Vortex states in micron-sized Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ crystals

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Abstract.
Large thermal fluctuation, owing to high superconducting transition temperature, short coherence length and quasi-two-dimensionality, brings about a rich variety of vortex phases in Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi2212). To study how the vortex states and the transitions would be modified when vortices are confined in a small-sized crystal, we have measured the c-axis resistance using a stack of the intrinsic Josephson junctions (IJJs) of Bi2212. In tiny Bi2212 crystals of several micron, it is possible to observe the series of vorticity transitions using the c-axis resistance measurements. Combining the observation of vorticity changes and detection of a melting transition, we found an oscillating behavior of melting transition temperatures $T_m$ as a function of magnetic field (or number of vortices) in small squared Bi2212 with a lateral dimension of 5-10 $\mu$m. In the case of the square-shaped crystals, it seems that $T_m$ is enhanced around the vortex numbers $N_v$ of $i^2$ ($i$: integer), indicating a matching of square vortex lattices in the square boundary. However, the frustration between the square boundary shape and vortex lattice that prefers a triangular lattice complicates the situation. A deformed square lattice without topological defects is probably realized at large $i^2$ as a geometrical matching state.

1. Introduction
Upon reducing the size of a superconductor, an Abrikosov vortex lattice realized in a clean bulk superconductor is strongly influenced by the screening current circulating around the sample edge. The modification of the vortex state confined in a small area has been frequently studied in various mesoscopic conventional superconductors in past decades. In a superconductor whose lateral dimension is comparable to the coherence length, a giant vortex sustaining a multiquanta fluxoid of $2\Phi_0$ or more has been predicted theoretically [1] and explored by various experimental approaches [2–4]. In mesoscopic superconducting disks with a larger lateral dimension, concentric shell structures of vortices (vortex shells) have been studied theoretically [5] and experimentally by the Bitter decoration technique [6] and a scanning SQUID microscope [7]. Direct visualization of vortex configurations has also been attempted in samples with other shapes, e.g., triangles, squares, and pentagons [8–11].

Also, in mesoscopic high-$T_c$ superconductors in a field perpendicular to the superconducting planes, the vortex state of a small number of vortices confined in a restricted area should be different from that in bulk samples. This has been investigated in Bi$_2$Sr$_2$CaCu$_2$O$_{8+y}$ (Bi2212) using magnetical techniques [12–15]. The first-order melting transition of the Bragg glass and the disorder-induced phase transition (the second magnetization peak effect) in mesoscopic Bi2212...
down to 30 μm were originally explored by Wang et al. [12]. They found the disappearance of the second magnetization peak in samples smaller than a critical length, while the melting transition was insensitive to the sample size. The persistence of the melting transition line in the vortex phase diagram was also confirmed in smaller samples down to 20 μm by magnetic permeability measurements using a Hall probe with an excitation microcoil [16].

As an alternative method, transport measurements in a stack of IJJs facilitate the detection of the melting transition in a very small crystal [17]. The transitions have been successfully observed as a resistive jump of the c-axis resistance in a $47 \times 79 \mu m^2$ stack [17] and as an anomaly in the c-axis critical current in a $7.3 \times 13 \mu m^2$ stack [18]. Furthermore, it is possible to detect the penetration of a single vortex into a mesoscopic stack of IJJs of Bi2212 by c-axis transport measurement, which was first found by Kakeya et al. [19]. Therefore, simultaneous observation of the melting transition and the penetration of individual vortices in the same IJJ stack can provide another route to unveiling the vortex states in mesoscopic Bi2212.

2. Experimental

High-quality single crystals of Bi2212 were grown by the traveling-solvent floating-zone method [20]. Our fabrication process to form a z-shaped bridge containing a stack of IJJs of Bi2212 is based on the double-side etching technique [12], and it is also similar to the method used to fabricate whiskers by Latyshev and co-workers [21]. Details of the fabrication are described in ref. [22]. Transport measurements were performed using the four-probe technique with a current source (Keithley 6430) and a nanovoltmeter (Keithley 2182) in a chamber with a cryocooler. Data of the c-axis resistance shown here were acquired in repeats of field-scans at various fixed temperatures. Magnetic fields were applied parallel to the c axis.
Figure 2. c-axis resistance of a $10 \times 10 \mu m^2$ IJJ stack as a function of magnetic field from 72.0 to 88.4 K at intervals of 0.2 K. With increasing temperature, the curves shift from right to left. Resistive jumps of the melting transition are observed more clearly at lower temperatures, and fine spikes caused by the penetration of individual vortices appear at low fields and high temperatures.

3. Results and discussion

3.1. Penetration of individual vortices

Primarily, the penetration of individual pancake vortices into IJJ stacks has been found in a series of experiments to determine the out-of-plane angular dependence of a Josephson vortex flow [19]. As the magnetic field is tilted from parallel to the superconducting planes, oscillating behavior of the c-axis resistance appears away from the lock-in angle in mesoscopic IJJ stacks, which is induced by the penetrations of pancake vortices. The suppression of the Josephson vortex-flow resistance by individual fluctuating pancake vortices near the lock-in angle has been studied theoretically and experimentally [23]. The experimentally-observed exponential dependence of the c-axis conductivity was well explained by the theoretical model.

Figure 1(a) shows c-axis resistance as a function of magnetic field for a $2.3 \times 2.2 \mu m$ IJJ stack, where the penetration of each vortex can be observed as a step, spike, or sawtooth shape, depending on the temperature and magnetic field, on a gradually increasing background. At higher temperatures, the resistance suddenly increases once a vortex penetrates and the $R-H$ curves show step-like changes. At lower temperatures, vortex penetration brings about a sudden decrease in the resistance, causing the curve to become sawtooth shaped. At intermediate temperatures, for example, 76 K in Fig. 1(a), both increases and decreases in the resistance sequentially occur, leading spike-like shapes. Kakeya et al. found step-like changes in tiny stacks with in-plane areas of less than $2 \mu m^2$ [19]. Thereafter, the penetrations of individual vortices were confirmed in samples with much larger sizes of up to $100 \mu m^2$, and the appearance of $R-H$ and $I_c-H$ curves during the penetration of vortices was studied in samples with different sizes [24]. A vortex phase diagram constructed from the $R-H$ curves of Fig. 1(a) is presented in Fig. 1(b). Transitions of the vortex numbers are clearly visualized, enabling us to determine the number of vortices in the stack at a certain point on the diagram.
3.2. Oscillations of the melting transition line in confined vortex matter

In very small stacks such as the sample used in Fig. 1, it has been difficult to find evidence of a melting transition. In the first place, its existence is not self-evident in a system containing only a small number of vortices less than 10. In relatively large stacks, however, a resistive jump accompanied by a melting transition is clearly observed as shown in Fig. 2. The sharp jumps at lower temperatures gradually broaden at higher temperatures and finally disappear near $T_c$. One can also observe very fine spikes below 10 Oe corresponding to the penetration of individual vortices. Extracted melting transition fields $H_m$ at the onset of jumps are plotted in Fig. 3 as a function of temperature. Figure 3 appears to reproduce the behavior of the melting transition line in bulk crystals, and the temperature dependence can be fitted by $H_m = H_0(T_c/T - 1)$, theoretically predicted for the decoupling transition of vortex lines [25, 26]. However, by subtracting the fitting curve as a background, oscillatory behavior of the melting transition line is unveiled as shown in the inset of Fig. 4. This oscillating phenomenon has been confirmed in other square samples of a side length $l$ from 5 to 10 $\mu$m [22]. In 5$\mu$m square stack, the penetrations of over 100 individual vortices were observed, making it possible to count the number of vortices in the vortex phase diagram. Interestingly, enhancements of the melting temperature occurred around square numbers of vortices, especially in higher fields [22].

In the case of a system of Josephson vortices in underdoped Y123 single crystals, the oscillation of the melting transition line is a manifestation of commensurability and incommensurability between the regularity of a vortex lattice and the underlying intrinsic pinning potential [27]. In a confined vortex system like present study, the two-dimensional geometrical matching of vortex lattice with the boundary shape is an important factor for the stability of a vortex crystal (or cluster) for each vortex number.
The sample-size dependence of the oscillations of the melting transition line supports the scenario of the matching effect by the square lattice structure [22]. There is a tendency for the oscillation period to increase with increasing magnetic field and with decreasing sample size. By converting from the magnetic field $H$ to the roughly estimated vortex number $N$ using $N = H/\Delta H_p$ with a field interval $\Delta H_p$ of the penetration of individual vortices, all the results for different samples appear to collapse onto a single curve as shown in Fig. 4(a). If the oscillation period is determined by the formation of square lattices by $4, 9, 16, \ldots , i^2$ vortices (where $i$ is an integer), the periodicity is expected to be $2\sqrt{N_{total}} + 1$ as a function of the total number of vortices $N_{total} = i^2$, which is indicated as a dashed line in Fig. 4(a). This line is in reasonable agreement with the experimental results. The amplitude of the $\Delta T_m$ oscillations ($\Delta T_m^{amp}$) increases with reducing sample size as shown in Fig. 4(b). In the log-log plot, the data aligns on a linear line, indicating a power law relation. The dashed line in Fig. 4(b) is a fitting result of $\Delta T_m^{amp}[K] = 66.6 \cdot (l[\mu m])^{-2.95}$. This indicates that the influence of the confinement by a screening current on the melting becomes more noticeable in smaller Bi2212, especially less than 10 $\mu$m.

The vortex configurations and the filling rule in mesoscopic superconducting squares have been studied for patterned Nb films by the Bitter decoration technique with numerical simulations [9]. The formation of shell structures and the periodic filling of the outermost and internal shells were found. With increasing $N_{total}$, the outermost shell is filled until the number of vortices in it becomes $4i$, i.e., commensurate with a square shape. The vortices then fill the internal shells until their number becomes sufficiently large to create the next outermost shell. Whereas at small $N_{total}$, i.e., 4, 9, and 16, perfect square lattices are observed, for sufficiently
large $N_{\text{total}}$ the vortices do not form perfect square lattices even with square numbers in the simulation, and the lattices are deformed because the vortices tend to recover the triangular structure far from the boundary. Thus, it is difficult to expect the matching effect for perfect square lattices at large vortex numbers. Probably, the configuration of a deformed square lattice at large $i^2$ be related to the oscillations. Recently, the structural properties of a vortex solid confined in 30 $\mu$m Bi2212 squares and disks have been investigated by the Bitter decoration technique with single-vortex resolution [15]. An increase in the number of topological defects in the vortex solid was observed, particularly near the edge. A study on the relation between the defect density and the melting transition will be of interest to elucidate the mechanism of the melting-temperature oscillations.

An alternative explanation of the oscillations is the periodic filling of the outermost and internal shells. Dolz et al. found oscillatory behavior in the magnetic transmittivity as a function of magnetic field in rather large Bi2212 disks of 50 $\mu$m diameter, which was interpreted as the discretized entrance of single shells [14]. In their simple model, $\sqrt{B}$ dependence of the oscillation period is expected, which resembles the oscillations of the melting transition. Although the numbers of vortices involved in both oscillations are considerably different, an intriguing issue is whether there is a correlation between these phenomena.

4. Summary
We have studied the vortex states confined in micron-sized Bi2212 single crystals by $c$-axis resistance measurements of a stack of IJJs. In Bi2212 crystals of about 2 $\mu$m, the penetrations of individual vortices were observed in a wide range of magnetic field at high temperatures. For square-shaped samples of 5-10 $\mu$m in side length, oscillating behavior in the melting transition line emerges. Results of the simultaneous observations of the melting and the penetrations of individual vortices suggest that a geometrical matching of deformed square vortex lattices with the square boundary shape cause the enhancement of the melting temperature at the square numbers of vortex.

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