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# Dynamic Observation of Vortices in High-$T_c$ Superconductors by Lorentz Microscopy

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The behaviors of quantized vortices in superconductors affect the practical applications of superconductors. This is because the vortex motion due to the current-induced Lorentz force eventually leads to the breakdown of superconductivity. Therefore, vortex-pinning is a key problem for developing high-critical current materials, especially in high-$T_c$ superconductors where vortices tend to move easily due to high-temperature operation and layered material structures.

Previously, we developed a method to directly and dynamically observe vortices in superconducting thin films by using the phase information of an electron beam transmitted through the films using our 350-kV field-emission electron microscope. Individual vortices can be observed as spots by Lorentz microscopy [1], and projected magnetic lines of force of the vortices were observed by holographic interference microscopy [2]. However, it is mainly effective for conventional metal superconductors such as Nb but not for high-$T_c$ superconductors. This is because 350-kV electrons cannot pass through high-$T_c$ films thicker than their magnetic penetration depths, which are one order of magnitude greater than that of Nb. The recently developed 1-MV electron microscope [3] has enabled to observe vortices in high-$T_c$ superconducting films.

The observation method for Lorentz microscopy is illustrated in Fig. 1. A superconducting thin film is tilted at 30º - 45º to an incident electron beam and a magnetic field is applied from various directions. The phase distribution of an electron beam transmitted through the film is determined by the projected magnetic flux distribution along the direction of the electron beam due to the Aharonov-Bohm effect [5]. The phase distribution cannot be observed by an in-focus image but can be transformed into an intensity distribution by image defocusing as in a Lorentz micrograph.

This method of observing vortices is different from other methods, such as the Bitter method [6] or methods using scanning probe microscopes [7-9], in that it quantitatively detects not only the magnetic field leaking outside from the sample surface, but also the magnetic flux inside the superconductor. Therefore, we can obtain direct information about vortices and observe pinning centers simultaneously inside the sample though the images are blurred by image defocusing [10].

Our 1-MV microscope, which has the brightest beam ever obtained, is very suitable for observing fine magnetic structures for the following reason. The attainable precision in the phase measurement is determined by the collimation angle of the incident electron beam, and therefore a brighter electron beam is required. In addition, a higher accelerating voltage is desirable for the magnetic flux observation, since the magnetic flux sensitivity remains the same, *i. e.* a vortex magnetic flux of $h/2e$ always produces an electron phase shift of p, even when faster electrons are used. The other phase shifts of faster electrons such as those caused by thickness variations or by electric fields are decreased in general. Therefore, a 1-MV field-emission electron beam is suited for magnetic field observations.

In fact, we have obtained new results [4, 11] on magnetic vortices peculiar to high-$T_c$ superconductors with this microscope that we could not achieve with our previous 300-kV microscope. One example is the observation of the chain-lattice state of vortices in Bi-2212 that was obtained when a magnetic field was applied obliquely to the layer plane (See Fig. 2). We found that chain vortices gradually began to disappear at high temperatures and attributed this phenomenon to the oscillation of vortices along the chain direction [11].

**References**


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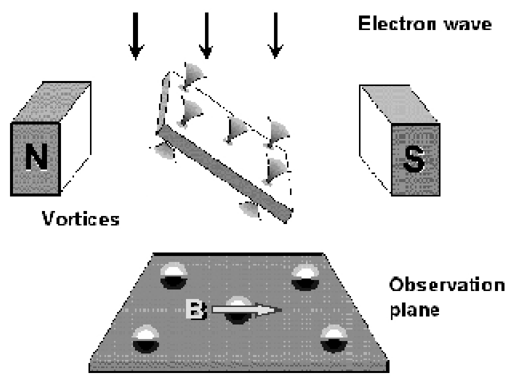


FIG. 1. Principle behind Lorentz microscopy of vortices.

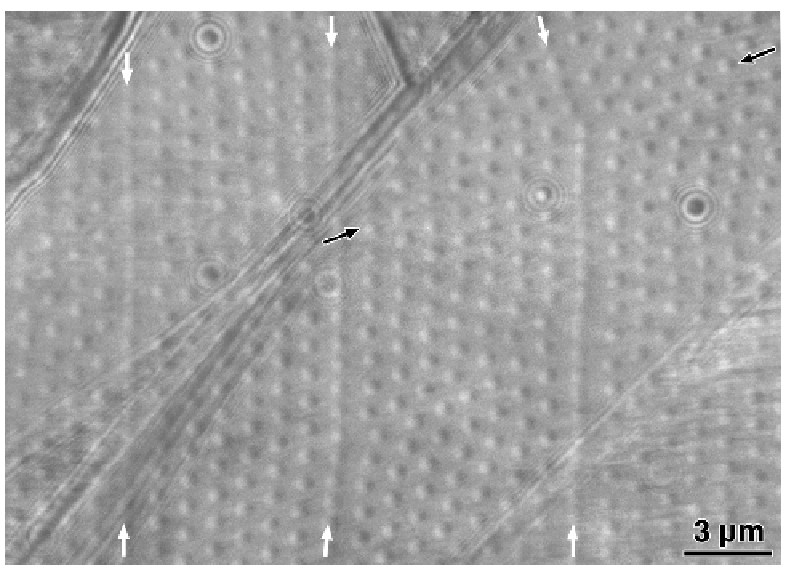


FIG. 2. Lorentz micrograph of vortices in the chain-lattice state (Sample temperature = 50 K, incidence angle of magnetic field = 80º)

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