Observation of an anisotropy of the vortex lattice in the basal plane of a $YBa_2Cu_3O_x$ single crystal

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A technique of decoration by means of finely divided ferromagnetic particles has revealed a contraction of the regular triangular lattice of vortices in the ab plane of a $YBa_2Cu_3O_x$ single crystal. This contraction is evidence of an anisotropy of the interaction of the vortices in this plane. The ratio of the effective masses of the superconducting carriers along the *a* and *b* directions is estimated: $\mu_a/\mu_b = 1.4 \pm 0.2$.

At low temperatures, the high-temperature superconductor $YBa_2Cu_3O_x$ has an orthorhombic structure of the P_{mmm} type,[1] so the superconducting properties should be anisotropic along all three axes. In a description of these superconductors on the basis of the Ginzburg-Landau theory, the meaning is that all three components of the effective-mass tensor μ_{ik} must be different.[2]

The anisotropy of the upper critical field in YBaCuO has been determined in many studies with an external magnetic field oriented along the *c* axis and in the *ab* basal plane. Its value is $H^{\parallel}_{c_2}/H^{\perp}_{c_2} \approx 3$–6, according to different studies,[3] so the corresponding anisotropy of the effective mass is

$$M^{\perp}/M^{\parallel} = (H^{\parallel}_{c_2}/H^{\perp}_{c_2})^2 \approx 10 \div 40.$$

It has not been found possible, however, to determine the anisotropy in the superconducting properties between the a and b directions by means of magnetic measurements in the single crystals available. The reason is that YBaCuO single crystals contain large numbers of twin domains with typical sizes $\lesssim 10\ \mu m$, while the sizes of the samples used in magnetic measurements are usually $> 100\ \mu m$.

In the present study we have found it possible to observe an anisotropy of the vortex lattice in the ab plane through a technique involving a decoration with finely divided ferromagnetic particles.[4] This technique makes it possible to directly observe the distribution of Abrikosov vortices and possible distortions within a single domain.

We used $YBa_2Cu_3O_x$ single crystals grown from a nonstoichiometric melt of oxides.[5] The surfaces of the samples were optically smooth and were subjected to no further processing. A vortex lattice could be observed on a sample with dimensions of $1\times1\times0.03$ mm, which contains domains whose dimensions ($50\times50\ \mu m$) were large in comparison with the distance (d) between vortices in the fields used ($d = 0.5;1.5\ \mu m$). The sample is cooled from room temperature to 4.2 K in an external magnetic field (the "frozen-field regime") and then decorated bu the technique of Ref. 6. Experiments were carried out at two values of the external magnetic field[1)]: $H_e = 10$ Oe and 100 Oe. The resulting vortex distribution patterns were observed in a scanning

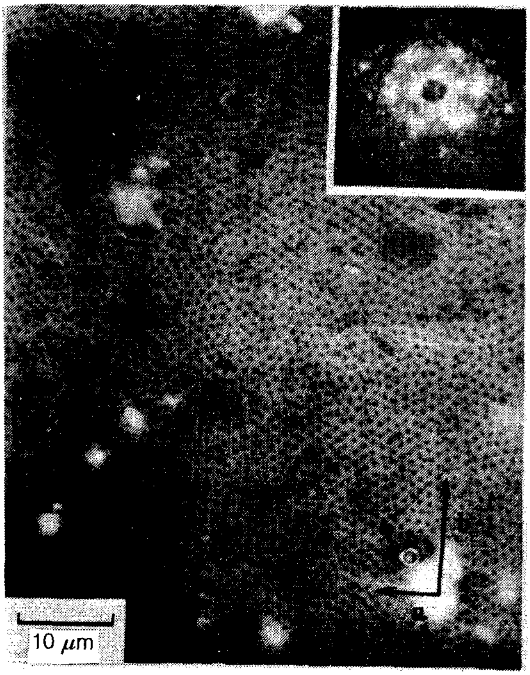

FIG. 1. Vortex lattice in a region of a $YBa_2Cu_3O_x$ single crystal which does not contain twin boundaries. The average magnetic induction is $B \approx 10$ G. The inset shows a diffraction pattern from the same region of the sample (the photograph was taken under an optical microscope).

electron microscope and under an optical microscope. The regions of a vortex lattice belonging to a single domain were distinguished by means of a polarizing optical microscope.[7] The images of the vortex lattices in these regions were then processed on a laser diffractometer. The angles on the diffraction patterns were determined within $\approx 1°$ with a measuring microscope (the blurring of the reflections was taken into account).

Figure 1 show the typical image of the distribution of vortices on the surface of a sample (this distribution was produced in a field of 10 Oe), along with the diffraction pattern found from it.

We see that on the images of the vortex lattices it is difficult to directly distinguish any systematic deformations of the regular triangular lattice, because of both local defects in the vortex lattice and the general mosaic nature of the pattern. It can be seen from the optical diffraction patterns, however, that the lattice is hexagonal. The systematic nature of the observed distortions becomes obvious if they are represented as a contraction by a factor of η of a regular triangular lattice along an axis which runs at an angle φ with respect to one of the lattice vectors (see the diagram in Fig. 2). This representation is equivalent to the inscription of a distorted hexagonal cell in an ellipse with a semi-axis ratio η. (In actuality, η is found through a numerical calculation from the angles α, β, and γ in the distorted triangular cell of the vortex lattice, measured on the diffraction patterns.) It turns out that in this representation the contraction factor η is the same in the different parts of the vortex lattice. Also, despite the weakening of the interaction between the vortices as the field is reduced

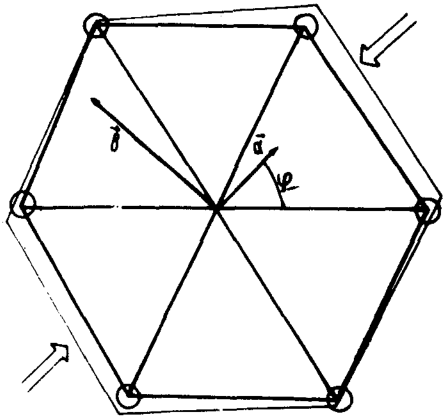

FIG. 2. Diagram illustrating the contraction of a regular triangular lattice along the **a** axis.

from 100 to 10 Oe, the contraction factor again remains the same, at $\eta = 1.2 \pm 0.1$. Furthermore, the direction of the contraction axis is always the same for domains with a common orientation of **a** and **b** (such domains are identical in color when the surface of the sample is observed in polarized light), and it is perpendicular to the **b** axis,[2)] which was determined with the help of a Berek phase compensator as the phase-lag axis of reflected light.[8] The angle φ was usually close to 30° or 0° (Fig. 3), indicating that one of the close-packed directions in the vortex lattice runs parellel to the **a** or **b** axis, as in Fig. 1.

The experimental results presented above are obviously evidence of an anisotropy of the interaction between vortices. According to the theoretical results of Ref. 9, such an anisotropy is a consequence of an anisotropy of the effective masses of the superconducting carriers, and it is manifested as a contraction of the vortex lattice along an axis for which the effective mass is relatively large, with a contraction factor $\eta = \sqrt{\mu_a/\mu_b}$ $(\mu_a > \mu_b)$ even in the case $d \gg \gamma$.

Following Ref. 9, and working from the value found experimentally for η, we can

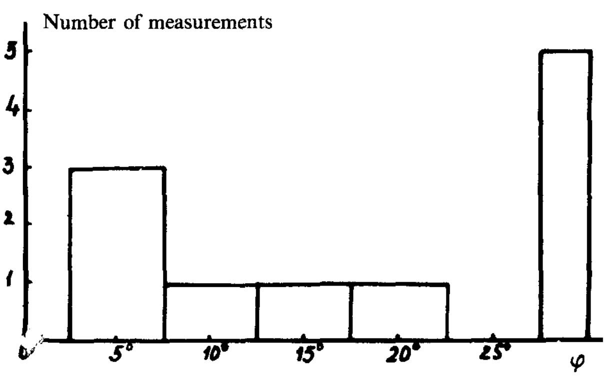

FIG. 3. Distribution of regions of the vortex lattice in the angle φ, between the vectors of the vortex lattice and the **a** axis of the crystal.

estimate the ratio of the effective masses in the (ab) plane: $\mu_a/\mu_b = 1.4 \pm 0.2$. This figure is equivalent to an anisotropy in the penetration depth and in the lower critical field: $\lambda_a/\lambda_b = H^b_{c_1}/H^a_{c_1} \approx 1.2$.

Unfortunately, we are left with the question of how well this estimate of the anisotropy μ_a/μ_b compares with the results of measurements of other quantities, e.g., H_{c_2}, since the experiments which have been reported on Nb (Ref. 10) and V_3Si (Ref. 11) have not revealed a quantitative correlation between the anisotropy and the distortions of the regular vortex lattice in fields $H \ll H_{c_2}$.

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[1)]The demagnetizing factor for the sample with $H_e \| c$ was ≈ 1, so it was possible to work in fields $H_e < H_{c_1}$.
[2)]The vectors on the diffraction pattern are rotated 90° from the vortex lattice (the corresponding comment applies to the diagram in Fig. 2).

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