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Microscopic measurement of penetration depth in $YBa_2Cu_3O_{7-\delta}$ thin films by scanning Hall probe microscopy

A Oral†, S J Bending†, R G Humphreys‡ and M Henini§

† School of Physics, University of Bath, Claverton Down, Bath BA2 7AY, UK
‡ DRA Electronics Division, St Andrew's Road, Malvern,
Worcestershire WR14 3PS, UK
§ Department of Physics, University of Nottingham, Nottingham NG7 2RD, UK

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Abstract. We have used a low noise scanning Hall probe microscope to measure the penetration depth microscopically in a $YBa_2Cu_3O_{7-\delta}$ thin film as a function of temperature. The instrument has high magnetic field ($\approx$2.9 $\times$ 10^{-8} T $Hz^{-1/2}$ at 77 K) and spatial resolution ($\approx$0.85 μm). Magnetic field profiles of single vortices in the superconducting film have been successfully measured and the microscopic penetration depth of the superconductor has been extracted. We find surprisingly large variations in values of λ for different vortices within the scanning field.

1. Introduction

Understanding the nature of superconductivity and the behaviour of magnetic flux vortices in high-temperature superconductors remains a major challenge for contemporary condensed-matter physics. A variety of techniques have been used to study flux vortices, most of which (e.g. bulk magnetization, muon spin relaxation [1], neutron diffraction [2]) yield values for physical quantities which are averaged over macroscopically large samples. The microscopic techniques that can resolve individual vortices tend to have drawbacks of one kind or another. Bitter decoration with fine magnetic particles [3] yields little quantitative information, scanning SQUID systems [4, 5] currently lack high spatial resolution, magnetic force microscopy [6, 7] is invasive and electron holography [8] requires very large amounts of computer processing power, and only works with thin films. It is widely becoming recognized that systems based on scanning submicron Hall probes overcome most of the problems associated with these techniques and can yield a quantitative measure of the perpendicular component of the magnetic field near a sample surface with high spatial resolution. Building on the experience gained with the first prototype scanning Hall probe microscopes [9, 10] we have been able to improve Hall probe design and to achieve very high magnetic field resolution ($\approx 2.9 \times 10^{-8}$ T $Hz^{-1/2}$ at 77 K) with a spatial resolution of about 0.85 μm. This has allowed us to image individual vortices in thin films of high-temperature superconductors with fast acquisition rates, even very close to T_c [11].

The temperature dependence of the magnetic field penetration depth, $\lambda(T)$, has attracted particular interest in the last few years since it reflects the nature of the superconducting pairing state. At low temperature the following functional forms are predicted [12]; $\lambda(T) \sim$ constant (s wave), $\lambda(T) \sim T$ (d wave) and $\lambda(T) \sim T^2$ (s + id or mixed state). The origin of these results lies in the zero nodes of the d-wave gap function which give rise to low energy excitations and a qualitatively different dependence for $\lambda(T)$. A number of recent penetration depth measurements show linear [13] and quadratic [14] dependence at low temperatures, while Klein *et al* [15] have observed BCS-like exponential temperature dependence. All of these measurements represent macroscopic averages over large sample volumes. The short coherence length of high T_c superconductors makes them extremely sensitive to defects such as twins and grain boundaries as well as point defects and local stoichiometry variations and even though all the measurements quoted above were performed on high-quality films or single crystals, they will still be substantially influenced by these. Measurements are therefore likely to be highly sample dependent as illustrated by the fact that different groups infer different pairing mechanisms from measurements on similar samples. Microscopic measurements are clearly needed to resolve these issues in high T_c superconductors. Recently, scanning tunnelling microscopy (STM) and tunnelling spectroscopy have been successfully applied to image the vortex lattice [16] in a $YBa_2Cu_3O_{7-\delta}$ crystal. The method differentiates between the normal core of the vortex and

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the surrounding superconducting regions, but does not directly give information about the magnetic properties, i.e. penetration depth. On the other hand, muon spin relaxation [1] experiments are intrinsically microscopic, however results still average across the sample yielding a mean value of the penetration depth. We have therefore attempted to use our scanning Hall probe microscope to measure the temperature dependence of the penetration depth from a number of individual vortices in a $YBa_2Cu_3O_{7-\delta}$ thin film to see wether similar results apply at the microscopic level. Surprisingly we find a large variations in values of λ for different vortices within the scanning field which, if correct, suggests that data from macroscopic measurements of penetration depth must be viewed with some caution.

2. Experimental details

The Hall probe for this work was fabricated from a GaAs/AlGaAs heterostructure two-dimensional electron gas ($n_{2D} = 2.7 \times 10^{11}$ cm^{-2} and $\mu = 300\,000$ cm^2 V^{-1} s^{-1} at 4.2 K in the dark). The Hall sensor was defined by the intersection of two lithographically patterned wires of geometrical width 1 μm and effective electrical width $\approx$0.85 μm after sidewall depletion. The metallized corner of an etched mesa 13 μm from the Hall sensor served as an STM tip for finding and scanning the sample surface. Measurements can be performed while the STM tip is in tunnelling contact with the sample and simultaneous images of the flux distribution and surface topography can be acquired. An alternative approach, which was used to take the data presented here, is to retract the sample about 0.5 μm allowing much more rapid measurements of the magnetic field profile alone with slightly lower spatial resolution. A detailed description of the instrument is given elsewhere [11, 17]. The high-quality $YBa_2Cu_3O_{7-\delta}$ thin film used in this study was grown by electron beam evaporation of the metals in the presence of atomic oxygen on an MgO substrate at 690 °C [18] and had a thickness of 0.35 μm and $J_c = 1.4 \times 10^6$ A cm^{-2} at 77 K. The critical temperature of the film was found to be $\approx$90.4 K by magnetization measurements performed with the Hall probe itself which agrees well with the 90.8 K measured by DC magnetization on the whole sample. These properties suggest that the sample was close to optimal doping or perhaps slightly underdoped. Detailed investigation of the microstructure of similar films reveals them to be composed of highly twinned growth islands $\approx$0.2 μm in diameter. The scale of the twinning is much finer than our instrumental resolution, so in this sense our results must be viewed as averages over the *a* and *b* directions. The Hall probe was mounted directly on the piezo tube of a commercial low-temperature scanning tunnelling microscope with a stick–slip coarse approach mechanism and was tilted approximately 1°–2° with respect to the plane of the superconducting film. The tilt angle between tip plane and sample plane can be measured precisely in the STM mode by measuring the tip height at three corners of the scan area. This tilt angle is then electronically compensated during scans so that the Hall probe remained at a fixed height above the sample. The entire scanning Hall probe microscope assembly sat at the centre of a commercial temperature-controlled cryostat (1.5–300 K) containing a 7 T superconducting magnet.

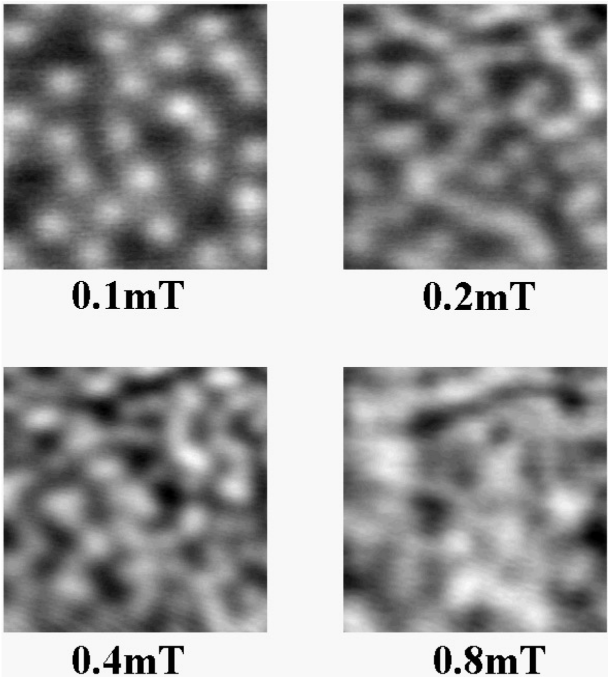

Figure 1. SHPM image of $YBa_2Cu_3O_{7-\delta}$ thin film at 77 K, field cooled at 0.1, 0.2, 0.4 and 0.8 mT. The scan range is 24×24 μm^2.

3. Experimental results

Figure 1 shows typical scanning Hall probe microscope (SHPM) images for the $YBa_2Cu_3O_{7-\delta}$ sample after it has been field cooled to 77 K at four different applied fields. At 0.1 mT about 30 individual vortices can be clearly resolved in the 24×24 μm^2 scanning field which is in good agreement with the expected number of 28 at this field. As the field is increased the tails of the vortices increasingly overlap and the image contrast rapidly degrades. At 0.2 mT it is just possible to decipher individual fluxons, but at higher fields one merely resolves regions of high and low vortex density. Even at 0.4 mT the flux distribution is highly inhomogeneous with clear black regions where no vortices reside and bright peaks where they have clustered. This gives one a graphic feeling for the relatively strong disorder in these high critical current films.

Figure 2 shows images of a 0.1 mT field-cooled sample at five different temperatures. Note that the scanning range becomes smaller at low temperatures owing to a reduction of the piezoelectric coefficient of the scanner tube. This has, however, been precisely calibrated in a series of STM measurements on a periodically patterned sample. As one expects, the vortex diameter decreases and the contrast improves at low temperatures owing to a reduction in the superconducting penetration depth, λ.

Figure 3 shows sets of penetration depth, λ, measurements which have been extracted from images of

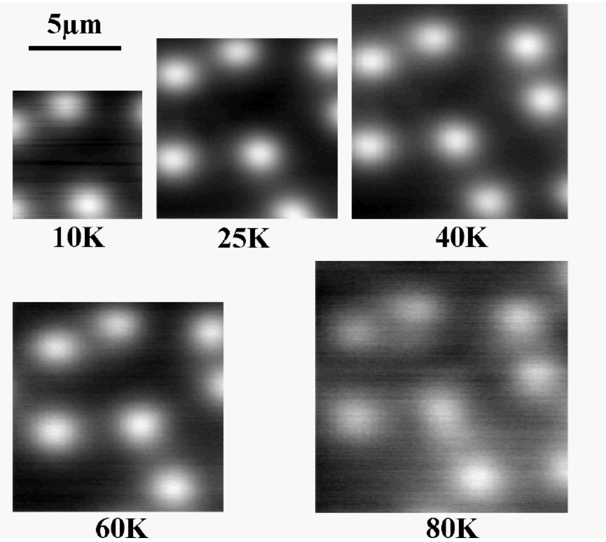

Figure 2. SHPM image of $YBa_2Cu_3O_{7-\delta}$ thin film at different temperatures. The sample is field cooled at 0.1 mT.

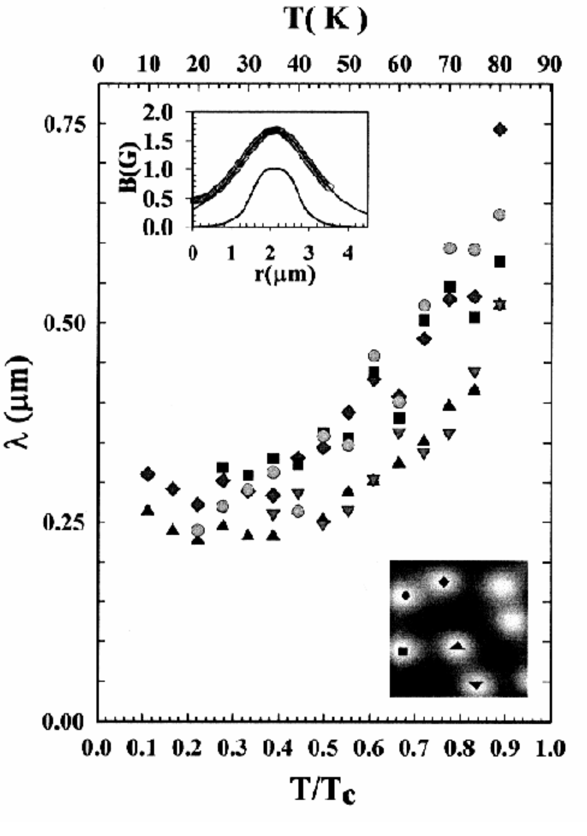

Figure 3. Penetration depth, λ, as a function of temperature measured from individual vortices labelled on the image displayed. Inset shows the fit at 10 K. The response function of the Hall probe is plotted beneath the fit.

the type shown in figure 2 measured in 5 K steps from 10 to 80 K. A detailed theoretical description of the field distribution at a vortex and the response of the Hall probe have been developed in order to fit our SHPM data and to extract a value of λ for a given vortex at a given temperature as illustrated in the inset to figure 3. We adopt the same model of the vertical component of the magnetic field near a vortex in a thin superconducting film as used in previous SHPM studies [19]:

$$B_z(r, z, \lambda) = \frac{\Phi_0}{2\pi\lambda^2} \int_0^\infty \mathrm{d}\gamma \, \frac{J_0(\gamma r)\exp[-\gamma(|z| - d/2)]}{k_\gamma[\coth(k_\gamma d/2) + k_\gamma/\gamma]} \tag{1}$$

where $k_\gamma = (\gamma^2 + 1/\lambda^2)^{1/2}$, z is measured from the centre of the film, d is the film thickness and λ is the penetration depth. The integral is calculated numerically using the known value of $d = 0.35$ μm and the height that the Hall probe was set above the sample (0.67 μm). We have developed a theoretical model of the response of a Hall probe to a local region of magnetic flux much smaller than the geometrical size of the Hall probe which takes into account currents which decay exponentially into the voltage probes [20]. This allows us to calculate a response function which is defined as the position-dependent response of the Hall probe to a narrow tube of flux, expressed in terms of the homogeneous field that would generate the same Hall voltage. This response function is shown beneath the data in the inset of figure 3 and note that even at 10 K it is appreciably narrower than the measured cross-section. In order to extract a value of λ for a given vortex, solutions of equation (1) are two-dimensionally convoluted with the Hall probe response function and then fitted to the SHPM data using a three-parameter least-squares fit with λ, position of vortex and the offset of the Hall probe as free variables. Agreement between the model and data is excellent as shown in the inset to figure 3 for the vortex labelled with a triangle at 10 K. The values of $\lambda(T)$ extracted in this way are shown in the main plot of figure 3 versus reduced temperature for five of the vortices in the scanned field (see labels superimposed on the SHPM image). Note that for a given vortex there is a modest scatter in the measured penetration depth of the order of ±0.03 μm as the temperature increases. This presumably arises from random errors which are introduced during the extensive calibration procedures for the temperature dependence of the Hall coefficient of the sensor, the scanner range and the sample–probe separation. Most significantly, however, we observe a much wider distribution of λ for the different vortices at any given temperature when such errors would affect all data in the same fashion. At 35 K, for example, the fitted values span a range from 0.23 to 0.34 μm, and the spread is even larger at higher temperatures. There is a clear correlation between the position of the vortex in the scanned field and the penetration depth which appears become systematically smaller as one moves from the left to the right of the image. Such an effect would be an obvious artefact of a finite tilt angle between the sample surface and the plane in which the Hall probe is scanned. However, as explained earlier, we measure and electronically compensate for any tilt angle with great precision and we do not believe that this is the source of the variation. Alternatively, this could arise as a result of local fluctuations in the oxygen concentration in the sample. Recently, Fuchs *et al* [21] have shown that the penetration depth λ is a sensitive function of oxygen deficiency δ in $YBa_2Cu_3O_{7-\delta}$. In addition, thickness variations and various defects in the film can also result in the different penetration depths we measure. The low-temperature values of

λ, $\lambda(0) \approx 220$–300 nm, measured here can be compared with the bulk penetration depth of $YBa_2Cu_3O_{7-\delta}$ as measured by other techniques. Microwave measurements on our films [22] give $\lambda(0) \approx 160$–260 nm. Our measurements seem to be systematically larger than values extracted from mutual inductance ($\lambda(0) \approx 210$ nm) [23], microwave surface impedance ($\lambda(0) \approx 165$ nm) [15] and muon spin relaxation measurements ($\lambda(0) \approx 140$ nm) [1], and a similar conclusion was drawn in an earlier study of $La_{1.85}Sr_{0.15}CuO_4$ by SHPM [19]. Our low-field measurement method samples the worst part of the film because we measure the penetration depth from vortices pinned at the defects during field cooling. Therefore, one would expect to obtain longer penetration depths by this method compared with other techniques. In view of the large scatter in our data it is difficult to identify a generic temperature dependence and it seems quite conceivable that different weighted averages of such inhomogeneous distribution could be the origin of the number of apparently conflicting experimental results.

In conclusion we have used a scanning Hall probe microscope to measure the microscopic penetration depth in a $YBa_2Cu_3O_{7-\delta}$ thin film for the first time. Our results suggest that there may be a large variations in the value of λ across a region of the sample a few tens of microns wide. If this is indeed the case it indicates that the characteristic properties of high T_c films may be much more inhomogeneous than was previously realized, and some caution should be exercised in the interpretation of measurements on macroscopic samples.

Acknowledgments

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