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DETERMINATION OF THE CRITICAL CURRENT DENSITY IN SUPERCONDUCTING FILMS: COMPARISON OF A MEASURED MAGNETIC FLUX DISTRIBUTION WITH MODEL CALCULATIONS

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ABSTRACT

We have investigated the magnetic field distribution of an epitaxial $YBa_2Cu_3O_{7-x}$ film and compared the result with a theoretical calculation which has recently been proposed. This model takes into account the strong demagnetization effects that occur if a thin superconducting film is exposed to an external magnetic field perpendicular to the sample plane. It describes the magnetic field distribution of a two dimensional current distribution under the assumption that there are two opposing current bands, both carrying the critical current density j_c. We use j_c as a fit parameter and find very good agreement between the measured and the calculated field distributions.

Keyword: critical current density

Running title: Determination of the critical current density

INTRODUCTION

The flux distribution in superconductors exposed to a magnetic field yields important information about the superconducting properties, like critical current density or sample homogeneity. Consequently there have been several investigations recently about the magnetic flux distribution in thin high T_C films with the external field perpendicular to the sample surface [1-5]. Those experiments typically determine only the horizontal gradient of the normal component of the flux density with respect to the sample plane $\partial B_z/\partial x$ (the sample plane being in xy-direction). If one wants to derive critical current densities or pinning forces from these data, one also has to take into account the strong influence of the tangential field component parallel to the sample surface, as has been pointed out by Baczewski et al. [3], and Theuss et al.[4]. In order to investigate this problem in more detail, we have studied the flux distribution in epitaxial $YBa_2Cu_3O_{7-x}$ films by means of a contactless magnetooptical experiment [5] and compared the resulting field distribution with a calculation analogous to that in ref.[3].

EXPERIMENT

The YBCO films were sputtered onto $2\cdot 10mm^2$ ZrO_2 substrates and had a size of 2mm by 10mm and a thickness of approximately t=500nm. The transport critical current density for these films was found to be $j_C=5\cdot 10^6 A/cm^2$ at T=77K, implying their high quality.

The measurement of the magnetic flux distribution is performed using a magnetooptic setup as described earlier [5]. The YBCO films are immersed in superfluid ^{4}He at a temperature of 2K, and magnetic fields up to 1T are applied perpendicular to the film plane after zero field cooling (ZFC). The light intensity distribution of the images recorded with a video camera corresponds to the normal component of the magnetic field distribution, B_z, bright areas indicating high magnetic fields. For deriving quantitative results the images are analyzed with the help of an image processing system. The intensity of the Faraday rotated light is in good approximation proportional to the square of the magnetic field, as has been checked experimentally.

RESULTS AND DISCUSSION

The elongated shape of the samples allows to apply a simplified model which assumes the film to be infinitely long. This is justified also by the fact that the measured field distribution in the middle of the film is not affected by the corners significantly (in contrast, for example, to a square shaped sample [5]). In Fig.1 the field distribution is shown for an external field of 0.4T. The flux expulsion leads to a field enhancement and thus to an increase of the brightness along the sample edges. Superimposed on the overall light intensity distribution due to the Faraday rotation is an interference pattern resulting from spurious reflections from the cryostat windows. For the data analysis these fringes are partly eliminated by proper averaging. The convex shape of the flux fronts penetrating the sample from the left and right side is due to the

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We now turn to a comparison of the experimentally determined data with theoretical calculations. Baczewski et al. [3] have proposed a two-dimensional critical state model for deriving the critical current density j_c from the gradient of the z-component of the magnetic field at the position $\pm w/4$, where w is the width of the film (2mm in our case). In this model the magnetic field component B_z perpendicular to the sample plane, in the case of full penetration, was shown to be given by

$$B_z(x)=-(\mu_0/2\pi)tj_c\ln|1-0.25(w/x)^2|+B_{ext} \qquad (1)$$

where t is the sample thickness, and B_{ext} the externally applied field, and for simplicity the current density was assumed to be constant at a value of $\pm j_c$ in either half of the film. We have plotted this function in Fig.2 as a dashed curve for comparison with the experimental data. The discontinuity of the current distribution at the edges and in the center of the sample leads to a divergence of the magnetic field at $x=\pm w/2$ and $x=0$.

In contrast to the analysis in ref.[3] we have not determined the value of the critical current density by measuring a local value of the flux gradient, but by fitting the whole flux distribution across the sample, using j_c as a fit parameter.

Therefore the uncertainty of the resulting value for j_c is further reduced. We get very good agreement of theory and experiment experiment as can be seen in Fig.2. The slight deviation between the fit and the experimental data on the left side of the sample could be due to a slight spatial asymmetry of the superconducting properties.

The above results demonstrate the validity of the model, and appear to verify the assumption that there are two opposing current bands, each carrying the critical current density j_c. This is also confirmed by the results in Ref.[4] where the current distribution inside a disc shaped sample is simulated and the resulting magnetic field distribution is compared with measured flux profiles. In the case of flux fronts meeting in the sample center the current density which is calculated to reproduce the field distribution is essentially constant across the sample. In fact this result is identical with the assumption of the Bean critical state, although in the present case the critical state (concerning the current distribution) is actually established through the tangential field components B_{x0} on the sample surface. The absolute value obtained for j_c from the fit of the theoretical curve (Eq.(1)) to the experimental data in Fig.2 is $3\cdot10^7 A/cm^2$. This has to be compared with the transport measurements, which for samples of similar quality, as mentioned above, have yielded $j_c=5\cdot10^6 A/cm^2$ at 77K. An empirical result suggests an increase of j_c by one order of magnitude as the sample is cooled to liquid He temperature [6]. Taking into account that transport measurements in microbridges probe the film quality on a local scale, whereas our analysis yields an averaged value for the whole sample, the

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Furthermore this implies the importance of the tangential field component B_{x0} at the sample surface for the actual value of the shielding current in thin films. As has been pointed out already in ref.[3] the gradient of the normal field component in the position $x=\pm w/4$ is given by:

$$\partial B_z/\partial x=(16\mu_0 t/3\pi w)j_c$$

which shows that the gradient of the z-component of the magnetic field is only responsible for a minute part of the total shielding current, namely of the order $t/w=10^{-4}$. To estimate the maximum tangential field component B_{x0} in our case we assume that the whole sample is carrying $j_c=3\cdot10^7 A/cm^2$. With the film thickness being t=500nm, the maximum value for B_{xo} is about ±135mT on either side of the film. Although the gradient of the tangential field component is responsible for the main part of the current distribution inside the superconductor the absolute values of B_{x0} (135mT) and B_z (as in Fig.2 for B_{ext}=400mT) are of the same order of magnitude. In about half the film ($0.5mm\leq|x|\leq1mm$) the normal field component B_z even exceeds the tangential field component on the sample surface B_{x0} at least by a factor of two.

CONCLUSIONS

Many applications of HTSC thin films require a better understanding of the influence of demagnetization effects in the case that the magnetic field is perpendicular to the sample plane. In this letter we have compared an experimentally determined flux distribution in a high T_C film with a model which has recently been proposed. The analysis allows to determine the averaged critical current density, which acts as a fit parameter, and the result derived is in quite good agreement with transport measurements. Furthermore this work underlines the importance of the tangential field component for the shielding current density.

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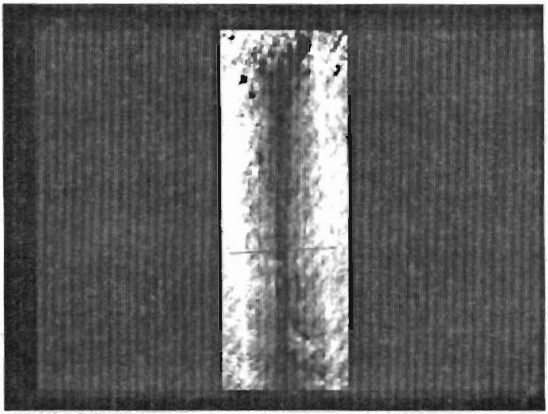
FIGURE CAPTIONS

Fig.1: Flux distribution in an epitaxial 500nm thick YBCO film, 2mm by 10mm in size on a ZrO_2 substrate. The sample was cooled in zero field to 2K and then exposed to an external field of 0.4T perpendicular to the sample plane. The light intensity distribution corresponds to the magnetic field distribution. On the left and right edge of the sample the magnetic field (and thus the light intensity) is maximal due to the flux expulsion from the sample. The analysis of the field distribution is performed along the dark line crossing the center of sample.

Fig.2: Measured (solid curve) and calculated (dashed curve) field distribution for the same sample as in Fig.1. The dashed line is derived by means of Eq.(1), using the critical current density j_c as a fit parameter. The divergence at $x=0$ and $x=\pm 1mm$ for the theoretical curve, which is due to the discontinuity of the current density at these positions, has been cut off.



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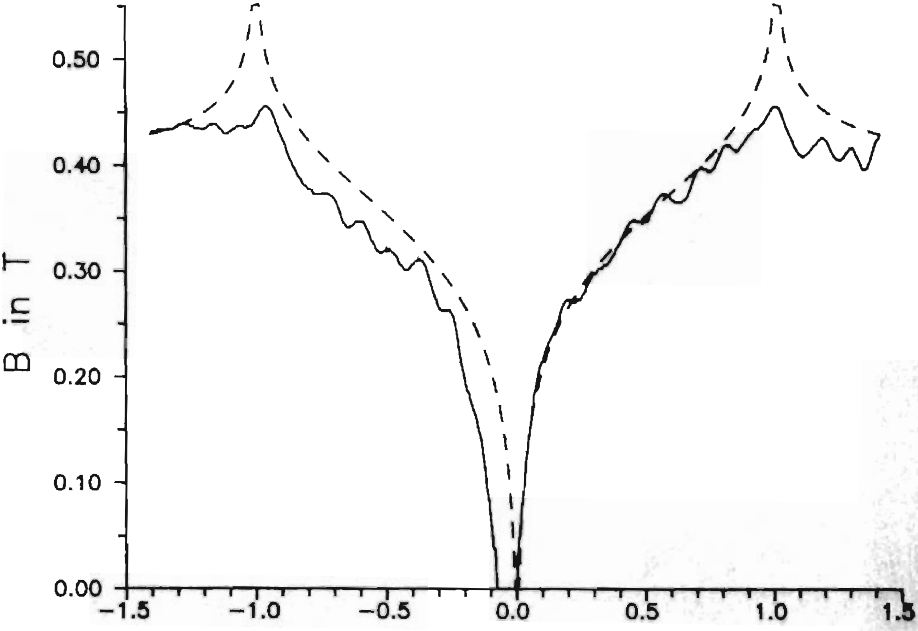
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