Journal of Low Temperature Physics, Vol. 131, Nos. 3/4, May 2003 (© 2003)

Cross-Whisker Intrinsic Josephson Junction as a Probe of Symmetry of the Superconducting Order Parameter

Yoshihiko Takano, Takeshi Hatano, Masashi Ohmori, Shinichi Kawakami, Akira Ishii, Shunichi Arisawa, Sang-Jae Kim, Tsutomu Yamashita, Kazumasa Togano, Masashi Tachiki *

National Institute for Materials Science, 1-2-1 Sengen, Tsukuba 305-0047, Japan
**CREST, Japan Science and Technology Corporation, 2-1-6, Sengen, Tsukuba 305-0047, Japan*

As a test of the superconducting order parameter, we have developed an intrinsic Josephson junction by the name of cross-whisker junction. This junction was made using two $Bi_2Sr_2CaCu_2O_{8+d}$ single crystal whiskers. Two whiskers were connected at their c planes with various cross-angles. Angular dependence of the critical current densities shows d-wave-like fourfold-symmetry. However, the angular dependence is much stronger than that of the conventional $d_{x^2-y^2}$ wave. The Jc shows its smallest value around 45 deg, which suggests that the Josephson penetration depth becomes longer. We have successfully observed a Fraunhofer pattern in the cross-whisker junction with cross-angle 45 deg.

PACS numbers: 74.50.+r 74.72.Hs

1. INTRODUCTION

To elucidate the mechanism of high-Tc superconductors, it is necessary to clarify the pairing symmetry of the order parameter. Li et al.[1] measured the angular independent Jc in twisted junctions using Bi2212 single crystals, on the basis of which they claimed an s-wave symmetry. However, their single crystal is much larger than the c-axis penetration depth, and hence it is conceivable that the applied current flowed on the surface of the sample. Because the junction showing intrinsic Josephson properties sug-

0022-2291/03/0500-0533/0 © 2003 Plenum Publishing Corporation

gests the homogeneity of the Josephson current and thus good quality of the joining, the angular dependence of Jc must be examined with the junctions which show intrinsic Josephson effects. The purpose of the present work is to demonstrate a test of pairing symmetry with the intrinsic Josephson junctions such as the cross-whisker junction.[2–4] In this cross-whisker junction, the multi-branch structures that were a feature of the intrinsic Josephson effects were observed in current-voltage (I-V) curves at any cross-angle. In this paper, we present the d-like pairing symmetry behavior of the angular dependence of Jc, the intrinsic Josephson effects and the Fraunhofer pattern in cross-whisker junction.

2. Experimental

The details of the fabrication process of the cross-whiskers junction is presented in our previous papers.[2–4] Two appropriate pieces of whiskers were intersected, and flatly put on the MgO substrate. The Tc of the whisker is around 80K, which suggests the whisker is slightly over-doped. The shape of the whisker is flat, and is long and slender. The direction of length is the a-axis, and the flat surface is the c-plane. The thickness is 1-3 μm, and the width is 10-30μm. The typical length is about 4 millimeters.[5] Because the widths of the whiskers is within the range of 10 to 30 mm, the junction area is 2 orders of magnitude smaller than that of single crystal twist junctions of Li et al.[1] The two whiskers were mutually contacted at the c-plane. To study the angular dependence of the intrinsic Josephson properties, samples with various cross-angles were made. The suitable cross-angles were chosen in the range of α=0-90°. Two whiskers were joined crosswise by short time annealing at 850°C for 30 min in flowing N_2-70%O_2 gas mixture. The gold lead wires were attached to the four ends of the crossed two whiskers by silver paste for electronic measurements. The transport properties of cross-whisker junctions were measured by the four-probe method. I-V characteristics measurements were performed in the current-biased mode.

3. Results and discussions

Figure 1 shows the I-V characteristics of the cross-whiskers junctions with the cross-angle of $\alpha \sim 90°$ and 60° measured at 5K. The multiple-branch structure that is characteristic of the intrinsic Josephson junction was observed. The magnitude of the first voltage jump is ~15 mV, corresponding to the typical voltage of the intrinsic Josephson junction. A critical current density with the cross-angle of $\alpha \sim 90°$ is estimated to be ~1170A/cm^2. This value is consistent with the typical Jc observed in mesa-

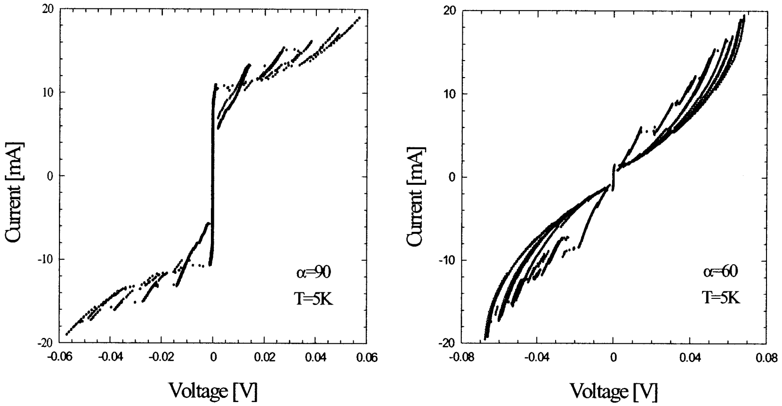

Fig. 1. I-V characteristics of the cross-whisker junctions with cross-angles of 90° and 60°.

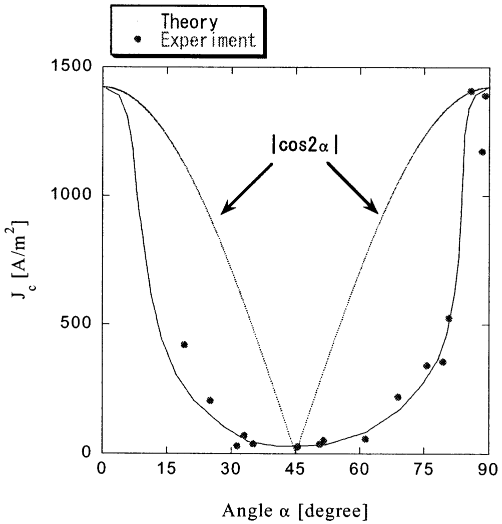

Fig. 2. Angular dependence of the critical current densities Jc in the cross-whisker junction.

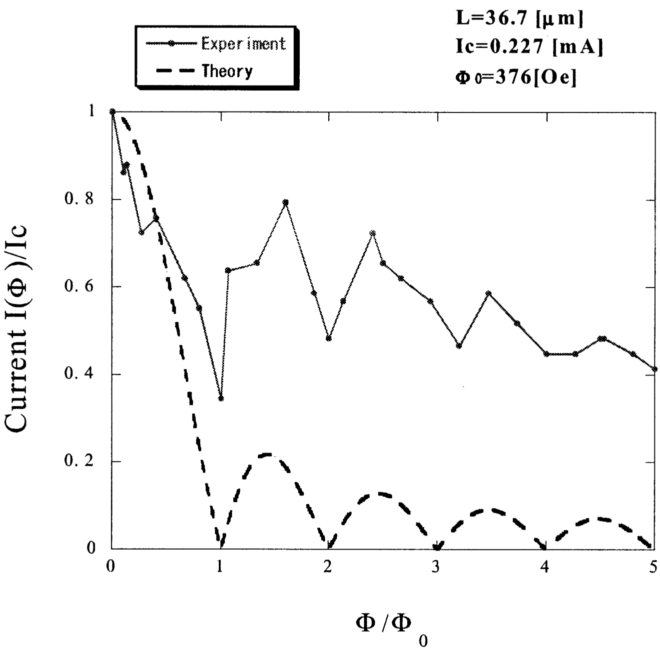

Fig. 3. The magnetic field dependence of the critical current of the cross-whisker junction for cross-angle of 45 deg.

type intrinsic Josephson junctions fabricated on Bi2212 single crystals.[6,7] The critical current density for $\alpha \sim 60°$ is suppressed compared to that for $\alpha \sim 90°$. The angular dependence of Jc is plotted in figure 2. The Jc showed a maximum value at around 0° and 90°, and decreased dramatically as the cross-angle 45° was approached, and become minimum at around 45°. The angular dependence of Jc has a d-wave like 4-fold symmetry. Assuming that the pairing symmetry of the order parameter is of the conventional $d_{x^2-y^2}$ and the c-axis pair tunnelling process conserves in-plane momentum and that the transfer integral is independent of α, the critical current density across the cross-whiskers junction is proportional to the overlap integral and can be expressed in terms of the joint angle as[8] $J_c = A\cos(2\alpha)$. The order parameter obtained from the angular dependence of Jc has a d-wave like 4-fold symmetry, but angular dependence is much stronger than estimated from the conventional d-wave state. The obtained Jc shows the smallest value at around 45 deg, but it does not approach to zero. This suggests that the Josephson penetration depth becomes comparable in length to the cross-whisker junction. Figure 3 shows the magnetic field dependence of the critical current densities of the cross-whisker junction with cross-angle 45 deg. We have successfully observed a Fraunhofer pattern in the cross-whisker junction with cross-angle around 45 deg, contrary to what one would expect based on a pure d-wavy picture. This result proves that the small superconducting gap exists even at this direction in the over doped Bi2212 high-Tc superconductors. In conclusion, the Fraunhofer pattern is clearly observed in the 45 deg twisted cross-whisker junction. This cross-whiskers junction gives us fundamental data, and direct information on the symmetry of the order parameter, which will elucidate the mechanism of high-Tc superconductors having a layered perovskite structure.

REFERENCES

1. Qiang Li et al., *Phy Rev Lett.* **83**, 4160 (1999).
2. Y. Takano et al., *Phys. Rev. B Rapid Communication,* **65**, 140513 (2002).
3. Y. Takano et al., *Supercond. Sci. Technol.,* **14**, 765 (2001).
4. Y. Takano et al., *Physica C,* **362**, 261 (2001).
5. T. Hatano et al., *IEEE trans.,* **11**, 2846 (2001).
6. R. Kleiner et al., *Phys. Rev. Lett.,* **68**, 2394 (1992).
7. G. Oya et al., *Jpn. J. Appl. Phys.,* **31**, L829 (1992).
8. C. C. Tsuei et al., *Rev. of Mod. Phys.,* **72**, 969 (2000).