discuss the shapes of the gap structures. As stated before, no peaks are observed around the superconducting gap energy in the Co/I/BSCCO junctions. It is considered that the disappearance of the peaks is due to the effect of temperature or the disorder of the interface of the tunnel junction. However, we suggest other possibilities to explain this result. One is that the dI/dV spectra of the Co-junctions are strongly affected by the spin current. Kashiwaya *et al.* have shown that the peaks around gap energy disappear for the F/I/S junction along [110].[5] This is consistent with our results if the current flows in the [110] direction in addition to the [001] direction, as discussed above. The other possibility is that the spectra of the Co-junctions show pseudo-gap structures. The shapes of gap structures are similar to those of BSCCO single crystals measured at temperatures above T_c by STS.[13] In this case, a gap for the spin excitation, the so-called the pseudo-gap, may appear in the tunneling spectra measured by the spin-polarized current measurement if the superconductivity is suppressed by the spin-polarized current. In both cases, the contribution of the spin current must be considered. In order to obtain further evidence for these considerations, systematic studies performed by changing the doping level of superconductors and the temperature as well as the degree of spin polarization of ferromagnetic metals will be helpful.

4. Summary

Effects in conductance spectra induced by spin-polarized current were investigated using the Co/I/BSCCO tunnel junctions. The characteristics were compared with those of the Au/I/BSCCO tunnel junctions fabricated using the same procedure. V-shaped gap structures were observed for all Co/I/BSCCO junctions. The value of the gap energy was about one half of that of the Au/I/BSCCO junction. The ZBCP was not observed in the Co/I/BSCCO junctions while it was clearly observed for Au/I/BSCCO. We believe that these suppressions of the gap as well as of the ZBCP are caused by the spin-polarized current flowing through the tunnel junctions. Furthermore, it was considered that the shape of the gap without DOS peaks immediately above the gap was also due to the spin-polarized current. These results indicate that the superconducting properties are strongly affected by the spin-polarized current flowing through F/I/S tunnel junctions.

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