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Probing the order parameter using cross-whisker junction with adjustable Josephson characteristics

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Abstract

Cross-whisker intrinsic Josephson junction has been developed as a probe of symmetry of the superconducting order parameter. Two B2212 single crystal whiskers were connected on a MgO substrate at their *c*-plane with various crossing angles. Angular dependence of the critical current densities showed d-wave-like 4-fold symmetry. However, the angular dependence was much stronger than that of the conventional $d_{x^2-y^2}$-wave. The critical current density of the cross-whisker junction with cross-angle $\alpha = 45°$ was not completely zero. Shapiro steps and Fraunhofer pattern were clearly observed in 45° twisted cross-whisker junctions. It is suggested that the superconducting gap exists even at nodal direction.

Keywords: Symmetry; Order parameter; High-T_c; Superconductivity; Josephson junction

1. Introduction

Probing the superconducting order parameter is necessary to elucidate the mechanism of oxide high-T_c superconductors. Josephson effects in the twisted tunnel junctions directly reflect the pairing symmetry of the superconducting order parameter. The angular dependence of the critical current densities has been examined in the YBCO grain boundary junctions fabricated on the bi-crystal substrate. Since the critical current density was exponentially suppressed with the grain boundary angle, they conclude that the order parameter has d-wave pairing symmetry [1]. On the other hand, the *c*-axis twist junction using Bi2212 single crystal showed angular independent critical current densities. Li et al. claimed that the pairing symmetry is isotropic s-wave from their result [2]. However their junction size is around 300 μm being much larger than the *c*-axis penetration depth. Thus, Josephson current assumably flowed on the surface of the junction.

We have developed a cross-whisker junction to probe the superconducting order parameter [3–5]. The junction shows a multiple branch structure in the current vs. voltage characteristics, which indicate the formation of intrinsic Josephson junction [6,7]. We examined the angular dependence of critical current densities using the cross-whisker junction, because the junctions showing intrinsic Josephson properties suggest a homogeneous flow of the Josephson current. The angular dependence of critical current densities shows d-wave-like 4-fold symmetry. However, the angular dependence is much stronger than that of conventional d-wave [3,4]. The critical current density at nodal direction shows small finite value [5]. In this paper, we present the d-like pairing symmetry behavior of the angular dependent of the J_c at various temperatures and Shapiro steps in 45° twisted cross-whisker junction.

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2. Experimental

The cross-whisker junction was made using two Bi2212 single crystal whiskers. The growth conditions of whiskers were presented in our previous papers [8,9]. The shape of whiskers used in this study was like a ruler, narrow and flat and long. The growth direction is the *a*-axis, and the typical length is about 4 mm. The flat surface is the *c*-plane. The thickness is 1–2 μm and the width is 10–20 μm.

The schematic of fabrication process and geometry of transport measurements are shown in Fig. 1. A MgO single crystal was chosen as a substrate, because its thermal expansion is approximately equal to that of Bi2212 superconductor. The two high quality whiskers were laid cross-wise on the MgO substrate. Since the flat surface is the *c*-plane, the whiskers were attached each other by their *c*-planes. The crossing angles of two whiskers are changed from 90° to 20° to analyze the angular dependence of Josephson properties and critical current densities. To connect two whiskers, the cross-whisker junction was heated at 850 °C for 30 min in Ar–70%O_2 gas mixture. While in this heat treatment, the sample was encased with Bi2212 bulk sample in Ag-box to prevent Bi in the whiskers from evaporating.

To confirm the joint condition, the cross-section of the sample was observed by high-resolution transmission electron microscope (HRTEM). The HRTEM picture of the cross-whisker junction with 90° is shown in Fig. 2a, and naturally grown about 18° twisted boundary is shown in Fig. 2b. The striped pattern in the pictures corresponds to the stacking of Cu–O and Bi–O layers of Bi2212 superconductors. The arrows in these pictures indicate the interfaces of upper and lower whiskers, and the interfaces are extremely flat on an atomic scale. The interface found to exist between two Bi–O layers where the bonding is weakest in this crystal. The surface of whisker crystal is considered to be Bi–O layer. The single crystal Bi2212 superconductors can be cleaved at Bi–O layer, since two BiO layers are bonded by van der Waals' force.

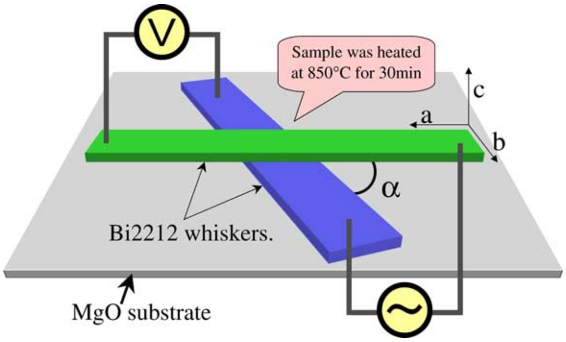

Fig. 1. Schematic of fabrication process of the cross-whisker junction.

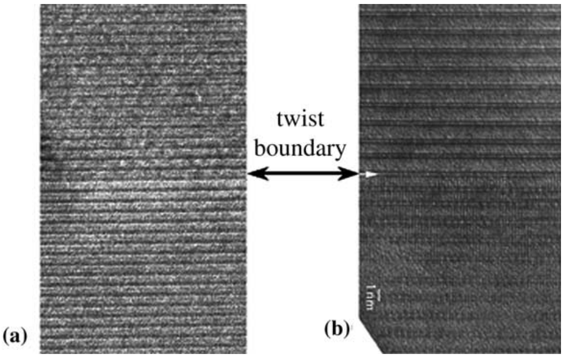

Fig. 2. TEM pictures of the cross-section of the cross-whisker junction with cross-angle 90° (a), and naturally twisted boundary with cross-angle 13° (b).

Temperature dependences of resistance of the cross-whisker junctions with crossing angle $\alpha = 90°$, 75°, 60°, 45° around transition temperature are plotted in Fig. 3. All the samples show almost the same transition temperature around 80 K. Because the twist boundary exists insulating Bi–O layer and far from Cu–O layers, superconductivity does not suppressed by the mismatch of the crystal structure around the twist boundary in the cross-whisker junction.

Fig. 4a shows the angular dependence of critical current densities J_c at 5 K. The J_c showed maximum value at ~90° and was dramatically decreased with a

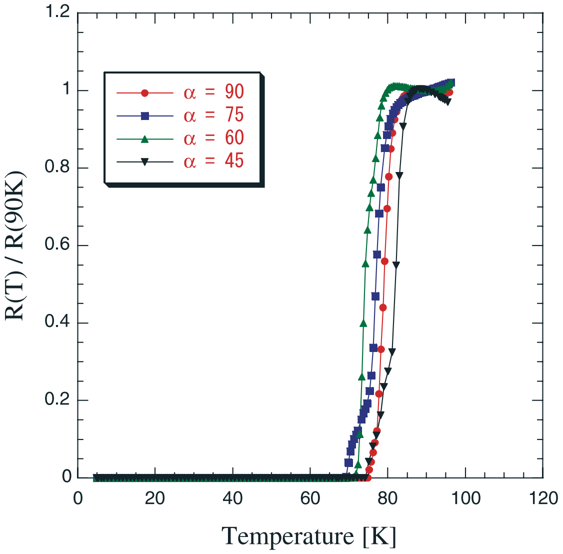

Fig. 3. Temperature dependence of normalized resistances of the cross-whisker junctions with cross-angles around 90°, 75°, 60°, and 45°.

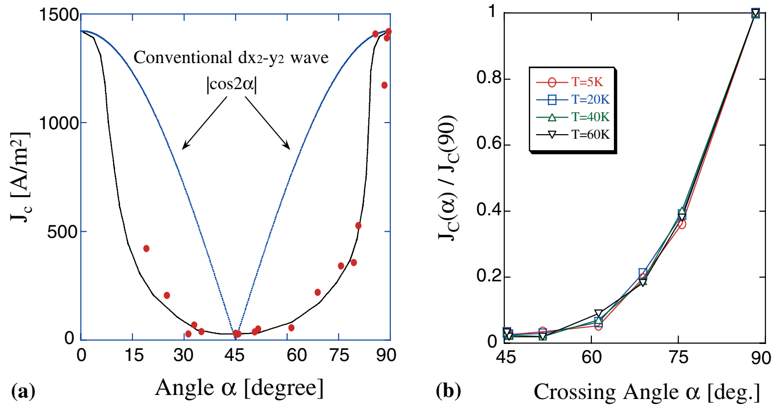

Fig. 4. Angular dependence of the critical current densities J_c at 5 K in the cross-whisker junctions (a). Temperature variation of the angular dependence of J_c observed at 5, 20, 40, and 60 K (b).

decrease in the cross-angle, and the finite minimum J_c was obtained around 45°. The angular dependence of the J_c has d-wave like 4-fold symmetry. Fig. 4b shows the angular dependence of normalized J_c observed at 5, 20, 40, and 60 K. Almost the same angular dependences of J_c were observed at each temperature. It suggests that this angular dependency originates in the temperature independent factors, such as symmetry of the order parameter and transfer integral.

If the pairing symmetry of the order parameter is conventional $d_{x^2-y^2}$-wave, gap functions $\Delta(\theta)$ for joined two whiskers take the forms,

$$\Delta_1 = \Delta(\cos^2\theta - \sin^2\theta)$$

$$\Delta_2 = \Delta(cos^2(\theta+\alpha) - \sin^2(\theta+\alpha))$$

Assuming that the c-axis pair tunneling conserves in-plane momentum and transfer integral is independent of α, the critical current density across the cross-whisker junction is proportional to the overlap integral [10].

$$J_c \propto \int_0^{2\pi} \Delta_1\Delta_2\,d\theta = \pi\Delta^2\cos(2\alpha) \tag{1}$$

The angular dependence of J_c estimated by this equation was plotted in Fig. 4a. The J_c observed in the cross-whisker junctions is qualitatively consistent with Eq. (1). However, the angular dependence of J_c in the cross-whisker junctions exhibited a drastic reduction with decreasing cross-angle toward 45°. And J_c in the cross-whisker junction at 45° is 2 order suppressed. However J_c at the nodal direction is not perfect zero. It shows that the order parameter in Bi2212 high-T_c superconductor is not simple d-wave.

Fig. 5 shows the Shapiro steps observed in the cross-whisker junction with cross-angle 45°. Frequency of the applied microwave is 20 GHz, and the power is changed from −10 to 0 dBm. We have successfully observed clear Shapiro steps in the cross-whisker junction with cross-angle 45°. The voltage of a step is about 40 μV, which suggest that there is only one junction, 45° twisted junction, responding to the microwave.

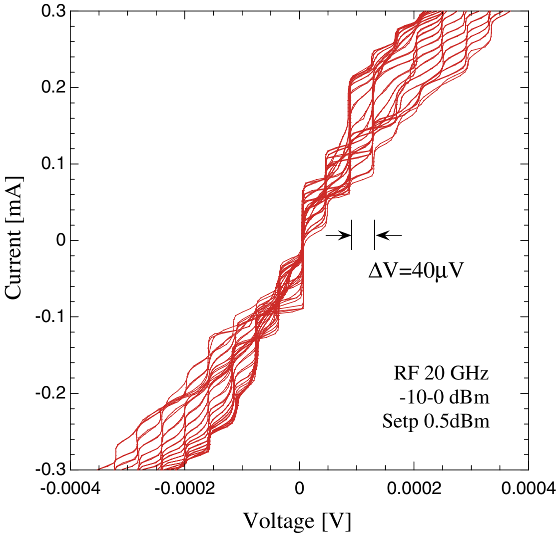

Fig. 5. Shapiro steps observed in the cross-whisker junction with cross-angle 45°.

In conclusion, we have successfully fabricated the cross-whiskers junction as a prove of the symmetry of the order parameter. The J_c was dramatically reduced with decreasing cross-angle from 90° to 45°. The order parameter obtained from the angular dependence of J_c is a d-wave like 4-fold symmetry, but much stronger than the angular dependence of the conventional d-wave. The critical current density of the cross-whisker junction with a cross-angle $a = 45°$ was not completely zero. Shapiro steps and Fraunhofer pattern were clearly observed in 45° twisted cross-whisker junctions. This result proves that the superconducting gap exists even at the nodal direction. The cross-whisker junction will give us the symmetry of the order parameter to elucidate the mechanism of high-T_c superconductors.

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