Magnetization-Dependent Critical Current of intrinsic Josephson junctions in Co/Au/Bi$_2$Sr$_2$CaCu$_2$O$_y$ mesa structures

Akinobu Irie, Naohiro Arakawa, Hiroshi Sakuma, Michihide Kitamura, Gin-ichiro Oya
Department of Electrical and Electronic Systems Engineering, Utsunomiya University, 7-1-2 Yoto, Utsunomiya 321-8585, Japan
E-mail: iriea@cc.utsunomiya-u.ac.jp

Abstract. We have investigated the critical current $I_c$ of intrinsic Josephson junctions (IJJs) in Co/Au/Bi$_2$Sr$_2$CaCu$_2$O$_y$ mesa structures as a function of magnetic field. The current-voltage characteristics of the mesas before a magnetization of Co layer showed the multiple quasiparticle branches with hysteresis similar to that of conventional IJJs. On the other hand, the magnetic field dependence of $I_c$ clearly showed hysteretic behavior different from that of conventional IJJs. It is found that such dependence corresponds to the magnetization curve of the Co layer and the $I_c$ has a maximum at the coercive field of the Co layer. The observed modulation of $I_c$ of the Co/Au/Bi$_2$Sr$_2$CaCu$_2$O$_y$ mesa is attributed to the injection of the spin-polarized current.

1. Introduction
The spin-dependent electronic transport in the system of ferromagnet/superconductor (F/S) hybrid structure is a topic of great current interest because it is not only important for fundamental understanding of the physics but also has potential application as spintronics. In such a system, spin injection is the key technique for introducing steady-state spin nonequilibrium into superconductors. Therefore, there have been a number of studies on the spin injection into the low and high $T_c$ superconductors so far [1, 2, 3, 4, 5]. Recent experiments of Vas’ko et al. for epitaxial La$_{2/3}$Sr$_{1/3}$MnO$_3$/La$_2$CuO$_4$/DyBa$_2$Cu$_3$O$_7$ heterostructures show that current injection from the ferromagnetic layer reduces the critical current of the superconductor significantly [2]. This implies that F/S hybrids based on high-$T_c$ superconductors is one of good candidates for the spin device operating at higher temperature. Furthermore, the experiments of spin injection into high $T_c$ superconductors can be expected to provide new information on the nature of $c$-axis transport properties.

Now, it is established that the high-$T_c$ superconductors such as Bi$_2$Sr$_2$CaCu$_2$O$_y$ (BSCCO) and (Bi$_{1-x}$Pb$_x$)$_2$Sr$_2$CaCu$_2$O$_y$ (BPSCCO) consist of a stack of atomic-scale Josephson junctions called intrinsic Josephson junctions (IJJs) [6, 7]. In this case, the thickness of the CuO$_2$ superconducting layer is only 0.3 nm, and hence IJJs may be more sensitive to the spin injection compared with the superconducting bulk and thin film. That is, IJJs may act as a sensor of the spin-polarized current. Indeed, recent experimental studies show that the spin injection leads to the reduction of the critical current of IJJs and the superconducting gap [8, 9].
addition, the study of the spin-injection effect on IJJs may provide useful information on the pairing mechanism because in the case of IJJs the spin-polarized electrons are injected into CuO$_2$ planes through other insulating layers by tunneling process. However, there is no systematic study of the spin injection into IJJs and the effect has been hardly understood.

Here, we investigate the field dependence of the critical current $I_c$ of IJJs in the Co/Au/BSCCO mesa structures and find that $I_c$ is suppressed depending on the magnitude of the magnetization of the Co layer.

2. Experimental
We have measured the superconducting and magnetic properties of mesa structures consisted of Co/Au/BSCCO. We used as-grown BSCCO single crystals prepared by a conventional melting method [10]. The critical temperature of the crystals was 83-87 K. For mesa fabrication, a thin Au film of 10 or 30 nm, which is thinner than the spin diffusion length of $\sim$ 60 nm [11], was thermally evaporated on the surface of cleaved crystal and then a 20 nm Co layer was sputtered. Six square mesas with lateral dimensions $S$ of 25, 64, and 144 $\mu$m$^2$, consisting of 9-40 IJJs, were fabricated by using electron beam lithography and Ar ion milling. For electrical insulation of the lead contacting the top of mesa, SiO layer was evaporated. The top contact was provided by a 200 nm thick Au layer. A schematic view of the sample and mesa structure is shown in Fig. 1. Current-voltage ($I-V$) characteristics of the mesas along the c-axis direction were measured at 77 K by means of a three terminal method with the magnetic field $B$ applied parallel to the layers.

3. Results and Discussion
3.1. $I-V$ characteristics
Figure 2(a) shows typical $I-V$ characteristic of the Co/Au/BSCCO mesa with $S = 25\mu$m$^2$ before the magnetic field was applied, that is, Co layer was not magnetized yet. It is found that the mesa exhibits the hysteretic $I-V$ curve even at 77 K although due to three terminal measurement a contact resistance was observed. From the number of resistive branches, the number of IJJs in the mesa can be estimated to be 17. The switching currents of the branches, which correspond to $I_c$ of the IJJs, range from 300 $\mu$A to 370 $\mu$A. On the other hand, a conventional Au/BSCCO mesa exhibits almost equal $I_c$’s as shown in Fig. 2(b). The $I_c$ distribution in the Co/Au/BSCCO mesa may be due to spin-polarized current injection because Co has some magnetic domains with differently polarized spins even without applied magnetic field while the discrepancy in their critical current densities arise from the different $T_c$ values of the samples.
3.2. Magnetic field dependence of \( I_c \)

The magnetic field dependence of \( I_c \) of the samples shown in Figs. 2(a) and (b) are presented in Figs. 3(a) and (b), respectively, where the \( I_c \) value has been derived from an average of the maximum current of each branch. As can be seen in Fig. 3(a), the \( I_c - B \) curve of the Co/Au/BSCCO shows a hysteretic behavior. Here, the arrows indicate the direction of the field sweep. By applying magnetic field, \( I_c \) gradually decreases similar to that of the Au/BSCCO mesa. Subsequently, as \( B \) is swept from 60 mT to \(-60\) mT, \( I_c \) increases and reaches its maximum at \( B = \sim 10 \) mT. Then, \( I_c \) decreases again. As a result, the \( I_c \) is reduced by 30% at zero magnetic field compared with before the field was applied. Reversing the sweep from the negative magnetic field side, the behavior is approximately symmetric. We have also observed similar dependence.

Figure 2. Current-voltage characteristics of (a) Co/Au/BSCCO mesa with 17 IJJs and (b) Au/BSCCO mesa with 9 IJJs. The temperature is 77 K.

Figure 3. Magnetic field dependence of \( I_c \) of the mesas shown in Fig. 2 at 77 K. (a) Co/Au/BSCCO mesa, (b) Au/BSCCO mesa.
of $I_c$ for larger samples as shown in Fig. 4.

From Figs. 3 and 4, it is found that the field dependence of $I_c$ of Co/Au/BSCCO mesa is very different from that of the conventional Au/BSCCO mesa. This suggests that such difference comes from the magnetic property of Co layer. Indeed, we have found that the hysteresis loop of the sample corresponds to the $I_c(B)$. The magnetization curve $M(B)$ of the Co/Au/BSCCO sample measured at room temperature is shown in Fig. 5. It is found that $M(B)$ curve is consistent with $I_c(B)$ and $I_c$ becomes maximum at the coercive field of Co layer. The correlation between $I_c(B)$ and $M(B)$ implies that the observed $I_c(B)$ reflects the domain structure of the Co layer. Therefore, we attribute the observed $I_c(B)$ of the Co/Au/BSCCO mesa to the spin injection effect. Namely, at the saturation field $B_s$, the ferromagnet magnetization is parallel to the applied field and the domain with polarized spins is formed in the Co layer, so that the polarized current is injected from the Co layer into IJJs. This leads to the suppression of $I_c$ of IJJs. In the field range $-B_s < B < B_s$ corresponding to the hysteretic portion in $I_c(B)$ curve,
there are coexisting domains with differently polarized spins and hence $I_c$ depends on the net polarization of the transport current. When $B$ is equal to the coercive field, the net polarization becomes zero and $I_c$ becomes maximum.

While we believe that the observed hysteretic $I_c(B)$ curve is caused by the spin-injection effect we have also considered another possible mechanism. The transport current in IJJs will also be affected by any stray field from the Co layer. Assuming that the internal field $B_{int}$ in IJJs is simply given by the summation of the applied field and the stray field, the $I_c$ will have a maximum at a minimal $B_{int}$. Such a situation will occur in the positive field side for decreasing sweep and in the negative field side for increasing sweep because the $B_{int}$ will be always reduced by the stray field when the orientation of the net ferromagnet magnetization is parallel to the applied field. However, this is inconsistent with the experimental results shown in Fig. 3. Therefore, we ignore the effect of the stray field on the $I_c(B)$ curve.

4. Conclusion
The influence of the ferromagnet magnetization on transport critical current of intrinsic Josephson junctions have been investigated on Co/Au/BSCCO mesa structures. We have shown that the spin-polarized current injection reduces the critical current of the intrinsic Josephson junctions significantly. Our results indicate that the ferromagnet/IIJs hybrid structure can be used as superconducting spintronics devices such as spin valves and memories.

Acknowledgments
This work was partially supported by Japan Society for the Promotion of Science(JSPS), Grant-in-Aid for Scientific Research (B) and (C).

References
[1] Tedrow P M and Meservey R 1971 Phys. Rev. Lett. 26 192
[2] 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. B 78 1134
[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] Wei J Y T, Yeh N -C and Fu C C 1990 J. Appl. Phys. 85 5350
[5] Yeh N -C, Vasquez R P, Fu C C, Samoilov A V, Li Y and Vakili K 1999 Phys. Rev. B 60 10522
[6] Kleiner R, Steinmeyer F, Kunkel G and Müller P 1992 Phys. Rev. Lett. 68 2394
[7] Oya G, Aoyama N, Irie A, Kishida S and Tokutaka H 1992 Jpn. J. Appl. Phys. 31 L829
[8] Shin H S and Lee H J 2004 Physica C 408-410 623
[9] Ozdemir M, Ozuyzer L and Kurter C 2007 phy. stat. sol (c) 4 563
[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