Quantum Oscillation of the c-axis Resistivity due to Entrance of Pancake Vortices into Micro-fabricated $Bi_2Sr_2CaCu_2O_{8+\delta}$ Intrinsic Josephson Junctions

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Abstract

The c-axis resistance in $Bi_2Sr_2CaCu_2O_{8+\delta}$ intrinsic Josephson junctions (IJJs) with areas of the ab-plane less than 2 μm^2 were measured as functions of applied magnetic field and angle to the crystalline axes. When the magnetic field is tilted off from the lock-in state of Josephson vortices, several sharp dips are found. The separation between the dips approaches to the value corresponding to ϕ_0 with further tilting the external magnetic field. This behavior is attributed to the penetration of a quantized pancake vortex into the tiny IJJ. This argument is further supported by the result that the c-axis resistance under magnetic fields parallel to the c-axis shows identical stepwise behavior.

Key words: intrinsic Josephson junction, Josephson vortex, flux quantization, penetration depth, mesoscopic superconductors
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1. Introduction

It has been known that flux begins to penetrate into a type II superconductor as a quantized vortex ϕ_0 just above the lower critical field H_{c1}. This was firstly demonstrated by historical experiments by Doll-Näbauer[1] and Deaver-Fairbank[2]. The Little-Parks effect[3,4], oscillation of the critical temperature T_c of superconductors with tiny halls is one of the most beautiful evidences of the flux quantization. In high-T_c superconductors, the Little Parks effect was firstly claimed in $YBa_2Cu_3O_{7-\delta}$ thin films patterned with the focused ion beam (FIB) method[5].

Quite recently, several oscillating phenomena attributed to the flux quantization have been investigated on Josephson vortices (JVs) which are induced by magnetic field parallel to the ab-plane of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) intrinsic Josephson junctions (IJJ) with widths of less than 50 microns. The c-axis resistance as a function of magnetic field oscillates with a period of the field inducing a half or one ϕ_0 in a Josephson junction stacking along the c-axis[6–10]. In narrower junctions with respect to the external magnetic field, oscillation of the critical current $J_c(H)$ and Fiske step in current-voltage $(I-V)$ characteristics along the c-axis were also reported by several authors[11–13]. These phenomena are not the results of penetrations of a single vortex but mainly attributed to the intrinsic pinning[14] which confines JVs into block layers and restricts their arrangements one dimensionally along the layers.

Moreover, interaction between JVs and pancake vortices (PVs) has also been an interesting issue in IJJ. Variety of phases have been predicted theoretically[15] and observed by couple of imaging techniques[16,17]. Although such imaging techniques have a great advantage that arrangements of vortices can be revealed without an ambiguity,

Table 1
List of samples.

	$L \times W \times t$ [μm^3]	ϕ_0/A [G]	T_c [K]
#40	$1.10 \times 1.13 \times 0.25$	17	84
#42	$1.53 \times 1.45 \times 0.26$	9.3	86
#46	$0.80 \times 2.06 \times 0.51$	13	87

it is difficult to obtain thermodynamic changes of sample quantitatively and to use at high magnetic fields. Transport measurements in samples with a few JVs and PVs allow us to estimate thermodynamic properties of the interaction between two types of vortices and various vortex phases.

This paper reports on oscillating or stepwise behavior of the *c*-axis resistance in IJJs with areas of the *ab*-plane (superconducting electrodes) less than 2 square-microns. This phenomenon is interpreted to be attributed to penetration of quantized vortices one-by-one. The results enable us to estimate the penetration depth for the *ab*-plane λ_{ab} as a function of magnetic field and lower critical field H_{c1} without complicated assumptions.

2. Experimental

Bi2212 sub-micron junctions were fabricated by the FIB machine SMI2050 as shown in Fig. 1. This method is based on the technique invented by Kim et al.[18]. In advance of the fabrication, a single crystal glued on a MgO substrate was cleaved with Scotch adhesive tapes and the fresh surface was immediately covered by evaporated silver (gold) with a shadow mask which makes four electrodes. We had prepared samples listed in Table 1 and an image of a junction is shown in Fig. 2.

Measurements of the *c*-axis resistivity ρ_c were done with the four-probe method with either DC or AC bias. Voltage between the electrodes is considered to be equivalent to the voltage along the junction because current supplied with the current electrodes is concentrated within the small cross-section $A = L \times W$. For AC measurement, the SR850 lock-in amplifier was employed and the excitation current was sinusoidal with frequencies being 17 and 31 Hz. External magnetic field was applied by a split-pair superconducting magnet and the samples were rotated by a precise goniometer in fixed horizontal magnetic fields. Angle θ is measured from the *ab*-plane as seen in Fig. 1 (d).

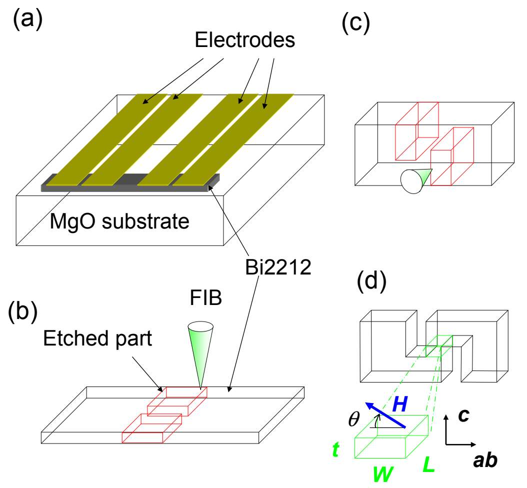

Fig. 1. (a) Sample before the fabrication. Width, thickness, and length of the crystals are $\sim 100\mu$m, $\sim 10\mu$m, $\gtrsim 2$ mm respectively. (b) Etching from the top. Red contours are etched to reduce the width. (c) Lateral etching for the reduced part. Two gaps from the top and the bottom are formed so as to overlap along the *c*-axis. (d) Finished shape and correspondence L, W, and t against the external field direcion.

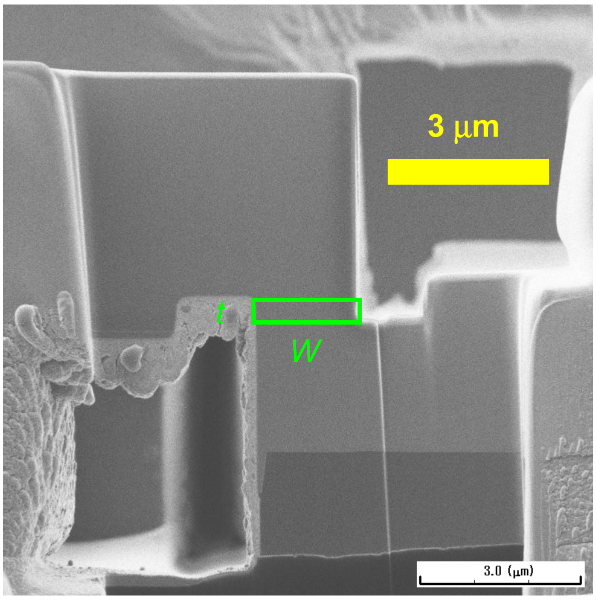

Fig. 2. Lateral image of #44. Measured resistance is from contoured part.

3. Results and Discussion

Figure 3 represents $\rho_c - \theta$ curve in sample #42 for various external magnetic fields. In data above 4 kOe, one finds several sharp dips in ρ_c besides an angle-independent resistance in the very vicinity

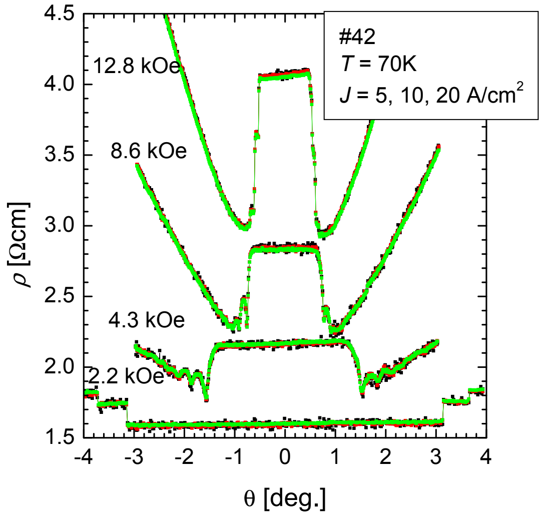

Fig. 3. Angular dependence of the c-axis resistance of #42.

of $\theta = 0$. The angle-independent resistance is attributed to flow of JVs, which would be realized in the lock-in state without pancake vortices.

In previous measurements in junctions with the width more than 2 μm[8], only one sharp drop was found besides the JV flow resistance. This is interpreted as a transition from the lock-in state to the crossing or tilted lattice state accompanied by penetrations of PVs because PVs impede flow of JVs by an attractive force in-between.

In order to emphasize effect of the c-axis field, ρ_c is plotted as a function of the c-axis component of the external magnetic field $H_\perp = H \sin\theta$ in Fig. 4. The dips are observed at the same $H_\perp$ irrespective to the parallel component of the field $H_\parallel \simeq H$. Since the penetrations of PVs impede the JV flow as described before, we interpret that these dips are attributed to the penetrations of PVs.

One expects that this phenomena are attributed to the penetrations of a *single* quantized vortex ϕ_0, which would appear every ϕ_0/A=13 Oe for the sample #46. However, it was found that the separations between the dips ΔH is not a constant but decreases with increasing $H_\perp$. Figure 5 shows ΔH as a function of $H_\perp$. ΔH between the first and the second dips are 26, almost the double of ϕ_0/A, and approaches to ϕ_0/A around $H_\perp \simeq 250$ Oe for the case of #46.

It can be considered that effective area of the ab-plane is reduced due to current penetrating from the surface with a depth of λ. Assuming that the effective area of #46 is $A_{eff} = (0.80 - 2\lambda) \times (2.06 - 2\lambda)$

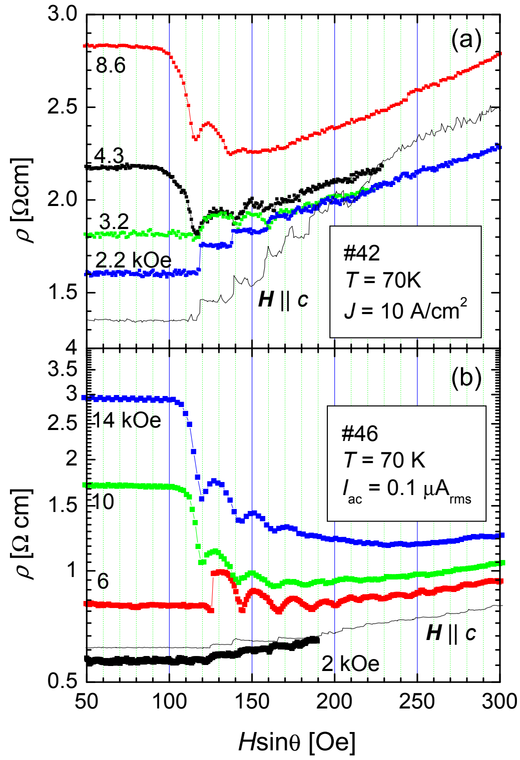

Fig. 4. ρ_c as a function of the c-axis component of the external field. Solid symbols and solid lines represent data obtained by tilting constant magnetic fields and by sweeping magnetic field, respectively.

μm^2 with $\phi_0/A_{eff} = 27$ Oe, λ is derived as 1760 Å, which is considered as the ab-plane penetration depth in the presence of magnetic field $\lambda_{ab}(H)$. The London penetration depth of the ab-plane λ_{ab} may be estimated by extrapolating $\lambda_{ab}(H)$ to $H = 0$, resulting in 2650 Åin case of $\Delta H = 50$ Oe. Since this method to estimate λ_{ab} is based on only one assumptions that vortices penetrate with a unit of ϕ_0, the value of λ is considered to be quite reliable comparing with other methods like surface impedance measurements and so on.

In a low magnetic field region below 3 kOe, we observed step-like behaviors instead of the dips. The steps correspond to dips at higher applied fields concerning on the perpendicular component of the applied field $H_\perp$, thus it is interpreted that the step is also an indication of the penetration of a quantized vortex. Since the magnetic field which induces a JV in a block layer with the area of sL is $H_0 = \phi_0/sL = 9.01$ kOe for #42, only less than half numbers of block layers are occupied by JVs in this field region.

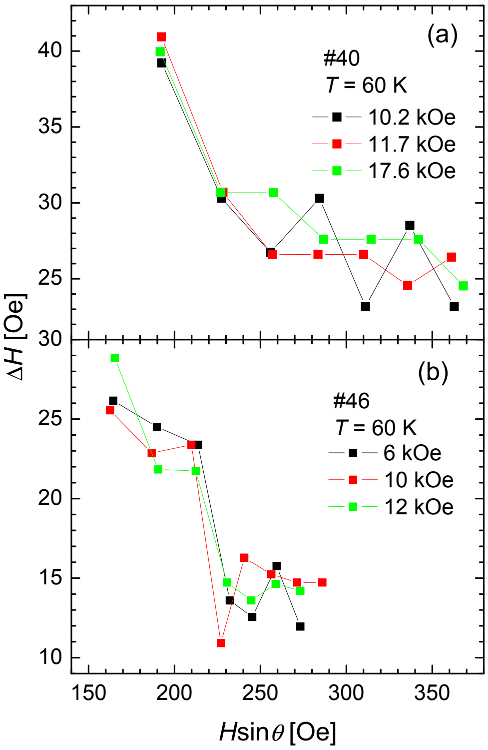

Fig. 5. Separation of adjacent dips (steps) ΔH in ρ_c as a function of $H_\perp$ taken from their midpoint for various magnetic fields.

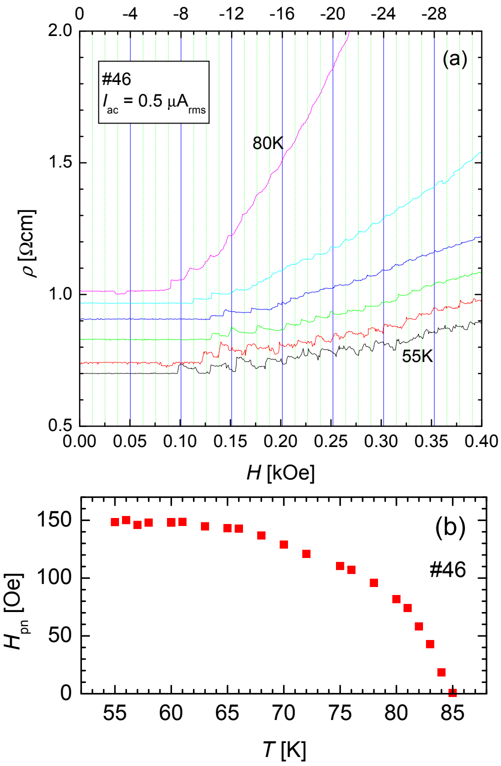

Fig. 6. (a) ρ_c as a function of the applied magnetic field parallel to the c-axis. (b) Temperature dependence of the c-axis field where the first penetration was obtained.

This situation would make contribution of the JV flow resistance to the c-axis resistance much smaller, resulting in the step like behavior attributed to the penetrations of quantized vortices.

This result suggests that even in the absence of JVs ρ_c may increase stepwise. Figure 4 includes $\rho_c(H)$ with magnetic field parallel to the c-axis. Step-like behaviors in ρ_c as well as the angular dependence in the low field region was found. Comparing with $\rho_c(H_\perp)$ at $H = 2$ kOe, all of the steps agree surprisingly well in the c-axis component of external field. Therefore, we understand that a penetration of a PV gives not only a sharp decrease in the JV flow resistance due to the attractive interaction between a JV and a PV, but also stepwise increase in ρ_c.

The increase of the c-axis resistance accompanied by a penetration of a quantized vortex under magnetic fields parallel to the c axis cannot be explained by the flux flow mechanism because the situation is under the Lorentz-force-free configuration ($\mathbf{I} \parallel \mathbf{H}$). One of other plausible origins is thermal fluctuation of a PV stack. A PV stack introduces a certain amount of fluctuation depending upon temperature, which increases ρ_c every PV penetration. Temperature dependence shown in Fig. 6 (a) supports this argument: step height at 70 K is larger than one at 60 K although some exceptions would be found.

With decreasing temperature, the data become noisy and hysteresis between increasing and decreasing field is pronounced. These features are significant below 60 K. The hysteresis would be attributed to the pinning effect for PVs because it is suppressed by temperature and magnetic field. Since the noise-like increase of the resistance also suppressed by such perturbations, it is interpreted that the noisy behavior of ρ_c is attributed to the pinning effect of PVs.

Figure 7 shows $\rho_c(H)$ for both increasing and decreasing fields at 60K. Looking at the data carefully, the hysteresis is closed around 350 Oe, which seems to correspond with the irreversibility field. At further high magnetic fields, smooth oscillating change

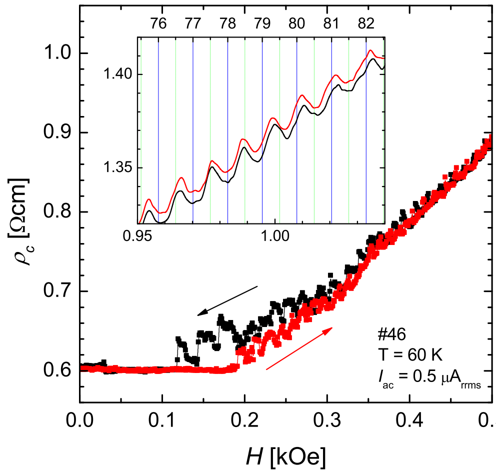

Fig. 7. $\rho_c(H)$ with increasing (red) and decreasing (black) magnetic field. Axes of the inset is not scaled with the main panel. The grid separation of the inset corresponds to $\phi_0/A = 12.6$ Oe.

with a certain period in ρ_c can be found up to 1.5 kOe and the period almost agrees with ϕ_0/A as shown in the inset of Fig. 7. This result confirms that the flux quantization is realized even in the vortex liquid state, where any long-range correlations between vortices are lost.

Figure 6 (b) displays the first penetration field H_{pn} where ρ_c shows the first step as a function of temperature. With decreasing temperature, H_{pn} increases rapidly just below T_c, and saturates around 60 K at 150 Oe. It is natural to consider H_{pn} as the lower critical field H_{c1} because width of the superconductors with respect to the external magnetic field ($< 1\mu$m) is negligibly smaller than the length along the field ($\simeq 10\mu$m), resulting in the demagnetizing modification being unnecessary. Using $H_{c1} =$ 150 Oe and $\lambda = 2650$ Å, the GL parameter κ and coherence length ξ can be estimated as $\kappa = 592$ and $\xi = 4.47$ Å, respectively. Although these estimations are so crude that some corrections will be required, obtained values are fairly reasonable comparing with known values.

4. Summary

We found clear change in the c-axis resistance accompanied by penetrations of a quantized vortex into Bi2212 intrinsic Josephson junctions with cross-sectional areas less than 2 square-microns. By tilting magnetic field from the ab-plane, sharp drops and steps were observed at the same $H_\perp$ in high and low $H_\parallel$ range, respectively. The stepwise behavior was observed even in magnetic field parallel to the c-axis. From the deviation of the step width ΔH from the ideal value ϕ_0/A and the first penetration field H_{pn}, we estimated the London penetration depth and the GL coherence length.

Acknowledgements

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References

[1] R. Doll, M. Näbauer, "experimental proof of magnetic flux quantization in a superconducting ring", Phys. Rev. Lett. 7 (2) (1961) 51–52.
[2] B. S. Deaver, W. M. Fairbank, "experimental evidence for quantized flux in superconducting cyclinders", Phys. Rev. Lett. 7 (2) (1961) 43–46.
[3] W. A. Little, R. D. Parks, Observation of quantum periodicity in the transition temperature of a superconducting cylinder, Phys. Rev. Lett. 9 (1) (1962) 9.
[4] R. D. Parks, W. A. Little, Fluxoid quantization in a multiply-connected superconductor, Phys. Rev. 133 (1A) (1964) A97.
[5] P. L. Gammel, P. A. Polakos, C. E. Rice, L. R. Harriott, D. J. Bishop, Little-parks oscillations of t[sub c] in patterned microstructures of the oxide superconductor yba$_2$cu[sub [bold 3]]o[sub [bold 7]]: Experimental limits on fractional-statistics-particle theories, Physical Review B (Condensed Matter) 41 (4) (1990) 2593–2596. URL `http://link.aps.org/abstract/PRB/v41/p2593`
[6] S. Ooi, T. Mochiku, K. Hirata, Periodic oscillations of josephson-vortex flow resisitance in bi$_2$sr$_2$cacu$_2$o$_{8+y}$, Phys. Rev. Lett. 89 (2002) 2427002.
[7] M. Machida, Dynamical matching of josephson vortex lattice with sample edge in layered high-t_c superconductors: Origin of the periodic oscillation of flux flow resistace, Phys. Rev. Lett 90 (2003) 037001.
[8] I. Kakeya, M. Iwase, T. Yamamoto, K. Kadowaki, "Josephson lattice structure in mesoscopic intrinsic Josephson junctions by means of flux-flow resistance in $Bi_2Sr_2CaCu_2O_{8+\delta}$", cond-mat/0503498 (2005).
[9] M. Machida, S. Sakai, Unified theory for magnetic and electric field coupling in multistacked josephson junctions, Phys. Rev. B 70 (2004) 144520.
[10] B. Y. Zhu, H. B. Wang, S. M. Kim, S. Urayama, T. Hatano, X. Hu, Periodic oscillations, peak-splitting and phase transitions of josephson vortex flow resistance in bi2sr2cacu2o8+delta, PHYSICAL REVIEW B 72 (17) (2005) 174514.

[11] V. M. Krasnov, et al., Fiske steps in intrinsic $\mathrm{bi_2sr_2cacu_2o_{8+x}}$ stacked josephson junctions, Phys. Rev. B. 59 (1999) 8463.
[12] S. M. Kim, H. B. Wang, T. Hatano, S. Urayama, S. Kawakami, M. Nagao, Y. Takano, T. Yamashita, K. Lee, Fiske steps studied by flux-flow resistance oscillation in a narrow stack of bi[sub 2]sr[sub 2]cacu[sub 2]o[sub 8 + delta] junctions, Physical Review B (Condensed Matter and Materials Physics) 72 (14) (2005) 140504.
[13] I. Kakeya, T. Yamzaki, M. Kohri, T. Yamamoto, K. Kadowaki, "Periodic and non-periodic current steps in $I-V$ characteristics in mesoscopic intrinsic Josephson junctions of Bi2212", Physica C 437-438 (2006) 118–121.
[14] T. Tachiki, S. Takahashi, Solid State Commun. 70 (1989) 291.
[15] S. E. Savel'ev, J. Mirkovic, K. Kadowaki, London theory of the crossing vortex lattice in highly anisotropic layered superconductors, PHYSICAL REVIEW B 6409 (9) (2001) 094521.
[16] A. Grigorenko, S. Bending, T. Tamegai, S. Ooi, M. Henini, A one-dimensional chain state of vortex matter, Nature 414 (6865) (2001) 728–731.
[17] M. Tokunaga, T. Tamegai, Y. Fasano, F. de la Cruz, Direct observations of the vortex chain state in $bi_2sr_2cacu_2o_{8+y}$ by bitter decoration, Phys. Rev. B 67 (13) (2003) 134501.
[18] S.-J. Kim, Y. I. Latyshev, T. Yamashita, Supercond. Sci. Tech. 12 (1999) 729.