Magnetic imaging and dissipation force microscopy of vortices on superconducting Nb films

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Abstract

Constant height imaging using a custom built low temperature magnetic force microscope has been performed on patterned and unpatterned superconducting Nb films. Tip induced motion of the vortices is shown, as a function of both tip–sample separation and temperature. Constant height dissipation images of vortices suggest eddy current damping as well as vortex motion within potential wells as major sources of energy loss. © 2002 Elsevier Science B.V. All rights reserved.

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Low temperature magnetic force microscopy (MFM) is ideally suited for the study of superconducting materials. It combines the power of a local probe, capable of resolving structures with a lateral resolution less than 100 nm, with an ability to produce real space, three-dimensional images of the magnetic structure of materials. These features, coupled with low temperature capabilities, makes MFM a versatile and useful technique with which to study superconductivity. Research on both conventional and high-$T_c$ superconducting materials using MFM have been previously reported in the literature by several groups [1–4].

Using a custom built cryogenic magnetic force microscope [5], we have investigated the vortex state of two 100 nm thick superconducting Nb films. Deposited by magnetron sputtering onto a silicon substrate, one film ($T_c = 8.95$ K) has a uniform coating, while the other ($T_c = 6.5$ K) has been patterned with a square lattice of antidots, which serve as artificial pinning centers [6].

Measurements were made using commercially available silicon nitride cantilevers, with nominal spring constant $k = 0.1$ N/m. Each cantilever was made magnetically sensitive by the evaporation of Co onto one face of the pyramidal tip, which was magnetized along the tip axis prior to installation in the microscope. The data for the unpatterned Nb film was acquired using a cantilever with a resonance frequency $f = 36,585$ Hz and a quality factor $Q = 4573$, onto which 30 nm of Co was evaporated. Results for the patterned Nb film were acquired using a cantilever with a resonance frequency $f = 31,222$ Hz and a quality factor $Q = 19,514$, onto which 20 nm of Co was evaporated.
The data presented here consists of constant height images, which record changes in the resonance frequency of the cantilever (indicative of conservative interactions between the cantilever and the sample), as well as simultaneously acquired dissipation images (indicative of non-conservative interactions). Dissipation images were acquired in constant amplitude mode, using a separate feedback system to adjust the cantilever drive amplitude [7,8].

Illustrated in Fig. 1 are constant height MFM images of the unpatterned Nb film, acquired at 5 K. A field of 0.5 mT was used to generate the vortices. Scan heights correspond to: (a) 75 nm; (b) 50 nm; (c) 60 nm; (d) 35 nm. The vortex polarity for (a) and (b) is opposite to that for (c) and (d). While all figures share a common scale, the baseline offset has been independently adjusted for ((a), (b)) and ((c), (d)) in order to maximize contrast.

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Illustrated in Fig. 1 are constant height MFM images of the unpatterned Nb film, acquired at selected tip–sample separations. The sample was prepared by heating it to 10 K, at which point a field of 0.5 mT was applied in order to generate magnetic vortices for imaging. Upon cooling to 5 K, the applied field was removed, and imaging was performed in a zero field environment (Fig. 1(a) and (b)). The applied field polarity was then reversed for Fig. 1(c) and (d). Light vortices correspond to a magnetic field parallel to the z-component of the tip magnetization and are attracted to the tip, while dark vortices correspond to a field anti-parallel to the z-component of the tip magnetization and are repelled by the tip.

It is immediately clear from the data that the dominant interaction observed with MFM is that of the tip magnetic moment with the magnetic field of the vortex. An interaction dominated by the absence or weakening of the Meissner force over the normal conducting core of a vortex would lead only to constant contrast, irrespective of vortex polarity. Such variations in the Meissner force are easily detected by our instrument [4].

The similarity in spatial arrangement between attractive and repulsive vortices attests to the influence of specific material pinning sites, which prevent the formation of a regular Abrikosov lattice. Vortices may become depinned, however, through interactions with the magnetic field of the tip, as evidenced by tip induced vortex motion in Fig. 1(b) and (d). We note that the behavior of attractive and repulsive vortices in this respect is not symmetric. Attractive vortices appear to be more easily displaced by the tip field as compared to repulsive vortices; three attractive vortices in Fig. 1(b) at a tip–sample separation of 50 nm appear displaced, compared with one repulsive vortex in Fig. 1(d) at a tip–sample separation of 35 nm. As well, while the attractive vortices appear elongated and laterally displaced, the top part of the repulsive vortices appears to terminate abruptly as the vortex is pushed from the field of view.

The phenomenon of tip induced vortex motion is clearly illustrated in Fig. 2, which shows a sequence of images acquired at selected temperatures, with a constant tip–sample separation of 75 nm. Prior to imaging, the sample was field cooled within a 0.4 mT field in order to generate ~20 vortices within the 10 × 10 μm² scan area. At temperatures below 6.0 K, pinning is sufficiently strong so as to prevent any vortex motion. However, as temperatures rise, an increasing number of vortices are observed to move, often appearing as streaks. The origin of the driving force, which tends to move vortices towards the left side of the image, is the inhomogeneous magnetic field of the tip, the product of a combination of two effects: the dipolar nature of the tip magnetic field, and a canting of the tip with respect to the sample surface.

Similar evidence of tip induced movement of vortices is observed in constant height images for the patterned Nb film, acquired at 5.5 K in a field of 6.21 mT, shown in Fig. 3. Under these conditions, each antidot is saturated, with additional vortices resident at interstitial locations. The interstitial vortices are less securely pinned than those within the antidots, and are more susceptible to tip induced movement. These
vortices are observed to circulate around the antidots, being forbidden to enter for energetic reasons [9].

Constant height and corresponding dissipation images acquired for the unpatterned Nb film are illustrated in Fig. 4. The sample was field cooled from 10 K in a 0.5 mT field in order to generate the vortices. At 5 K, the field was removed and imaging was performed in a zero field environment. Fig. 4(a) and (c) are similar to those in Fig. 1, which illustrate the resonance frequency shift of the cantilever. The dissipation images of Fig. 4(b) and (d) are particularly interesting, owing to the fact that the location of the vortices is clearly indicated. We also note the contrast reversal between the two images; at a tip–sample separation of 40 nm, dissipation across a vortex is greater than that of the surrounding region, whereas at a scan height of 15 nm, dissipation associated with the vortex is less than that of the surrounding region.

Cross-sections of the dissipation images for the two scan heights are shown in Fig. 5(a). The difference in the baseline energy loss in one oscillation cycle of the cantilever is calculated to be $4.3 \times 10^{-22}$ J, approximately 10 times larger than the energy associated with the thermal motion of the cantilever at 5 K. We attribute this baseline shift as arising from an increase in eddy current damping at reduced scan heights. Recall that supercurrents on the sample surface act to screen the magnetic stray field of the tip. These supercurrents induce eddy currents in the tip, an effect that increases as tip–sample separations decrease. Note, however, that this effect occurs only over the superconducting regions of the sample, and not over the normal conducting cores of the vortices.

We interpret the dissipation signal across a vortex as an indication of tip induced motion of the vortex.
within its potential well, where the associated energy cost is related to the steepness of the walls of the well. As shown in Fig. 5(b), at larger tip–sample separations (40 nm) the vortex pinning potential landscape is only weakly disturbed by the repulsive stray field of the tip, and the vortex is pinned within a deep potential well. At smaller tip–sample separations (15 nm) the energy landscape is more strongly distorted, and potential wells become flatter. For a given distance $\Delta x$ by which interactions with the tip wiggle the vortex, the associated energy costs vary depending on the potential well profile, with more energy dissipated over vortices at larger tip–sample separations ($E_1$) than at smaller tip–sample separations ($E_2$).

In summary, we have imaged magnetic vortices of both polarities at constant height, noting that the major contrast source arises from the interaction between the tip magnetization and the magnetic stray field of the vortex. Tip induced movement of the vortices is observed at close tip–sample separations, as well as for increasing temperatures, as the force exerted by the tip overcomes the local pinning of the vortices. Dissipation images suggest that eddy current damping is a major contribution to energy loss over superconducting regions of the sample, while a tip induced distortion of the vortex pinning potential landscape influences the dissipation signal associated with the motion of vortices within their potential wells.

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