1478
DOI: 10.1017/S1431927605510456
Microsc Microanal 11(Suppl 2), 2005

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

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The dynamics of individual quantized vortices in high-T_c superconducting thin films became observable using coherent Lorentz microscopy (1) with our 1MV field-emission transmission electron microscope (2). Since a vortex in a superconductor having magnetic flux of $h/(2e)$ is a phase object of π for an illuminating electron beam, it can be observed by interference microscopy or by Lorentz microscopy (3).

Using Lorentz microscopy, we observed various kinds of vortex motions in high-T_c superconductors. The vortex motions were elastic, plastic and even rectified (4) depending on the sample temperature and also on the distributions and strengths of the pinning centers. For example when the temperature of high-T_c Bi-2212 superconductors decreased, the vortex motion changed from hopping to slow migration due to increasing pinning force of abundant atomic-size defects, which hided even the pinning effect of columnar defects.

Since we were not able to identify the pinning centers for the vortex hopping at higher temperatures, we introduced well-defined defects (see Fig. 1), that is, columnar defects, which had been regarded as the most effective pinning lines.

We produced tilted columnar defects in a Bi-2212 thin film, which can be seen as tiny lines in the in-focus electron micrograph (Fig. 2a). In the defocused Lorentz micrograph shown in Fig. 2b, two kinds of vortex-images can be seen, circular spots and elongated spots. The elongated spots with a weak contrast are located just at the defects, and therefore indicate tilted trapped vortices. The circular spots indicate perpendicular untrapped vortices. This was confirmed by simulation (5).

The vortex motion at temperatures well below 25K was unexpected: the vortices moved uniformly at 7K as if there were no columnar defects. When we increased the temperature up to 18 K, some vortices began to be trapped at columnar defects, but most of the vortices remained migrating. It is interesting to note that the trapped vortex lines are tilted along columnar defects and the migrating vortices stand up perpendicular to the film plane. Above 25 K, the vortices became trapped at columnar defects, and suddenly hopped from time to time.

The reason why the pinning effect of columnar defects disappears at low temperatures was clarified by observing the images of the trapped vortices at various temperatures. The image of the trapped vortex indicated by the arrow in Fig. 3a has a weak contrast due to the tilting of the vortex line. When the temperature was reduced from 40K to 7K, we observed to our surprise that the contrast increased. The tilted vortex lines began to stand up perpendicular to the film plane. Although the vortex lines were located at the columnar defects, they did not follow the columns but took the shortest cut inside the film.

We interpret this behavior of vortices as follows. The columnar defects are hidden in densely distributed atomic-size defects, such as oxygen defects abundant in high-T_c materials (see Fig.1). Since a single vortex line is collectively trapped by many atomic-defects, the pinning force becomes very strong. At higher temperatures where the thermal vibration of vortex lines increases, the vortex lines trapped at the atomic-size defects become easily depinned from them, because a vortex line having an atomic-size normal core can easily escape from the atomically narrow pinning potential well; therefore, strong pinning due to the atomic-size defects decreases rapidly, and effectively disappears at higher temperatures. In contrast, the pinning force of columnar defects does not decrease so rapidly since a column is ten times larger and the vibration of the vortex lines cannot help them depin. Therefore, only the pinning force of columnar defects remain strong at higher temperatures. The trapped vortices at columnar defects, when driven by a force, hop from one defect to another.

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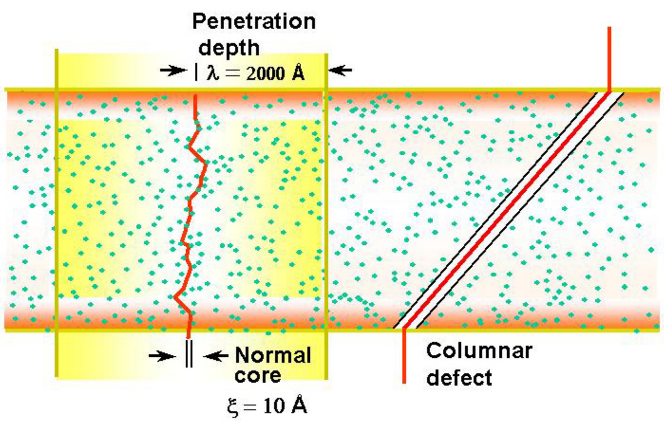
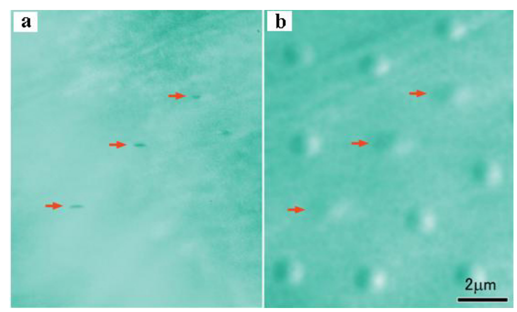
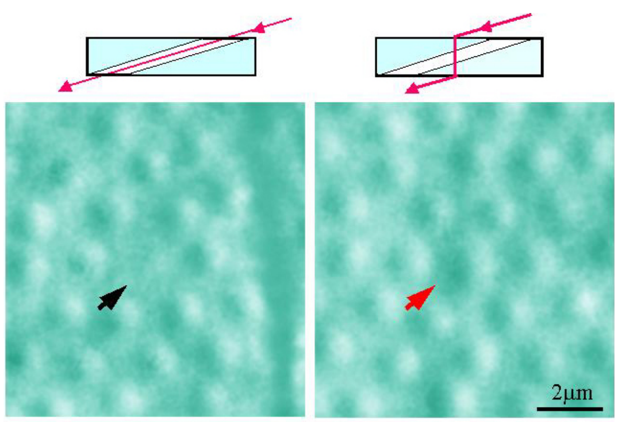


FIG. 1. Vortices trapped by many atomic defects and by columnar defects.



(a) Electron micrograph (b) Lorentz micrograph

FIG. 2. Vortices trapped by columnar defects.



(a) T = 40K **(b) T = 7K**

FIG. 3. Vortices trapped by columnar defects.

https://doi.org/10.1017/S1431927605510456 Published online by Cambridge University Press