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# Field penetration and surface barriers in superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ whiskers

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We have used an array of Hall probes to investigate the spatial dependence of the local magnetic induction of individual superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ whiskers. At low temperatures ($\leqslant 50$ K) the exponential temperature dependence of the field of first flux penetration, $H_P(T)$, is consistent with recent theories of flux penetration by two-dimensional pancake vortices. A power-law dependence at higher temperatures suggests that flux penetrates as three-dimensional lines nearer $T_c$. We also show directly that at high temperatures the flux distribution is dominated by a surface barrier, whereas at low temperatures bulk pinning appears to dominate. [S0163-1829(97)51934-5]

## INTRODUCTION

Since the discovery of superconductivity in the highly anisotropic thallium- and bismuth-based cuprate superconductors,[1,2] their magnetic properties have attracted considerable attention. Of particular interest in this paper is the behavior in the mixed state, i.e., when magnetic flux has partially penetrated into the sample in the form of quantized vortices. At the microscopic level, flux penetration is usually enhanced near surface defects and no two samples can be expected to behave in quite the same way. For this reason, we describe here the results of local induction measurements on individual $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) whiskers. These are crystallographically almost perfect single crystals in that they have no extended defects, although there may be some point defects. They also have very regular surfaces and therefore represent model systems for the study of flux penetration. In this work we use a micrometer-sized Hall probe array to study the temperature dependence of the field of first flux penetration $H_P(T)$, as well as the spatial distribution of flux.

It is well known that $H_P(T)$ is considerably larger than the lower critical field, $H_{c1}$, due to the influence of surface barriers at the sample edges,[3] and is sensitive to the dimensionality of the penetrating vortex.[4] Surface barriers result from an attraction between a vortex and its image within the sample, and a repulsion from Meissner screening currents flowing at the surface. Burlachkov has calculated the energy required to surmount these barriers[4] as well as the characteristic temperature dependence of the penetration field in two limits.

In certain regions of the $H$-$T$ phase diagram for highly anisotropic cuprate superconductors, and with the applied field perpendicular to the copper-oxide planes, vortices can be thought of as two-dimensional (2D) pancakes coupled by Josephson vortices. The penetration field for independent pancake vortices is found to be

$$H_P(T) = H_c e^{-T/T_0}, \tag{1}$$

where $H_c$ is the thermodynamic critical field and $T_0$ is a characteristic temperature, given by

$$T_0 = \frac{\varepsilon_0 d}{\ln\left(\frac{t}{t_0}\right)}. \tag{2}$$

Here, $d$ is the separation of the copper-oxide planes, $t$ is the time since application of the field, $t_0$ is a fundamental time scale for vortex oscillations, and $\varepsilon_0$ is the vortex line energy.

In contrast, the penetration of 3D flux lines is described by

$$H_P(T) \propto \frac{(T_c - T)^{3/2}}{T}. \tag{3}$$

A temperature dependence at low temperatures of the form (1) has been taken as evidence of the penetration of 2D pancake vortices in both large, single crystals of $YBa_2Cu_3O_{7-\delta}$,[5] and in grain-aligned mercury compounds.[6] In these works, however, the average magnetization of large single crystals, or an ensemble of various shaped crystallites, has been measured. The results presented here take this work a step further in that individual superconducting whiskers with highly regular morphology can be investigated and we are able to verify the importance of surface barriers directly. The penetration field will, clearly, be affected by the shape of the sample due to demagnetization effects, and Burlachkov[4] has shown that for platelet-shaped samples of width $w$ and thickness $d$, the actual penetration field will be a factor $\sqrt{d/w}$ smaller than the measured field. This is about 0.2 for our samples but only scales the prefactor of Eq. (1) and the values of $T_0$ deduced in the following results are not affected by demagnetization effects.

Measurements have been carried out using a miniature Ga-As/Al-Ga-As heterostructure Hall probe array based on a 2-$\mu$m-wide wire width with 4-$\mu$m center-to-center spacing between Hall voltage contacts. The probe was operated with a 2-$\mu$A 32-Hz ac current and the Hall voltage detected with a lock-in amplifier. The Hall bar is somewhat smaller than

 

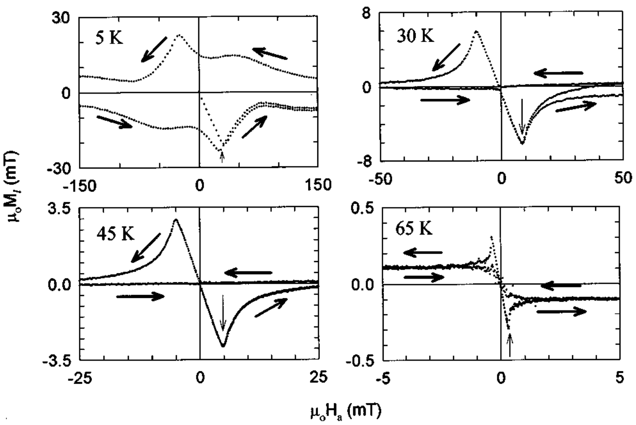


FIG. 1. Local magnetization loops at various temperatures for whisker I, measured at the sample center.

typical sample widths, allowing the spatial variation in flux density across the whisker to be investigated (see micrograph inset in Fig. 2). Two whiskers of $Bi_2Sr_2CaCu_2O_{8+\delta}$ were investigated. Whisker I had dimensions of 230 $\mu$m$\times$7.0 $\mu$m$\times$0.3 $\mu$m and whisker II had dimensions of 340 $\mu$m$\times$8.5 $\mu$m$\times$0.3 $\mu$m. A detailed description of the whisker growth and characterization is given in Ref. 7. Although the whiskers are of high crystallographic perfection, they do not have optimum oxygen stoichiometry as indicated by their critical temperatures which we estimate to be 75.2 and 78.9 K for whiskers I and II, respectively, on the basis of our magnetization measurements. These estimates were obtained by fitting a cubic polynomial to the high-temperature penetration field data and extrapolating to zero field to find $T_c$. The whiskers were positioned in the desired location on the Hall probe with a micromanipulator where they were held by their mutual electrostatic attraction. The samples were then mounted on a temperature-controlled probe and inserted into a He cryostat containing a small superconducting solenoid.

## RESULTS AND DISCUSSION

Figure 1 shows four ''local'' magnetization loops (derived from $\mu_0\mathbf{M}_l=\mathbf{B}_m-\mu_0\mathbf{H}_a$, where $\mathbf{B}_m$ is the measured induction and $\mathbf{H}_a$ is the applied field) measured at the center of whisker I (inset Fig. 2) at temperatures of 5, 30, 45, and 65 K. Here, we use the symbol $\mathbf{M}_l$ to differentiate between our ''local'' magnetization and the conventional bulk magnetization. The field is applied parallel to the crystallographic **c** axis. In each panel, $H_P$ can be identified as the field at which $\mathbf{M}_l$ deviates sharply from the linear diamagnetic behavior near the origin (labeled with vertical arrows). Clearly the penetration fields and the breadth of the hysteresis loops reduce rapidly as the temperature is raised. At 30 K and above, the asymmetric increasing and decreasing legs of the local magnetization loops are entirely characteristic of a system dominated by surface barriers.[3] This arises because surface barriers only affect vortex entry and not exit, and the interaction with surface screening currents tends to expel vortices from the sample upon field reversal when $M_l(H)$ drops almost to zero in a sample with low pinning. At low temperatures, e.g., at 5 K, the $M_l(H)$ loops become more symmetric and it appears that bulk pinning is beginning to play a role. The regions of almost constant reversible magnetization at 65 K were reproducible in all Hall probe pairs and disappeared above the critical temperatures of the samples, estimated on the basis of $H_P(T)$. The origin of these appears to be the presence of a surface barrier which occupies a significant fraction of these very narrow whiskers.

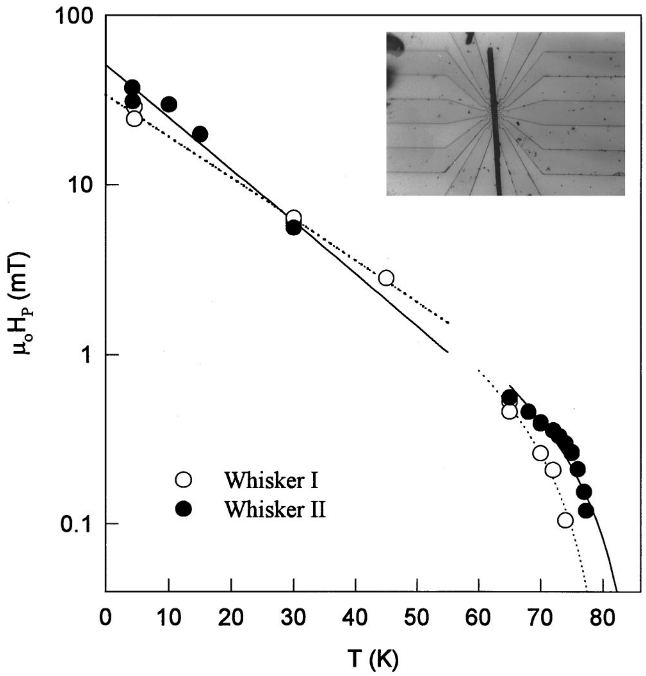


FIG. 2. Temperature dependence of the field of first flux penetration, $H_P(T)$, for whisker I and whisker II. The inset shows an optical micrograph indicating the relative orientation of whisker I and the Hall bar.

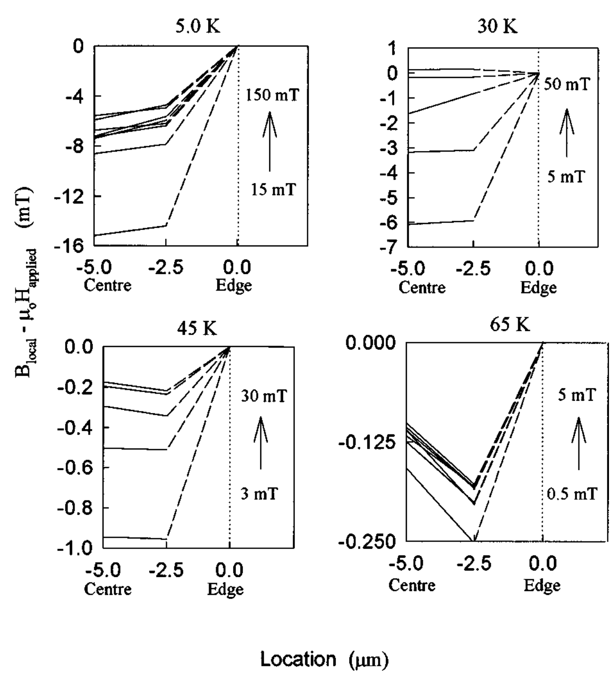


FIG. 3. Spatial distribution of flux at various temperatures, measured on the initial field increasing magnetization leg. The applied field values are uniformly distributed between the indicated limits.

The fact that the magnetization is field independent over an appreciable range is most unusual and appears to be linked to the 3D nature of the vortices and surface barriers at higher temperatures (discussed in more detail later).

In Fig. 2 we have plotted the temperature dependence of the penetration field, using the local magnetization plots described earlier to find $H_P$. We have fitted this data to both models calculated by Burlachkov.[4] At low temperatures ($T \leqslant 65$ K) a dependence of the form (1) is displayed over nearly two orders of magnitude in $H_P$. A linear regression of the logarithmic plot yields $T_0 = 18$ K and 14 K for whiskers I and II, respectively. These values compare well with those obtained by Lewis *et al.*[5] for their Hg-based compounds, which varied between 14.0 and 46.3 K, depending on which phase of the Hg sample was measured. To get an estimate for $T_0$, Eq. (2) was used with a periodic spacing of 15 Å, a penetration depth of 2000 Å, and the parameter $\ln(t/t_0)$ set to 30, as suggested by Burlachkov for bismuth-based compounds.[4] These parameters yield a value of 25 K for $T_0$, which compares well with our measured values of 18 and 14 K. It was also possible to obtain estimates for the thermodynamic critical fields, $\mu_0 H_c$, from Eq. (2). These values were calculated from a least-squares-fit method and were found to be 170 and 255 mT, respectively, for whiskers I and II, assuming $H_c$ is independent of temperature and accounting for demagnetizing effects. It should be noted that $\epsilon_0$ (used to calculate $T_0$) is also a temperature-dependent quantity, but is treated as a constant in the above experimental analysis. Also, more accurate estimates of the sample parameters, such as the penetration depth, should yield even better results.

In the high-temperature limit of Eq. (3), a best fit gives a value for $T_c$ of 80.8 and 86.0 K for whiskers I and II, respectively (curved lines in Fig. 2). The agreement here, however, is by no means as impressive as in the low-temperature limit, indicating that the full three-dimensional vortex limit is not quite appropriate here.

Figure 3 shows the spatial variation of the local flux density across the whisker, measured at two adjacent pairs of Hall probes (see inset, Fig. 2) at different points on the initial field increasing leg of the hysteresis loops of Fig. 1. Here, we have made the ad hoc assumption that the induction at the edge of the crystal is exactly $\mu_0 H_a$. This is certainly not the case, but nevertheless gives us a useful reference level for the data. At low temperatures these profiles are similar to those predicted by the Bean model,[8] with lower flux density at the center and higher flux density near the sample edge. Hence the flux profiles appear to be dominated by bulk pinning at very low temperatures ($<10$ K). At higher temperatures, the flux appears to become increasingly concentrated at the whisker center, which is consistent with surface barriers effectively ‘‘pushing’’ the vortices towards the center, while depleting it at the edges. Note that at 65 K above the penetration field the profiles cluster, reflecting the almost constant magnetization in this regime as discussed earlier. This is the most direct evidence of the importance of surface barriers yet obtained in highly regular whiskers of this type. Similar high-temperature flux profiles have been observed by Zeldov *et al.*[9] in much larger BSCCO single crystals.

In conclusion, we have shown directly that the flux distribution in BSCCO whiskers is strongly determined by the presence of surface barriers, except at very low temperatures ($T<10$ K) when bulk pinning appears to play the dominant role. We have also shown, via measurements of $H_P(T)$, that at low temperatures the vortices penetrate as individual two-dimensional pancakes in the copper-oxide planes, whereas at higher temperatures they penetrate as conventional three-dimensional flux vortex lines, with each pancake strongly correlated with its neighbors above and below.

## ACKNOWLEDGMENTS

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