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Citation	Physica C: Superconductivity , 367 (1-4) : 28 - 32
Issue Date	2002-02-15
DOI	10.1016/S0921-4534(01)00982-0
Self DOI	
URL	https://ir.lib.hiroshima-u.ac.jp/00046732
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Relation	

Temperature Dependence of Half Flux Quantum in $YBa_2Cu_3O_{7-y}$ Tricrystal Thin Film Observed by Scanning SQUID Microscopy

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(August 30, 2001)

One of the most important topics in high critical-temperature superconductors is the symmetry of order parameter. The most powerful and direct method to show the evidence of d-wave symmetry is the measurement of half flux quantum at tricrystal boundary of a superdconducting thin film. We present the observation of the half flux quantum in a $YBa_2Cu_3O_{7-y}$ (YBCO) thin film on a $SrTiO_3$ tricrystal substrate by using a scanning SQUID microscope (SSM). The SSM observation is done from 3 K to 90 K. The vortex at the tricrystal point corresponds to $\Phi_0/2$ ($= 1.03\times10^{-15}$Wb) and this half vortex is observable up to near the critical temperature. The results indicate the evidence of $d_{x^2-y^2}$ symmetry of superconducting order parameter. The Josephson vortices at grain boundaries are also observable and some of them are mobile with increasing the temperature.

PACS Codes: 74.50.+r; 74.60.Jg; 74.60.Ge; 74.76.Bz
Keywords: Scanning SQUID Microscope; half vortex; d-wave pairing symmetry

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I. INTRODUCTION

The pairing symmetry of high T_C cuprate superconductor is closely related to the mechanism of superconductivity and many experiments has been investigated for the clarification of symmetry by various methods [1]- [6]. The most of these experiments led to the result that the hole-doped high T_C cuprate superconductors have predominantly $d_{x^2-y^2}$-wave paring symmetry. Such a pairing state gives rise to an anisotropic energy gap, which is zero along the node of an essentially cylindrical Fermi surface. A sign change of pairing symmetry induces a π-phase shift of wave function at the anisotropic Josephson junctions (π- junctions) and gives rise to negative Josephson current. If the superconducting loop contains an odd number of π-junctions with frustrated geometry, the ground state of this system produces spontaneous magnetization of half-integer flux quantum $\Phi_0/2$ ($\Phi_0 = 2.07 \times 10^{-15}$ Wb) in the loop [7]. This method is the most unambiguous and direct experimental determination of paring symmetry. Kirtley, Tsuei and co-workers have shown the detection of half-integer flux quantum in $YBa_2Cu_3O_{7-y}$ (YBCO), $Bi_2Sr_2CaCu_2O_{8+y}$ and $Tl_2Ba_2CuO_{6+y}$ thin films at 4.2K using tricrystal junctions [8]. For YBCO thin films, its existence up to T_C was confirmed [9]. For electron-doped cuprate superconductor $Nd_{2-x}Ce_xCuO_{4-\delta}$, in spite of large Josephson penetration depth due to small Josephson current, the half flux quantum has been also found [10], again suggesting the $d_{x^2-y^2}$-wave pairing symmetry.

In this paper, we show the evidence of $d_{x^2-y^2}$-wave pairing symmetry by observing the half flux quantum using a scanning SQUID microscope. We also investigate the temperature dependence of half flux quantum vortex from 3 K to around T_C by SSM, and discuss the pairing symmetry.

II. EXPERIMENTAL

YBCO thin films were deposited on a tricrystal $SrTiO_3$ substrates, with 30° of the misorientation angle across each boundary (see Fig. 2(a)), by a pulsed laser deposition method. The film thickness was about 200 nm and the critical temperature was about 90 K. The deposited films were patterned into a disk shaped of diameter 400 $\mu m\phi$ and 15 μm striplines across the horizontal boundaries by conventional photolithography and Ar ion milling technique.

The SSM system (SII SQM2000) [11] contains a dc-SQUID magnetometer made of Nb/Al-AlO_x/Nb tunnel Josephson junctions fabricated on a 3×3 mm^2 Si chip. The magnetometer had a one-turn pickup coil of 10 μm effective diameter and the magnetic flux sensitivity was better than 5 $\mu\Phi_0/\sqrt{Hz}$. The sample–coil distance was about 4–5 μm. The sample temperature was controllable between 3.0 K and 90 K by a dc current heater and controll of helium gas flow. A copper coil wound around the sample holder was used to reduce background field below 0.01 μT in a quadruple μ metal shield. The xyz stage with stepping motors and the SQUID were controlled by personal computer, and the magnetic-field signal was recorded.

III. RESULTS AND DISCUSSIONS

To evaluate the quality of the grain boundary junctions on a tricrystal substrate, the $I - V$ characteristics of the grain boundary junction were investigated. The independent stripline was formed across the asymmetric 0°–30°the horizontal boundary. Fig. 1(a) shows the current-voltage characteristic curve ($I - V$ curve) at T = 4.2 K and B = 0 T. The $I - V$ curve was typical RSJ type and the Josephson critical current density was estimated to be about 2×10^4 A/cm^2, large enough to generate spontaneous half flux quantum. Fig. 1(b) shows the dependence of critical current on external magnetic-field. The magnetic field was applied normal to the substrate surface and the observed period was about 50–100 μT. The curve has a dip around zero magnetic field, indicating that the junction has a phase difference of π and one of the evidence of $d_{x^2-y^2}$-pairing symmetry [12] [13]. The results show the grain boundaries made by the trisrystal substrate was good enough to exchange the phase of superconducting pair across the boundary.

Fig. 2 (a) shows the observed typical magnetic-field images on the tricrystal substrate at 3.2 K. The appearance of half quantum vortex is clearly visible at the tricrystal point. The background field while cooling was about 0.2 μT. The half vortex was also observed under the extremely low field less than 10 nT, in which no bulk vortex was detected. In Fig. 2(b), the cross-sectional views of a bulk trapped vortex and a vortex at the tricrystal point vortex are given. The solid curves are based on monopole approximation in which the field from an isolated vortex is described by $\boldsymbol{B}(\boldsymbol{r}) = \Phi_0 \boldsymbol{r}/2\pi r^3$, where r is distance between the center of a vortex and the detection point. The calculation was done by taking the effective pick up coil diameter of 10 μmϕ into account. The small vortex at the tricrystal point was estimated as follows. First, the sample–coil distance (z_0) was estimated by measuring the bulk vortex peak height and assuming that one bulk vortex has completely 1Φ_0. Next, using the obtained z_0 value, the curve was fitted to the experimental data of the small vortex. As a result, the total flux at the tricrystal point was found to be (0.51±0.04)Φ_0 at 3.2K. The result indicates that the total phase change corresponds to π around the junctions, showing that the spontaneous current is generated due to the $d_{x^2-y^2}$-wave pairing symmetry. The result is consistent with the observations by IBM group [3] [8].

The images of vortices were recorded at 8 K to 86 K as shown in Fig. 3. The solid lines represent tricrystal boundaries. The half-integer vortex was observed up to temperature very close to T_C. In Fig. 3 (a), there are two Josephson vortices in the grain boundaries, one bulk trapped vortex and one half vortex at 8 K. The image of Josephson vortex at the right horizontal boundary was deformed, showing that this vortex was moving while scanning the pick-up coil. The same thing can be also mentioned for the vortex at tilted boundary as seen in Fig. 3 (b) and 3 (c). While the bulk vortex trapped in the film was not movable with varying temperature, the Josephson vortices were found to be quite mobile with temperature. At 82 K (Fig. 3(d)), the vortex at the tricrystal point changed from upward to downward direction, but the absolute magnitude of flux was found to be unchanged ($\Phi_0/2$). Similar phenomenon has been also observed by IBM group [9]. At 86K very close to T_C, the bulk vortex was still recognized, but the half-integer vortex signal became almost vanishing, reflecting that the coupling in the Josephson boundary was almost lost at the temperature. Fig, 3(f) shows the temperature dependence of the peak height of the half-integer vortex, which was found to be about $\Phi_0/2$ almost independent of temperature, consistent with the previous measurements [9]. The half vortex became slightly lower with increasing temperature, which is consistent with the fact that the temperature dependence of Josephson penetration depth (λ_J) is different from that of London penetration depth (λ_L). However, the results indicate that the $d_{x^2-y^2}$- pairing symmetry dominated up to near the critical temperature of Josephson coupling between the boundary.

IV. SUMMARY

We have presented the evidence of $d_{x^2-y^2}$-wave pairing symmetry in a YBCO superconductor by observing the half vortex used by SSM. The results showed the evidence of $d_{x^2-y^2}$ pairing symmetry. The temperature dependence of magnitude of vortex was also determined and half vortex was found to be unchanged up to the temperature at which Josephson coupling disappeared, hence the $d_{x^2-y^2}$- pairing symmetry did not change up to $T \simeq T_C$.

ACKNOWLEDGMENTS

This work has been supported by CREST (Core Research for Evolutional Science and Technology) of the Japan Science and Technology Corporation (JST).

[1] D. A. Wollman, D. J. Van. Harlingen, J. Giapintzakis, and D. M. Ginsberg, Phys. Rev. Lett. 74, 797 (1995).
[2] A. Mathai, Y. Gim, R. C. Black, A. Amar, and F. C. Wellstood, Phys. Rev. Lett. 74, 4523 (1995).
[3] C. C. Tsuei, J. R. Kirtley, C. C. Chi, Lock See Yuu-Jahnes, A. Gupta,T. Shaw, T. Z. Sun, J. Z. Sun, and M. B. Ketchen, Phys. Rev. Lett. 73, 593 (1994).
[4] S.Kashiwaya and Y. Tanaka, Rep. Prog. Phys. 63, 1641(2000).
[5] I. Iguchi, W. Wang, M. Yamazaki, Y. Tanaka, and S. Kashiwaya, Phys. Rev. B 62, R6131 (2000).
[6] M. Convington, M. Aprili, E. Paraoanu, L. H. Greene, F. Xu, J. Zhu, and C. A. Mirkin, Phys. Rev. Lett. 79, 277 (1997).
[7] M. Sigrist and T. M. Rice, J. Phys. Soc. Jpn. 61, 4283 (1992).
[8] C. C. Tsuei and J. R. Kirtley, Rev. Mod. Phys. 72, 969 (2000).
[9] J. R. Kirtley, C. C. Tsuei, and K. A. Moler, Science 285, 1373 (1999).
[10] C. C. Tsuei and J. R. Kirtley, Phys. Rev. Lett. 85, 182 (2000).
[11] T. Morooka, K. Tanaka, A. Odawara, S. Nakayama, A. Nagata, M. Ikeda, and K. Chinone, Physica C 335, 157 (2000).
[12] H. Hilgenkamp, J. Mannhart, and B. Mayer, Phys. Rev. B 53, 14586 (1996).
[13] Y. Ishimaru, J. Wen, N. Koshizuka, and Y. Enomoto, Phys. Rev. B 55, 11851 (1997).

Figure Captions

Fig. 1(a) Current-voltage characteristics of the grain boundary junction across the horizontal boundary. ; (b) Dependence of Josephson critical current on magnetic field. The curve has a dip around zero magnetic field.

Fig. 2(a) The magnetic image of integer and half integer vortices at 3.2K and the schematic geometry of tricrystal substrate. ; (b) The cross-sectional views of integer and half-integer vortices together with theoretical fittings.

Fig. 3(a)-(e) Three dimensional magnetic images of Josephson and trapped vortices and a half vortex at the tricrystal point at different temperatures. ; (f) Estimated magnitude of a vortex at the tricrystal point.

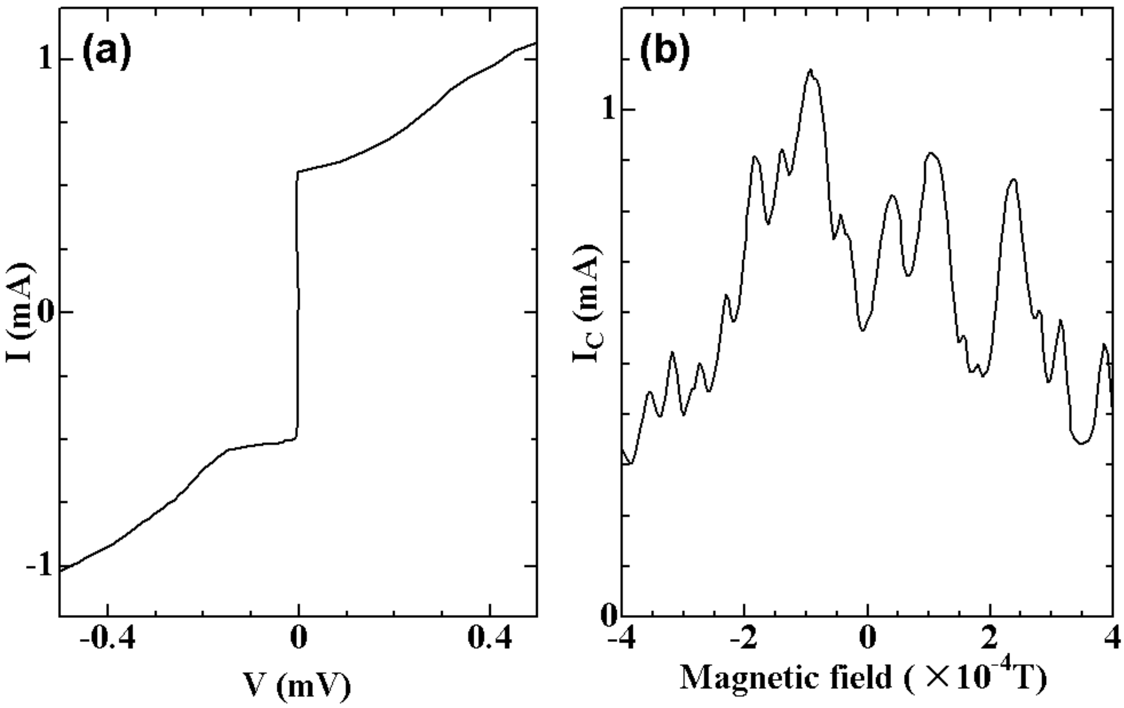
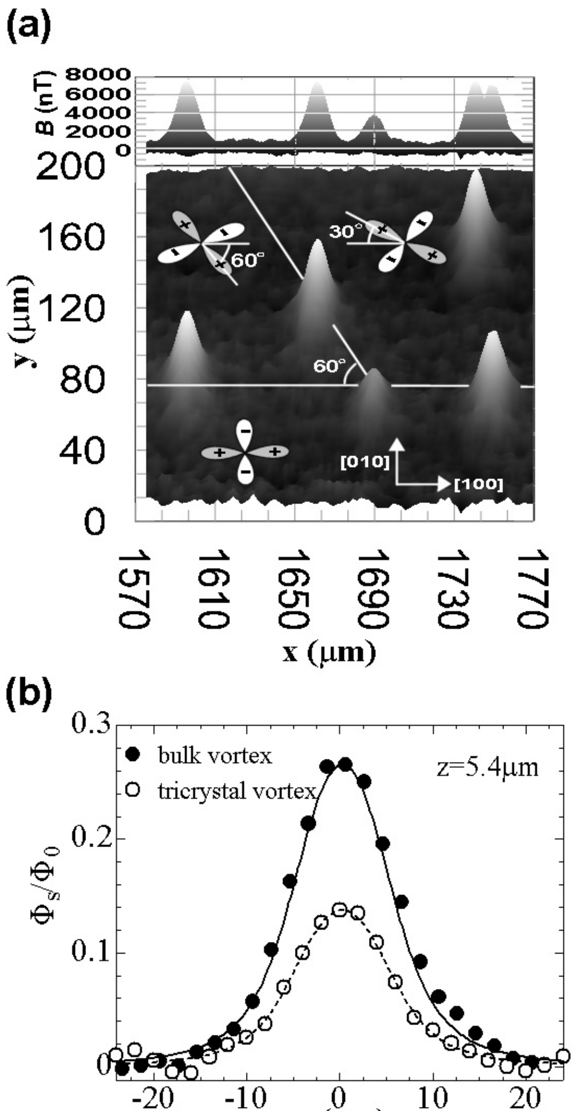


Fig. 1



(a)
B (nT)
8000
6000
4000
2000
0
200
160
120
80
40
0
y (μm)
30°
60°
60°
[010]
[100]
1570
1610
1650
1690
1730
1770
x (μm)
(b)
0.3
0.2
0.1
0
Φs/Φ0
bulk vortex
tricrystal vortex
z=5.4μm
-20
-10
0
10
20
x (μm)

Fig. 2

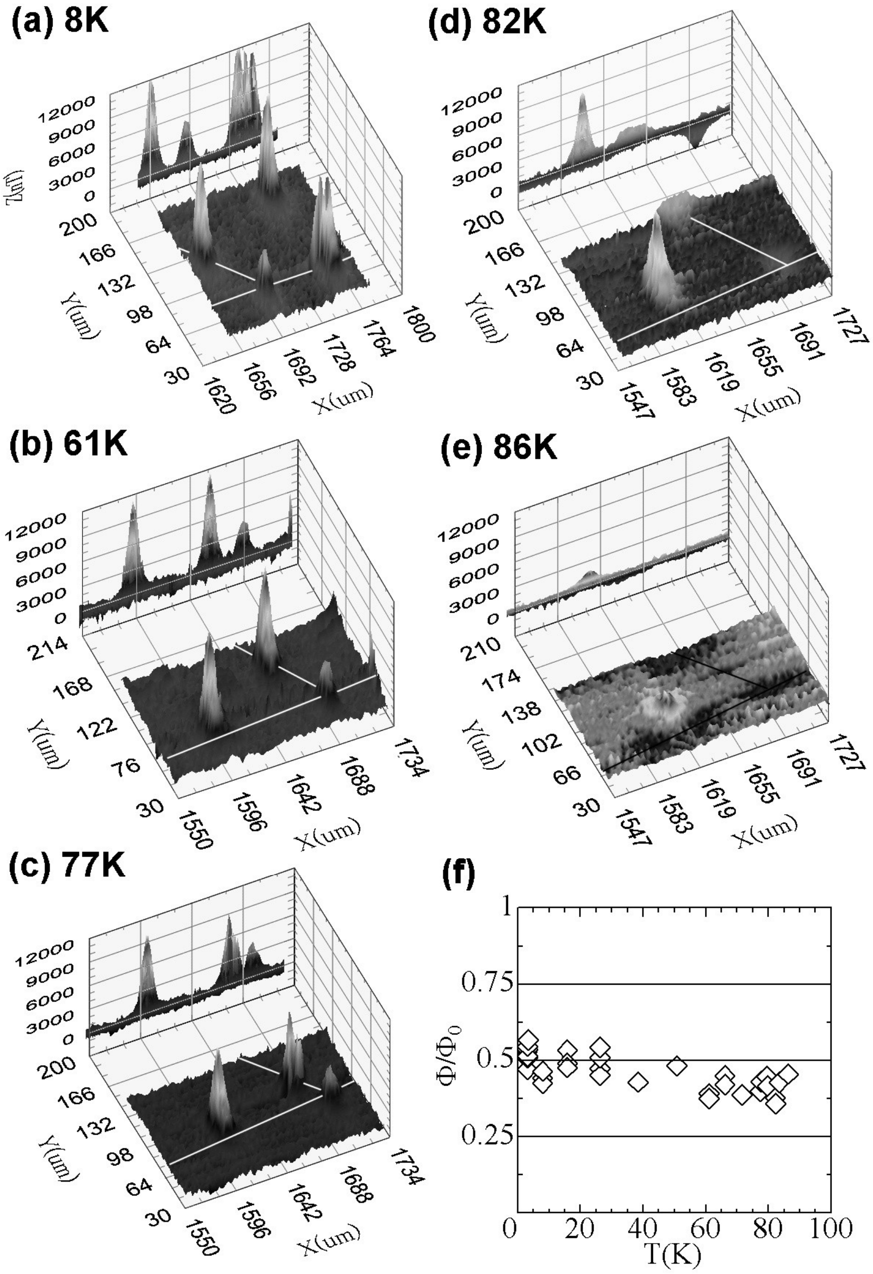


Fig. 3