Direct observation of the Abrikosov vortices in the single crystal of a high-temperature superconductor $YBa_2Cu_3O_x$

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(Submitted 7 December 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 2, 109–111 (25 January 1988)

The magnetic structure of a $YBa_2Cu_3O_x$ single crystal was studied by decorating it with disperse ferromagnetic particles. The magnetic-flux distribution patterns with a resolution of the Abrikosov vortices, whose rows are oriented principally along the twinning boundaries, have been obtained.

It follows from the results of the measurements of the electrical and magnetic properties which have already been carried out that the new class of high-temperature superconductors based on copper oxides belongs to type-II superconductors with a large value of the Ginzburg-Landau parameter κ.[1] There are still some discrepancies, however, in the data used for order-of-magnitude estimates of such important parameters of type-II superconductors as the lower critical field H_{c1} and the penetration depth $\lambda(T)$.[1,2] There are also no data on the direct observation of the magnetic vortex structure, which is attributable to considerable methodological difficulties not only in the case of high-temperature superconductors but also in the case of ordinary superconductors with high values of κ.[3] We have been able to overcome these difficulties and to observe the magnetic vortex structure at the surface of the $YBa_2Cu_3O_x$ single crystals which were grown from a melt.[4] This was accomplished by using a previously developed high-resolution method of decorating the surface with small ferromagnetic particles with the help of a scanning electron microscope.[5] Below we show several electron micrographs which were obtained by using a single crystal with dimensions 0.7×0.5 mm and a thickness of about ten microns with the wide face oriented parallel to the (001) plane. The magnetic field $H = 20$ Oe perpendicular to the wide face of the sample was applied above T_c and the single crystal was cooled down in a field to a temperature of 4.2 K at which the decorating was carried out. The original face of the grown single crystal, which was optically smooth, was not polished. A microrelief (Fig 1) which did not prevent, as it turned out, the resolution of the magnetic-flux distribution by the decoration method was seen occasionally in certain sections of the surface, mostly in the central region of the sample. A typical pattern after the decoration is shown in Fig. 2. We see that single Abrikosov vortices (the light points on the positive image appearing as a cluster of dispersed ferromagnetic particles at the magnetic-flux-localization points at the surface of the single crystal) are clearly resolved (Fig. 2a). A photograph taken at a low magnification (Fig. 2b) shows that the vortex rows are oriented primarily in the ⟨110⟩ directions which are the directions of the diagonal of the (001) basal plane. In other parts of the sample the preferred orientation of the vortex rows is in the same ⟨110⟩ direction but one that is perpendicular to the basal

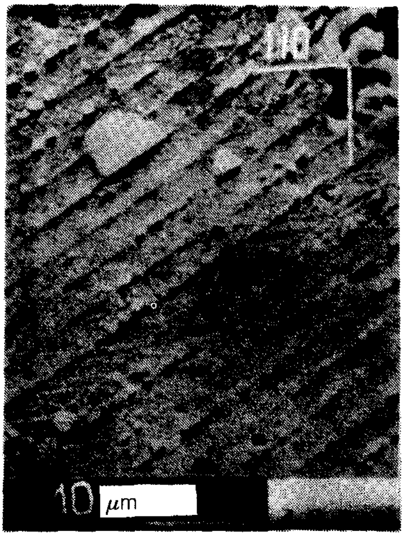

FIG. 1. Part of the (001) surface of the single crystal with a microrelief which exhibits the characteristic features of its growth (a negative image).

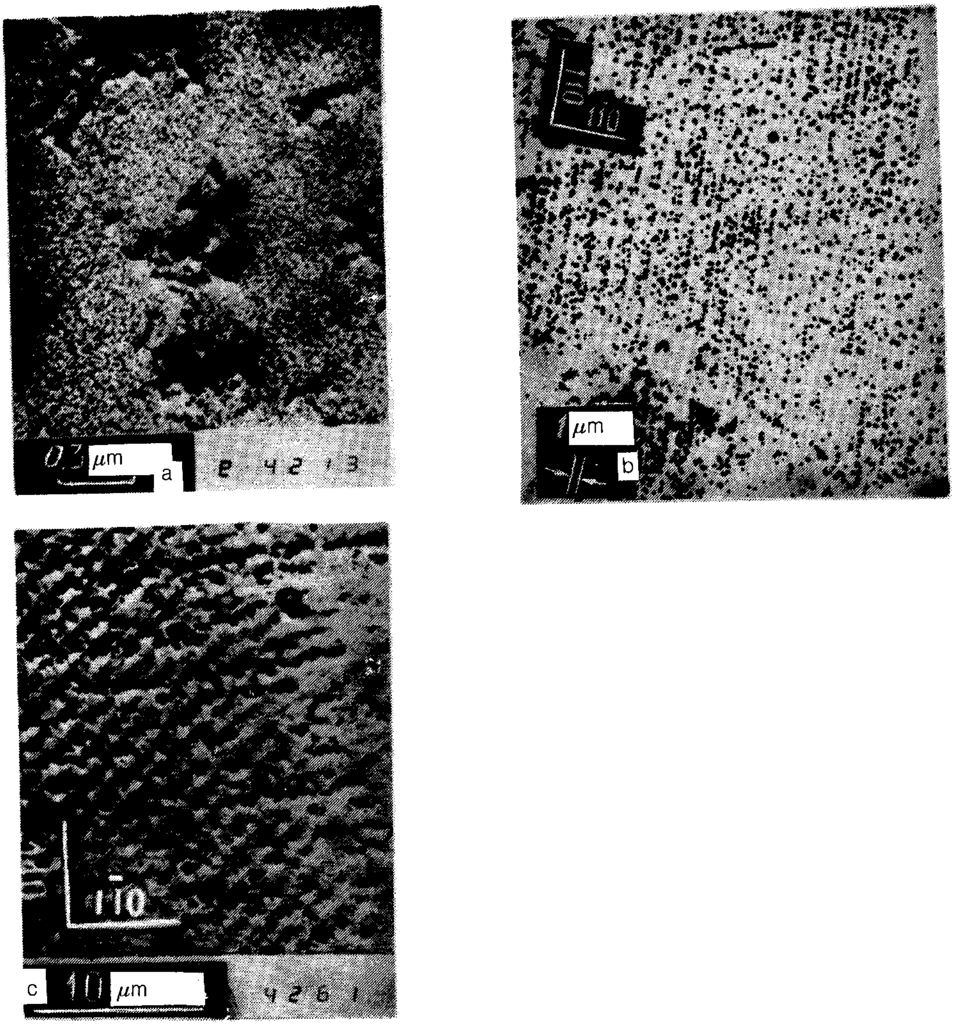

FIG. 2. Distribution of the magnetic flux at the (001) surface of a single crystal (a negative image). a—Resolution of single vortices; b—rows of vortices along the [110] direction; c—rows of vortices along the [110] direction.

plane (Fig. 2c). The average distance between the vortex rows and between the individual vortices in a row is $d \approx 1$ μm. The magnetic vortex structure, whose characteristics (the attitude of the vortex rows and the spacing between the vortices) are given above, was observed in the central part of the sample. A band of the vortex-free Meissner phase was observed on the periphery of the sample along its entire perimeter. The width of this band is ≈ 20 μm.

Here are some direct conclusions based on the given data on the magnetic vortex structure.

1. *Anisotropy of the vortex rows.* This anisotropy is obviously linked with the arrangement of the twins which are always seen in the orthorhombic $YBa_2Cu_3O_x$ phase[1] and for which planes of the $\{110\}$ type are the twinning planes. The ordered arrangement of the vortices along the $\langle 110\rangle$ direction in this case may be linked with the pinning at the twinning boundaries. The incomplete Meissner effect in single-crystal samples apparently is also attributable to this pinning.[6] Only a part of the sample on its periphery is free of the vortices, whereas a large part of the magnetic flux remains in the central part of the sample because of the pinning at the twinning boundaries.

2. *The distance between the vortices* was found to be considerably greater than the distance between the twinning boundaries, which is about 10^{-2} μm, never being greater than 10^{-1} μm. The distance between the vortices, $d \approx 1$ μm, observed experimentally is in good agreement with the vortex structure period if it is assumed that it is determined by the magnetic field, $d \approx \sqrt{\Phi_0/B}$, where $\Phi_0 = 2\times 10^{-7}$ G·cm^2 is a unit fluxoid and $B = H$ for a thin plate (in this case $H = 20$ Oe). One more estimate can be found for the penetration depth. If we assume that the ferromagnetic particles in an isolated vortex are localized in a region of order 2λ, then $\lambda(4.2)$ will be $\lesssim 0.3$ μm. Assuming $\kappa \approx 10^2$, the lower bound of H_{c1} in the [001] direction perpendicular to the wide face of the single crystal will be $H_{c1} \gtrsim 80$ Oe. Our results are therefore solid evidence of macroscopic bulk superconductivity of $YBa_2Cu_3O_x$ single crystals. They also present a strong case against the model for superconductivity at the twinning boundaries.

We wish to thank I. F. Shchegolev for useful discussions and L. G. Isaeva for assistance in this study.

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Translated by S. J. Amoretty