Estimating the magnetic penetration depth using constant-height magnetic force microscopy images of vortices

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Abstract. We present constant-height magnetic force microscopy images of magnetic vortices on a superconducting Nb film. From a comparison of the measured vortex profiles with theoretical models, as a function of scan height, we conclude that it is possible to determine the relative value of the magnetic penetration depth \( \lambda \) to within 10–20\% using an uncalibrated tip. If a quantitatively characterized tip with a known magnetization structure were used, this would then permit one to obtain an absolute value of \( \lambda \) with similar accuracy.

The magnetic penetration depth \( \lambda \) is one of the fundamental parameters of a superconductor, and is directly related to the concentration of superconducting electrons. Its temperature dependence reflects the symmetry of the superconducting state [1], and is thereby an indicator of the underlying microscopic mechanism of superconductivity. This dependence is often used as a benchmark against which various models of superconductivity are tested [2, 3, 4, 5, 6].

Numerous experimental methods routinely used to make bulk measurements of the penetration depth include mutual inductance techniques [7], resonant LC circuits [8], microstrip resonators [9], muon spin rotation [10] and polarized neutron reflectometry [11]. However, with growing interest in patterned and structured superconducting materials, the ability to perform characterizations on a local scale is becoming increasingly important. Consequently, in the following we shall focus on local measurements of the penetration depth, of which several scanning probe techniques have been applied, including scanning SQUID [12] and scanning Hall probe microscopes (SHPMs) [13, 14]. Both base their measurements of \( \lambda \) on the magnitude of the vortex magnetic field at a constant height above the sample surface, which is then

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fitted to a model in order to determine the penetration depth. To date, published values of \( \lambda \) determined by SHPM have been comparable to the active area of the probe [13, 14], typically about 0.25 \( \mu \)m for a state of the art system [15]. Values measured using the SQUID are slightly larger (\( \sim 0.5–3 \) \( \mu \)m), and require that \( \lambda \) be large compared with the sample film thickness in order to make a quantitative determination when \( \lambda \) is small compared with the pickup loop [12]. The samples of choice for these two techniques have therefore been limited to high-\( T_c \) materials, which exhibit large values of \( \lambda \) compared with conventional superconducting materials.

In this work, we demonstrate the application of magnetic force microscopy to determine the magnetic penetration depth of Nb, a conventional superconductor. This technique utilizes constant-height images of vortices, but in contrast to the aforementioned methods, \( \lambda \) is determined based on the spatial extent of the vortex stray field as opposed to its magnitude. This offers several advantages over existing methods, not the least of which is an ability to locally measure values of \( \lambda \) less than 100 nm, a feature afforded by the high spatial resolution achievable with MFM. As well, like other scanning probe techniques, it requires relatively small sample sizes, typically several \( \mathrm{mm}^2 \) down to a few 100 \( \mu \mathrm{m}^2 \) in area. This is particularly desirable when dealing with exotic new materials, which are often difficult to grow to large sizes. In addition, the technique requires minimal sample preparation, and is relatively insensitive to surface conditions. Finally, fast measurement times corresponding to \( \sim 10 \) min per image are routine, and may commence immediately after the system has reached thermal equilibrium at the desired temperature.

Imaging of vortices by MFM on both conventional and high-\( T_c \) materials has been reported in the literature by several groups in the past [16, 17, 18, 19]. Our experiments were performed using a custom-built cryogenic magnetic force microscope [20], within a temperature range of 5–10 K, with a routine thermal stability of 0.01 K. An 8 T superconducting solenoid was used to apply magnetic fields perpendicular to the sample surface. The magnitudes of the applied fields were verified using an \textit{in situ} flux gate magnetometer mounted within close proximity (\(< 1 \) cm) of the sample.

We used a commercially available silicon nitride cantilever, with a resonance frequency \( f = 36 585 \) Hz, nominal spring constant of 0.1 N m\(^{-1}\), a quality factor \( Q = 4573 \) and an oscillation amplitude \( A = 30 \) nm peak to peak. The cantilever was made magnetically sensitive by the evaporation of 30 nm of Co onto one face of the pyramidal tip, which was magnetized along the tip direction prior to installation into the microscope.

The sample, a 100 nm thick Nb film, was deposited by magnetron sputtering on a silicon substrate. From approach curves acquired as a function of temperature, the critical temperature was found to be \( T_c = 8.95 \) K, at which point no repulsive magnetic interaction (Meissner force) between the tip and sample was observed [21].

In order to cancel the component of the earth’s magnetic field perpendicular to the sample surface, the effect of which is easily observed during imaging, a nulling magnetic field was applied along the \( z \)-axis direction. All measurements requiring a zero-field environment were performed within the presence of this nulling field, and the magnitudes of any applied fields were adjusted to compensate for the background stray field.

With the tip positioned in the lower left corner of the scan region, the sample was heated to 10 K and a field of 0.5 mT applied. The sample was then cooled to 5 K, the applied field was removed and a \( 5 \times 5 \) \( \mu \mathrm{m}^2 \) area, centred about the middle of the scan region, was imaged at constant height as a function of tip–sample separation. Results are illustrated in figure 1. Scan heights were previously determined by approaching the tip to the sample surface at 10 K
Figure 1. $5 \times 5 \mu m^2$ area MFM images, acquired at 5 K, in a field of 0.5 mT, at various scan heights. The full scale of 0–8 Hz is identical for all images, and $\Delta f$ of 1 Hz $\approx 5.5 \times 10^{-6}$ N m$^{-1}$. In our system attractive interactions correspond to an increase in $\Delta f$ (i.e. lighter colours). Also shown are corresponding cross sections through the middle vortex in the $x$-direction, the location of which is indicated by the white line in the 50 nm image.

New Journal of Physics 3 (2001) 24.1–24.8 (http://www.njp.org/)
in zero applied field until tip–sample contact was made. Note that the sharpness, as well as the amplitude of the peak, decreases with increased scan height. This follows from the expected decay of the magnetic field and field gradient with increasing tip–sample separation.

The process was then repeated for an applied magnetic field of equal magnitude and opposite polarity. The results are illustrated in figure 2, which employs the same scale as figure 1. Note that dark vortices correspond to a magnetic field anti-parallel to the $z$-component of the tip magnetization, and exhibit a repulsive interaction with the tip, while light vortices correspond to a field parallel to the $z$-component of the tip magnetization, and produce an attractive interaction. While both figures share a common scale, the baseline offset has been independently adjusted in each case to maximize contrast. This accounts for the apparent discrepancy in the background value between the two figures.

We note in passing that both attractive and repulsive vortices exhibit similar size, shape and interaction strength, and appear to differ only in polarity, as expected. As well, the spatial arrangement and position of the attractive and repulsive vortices are extremely similar. Four of the six vortices appear to occupy identical positions for the two cases, suggesting strong pinning at particular sites. This phenomenon was observed during the experimental run over the course of several days, during which time vortices would repeatedly position themselves in specific locations.

Also apparent is the movement of some of the vortices during imaging at small tip–sample separations (e.g. figure 1, 50 nm scan), which occur when the force from the tip overcomes the local pinning force. Care must be taken to ensure that this effect, which becomes more pronounced as temperatures approach $T_c$, is minimized. Such influences however are easily recognizable during the scanning process.

Given that magnetic force microscopy is sensitive to the magnetic stray field produced by the vortices, and that the size of the vortices is determined in part by the magnetic penetration depth of the material, it is reasonable to conclude that one may extract a value for $\lambda$ based on MFM measurements.

It must be recognized however that a direct measure of the observed vortex radius will not yield the correct value for $\lambda$. In general, the radius of a vortex is not equal to the penetration depth, but is instead a function of the Ginzburg–Landau parameter $\kappa = \lambda/\xi$ (here $\xi$ is the coherence length), a characteristic parameter of all superconductors. It is in fact the value of $\kappa$ which determines the vortex profile, with low-$\kappa$ (conventional) superconductors exhibiting wide vortex profiles, and high-$\kappa$ (high-$T_c$) superconductors exhibiting narrow vortex profiles. Various theoretical models exist [22, 23, 24] which can simulate such vortex profiles; two examples are shown in figure 3, which illustrates the vortex profile at the surface of the superconductor for the high- and low-$\kappa$ cases. Here we have plotted both the first and second derivatives of the $z$-component of the stray field, the relevant form depending on whether the monopole or dipole tip model is used [25].

In the following analysis we adopt the monopole tip model, a reasonable assumption based on the fact that the decay length of the vortex field (on the order of 200 nm—see figures 1 and 2) is small compared with the dimensions of the magnetic volume of our tip (several $\mu$m). This assumption is also supported by the qualitative similarity between the $\partial B_z/\partial z$ curves of figure 3 and the cross sections in figures 1 and 2, especially for tip–sample separations greater than 50 nm.

In figure 4 we plot the experimentally determined half width at half maximum (HWHM) for all vortices in figures 1 and 2, as a function of height. We also include theoretical curves for three values of $\lambda$: $\lambda = 45, 90$ and $180$ nm. This follows from our estimation of $\lambda(T = 5$ K$) = 90$ nm, calculated using the dirty limit expression $\lambda = \lambda_L(\xi_0/l)^{1/2}$ [26], where $\xi_0 \approx 27$ nm and

New Journal of Physics 3 (2001) 24.1–24.8 (http://www.njp.org/)
Figure 2. $5 \times 5 \, \mu m^2$ area MFM images, acquired at 5 K, in a field of 0.5 mT, at various scan heights. The full scale of 0–8 Hz is identical for all images, and $\Delta f$ of 1 Hz $\approx 5.5 \times 10^{-6} \, \text{N m}^{-1}$. In our system, repulsive interactions correspond to a decrease in $\Delta f$ (i.e. darker colours). Also shown are corresponding cross sections through the middle vortex in the $x$-direction, the location of which is indicated by the white line in the 35 nm image.
Figure 3. The normalized first and second derivatives of the $z$-component of the stray field of a vortex, calculated at the surface of the superconductor. (a) For our Nb sample ($\kappa \sim 1$). (b) For a high-$\kappa$ material ($\kappa \sim 100$), such as the high-$T_c$ superconductor YBCO.

Figure 4. The HWHM of all vortices in figures 1 and 2, plotted as a function of scan height. The increase in uncertainties at larger tip–sample separations results from a reduction in the signal to noise ratio. Also shown are theoretical curves for three different values of $\lambda$.

the mean free path $l \approx 4.5$ nm for this sample [27], and $\lambda_L(T = 0 \text{ K}) = 35$ nm is the London penetration depth for Nb [11].

Note that all of the theoretical curves in figure 4 appear to converge to the same HWHM value at the surface of the superconductor. This suggests that a measurement of the vortex profile

† No correction is required for the penetration depth in a thin film [1], since at these temperatures the film thickness exceeds the penetration depth.

New Journal of Physics 3 (2001) 24.1–24.8 (http://www.njp.org/)
performed directly at the superconductor’s surface contains no information about the penetration depth. Rather, all of the penetration depth information is contained in the height dependence above the surface, a result which is perhaps not intuitive.

There is good qualitative agreement between the experimental and theoretical plots in figure 4. However, there is obvious quantitative disagreement; empirically, we see that the theoretical estimates of the HWHM are a factor of $\sim 2.5$ times smaller than that observed experimentally. We attribute this discrepancy to the fact that the observed vortex profile is a convolution between the vortex stray field and the extended tip geometry, and as such the measured profile is larger than the true vortex profile.

A measurement such as this performed with a tip of unknown magnetization (i.e. an uncalibrated tip) still lends itself to the possibility of acquiring relative measurements of the penetration depth. These include measurements as a function of location on the sample in order to map spatial variations in $\lambda$ (particularly relevant in the study of patterned superconducting samples) or as a function of temperature, or even to measure variations between various samples. To obtain a quantitative measure of $\lambda$, one must deconvolve the data and extract the pure vortex profile. This requires a detailed knowledge of the magnetization structure of the tip. Such an analysis is highly non-trivial to perform, and has so far only been demonstrated on Cu/Ni/Cu samples [28]. If such a calibration procedure were to be extended and applied to this situation however, it would then be possible to obtain a numerical estimate of $\lambda$. The accuracy with which $\lambda$ can be measured can be estimated to first order by applying a linear fit to the data in figure 4. The slope of the experimental data is $1.6 \pm 0.1$; the error in the slope corresponds to an uncertainty in the value of $\lambda$ of between 10 and 20% (e.g. the theoretical curve for $\lambda = 90$ nm has a slope of 0.66(1); the simple ratio $90/0.66 = x/0.1$ yields an error for $\lambda$ of $x = 14$ nm, or approximately 15%).

This work has dealt with the low-$\kappa$ case of Nb, whose vortices are difficult to image owing to their wide field profile; the more diffuse the field, the smaller the field gradient and resulting MFM signal. However, the applicability of this technique is not limited solely to this one material, but can in principle be extended to any type II superconductor. High-$\kappa$ materials in particular are relatively easy to image via MFM, owing to their narrow and correspondingly high gradient vortex profiles.

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