Direct Observation of Vortices in High-T_c Superconductors

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Abstract

The structures of vortices inside high-T_c superconductors are now observable using Lorentz microscopy with our newly developed 1-MV field-emission transmission electron microscope, which has the brightest electron beam with the narrowest monochromaticity yet reported. Using this microscope, we identified previously unseen unconventional behaviors of vortices in anisotropic high-T_c superconductors: we distinguished different structures of vortex lines inside high-T_c superconductors, such as vortex lines perpendicular to the layer plane and tilted ones trapped by columnar defects, as different images. We found to our surprise that when the sample temperature decreased below 14 K, the vortices trapped and strongly pinned along tilted columnar defects became perpendicular to the film plane, as if the defects had disappeared. We were also able to clarify the mechanisms of unconventional arrangements, such as the chain state of vortices in YBCO and the chain-lattice state of vortices in Bi-2212, in an inclined magnetic field and also the mechanism of the unexpected chain-vortices image disappearance in Bi-2212.

Key words: Lorentz microscopy; vortex; Bi-2212; columnar defects; chain state;

1. Introduction

The behaviors of vortices play an important role in the practical application of superconductors to dissipation-free electrical conductors. Especially in anisotropic high-T_c superconductors, vortices behave in complicated manners with respect to their structures and dynamics, reflecting the anisotropic layered structures of the materials.

However, the behaviors of vortices inside superconductors cannot be observed directly, because all the techniques reported so far for observing detect vortices only vortices at the superconductor surface, and not those inside the superconductor. Lorentz microscopy using our 1-MV electron microscope [1] now makes it possible to directly observe the structure of vortices inside high-T_c superconducting thin films. We used it in the present experiments to investigate the pinning characteristics of vortices at tilted columnar defects [2], the formation mechanisms of special arrangements of vortices in a tilted magnetic field [3], and the unexpected oscillation of chain vortices well below T_c [4].

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2. Direct observation of vortices trapped by tilted columnar defects

We directly observed individual vortices in Bi-2212 films, 0.4 μm thick, which had columnar defects tilted at 70°, and distinguished as different vortex images different arrangements of vortex lines trapped at columns and untrapped elsewhere. An example Lorentz micrograph at 30 K is shown in Fig. 1; it was obtained when a magnetic field was applied in the direction of the tilted columns. The white spots indicate vortex images. Careful examination revealed that there are two kinds of images: circular ones and elongated. The latter ones are indicated by the arrows

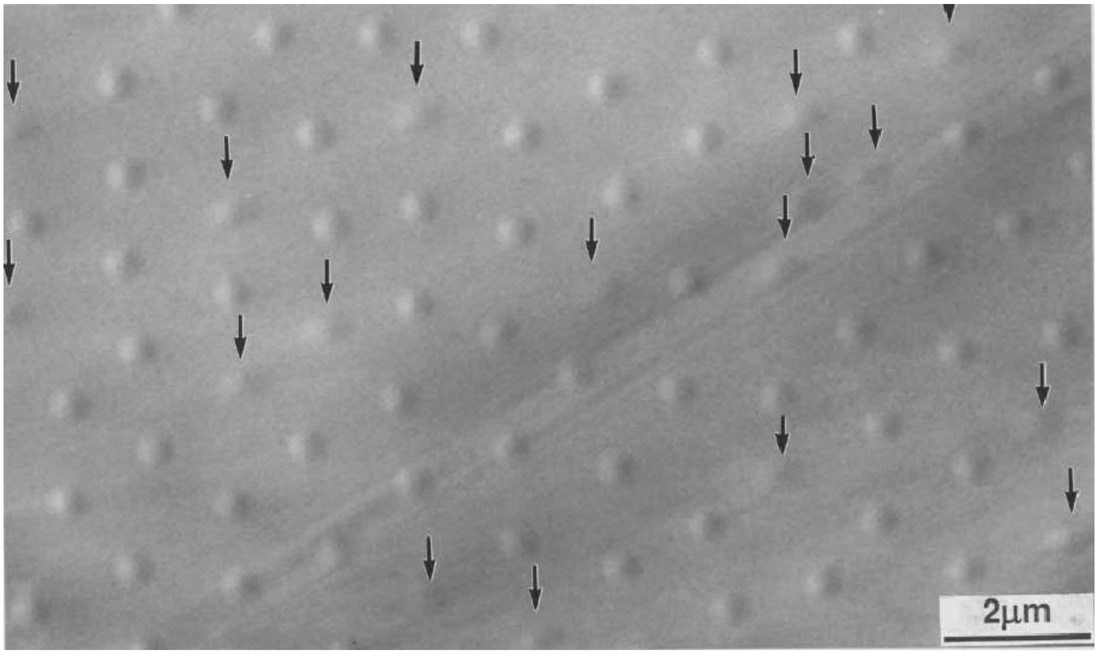

Fig. 1. Lorentz micrograph of vortices in Bi-2212 film containing columnar defects.
There are two kinds of vortex images: circular images and elongated images (indicated by the arrows).

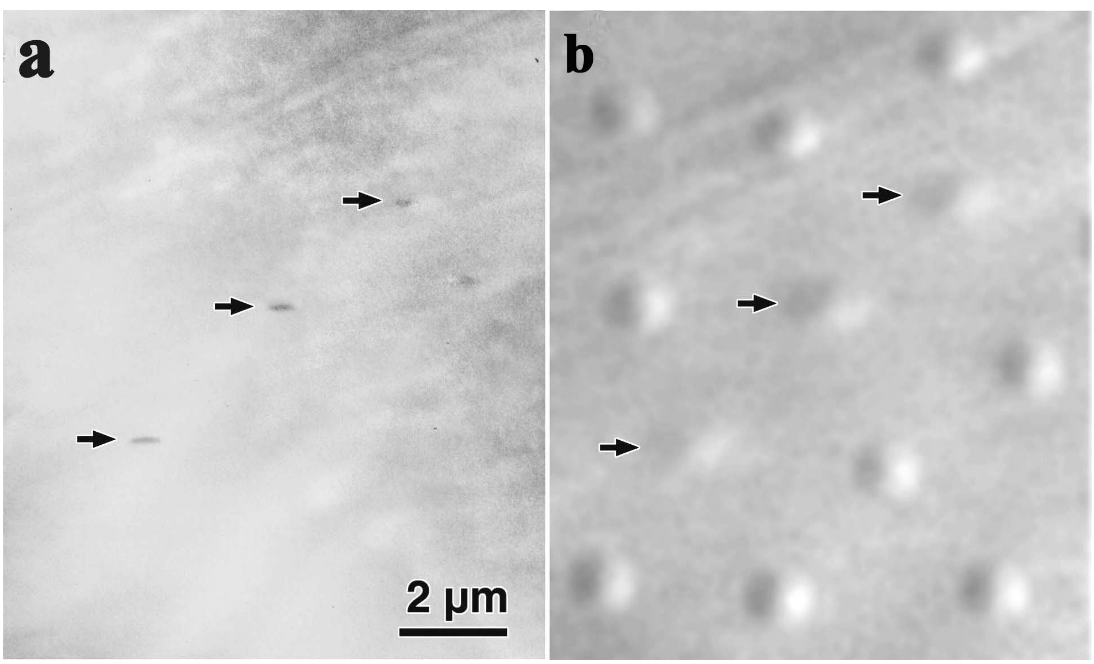

Fig. 2. Comparison of vortices and columnar defects in Bi-2212 thin film.
(a) electron micrograph, (b) Lorentz micrograph. The images of untrapped vortices perpendicular to the film plane are circular spots. Vortex images located at the positions of columnar defects are elongated spots indicated by the arrows.

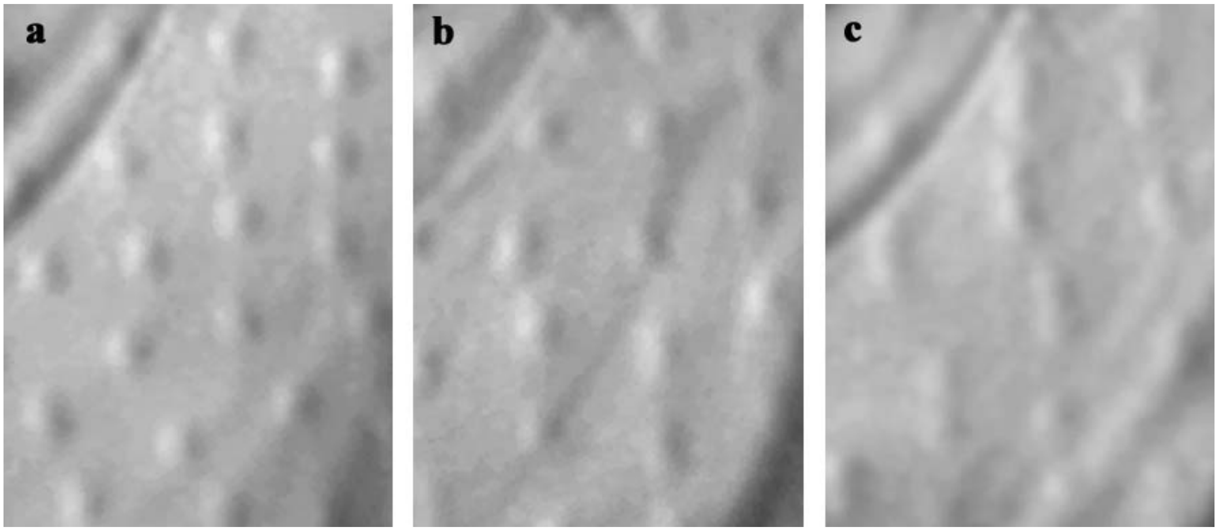

Fig. 3. Lorentz micrographs of vortices in YBCO thin film taken when the applied magnetic field is tilted (tilting angle: θ). (a) $\theta = 75^\circ$, (b) $\theta = 82^\circ$, (c) $\theta = 84^\circ$.

in the micrograph.

Comparison between an electron micrograph and the corresponding Lorentz micrograph (see Fig. 2) revealed that the elongated images correspond to vortices trapped along columnar defects, since elongated images are produced at the locations of tiny columnar defects. In the electron micrograph (Fig. 2(a)), the tiny thin lines indicate the projected images of tilted columnar defects. When the images were defocused, these column images became blurred, and they eventually disappeared completely by spreading out. However, when they were defocused further, new images, which corresponded to vortices, appeared as shown in Fig. 2(b). The reason why vortex images appeared when the images were defocused is because they are produced by the phase contrast. Using image simulations, we found that the circular images actually indicated vortex lines penetrating the film perpendicular to the film plane, and the elongated images indicate vortex lines trapped along tilted columns.

We then investigated what happened when the applied magnetic field was tilted away from the direction of the columns. We found that the vortex lines remained trapped even when we tilted the field greatly. We observed an unexpected behavior when the sample temperature was changed. The elongated vortex images did not change when the temperature was increased up to T_c. However, when it was reduced below 14 K, to our great surprise, the tilted vortex lines began to stand up, one after another, perpendicular to the film plane. The magnetic lines took a short cut through the film, even though the vortices were located at columnar defects.

We attribute this phenomenon to characteristics peculiar to high-T_c superconductors. Because the vortex core in high-T_c superconductors is atomically thin, vortices can become trapped not only at columnar defects but also at atomic-size defects, which are abundant in high-T_c superconductors. In addition, a single vortex line can be trapped collectively by many atomic-size defects. Thus, this pinning becomes very strong and dominant, hiding the effect of columnar- defect pinning. This characteristic is, however, limited to low-temperature regions.

When the temperature is increased, the situation changes. Vortices trapped at atomic- size defects can easily depin from them because when a vortex vibrates thermally, it can easily escape from an atomically narrow pinning potential. Therefore, the strong pinning due to atomic-size defects decreases rapidly and effectively disappears at higher temperatures. In contrast, the pinning force of columnar defects does not decrease as rapidly with the temperature because a column is ten times larger than an atomic-size defect, so the vibration of vortex lines cannot help them depin. Therefore, the columnar-defect pinning should become much stronger than the atomic-defect pinning at higher temperatures.

3. Unconventional arrangements of vortices in a tilted magnetic field

Vortices usually form a closely packed triangular lattice. When a magnetic field was applied obliquely to the layer plane, however, vortices were observed, using the Bitter method, to form linear chains in YBCO

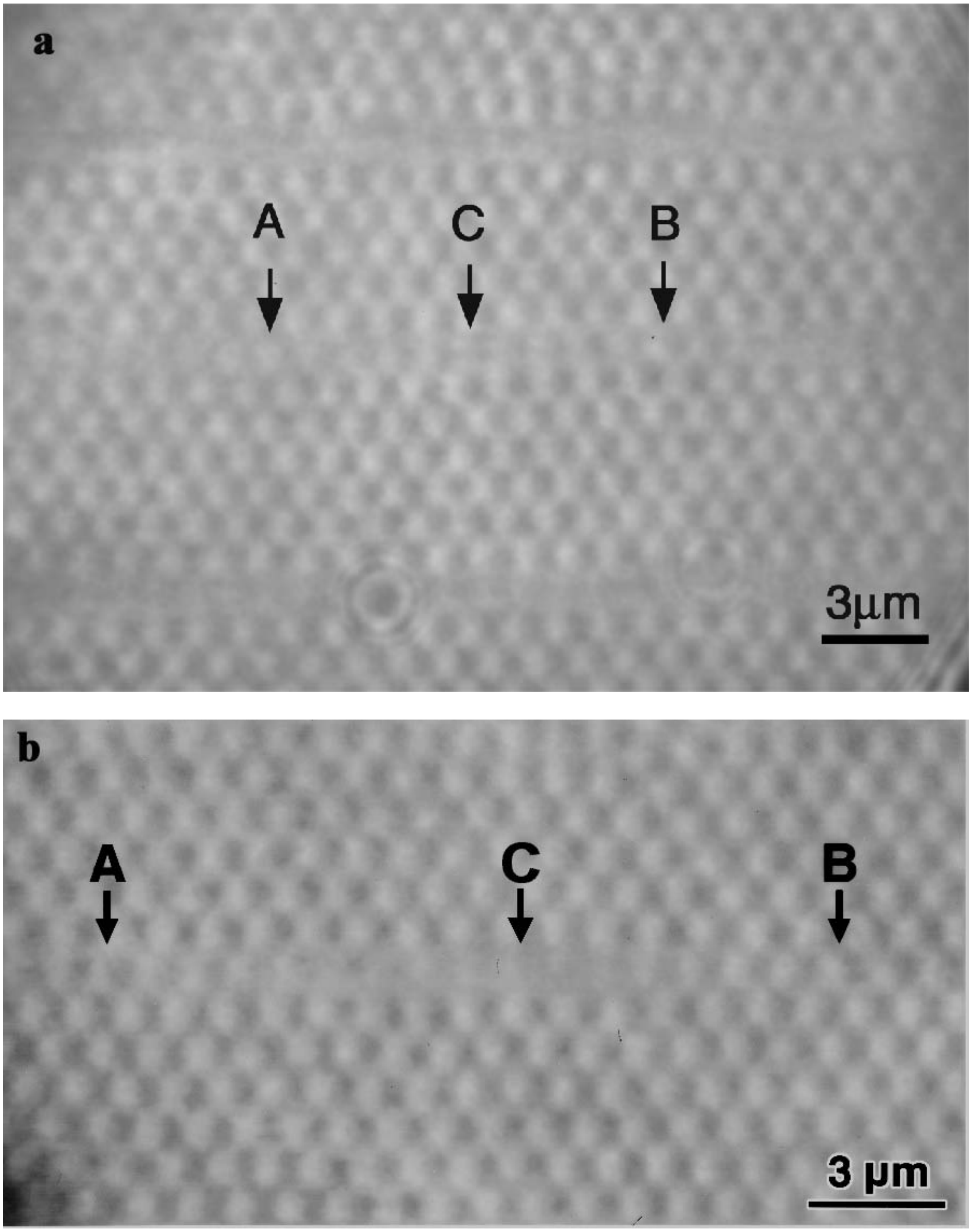

Fig. 4. Lorentz micrographs of vortices at $\theta = 80^\circ$ in Bi-2212 thin film.
(a) T = 70 K, (b) T = 57 K.
Only the images of chain vortices disappear at higher temperatures, which are well below Tc. Vortices A and B are stable, surrounded by six vortices. Vortex C is unstable and therefore tends to oscillate back and forth at higher temperatures.

[5] and alternate domains of linear chains and triangular lattices in Bi-2212 [6]. Although we attempted to clarify the mechanism of these vortex arrangements by using the 350-kV electron microscope, we were unable to observe even the chain state due to the small thickness of the film observable with 350kV electron beams. Using our 1-MV microscope, however, we observed such structures in thicker films and found that chain vortices in YBCO tilted to form chains in a tilted magnetic field, since the observed vortex images became more elongated together with the tilting angle of the magnetic field (see Fig. 3). With Bi-2212, we found that neither chain vortices nor lattice vortices tilted; but both stood up perpendicularly to the layer plane. There must therefore be some difference in their states between chain vortices and lattice vortices.

Grigorieva and Steeds [7] assert that chain and lattice vortices tilt at different angles. Koshelev [8] proposed an interesting mechanism for the chain-lattice state. Josephson vortices penetrate between the layers, and vortices perpendicularly crossing the Josephson vortices form chains. Our finding that both chain vortices and lattice vortices stand up and do not tilt is direct evidence of Koshelev mechanism.

4. Oscillation of chain vortices in Bi-2212

We found that only the images of chain vortices in Bi-2212 disappear when the sample temperature is increased. An example is shown in Fig. 4(a). Chains of vortices disappeared at 70 K, well below T_c. This does not mean that the vortices themselves disappeared, since vortex images gradually faded away with a rise in temperature. In the middle chain in Fig. 4(a), we can see vortices A and B clearly, but not vortices far from them. In both Figs. 4(a) and (b), vortices A and B are located "stably" in the midst of six surrounding vortices, while vortex C is sandwiched "unstably" between two vortices.

This vortex arrangement may be stable at low temperatures, but at higher temperatures, where vortices thermally vibrate, vortex C begins to oscillate back and forth like pinballs connected by springs on an incommensurate periodic potential, which is the Frenkel-Kontorova model. We attribute the disappearance of chain vortices to such longitudinal oscillation of vortices along chains.

5. Conclusion

The behaviors of vortices in high-T_c superconductors are predicted to be quite different in various ways reflecting the anisotropic layered structures of the materials, which makes their pinning difficult. The structures of vortices inside them can now be observed by using Lorentz microscopy with our 1-MV field-emission electron microscope. Using this microscope, we have just begun to clarify unconventional behaviors of vortices in high-T_c superconductors.

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