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Direct Observation of Unconventional Behaviors of Vortices in High-T_c Superconductors by Lorentz Microscopy

Akira Tonomura

Advanced Research Laboratory, Hitachi, Ltd. Hatoyama, Saitama 350-0395, Japan,
Frontier Research System, RIKEN, Wako, Saitama 351-0198, Japan
SORST, Japan Science and Technology Corporation (JST),
3-4-15 Nihonbashi, Chuo-ku, Tokyo 103-0027, Japan,

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 in their structures and dynamics, reflecting the anisotropic layered structures of the materials, and thus tend to move easily.

However, the behaviors of vortices inside superconductors can never be observed directly, since all the observation techniques of vortices up to now detect only vortices at the superconductor surface, and not those inside the superconductor. Lorentz microscopy using our 1-MV electron microscope [1] makes it possible to directly observe the structure of vortices inside high-T_c superconducting thin films, and is used for investigating 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].

Vortices usually form a closely packed triangular lattice. When a magnetic field was applied obliquely to the layer plane, however, vortices were found, using the Bitter method, to form linear chains in YBCO [5] and alternate domains of linear-chains and triangular-lattices in Bi-2212 [6]. Although we attempted to elucidate the mechanism of these vortex arrangements using the 350-kV electron microscope, we were unable to observe even the chain state due to the small thickness of the film observable. Using our 1-MV microscope, however, we observed such structures in thicker films and found that chain vortices in YBCO were actually tilted to form chains at a tilted magnetic field, since the observed vortex images become more elongated together with the tilting angle of the magnetic field (see FIG. 1). While in case of Bi-2212, we found that neither chain vortices nor lattice vortices tilted; but both stood up perpendicularly to the layer plane. There must exist some difference in their states between chain-vortices and lattice-vortices.

Grigorieva et al. [7] assert that chain- and lattice-vortices are tilted at different angles. Koshelev [8] theoretically proposes an interesting mechanism for the chain-lattice state; Josephson vortices penetrate between the layers, and vortices perpendicularly crossing the Josephson vortices form chains as illustrated in FIG. 2. Our results, as shown in FIG. 3, that chain-vortices and lattice-vortices both stand up and are not tilted provided direct evidence for the Koshelev mechanism of the chain-lattice state.

Although we were not able to directly observe Josephson vortices, we obtained evidence for the existence of Josephson vortices. That is, when we applied an in-plane magnetic field to form only Josephson vortices and then a vertical magnetic field B_v was applied and increased, vertical vortices began to penetrate along some straight lines (see FIG. 4). These lines must be determined by the Josephson vortices produced by the applied in-plane magnetic field.

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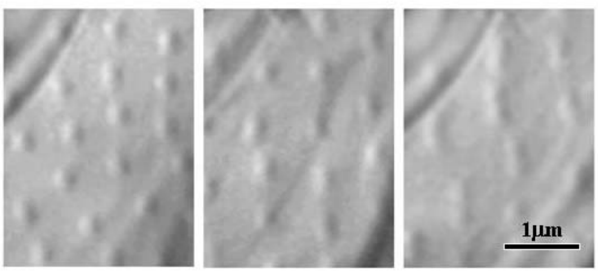


(a) (b) (c)

FIG. 1. Lorentz micrographs of vortices in YBCO taken when the applied magnetic field is tilted (tilting angle: θ).
(a) $\theta = 75^\circ$, (b) $\theta = 83^\circ$, (c) $\theta = 84^\circ$.

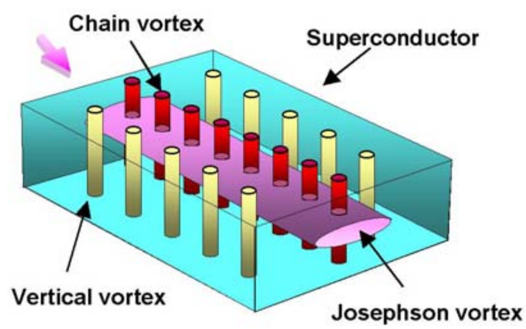


FIG. 2. Koshelev's model of crossing vortex-lattices.

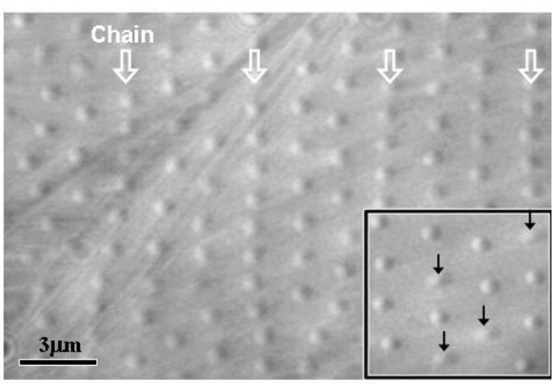
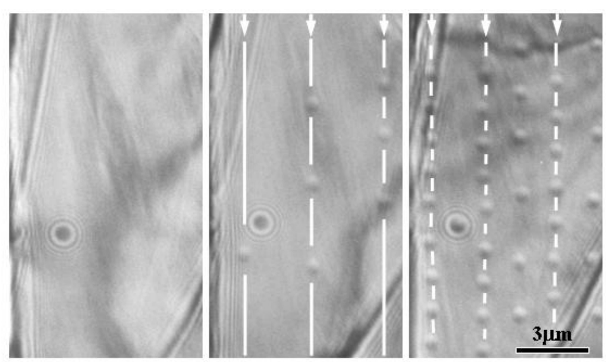


FIG. 3. Lorentz micrograph of vortices in Bi-2212 at a tilted magnetic field. All the vortex lines stand up perpendicularly to the layer plane. If tilted vortex images become elongated as shown in the inset.



(a) (b) (c)

FIG. 4. Lorentz micrographs showing the existence of Josephson vortices.
(a) $B_v = 0$ G , (b) $B_v = 0.2$ G , (c) $B_v = 1$ G

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