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Spin tunneling in Co/Au/I/BiSrCaCuO tunnel junctions

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Conductance spectra of $Co/Au/I/Bi_2Sr_2CaCu_2O_{x+8}$(BSCCO) tunnel junctions have been measured to investigate the tunneling of spin polarized quasiparticles. BSCCO thin films prepared by molecular beam epitaxy are used for the Co/Au/I/BSCCO tunnel junctions because those have flat surface without any large steps as observed on the cleaved surface of single crystals. The superconducting gap is clearly observed in the conductance spectra at the temperature below the critical temperature T_c. In addition, a splitting of the zero bias conductance peak and the imbalance of the peak heights are observed. This feature is induced by the spin polarization of quasiparticles injected into the superconductors. *© 2001 American Institute of Physics.*
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I. INTRODUCTION

In order to fabricate new functional devices using ferromagnet/insulator/superconductor (FM/I/S) tunnel junctions, it is important to understand transport properties in these junctions. A number of researchers have studied a normal-metal/insulator/superconductor (S/I/N) tunnel junction up to date, because the S/N junction is a good probe to understand supercomputing gap, transport properties between the normal metals and the superconductors etc. The transport properties in S/I/N junctions have been analyzed theoretically by Blonder–Tinkham–Klapwijk (BTK) theory.[1] Recently, the theoretical approach based on the BTK theory has been developed for the *d*-wave superconductors and the FM/I/S tunnel junctions.[2,3]

Although there are a few experimental reports about the FM/I/S tunnel junctions with high T_c superconductors,[4–6] most of which focused on the suppression of superconductivity and ignored transport properties of the FM/I/S tunnel junction itself. We must study the transport properties such as the spin polarization of quasiparticles, diffusion length, and mean free path in order to realize new functional devices. In the case of low T_c superconductors, on the other hand, the FM/I/S tunnel junctions are good probes for understanding the ferromagnets. Tedrow and Meservey determined the spin polarization of the ferromagnetic metals from the conductance spectra of the FM/I/S tunnel junctions in the 1970s.[7] We also consider it a useful way to analyze the conductance spectra in order to investigate the transport properties of the FM/I/S tunnel junctions using high T_c superconductors.

In this article, we report on conductance spectra of the $Co/Au/I/Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO) tunnel junctions prepared on epitaxially grown BSCCO thin films. We have reported Co/I/BSCCO tunnel junction prepared on BSCCO single crystals previously.[8] In that case, the surface of the single crystal has large steps. In order to prevent this problem, BSCCO thin films are used. 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.

II. EXPERIMENTS

Figure 1 shows a schematic diagram of the Co/Au/I/BSCCO tunnel junction used in this experiment. The junctions were prepared on epitaxially grown BSCCO thin films.[9] The x-ray diffraction and the reflection high energy electron diffraction showed that the BSCCO thin films having flat surfaces were grown with *c*-axis orientation. The chemical composition of Bi:Sr:Ca:Cu is 2:2:1:2. The junction area of 1×1 mm^2 was patterned by the metal mask. A Co metal of 50–300 nm thickness was deposited by an electron beam evaporator. Au metal was deposited on the BSCCO with a thickness of 10 nm to prevent the interface from chemicals and to decrease contact resistance.[6] The Au layer of 200 nm thickness was also deposited as electrodes. As a reference, Au/I/BSCCO tunnel junctions were also prepared.

Transport properties were measured by the conventional four probe method in a refrigerator-type cryostat between 25 and 150 K. Spectra of dI/dV were measured by the modulation method.

III. RESULTS AND DISCUSSION

Figure 2 shows $dI/dV-V$ curve of the Co/Au/I/BSCCO tunnel junction measured at 25–150 K. A superconducting gap structure, $\Delta = \sim 80$ meV, is observed clearly below 120 K. This temperature corresponds to an onset critical temperature ($T_{c(\mathrm{onset})}$). This higher $T_{c(\mathrm{onset})}$ is due to a mixture of the

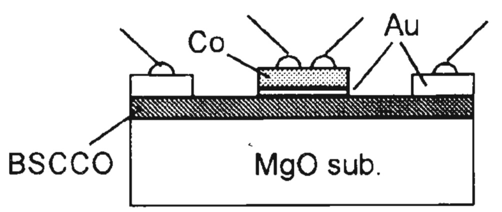

FIG. 1. A schematic drawing of the Co/Au/I/BSCCO tunnel junction.

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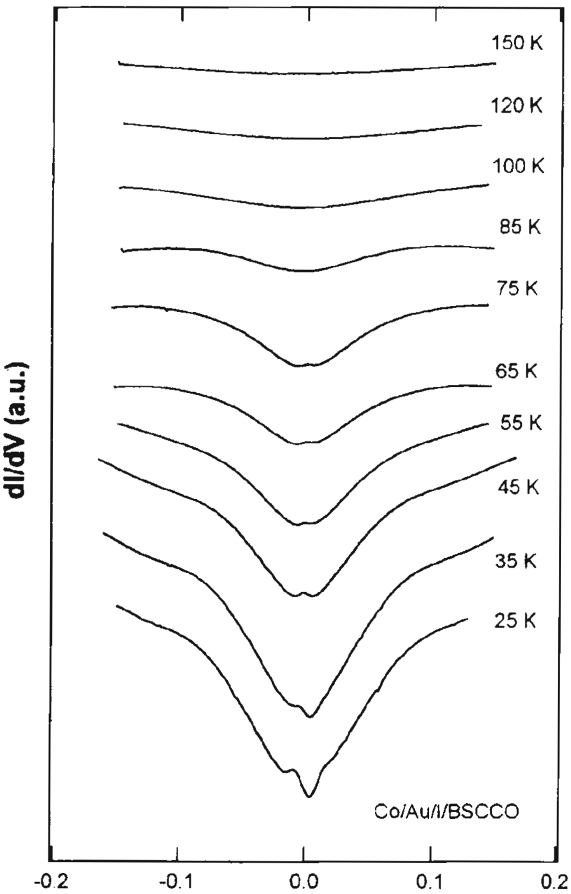

FIG. 2. Conductance spectra of the Co/Au/I/BSCCO tunnel junction measured at 25–150 K.

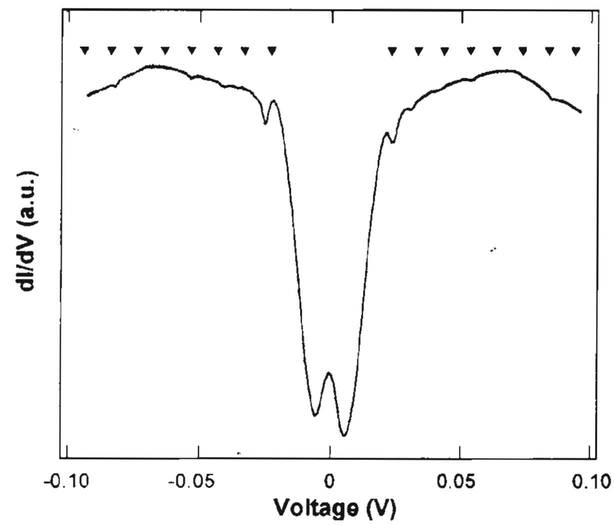

FIG. 3. A conductance spectrum of the Au/I/BSCCO tunnel junction measured at 15 K.

2212 and the 2223 phases. The $T_{c(R=0)}$ of this sample is 60 K. In addition, zero bias conductance peak (ZBCP) is observed around the zero voltage. The origin of the ZBCP is considered to be the Andreev reflection, which occurred at the interface between the superconductor and the normal metal. In the usual case, the ZBCP is observed at absolutely zero voltage. However, in this case, the ZBCP shifted from the zero voltage to -10 mV, and another smaller peak appeared at an opposite side. For comparison with the N/I/S junction without ferromagnetic materials, the Au/I/BSCCO tunnel junction was also measured as shown in Fig. 3. In the case of the Au/I/BSCCO junction the superconducting gap, $\Delta = 25$ meV, is also observed, although the ZBCP appears at the zero voltage.

The experimental observations of the splitting of ZBCP for N/I/S tunnel junctions with high T_c superconductors have been reported, and the theoretical calculations have also been reported. Various types of the ZBCP splitting are considered: the pairing symmetry of $d+is$ wave, the Zeeman effect, or the exchange interaction. In our result, the imbalance of the peak heights has been observed in addition to the ZBCP splitting. We are convinced that this feature is related to a ferromagnetism of the electrode: in other words, the spin polarization of quasiparticles flowing through the tunnel barrier. From this result, the first expectation due to pairing symmetry, the $d+is$ wave, is excluded as a candidate of the origin of these results, because the ZBCP splitting cannot be observed in the Au/I/BSCCO tunnel junctions.

We consider that the Zeeman effect may be the origin of the ZBCP splitting in the FM/I/S junctions. The ZBCP may split if the quasiparticles are affected by the effective internal magnetic field of the Co metal with an hexagonal crystal structure. The value of the internal magnetic field is 227 kOe, which is enough to split the ZBCP. The imbalance of the split ZBCP should occur due to the spin polarization of the quasiparticles.

Recently, Kashiwaya *et al.* calculated the conductance spectra of the FM/I/S tunnel junctions in the case which the exchange interaction exists in the insulator, and they have shown a splitting of the ZBCP and the imbalance of the peak heights.[2] It seems that our result is in good agreement with their results. Therefore, we consider that the spin polarized quasiparticles, which flow through the tunnel junctions, induce spin imbalance in the superconductors, although in our case, we do not understand what the magnetic layer working for the exchange interaction is.

In order to conclude the origin of the ZBCP splitting, further studies are needed, such as magnetic field dependence, a polarization dependence, carrier concentration dependence, etc.

Finally, we show a periodic oscillation observed in the conductance spectrum of the Au/I/BSCCO tunnel junction above the energy gap in Fig. 3. This oscillation is considered to be the MacMillan–Rowel oscillation[10] or the Tomasch oscillation.[11] In both cases, periodic dips appear on the conductance spectra above the energy gap. The voltage spacing between the dips in the MacMillan–Rowel oscillation are given by

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$$\Delta V = \frac{h v'_{FN}}{4 e d_N}, \qquad (1)$$

where v'_{FN} is the renormalized Fermi velocity in the normal metal and d_N is the thickness of the normal metal. Positions of the dips are shown in Fig. 3, where v'_{FN} of 1×10^8 cm/s and d_N of 100 nm are used. They are in good agreement with the experimental data. The value of v'_{FN} is suitable for that of Au. However, we cannot conclude whether this structure is due to the MacMillan–Rowel oscillation or the Tomasch oscillation. In order to confirm this, we must measure a thickness dependence of the Au and the BSCCO films. In any case, however, this result indicates that the interface of the junction is sufficiently flat to raise the interference effect of electrons in the Au layer or quasiparticles in the BSCCO. Therefore, we can consider that the Co/Au/I/BSCCO also has a good interface, because the configuration of the tunnel junction is the same as that of the Au/I/BSCCO tunnel junction.

IV. CONCLUSIONS

The splitting of the ZBCP and the imbalance of the peak heights are observed, in addition to the clear superconducting energy gap, in the conductance spectra of the Co/Au/I/BSCCO tunnel junctions. It is considered that this splitting of the ZBCP is due to the spin polarization of the quasiparticles flowing through the tunnel junctions. In the case of the Au/I/BSCCO tunnel junctions, the ZBCP splitting was not observed, and the periodic structure, which is due to the interference of carriers, appeared above the energy gap. This result indicates that the interface of the junctions used in this experiment was sufficiently flat.

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