Vortex penetrations in parallel-connected two stacks of intrinsic Josephson junctions

Shuuichi Ooi*, Takashi Mochiku, Minoru Tachiki, Kazuto Hirata

National Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan.

Abstract

In mesoscopic stacks of intrinsic Josephson junctions (IJJs) in Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi2212), the penetrations of individual vortices are detectable by the measurements of the transport properties, i.e., c-axis resistance or critical current. We have measured the c-axis resistance as a function of magnetic field in samples with two stacks of IJJs connected in parallel by Bi2212 itself to study any interaction of individual vortex penetrations into them. Since the superconducting loop containing two stacks of IJJs is the same geometry as that of superconducting quantum interference device (SQUID), we might expect a periodic resistance (or current) modulation as a function of magnetic field, whose period corresponds to the area in the loop. However, the results were just simple mixing of the resistive changes by the individual vortex penetrations into each of the stacks; behavior like SQUID has not been observed in present samples.

© 2016 The Authors. Published by Elsevier B.V. Peer-review under responsibility of the ISS 2015 Program Committee.

Keywords: Bi2212; intrinsic Josephson junctions; vortex; SQUID

1. Introduction

Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi2212) single crystals have a layered crystal structure that consists of alternate stackings of superconducting and insulating layers, i.e., intrinsic Josephson junctions (IJJs) [1]. While numerous efforts have
been devoted to study the properties of single IJJ stack [1-3], a coupling of two stacks of IJJs connected by a superconducting loop, which is important for applications as a superconducting quantum interference device (SQUID), was investigated only in several experiments [4-9]. In earlier studies, magnetic properties of the critical currents ($I_c$) in an IJJ stack with a single hole at the center along the $ab$ plane (the out-of-plane loop geometry), which is regarded as a SQUID made in IJJs, were theoretically studied [4], and experimentally tested in samples prepared by a three-dimensional fabrication technique using a focused ion beam (FIB) [5]. However, no clear magnetic modulation of $I_c$ by the quantum interference was reported [5]. On the other hand, in the in-plane loop geometry fabricated by the double-side etching technique [10], whose schematic illustration is shown in Fig. 1(a), clear voltage modulations with applied magnetic field have successfully been observed [6-9].

Recently, penetrations of individual vortex lines into an IJJ stack in field parallel to the $c$-axis have been found in stacks with a very small in-plane area less than $2 \, \mu m^2$ [11]. The same behaviors were reproduced in much larger stacks, also [12, 13]. Since there is no research studying an interaction of the individual vortex penetrations into two stacks connected by a single loop in the in-plane loop geometry, it is interesting to explore whether such an interaction exists. In this proceeding, we report on the penetrations of individual vortices into parallel-connected two IJJ stacks observed by the $c$-axis resistance ($R_c$) in magnetic field parallel to the $c$-axis. As a result, the vortex penetrations into each of the stacks were almost independent; a signature of interference effect was not detected in studied samples.

2. Experiments

High-quality single crystals of Bi2212 were grown by the traveling-solvent floating-zone method [14]. The double-side etching technique was employed to fabricate stacks of IJJs with superconducting electrodes on the top and bottom [6-10]. In milling processes, we used a FIB in addition to photolithography and Ar-ion milling. First of all, a trench with several micrometers in width was fabricated on a surface of a bulk single crystal using FIB, and the surface was then fixed on a MgO substrate with a polyimide adhesive. After cleaving another side of the crystal until the sample became slightly transparent on the position of the trench, Au was evaporated onto the fresh surface to form ohmic contacts and provide protection from the ion beams. A pattern of a wide single bar with terminals was formed on the Au covered surface by the pair of the photolithography and the Ar-ion milling. Then, the shapes of two IJJ stacks parallel-connected in the in-plane loop geometry (see Fig.1 (a)) were fabricated by FIB millings.

![Fig. 1. (a) Schematic illustration of parallel-connected two IJJ-stacks in the in-plane loop geometry. (b, c) SIM images of sample A and B, respectively. The positions of IJJ stacks are surrounded by red squares. The definitions of the inner dimensions of rectangular Bi2212 loops are drawn in (c).](image-url)
Finally, four electrodes were formed with Ag paste on the terminals. To remove the remaining Au, which can shunt the electrodes and sometimes cause non-zero resistance at the superconducting state, the entire surface of the sample was slightly milled with an Ar-ion beam. Two samples (A and B) were prepared, whose images taken by a scanning ion beam microscope (SIM) are shown in Fig. 1(b) and (c), respectively. Specifications and properties of these samples are listed in Table 1.

Transport measurements were performed using the four-probe technique with a current source (Keithley 6430) and a nanovoltmeter (Keithley 2182) in a chamber with a cryocooler. Data of the c-axis resistance shown here were acquired in repeats of field-scans at various fixed temperatures. Magnetic fields were applied parallel to the c axis.

Table 1. Table of specifications and properties of the fabricated samples.

| Sample name | In-plane size of stacks (w×L) | $a_1$ and $b_1$ of the inner rectangle | $T_c$ at midpoint | $\Delta H_p$ (exp.) | Period of $I_c$ modulation expected from the inner area |
|-------------|--------------------------------|----------------------------------------|------------------|-------------------|-----------------------------------------------|
| sample A    | $2.1 \times 2.5 \, \mu m^2$  | $4.3 \times 10 \, \mu m^2$            | 86.5 K           | 5.2 ~ 5.4 Oe      | 0.48 Oe                                        |
| sample B    | $2.5 \times 2.5 \, \mu m^2$  | $9.7 \times 12.7 \, \mu m^2$          | 87 K             | 4.2 ~ 4.8 Oe      | 0.17 Oe                                        |

3. Results and discussion

The temperature derivatives of $\log R_c$ for the two samples are mapped on the $H$-$T$ planes in Fig. 2 (a) and (b). In these maps, the brighter or darker lines with downward slopes to the right indicate the positions of steep changes of resistance (jumps or drops in $R$-$T$ curves), corresponding to the penetrations of individual vortices. While samples containing a single stack of IJJs show almost uniform magnetic field intervals $\Delta H_p$ for the individual vortex penetrations except in lower fields [11, 13, 14], both of the maps in Fig. 2 seem to be a superposition of two series of vortex penetrations. In Fig. 2(a), with increasing magnetic field, the alternating appearance of denser and fainter lines (indicated by white circles and yellow squares, respectively) is observed, which can be caused by the vortex penetrations for two stacks with different intervals. From the difference of the field intervals for the two series, we can estimate the difference of the in-plane area of the two stacks as 4%. In Fig. 2(b), the field intervals of the lines

![Fig. 2 Maps of dlogRc/dT on the H-T plane for (a) sample A and (b) sample B. Lines from the top-left to the bottom-right indicate the steep changes of resistance originating from the penetrations of individual vortices. Two kinds of markers (white circles and yellow squares) clarify the two different series of individual vortex penetrations.](image-url)
for the individual vortex penetrations in 60 and 100 Oe at 80 K become nearly half of those in the other fields. This is observed in Fig. 3(a) and (b) more clearly, which show $R_c$ as a function of magnetic field at 78.25 K in sample B and a result subtracted an exponential background from the raw data, respectively. This behavior like a beat is explained by the superposition of two oscillations with a slightly different period. The beat period $\Delta H_{\text{beat}}$ is roughly estimated to be $\sim 35$ Oe, corresponding to 13% difference in the in-plane areas of the two stacks in sample B.

As shown above, vortex penetrations into two IJJ stacks connected by a superconducting loop seem almost independent each other. Beside the individual vortex penetrations, since $I_c$ or $R_c$ modulations as a function of magnetic field like a dc-SQUID, whose periods are estimated in Table 1, can be expected in much lower fields than the fields of the first vortex penetration, we explored such signals by very fine scans of magnetic field at various temperatures. However, the expected behavior was not observed in the present samples. Although there are several possible reasons for the lack of $I_c$-modulations, i.e., the non-uniformity of two stacks, hysteretic $I$-$V$ characteristics, and the large number of IJJs in stacks [4,6-8], the true origins are not clarified in the present experiments.

References

[1] R. Kleiner, F. Steinnmeyer, G. Kunkel and P. Müller, Phys. Rev. Lett. 68 (1992) 2394-2397.
[2] R. Kleiner and P. Müller, Phys. Rev. B 49 (1994) 1327-1341.
[3] A. E. Koshelev, A. I. Buzdin, I. Kakeya, T. Yamamoto, and K. Kadowaki, Phys. Rev. B 83 (2011) 224515.
[4] V. M. Krasnov, Physica C 368 (2002) 246-250.
[5] S. J. Kim, J. Chen, K. Nakajima, T. Yamashita, S. Takahashi and T. Hatano, J. Appl. Phys. 91 (2002) 8495-8497.
[6] A. Irie and G.-i. Oya, IEEE Trans. Appl. Supercond. 15 (2005) 813-816.
[7] M. Sandberg and V. Krasnov, Phys.Rev. B 72 (2005) 212501.
[8] S. Okano, A. Irie and G. Oya, J. Korean Phys. Soc. 48 (2006) 1080-1083.
[9] T. Kato, N. Iso, A. Miwa, H. Suematsu, A. Kawakami, K. Yasui and K. Hamasaki, IEEE Trans. Appl. Supercond. 21 (2011) 379-382.
[10] H. B. Wang, P. H. Wu and T. Yamashita, Appl. Phys. Lett. 78 (2001) 4010.
[11] I. Kakeya, K. Fukui, K. Kawamata, T. Yamamoto and K. Kadowaki, Physica C 468 (2008) 669.
[12] S. Ooi, T. Mochiku, M. Tachiki and K. Hirata, Phys. Rev. Lett. 114 (2015) 087001.
[13] S. Ooi, T. Mochiku, M. Tachiki and K. Hirata, Phys. Procedia 65 (2015) 109-112.
[14] T. Mochiku, K. Hirata, K. Kadowaki, Physica C 282-287 (1997) 475.