Spin injection effect in thin Bi2212 single crystal

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Abstract. The influence of spin-injection on the in-plane transport properties of thin Bi2Sr2CaCu2O8 (BSCCO) single crystal has been investigated. The in-plane transport measurements without and with spin injection were carried out at 77 K by four terminal method. The in-plane critical current was strongly reduced by injecting the current from Co/Au electrodes formed on the BSCCO bridge with 50 nm wide and 450 nm thick. Furthermore, it was observed that magnetic field dependence of the magnetoresistance shows a hysteresis loop. These results indicate that the in-plane superconductive transport property is affected by the spin-injection related to the magnetization of Co.

1. Introduction

The control of superconductivity by spin-polarized quasiparticle injection (spin-injection) has been a subject of great interest from the point of view of development of novel superconducting spintronic devices as well as understanding of fundamental physics in a ferromagnet-superconductor hybrid system [1]-[4]. Although there have now been many works related to the spin-injection effect in high temperature superconductors (HTS) [2],[5],[6], in the case of HTS, it is important to classify the direction of spin-injection because superconducting properties of HTS are anisotropic. However, this may not be so simple for HTS film samples which have been used in most of spin-injection experiments because of interface roughness. Therefore, in order to understand the influence of the spin-injection effect on transport in detail, it is required to use the high-quality samples with flat surface in experiments.

It is well known that high Tc superconductor Bi2Sr2CaCu2O8 (BSCCO) single crystal can be regarded as a stack of two dimensional superconducting layer of 0.3 nm and insulating layer of 1.2 nm. Due to the layered crystal structure, the properties of BSCCO are strongly anisotropic. As a result, a single crystal of BSCCO acts as a densely packed naturally formed stack of intrinsic Josephson junctions (IJJs) [7, 8]. Thus, large spin injection effect can be expected in BSCCO single crystals because of extremely thin superconducting layer. From this point of view, in our previous work, we studied the transport properties of IJJs in Co/BSCCO hybrids under applied magnetic fields parallel to the layer and observed the hysteretic field dependence of critical current Ic of IJJs due to spin injection effect [9]. This suggests that the in-plane transport property of BSCCO is also affected by spin injection. In this paper, we report on the influence of the spin injection effect for the in-plane transport properties of thin flake BSCCO.
2. Experimental

An optical image and a schematic view of the fabricated sample are shown in figure 1. The sample is composed of BSCCO bridge and two Co/Au electrodes as spin injector. The width and thickness of BSCCO bridge are 50 mm and 450 nm, respectively, and Co (20 nm)/Au (10 nm) electrodes with lateral dimensions of $50 \times 50 \mu m^2$ are formed on the bridge separated by a distance of 50 $\mu m$.

BSCCO single crystals with critical temperatures of $85-90 K$ were grown by conventional melting method [10]. A piece of BSCCO single crystal of $400 \times 600 \mu m^2$ was adhered to glass substrate and was cleaved until its thickness was around 450 nm. Then, thin Au (10 nm) and Co (20 nm) layers were immediately deposited by thermal evaporation and DC sputtering. Here, Au layer which is thinner than the spin diffusion length of $\sim 60$ nm [11] was used to reduce the contact resistance between Co and BSCCO surface without spin scattering. The device structure shown in figure 1 was fabricated by photolithography and Ar ion milling.

The in-plane transport measurements without and with spin injection were carried out at 77 K by four terminal methods. The magnetic field was applied to parallel of the layer by solenoid coil and swept in both direction.

3. Results and Discussion

Figures 2(a) and 2(b) show the current-voltage ($I$-$V$) characteristics at 77 K for $I_{\text{inj}} = 0, 0.4, 0.5$, and 0.6 mA in the magnetic fields of (a) 0 mT and (b) 60 mT.

![Figure 1 Optical image and a schematic view of the fabricated sample.](image1)

![Figure 2 $I$-$V$ characteristics for different injection currents in the magnetic fields of (a) 0 mT and (b) 60 mT.](image2)
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Figure 3 (a) Critical current and (b) normalized critical current as a function of the injection current for $B=0$ and 60 mT. 0.6 mA in the magnetic field $B$ of zero and 60 mT, respectively. The critical current $I_c$ without injection is 2.1 mA for $B=0$ and 1.5 mA for $B=60$ mT. Here, we estimated the critical current $I_c$ from $(I_c^+-I_c^-)/2$ using $I_c^+$ and $I_c^-$ defined as the current values at $V=\pm15$ mV. One can see that the $I$-$V$ curves show considerably change with increasing $I_{inj}$, and nearly full suppression of $I_c$ could be achieved at $I_{inj}=0.6$ mA. In figures 3(a) and 3(b), $I_c$ and $I_c/I_c^0$ for $B=0$ and 60 mT are plotted as a function of $I_{inj}$, where $I_c^0$ is the critical current for $I_{inj}=0$ mA. As expected, $I_c$ decrease with increasing $I_{inj}$ and this indicates that the in-plane superconductive transport property is affected by the spin-injection related to the magnetization of Co. In this work, we did not demagnetize the sample before measurement, so that Co has some residual magnetization even without applied magnetic field. Therefore, the difference between the dependences without and with magnetic field comes from the magnetic property of Co, or polarization of Co layer.

As mentioned above, we observed the suppression of critical current by injecting the current from Co and attributed it to non-equilibrium superconductivity due to spin-injection. However, such a non-equilibrium state can be caused by the injection of non-polarized quasiparticle. Therefore, in order to check whether the observed suppression of $I_c$ is related with spin-injection, we measured field dependence of transport properties at constant injection current because the spin-polarized nature of

Figure 4 Magnetic field dependence of the sample voltage for $I=1$ mA.
Co has a hysteresis. Figure 4 shows the field dependence of the sample voltage $V$ at different injection currents when the sample was biased at $I = 1$ mA. The field was swept up and down between $B = -60$ mT and 60 mT. As seen from figure 4, the $V(B)$ behaviour is hysteretic, and the field at which $V$ becomes minimum is $-4$ and $+17$ mT independent of $I_{ij}$ in contrast to the voltage change. Therefore, the most likely explanation is that the observed $V(B)$ behaviour reflects the magnetic hysteresis loop of Co layer and the voltages with minima are observed at the coercive field of Co because a higher $I_c$ could be expected at the coercive field where the average spin polarization of Co becomes zero. On the other hand, in the case of non-polarized quasiparticle injection, we expect the hysteresis-free behaviour of $V(B)$. Indeed, we observed the non-hysteretic $V(B)$ behaviour for the device without Co layer. Figure 5 shows the $I$-$V$ and $V$-$B$ characteristics of the device without Co layer measured at 77 K. It is found from figure 5 that the critical current is suppressed by the non-polarised quasiparticle injection similar to that of the device with Co shown in figure 2 but the $V$-$B$ characteristic does not show hysteresis. Therefore, we believe that the observed suppression of superconductivity is caused by the spin-injection although we cannot exclude the possibility of heating-effect due to non-polarized quasiparticle injection completely.

4. Conclusion
We fabricated the in-plane spin-injection devices using thin flake BSCCO single crystals. The critical current of the sample decreases with increasing the spin-injection current. Magnetic field dependence of voltage showed hysteresis and the dip structure. It is found that spin injection into thin flake BSCCO affects superconductivity in surface of BSCCO transport.

References
[1] Vas’ko V A, Larkin V A, Kraus P A, Nikolaev K R, Grupp D E, Nordman C A and Goldman A M, 1997, Phys. Rev. Lett. 78 1134
[2] Fratila L, maurin I, Dubourdieu C and villégir J C 2005 Appl. Phys. Lett. 86 122505
[3] Dong Z W, Ramesh R, Venkatesan T, Johnson M, Chen Z Y, Pai S P, Talyansky V, Sharma R P, Shreekala R, Lobb C J and Greene R L 1997 Appl. Phys. Lett. 71 1718
[4] Soltan S, Albrecht J and Habermeier H-U 2004 Phys. Rev. B 70, 144517
[5] Yeh N-C, Vasquez R P, Fu C C, Samoilov, Li Y, Vakili K 1999 Phys. Rev. B 60, 10522
[6] Plausinaitiene V, Abrutis A, Vengalis B, Butkute R, Senator J P, Saltyte Z and Kubilius V 2001 Physica C 351, 13
[7] Kleiner R, Steinmeyer F, Kunkel G and Müller P 1992 Phys. Rev. Lett. 68 2394
[8] Oya G, Aoyama N, Irie A, Kishida S and Tokutaka H 1992 Jpn. J. Appl. Phys. 31 L829
[9] Irie A, Otsuka M, Murata K, Yamaki K and Kitamura M 2015 IEEE Trans. Appl. Supercond. 25 3
[10] Irie A, Sakakibara M and Oya G 1994 IEICE Trans. Electron. E77-C 1191
[11] Ji Y, Hoffmann A, Jiang J S and Bader S D 2004 Appl. Phys. Lett. 85 6218