Simultaneous observation of vortices and dislocations in thin BSCCO (2212) single crystals

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Dislocations and vortex structure were observed in thin BSCCO single crystals by the method of transmission electron microscopy. The vortex structure was visualized by a high-resolution technique of decoration with very small ferromagnetic particles. Individual dislocations oriented perpendicular to the vortices do not destroy the long-range order in the vortex lattice. A weak attractive interaction between the dislocations and vortices, which does not depend on the type of dislocations, was observed. © *1995 American Institute of Physics.*

1. It is well known that the interaction of Abrikosov vortices with defects in a superconducting material is responsible for the nondissipative current in type-II superconductors. In spite of the fact that the effectiveness of dislocations as vortex pinning centers has been established reliably by many experiments, mainly in standard (low-temperature) superconductors after cold working, the mechanism of the interaction of the vortices with individual dislocations remains unclear. It is possible that experiments on the simultaneous observation of vortices and dislocations could shed light on this question. In Ref. 1 a vortex structure was visualized by the decoration method with simultaneous observation of dislocations in thin samples of deformed niobium single crystals in a transmission microscope. It was shown that a cellular dislocation structure destroys the regular vortex lattice. A qualitatively similar result was obtained for Nb–Mo single crystals after low-temperature deformation.[2] However, the high density of dislocations and their complicated configuration in the deformed materials make it impossible to study the mechanisms for the interaction of the vortices with separate dislocations. Recently we were able to observe for the first time vortices and dislocations in single crystals of the high-T_c superconductor BSCCO (2212).[3] It was found that dislocation structures which make it possible to study the interaction of vortices and individual dislocations are often encountered in the initial (undeformed) single crystals. A similar problem was studied[2] in Ref. 4.

2. Thin samples prepared by repeatedly cleaving BSCCO (2212) single crystals until crystal sections which are transparent in the optical region appeared were investigated. The sections were thin enough so that they could be investigated in the transmission regime with an accelerating voltage of 100 kV. The samples were mounted on a copper grid (substrate), and after the vortices were decorated with very small ferromagnetic particles of iron[5] they were investigated in the frozen-flux regime at liquid-helium temperatures in a JEOL 100CX electron microscope in transmission or in reflection in the secondary-electron emission regime at room temperature. The optimal conditions for

visualizing clusters of ferromagnetic particles, marking the positions of the vortices, in transmission in an electron microscope are different from the conditions for dislocations. Dislocations, whose contrast is of a diffraction nature, are visualized best near dark curved contours, while the small (100 Å) iron particles give a contrast that is characteristic of polycrystalline material. Because the thin BSCCO (2212) samples are somewhat curved, it is difficult to observe dislocations and vortices simultaneously on large sections. We note that in the transmission regime the small iron particles look like dark dots against a light background, while in the scanning regime the contrast is reversed.

3. Figure 1a shows a typical transmission photomicrograph, where dislocations and vortices are observed simultaneously in a BSCCO (2212) crystal. Because of the aforementioned difficulties in obtaining a combined image of dislocations and vortices on large sections of a sample, we obtained a picture of the distribution of the vortices and dislocations by comparing a set of photomicrographs under conditions of optimal contrast. Such a picture is shown schematically in Fig. 1b. This same section of the crystal is shown in the photomicrograph in a scanning regime (Fig. 1b), where the vortices near the edge of the sample are not resolved because of the peculiarities of contrast formation in the reflection regime. In the transmission mode, however, it was possible to see that the outer vortex row passes along the edge of the sample at a distance equal to approximately the period of the vortex lattice. Analysis of the diffraction contrast of the dislocations and its extinction under the condition $\mathbf{g}\cdot\mathbf{b}=0$, where $\mathbf{g}$ is the reflection vector, and $\mathbf{b}$ is Burgers vector, showed that the single dislocation S has predominantly a screw orientation with $\mathbf{b}\langle 100\rangle$, while three close dislocations of a mixed type have predominantly a screw dislocation with $\mathbf{b}\langle 110\rangle$. These dislocations are close to 45-degree dislocations with an appreciable splitting in the (001) plane. One can see from Figs. 1a and 1b that one of the close-packed directions in the vortex lattice is approximately parallel to the dislocation lines and to the $\langle 100\rangle$ direction in the BSCCO (2212) crystal.

Examination of the figure and other similar patterns shows that single dislocations do not destroy long-range order in the vortex lattice. We note that in the present case the dislocation lines are perpendicular to the magnetic field and therefore to the vortices. At the same time, planar dislocation pile-ups produce large changes in the short-range order near dislocation lines. These changes are expressed as a deformation of the unit cell. These distortions can be interpreted as resulting from the attraction of vortices to dislocations, since the vortices predominantly "sit" on the dislocation lines. For a single screw dislocation a pronounced repulsion effect, which was predicted in Ref. 6 , was not observed.

4. The models of the interaction of a vortex with a dislocation which were developed for low-temperature superconductors are based on the interference that appears between the elastic stress field of the dislocation and the stress field from a vortex because of 1) the small difference in the specific volumes of the material in the normal and superconducting states (ΔV effect) (Ref. 7) and 2) the change in the stiffness (elastic moduli) for the vortex core with respect to the superconducting matrix (Ref. 6). The first mechanism is called paraelastic or dilatational interaction and the second is called dielastic. It is obvious that the result should depend strongly on the type of dislocation and on its orientation relative to the vortex. In the experimentally realized situation (see Fig. 1), when the lines of dislocations and vortices are perpendicular to one another, the interac-

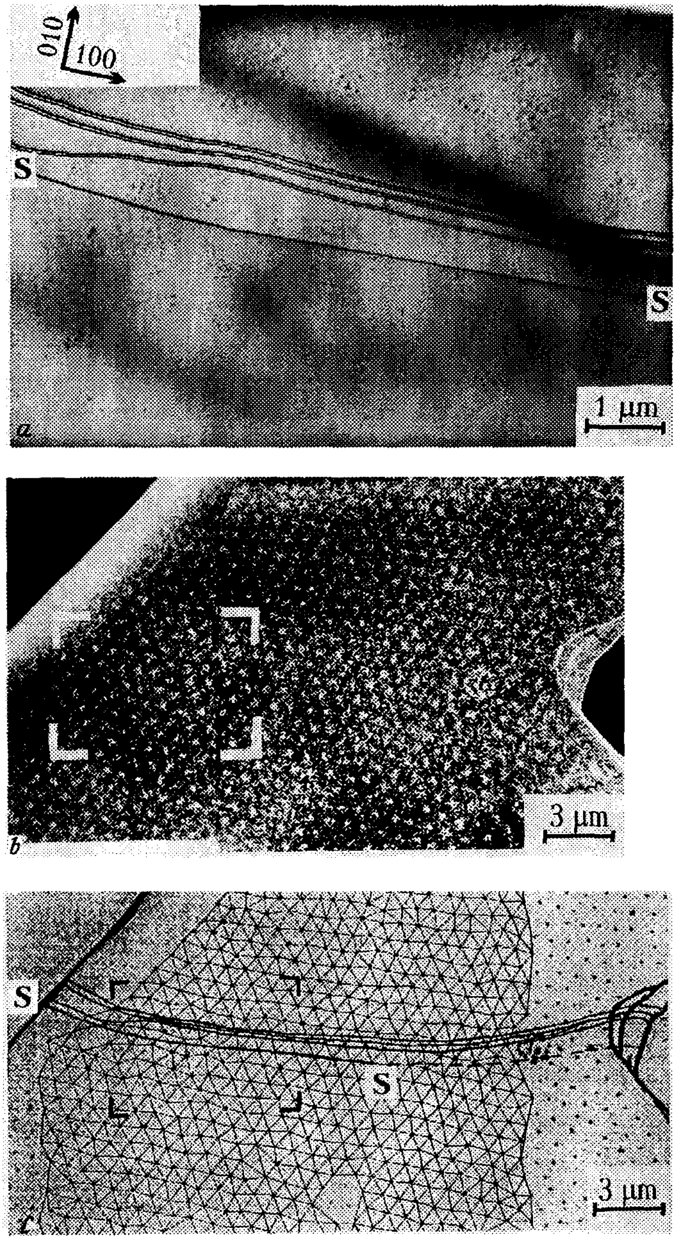

FIG. 1. Vortex and dislocation structure of a BSCCO single crystal in the field $H = 38$ Oe: a) Photomicrograph of a section of the crystal in the transmission regime of an electron microscope; b) photomicrograph with a smaller scale in the secondary-electron emission regime; c) diagram of the arrangement of vortices and dislocations. The corners in Fig. 1b separate the same section from Fig. 1a, and in Fig. 1c the section is marked with a rectangle. A screw dislocation is reliably observed on the section *SS*, and the rest is indicated by the dashed line.

tion forces are weakest and, most likely, close to the interaction with a point defect, rather than a linear defect. This assumption is confirmed by the fact that on sections of a crystal, where there are no dislocations, we see deformations of a regular hexagonal cell of the vortex lattice or defects in the vortex lattice, which are generally attributed to collective pinning on point defects in high-T_c crystals.[8] As for as the type of dislocation, for a screw dislocation there is no paraelastic mechanism, since the nucleus of such a dislocation does not produce dilatation. The dielastic interaction mechanism should lead to repulsion of the vortex from a dislocation. This is valid for edge and mixed dislocations. Therefore, the mechanism of elastic interaction of vortices does not explain the observed attraction of vortices and dislocations.[1,4]

The attraction could be due to the suppression of the order parameter in the nucleus of a dislocation. This mechanism is always attractive and can be especially effective for high-T_c superconductors with an atomic-scale coherence length, since the local suppression of superconductivity in the nucleus of a dislocation is also of the order of several interatomic distances. This mechanism was essentially proposed in Ref. 9 , where it was assumed that the accumulation of defects, specifically, dislocations, leads to a local change in the superconducting parameters of the material (k or H_{c2}). This agrees with the fact that interlacing dislocations are more effective than an individual arrangement of dislocations. In conclusion, we note that in our opinion the attraction of vortices which are oriented perpendicular to dislocations has not been strictly proved experimentally either in the present work or in Ref. 4 , since point defects also play an important role in the pinning of the vortex lattice. However, the proposed combination of methods for visualizing vortices and dislocations may make it possible to solve the problem posed by using better samples or heat treatment for annealing point defects.

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