Anisotropy dependence of triangular lattice formation of Josephson vortices in $Bi_2Sr_2CaCu_2O_{8+y}$

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To study the anisotropy dependence of the Josephson-vortex phase diagram, we measured the Josephson-vortex flow resistance as a function of magnetic field parallel to the *ab* plane in $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi-2212) single crystals. The anisotropy of samples was controlled over a wide range by annealing. Since the Josephson-vortex flow resistance oscillates periodically as a function of the magnetic field when a dense triangular lattice is formed, the lower boundary field of the triangular lattice phase is assigned from the magnetic field where the oscillations start. We observed that the lower boundary field of the triangular lattice phase decreases systematically with increasing anisotropy parameter γ of Bi-2212 at all measured temperatures. This behavior is consistent with theories which imply that the boundary field is inversely proportional to γ.

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Vortex matter physics in high-T_c cuprate superconductors has been a subject of extensive experimental and theoretical researches since they exhibit novel phenomena due to the large thermal fluctuation and strong anisotropy caused by the layered crystal structures. In highly anisotropic superconductors, such as $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi-2212), alternately stacked superconducting CuO_2 layers and insulating layers naturally form atomic-scale Josephson junctions along the *c* axis. This is the so-called intrinsic Josephson junction.[1] When a magnetic field is applied parallel to the *ab* plane, the flux is quantized into Josephson vortices without normal-state cores.[2] For the case where the magnetic field is applied perpendicular to the *ab* plane, the vortex phase diagram of Bi-2212 has been studied by various techniques. A first-order vortex lattice melting,[3] as well as a disorder-induced phase transition,[4] has been experimentally confirmed. In contrast, the phase diagram of Josephson vortices in Bi-2212 is less well understood, though Mirkovic *et al.* have suggested a second-order vortex-crystal–vortex-smectic phase transition in fields nearly parallel to the *ab* planes through measurements of in-plane resistance.[5] Theoretically, several solid phases[6–9] and a tricritical point on the melting transition line[10] in the Josephson-vortex system have been predicted. However, they have not been verified experimentally.

Recently, Ooi *et al.* have discovered novel periodic oscillations of the Josephson-vortex flow resistance as a function of the parallel magnetic field in Bi-2212 single crystals which persist over a wide range of magnetic fields and temperatures.[11] The period of the oscillations H_p depends only on the sample width w perpendicular to the magnetic field and corresponds to adding one vortex quantum per two intrinsic junctions. This phenomenon can be interpreted by assuming the formation of a triangular lattice of Josephson vortices and a matching effect between the sample width and the lattice spacing of the Josephson vortices. Subsequent theoretical analyses of this phenomenon have been made by several groups. The oscillations were reproduced in numerical simulations[12] and were explained from analytical calculations based on an edge critical current.[13] These theoretical studies also support the view that the periodic oscillations occur when the Josephson vortices fill all intrinsic junctions and form a triangular lattice. The starting field of the oscillations H_s is interpreted as the lower boundary of the triangular lattice phase. Thus, the measurement of flow resistance is a useful probe to investigate the magnetic phase diagram of Josephson vortices. Theoretically, the Josephson vortices are expected to form a triangular lattice when the magnetic field exceeds a crossover field H_{cr} which is inversely proportional to the anisotropy parameter $\gamma=\lambda_c/\lambda_{ab}$, where λ_{ab} and λ_c are the penetration depths for currents in the *ab* plane and along the *c* axis, respectively.[6–9] Experimentally, however, the question of how the anisotropy parameter γ influences the Josephson-vortex phase diagram has remained an unresolved issue, because there had been no means to detect the lower boundary field until the discovery of the periodic oscillations. In the present study, we measured the Josephson-vortex flow resistance of Bi-2212 single crystals with different doping levels, which cover from the overdoped to the underdoped states. Periodic oscillations of the flow resistance are observed in all samples from 5 K to near T_c. We found that the starting field of the oscillations decreases systematically with the change of doping level. From these results, we discuss how the lower boundary field of the triangular lattice phase depends on γ.

The single crystals of Bi-2212 used in the present study were grown using the traveling-solvent floating zone method. Details of the single crystal preparation are described elsewhere.[14] A platelet of single crystal was carefully cut into narrow strips with 2–3 mm in length and

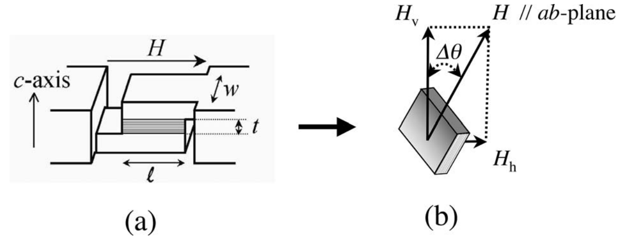

FIG. 1. (a) A schematic picture of the junction. The applied current I flows along the c axis in the junctions, and the magnetic field H is applied along the *ab* plane. (b) Alignment of the magnetic field H parallel to the *ab* plane.

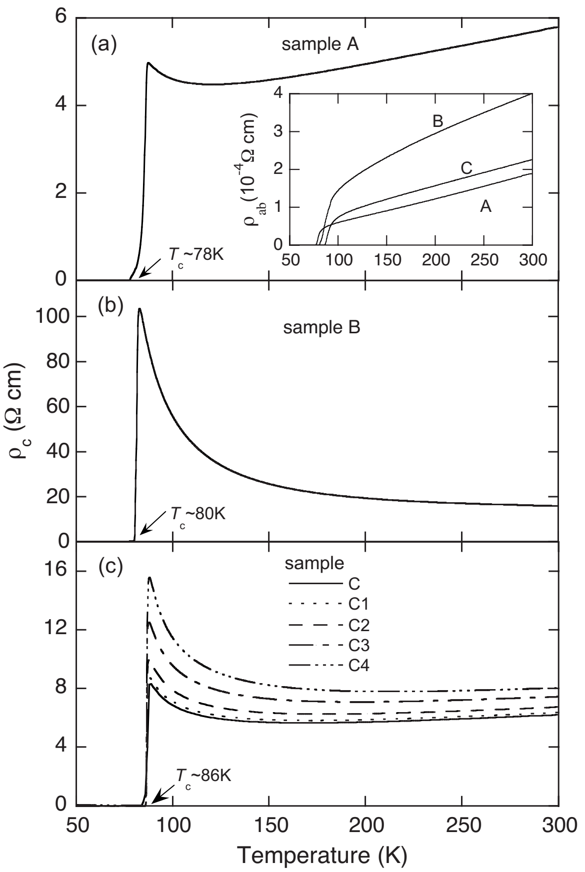

FIG. 2. Temperature dependence of ρ_c in sample A (a), sample B (b), and samples C-C4 (c). The inset presents temperature dependence of ρ_{ab} for samples A, B, and C.

50–55 μm in width. After forming a four-contact configuration using silver pastes, the samples were annealed at 430 °C in air for 5 min to form electrodes. The contact resistance of the electrodes was several ohms. The intrinsic Josephson junctions were then fabricated by milling the centers of the strips with a focused ion beam.[15] A schematic illustration of such a junction is shown in Fig. 1(a). We studied three samples, A, B, and C. In order to control the anisotropy, samples A and B were, respectively, annealed in O_2 and in a vacuum before the fabrication of intrinsic junctions. The annealing conditions, the junction dimensions, and T_c's of the samples are listed in Table I. The resistance of junctions at 300 K was 270, 6172, and 161 Ω for samples A, B, and C, respectively. These values are 3 or 4 orders larger than the

TABLE II. Sample C was successively annealed in a vacuum with the listed processes (1)–(4). After each annealing process, sample C was distinguished by labeling it as C1–C4.

Annealing process	Temperature (°C)	Time (h)	Sample
(1)	160	1	C1
(2)	170	12	C2
(3)	180	12	C3
(4)	190	12	C4

resistance prior to the fabrication. Therefore, the measured resistance is safely assigned to the c-axis resistance of the junction. For the case of sample C, we annealed it successively in a vacuum after the fabrication of the intrinsic junction. Such successive annealing enables us to modify the anisotropy systematically without changing other parameters such as junction dimensions. Hereafter, sample C, after each annealing process, was distinguished by labeling it as C1–C4. We list the successive annealing conditions for these samples in Table II. For samples A, B, and C, even though the sizes are different from each other, it would not alter seriously our discussion below since H_s has been found to be insensitive to sample size.[16,17]

We measured the temperature dependence of resistivity using a magnetic properties measurement system (MPMS-5S with EDC option, Quantum Design). The ab-plane resistivity ρ_{ab} was measured prior to the fabrication of intrinsic junctions while ρ_c was measured by using the junction. The measurement of Josephson-vortex flow resistance was carried out using the same system with a custom horizontal split magnet in addition to the standard vertical magnet. The vertical magnet is the main source of the magnetic field up to 50 kOe. The horizontal magnet with a maximum field of 3 kOe is appended to the equipment so that the field direction can be adjusted. The sample of the fabricated Josephson junctions was set with the ab plane parallel to the vertical magnetic field H_v. However, it is difficult to perfectly align the ab plane with the direction of the vertical magnetic field. The misalignment $\Delta\theta$ between the ab plane and the direction of the vertical field was compensated by the horizontal magnetic field H_h, as shown in Fig. 1(b).

The temperature dependence of ρ_{ab} and ρ_c is shown in Fig. 2. Samples A and B exhibit typical over- and underdoping behaviors while sample C, which has the highest T_c, is the closest to the optimal doping level among the three mea-

TABLE I. Annealing conditions, sample dimensions, and superconducting transition temperatures T_c's are shown.

Sample	Annealing conditions	dimensions (μm) w	l	t	T_c (K)
A	1 atm O_2, 430 °C, 10 min	15.90	16.20	1.20	~78
B	Vacuum, 370 °C, 12 h	6.40	14.40	3.57	~80
C	As grown	38.50	28.00	2.80	~86

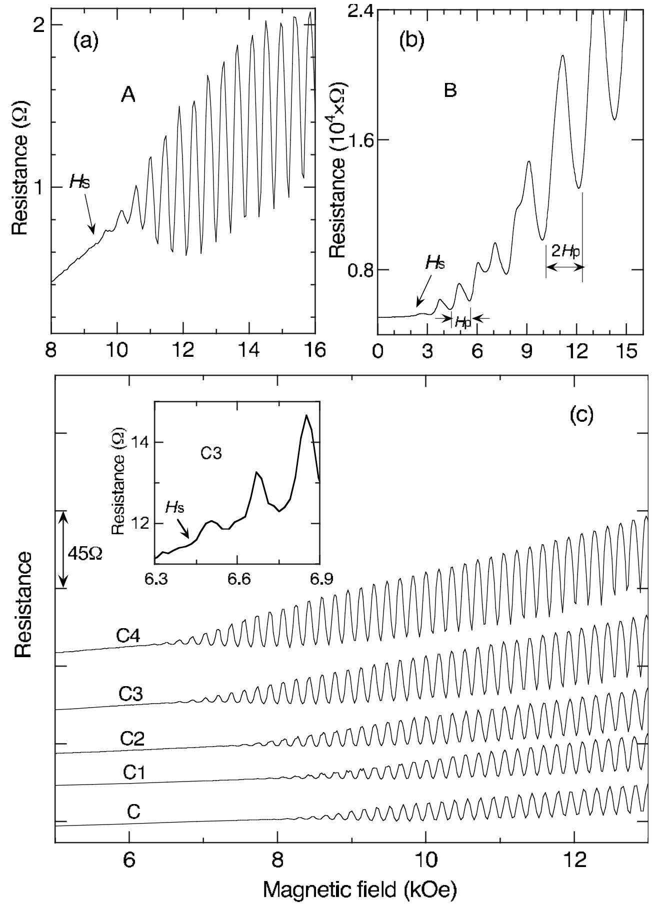

FIG. 3. Flow resistance of Josephson vortices as a function of the parallel magnetic field with a current of 0.93 A/cm^2 at 70 K in sample A (a), sample B (b), and samples C-C4 (c). The vertical axes are offset appropriately in (c). The inset shows an enlarged figure of the oscillations near H_s for sample C3.

sured samples. As sample C was successively annealed in a vacuum, the ρ_c of samples C–C4 increased systematically, as shown in Fig. 2(c), even though their T_c's were almost identical. Several experimental results for high-T_c superconductors such as Bi-2212 have indicated that the values of anisotropy parameter γ are comparable to the resistivity anisotropy $\sqrt{\rho_c/\rho_{ab}}$ obtained above T_c from the transport measurements.[18–21] For Bi-2212, the resistivity anisotropy at 100 K was typically used for the comparison.[18,21] Following these previous reports, we therefore estimated γ of our samples using the same definition. For samples A, B, and C, the γ value varied from ~270 to ~620. For samples C1–C4, we were not able to measure the change of ρ_{ab} during the successive annealing directly. However, the ρ_{ab} at 100 K was expected to be almost the same as that of sample C since ρ_{ab} is not so sensitive to the oxygen contents as ρ_c.[22] In addition, we have experimentally confirmed that when sample C before the fabrication was successively annealed in a vacuum, their ρ_{ab} at 100 K remained unaltered if their T_c was almost unchanged. The γ values of samples C–C4 as estimated from measured ρ_c and ρ_{ab} were found to increase with annealing from ~310 to ~400. These samples, hence, enable us to study the Josephson-vortex system under various anisotropy conditions.

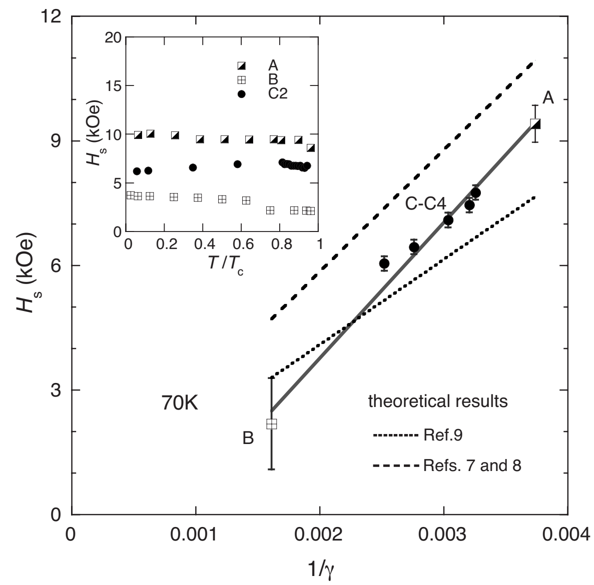

FIG. 4. H_s as a function of $1/\gamma$ for all samples at 70 K. As a comparison, theoretical predictions $H_s \sim \phi_0/\pi\gamma s^2$ (Refs. 7 and 8) and $H_s \sim 1.4\phi_0/2\pi\gamma s^2$ (Ref. 9) are shown by the dashed and dotted lines, respectively. The length of the error bars corresponds to the H_p of each sample. The inset shows the normalized temperature dependence of H_s for samples A, B, and C2.

Figure 3 displays the flow resistance of Josephson vortices as a function of the parallel field at 70 K with a current density of 0.93 A/cm^2 applied parallel to the c axis for all the samples. The flow resistance starts to oscillate periodically above a particular magnetic field H_s which depends on the samples. The period H_p was found to be ~445 Oe in sample A, ~1100 Oe in sample B, and ~175 Oe in samples C–C4. These values are in agreement with the theoretical periods, $\phi_0/2ws$, where s (=15 Å) is the distance between the CuO_2 layers, i.e., the thickness of a single intrinsic Josephson junction. For sample B shown in Fig. 3(b), the period of oscillations doubles at higher magnetic fields. As have been discussed elsewhere, this behavior has been observed depending on the applied currents and junction sizes and may correspond to the formation of a rectangular lattice of Josephson vortices.[23] Such a structural change in the Josephson-vortex lattice has been theoretically studied by Machida[12] and Koshelev.[13]

We found that the period H_p is unaffected by successive annealing and remains the same through samples C–C4. This indicates that the spacing between CuO_2 layers is hardly altered by the annealing even though the oxygen content is decreased. Indeed, Kotaka *et al.*[24] previously reported that the difference in the layer spacing is less than 0.1 Å for Bi-2212 single crystals with a wide range of oxygen contents, including overdoped and underdoped states. Thus, the doping level does not influence H_p within the accuracy of our measurements.

Next, we discuss the anisotropy dependence of H_s. Here, we define H_s as the magnetic field where the amplitude of the oscillation exceeds 1/100 of the maximum amplitude, which is larger than the background noise of our measurements. As an example of how we determine H_s, the inset in

Fig. 3(c) depicts an enlarged figure of the oscillations near H_s for sample C3. H_s's of samples A and B are indicated by the arrows in Figs. 3(a) and 3(b). We found that H_s decreases with increasing anisotropy, as depicted in Fig. 3. This behavior can be seen more clearly in Fig. 4, where we plot H_s as a function of $1/\gamma$. H_s is fitted by the function $a+b/\gamma$ with $a \approx -2.76$ and $b \approx 3266$, as shown by the solid line. This result suggests that H_s is approximately proportional to $1/\gamma$. Theoretically, Bulaevskii and Clem[7] and Ichioka[8] have predicted that a dense lattice of Josephson vortices is formed when a magnetic field exceeds the crossover field, $H_{cr} \sim \phi_0/\pi\gamma s^2$. Recently Ikeda[9] has studied the ground states of Josephson vortices and evaluated the lower boundary field of the triangular lattice phase as $1.4\phi_0/\pi\gamma s^2$. For a comparison, these theoretical equations are plotted by dashed and dotted lines in Fig. 4. The observed H_s's are quantitatively close to these theoretical estimations. Thus, our measurements support the theoretical interpretation that the dense lattice is formed when the core of Josephson vortices begins to overlap.

The temperature dependence of the flow resistance was also measured from 5 K to near T_c with an applied current density of 0.93 A/cm^2. The periodic oscillations were observed at all measured temperatures. H_s values extracted from the experimental data are plotted as a function of normalized temperature T/T_c in the inset of Fig. 4. We found that H_s is insensitive to temperature in all measured samples with different doping levels. This may be explained by a weak temperature dependence of γ. Indeed, there have been several experimental reports in Bi-2212 in which γ was not so sensitive to temperature except very near T_c. The γ value estimated from the Josephson plasma resonance and reversible magnetization by Colson *et al.*[25] decreases ~25% when T/T_c increases from ~0.4 to ~0.9. The γ value extracted from $\lambda_{ab}(T)$ and $\lambda_c(T)$ measured by Jacobs *et al.*[26] weakly depends on temperature. The difference of γ is less than 15% with a normalized temperature changing from ~0.1 to ~0.9. These variations of γ by temperature are comparable with the range of those observed in H_s.

In summary, we found that the onset field H_s of the oscillations decreases systematically with increasing γ. This indicates that the lower boundary field of the triangular lattice phase shifts to lower fields when γ increases. Our result is an experimental verification of the theoretical predictions.[6–9] Conversely, the theoretical expressions such as $H_s \sim 1.4\phi_0/2\pi\gamma s^2$ may be used to estimate γ from the experimental value of H_s. Furthermore, we showed that the boundary field is almost independent of temperature.

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