Microsc. Microanal. 8 (Suppl. 2), 2002
DOI 10.1017.S143192760210331X

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Low Temperature Magnetic Force Microscopy Studies of a Superconducting Nb Film

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Low temperature magnetic force microscopy (LTMFM) is ideally suited for the study of superconducting materials. The technique combines the power of a local probe, able to resolve structures with a lateral resolution better 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 LTMFM a versatile and useful technique with which to study superconductivity.

Using a custom built cryogenic magnetic force microscope [1], we have investigated the vortex state of a 100 nm thick superconducting Nb film with a critical temperature Tc = 8.95 K, deposited by magnetron sputtering onto a silicon substrate. A superconducting solenoid was used to apply magnetic fields perpendicular to the sample surface, in order to generate vortices for imaging. Results are illustrated in Fig. 1, and show excellent agreement with the expected relation between vortex number and applied field strength, although strong pinning at randomly distributed pinning sites prevents the formation of a regular Abrikosov lattice. The linear relation between vortex number and field strength demonstrates that only single vortices, each carrying one unit of the flux quantum, are observed.

Constant height images, which record changes in the resonance frequency of the cantilever, are illustrated in Fig. 2. Imaging was performed at selected tip-sample separations, where a field of 0.5 mT was applied in order to generate magnetic vortices of both polarities. 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. Measurements such as these can be used in order to determine the magnetic penetration depth of the sample [2].

Magnetic force spectroscopy data, which plots the change in the cantilever resonance frequency as a function of tip-sample separation, can be used to determine local values of the critical temperature Tc of the sample [3]. However, on occasion when the cantilever is approached towards the sample during these measurements, the magnetic field from the tip nucleates vortices. This phenomenon is shown in Fig. 3, which illustrates two such approach curves, where multiple vortices have been created both simultaneously and in succession.

References

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[3] This research was supported by grants from NSERC and FCAR

https://doi.org/10.1017/S143192760210331X Published online by Cambridge University Press

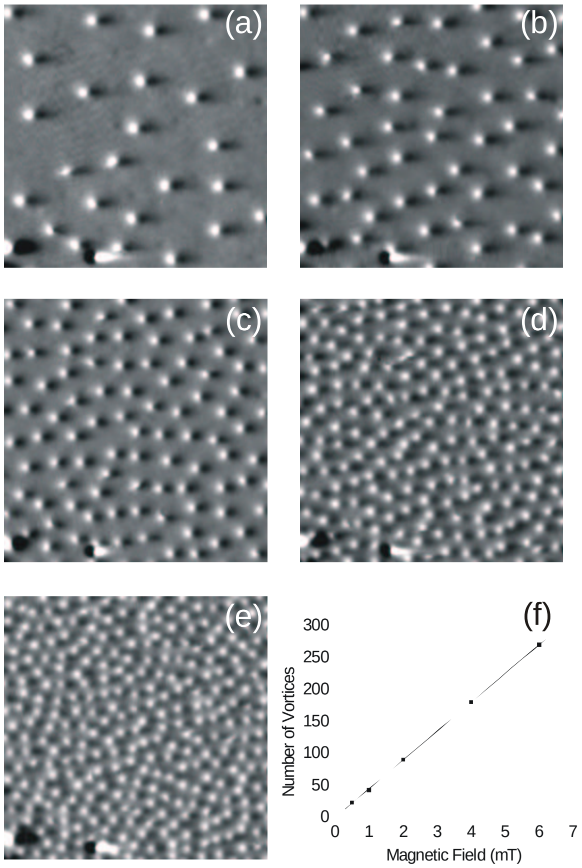

FIG. 1. (a)-(e) 10 x 10 μm^2 area MFM images of magnetic vortices, all acquired at 5 K. The images have been differentiated in the x-direction in order to enhance contrast. Fields correspond to (a) 0.5 mT, (b) 1 mT, (c) 2 mT, (d) 4 mT, and (e) 6 mT. The structures at the bottom of each image are topographical in nature, and serve as fiducial marks. (f) The number of vortices as a function of applied magnetic field, which exhibits the expected linear relationship.

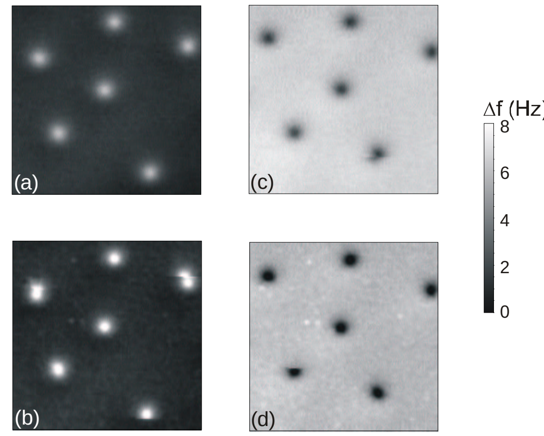

FIG 2. 5 x 5 μm^2 area constant height MFM images acquired at 5 K. A field of 0.5 mT was used to generate the vortices. Scan heights correspond to (a) 75 nm, (b) 50 nm, (c) 60 nm, and (d) 35 nm. The vortex polarity for (a) and (b) is opposite to that for (c) and (d).

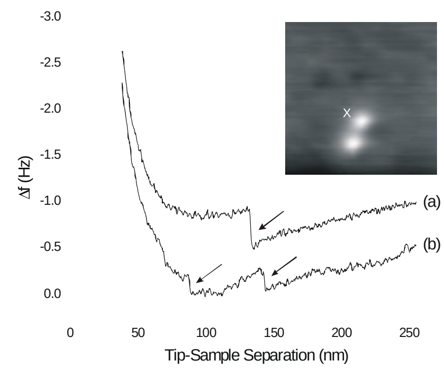

FIG 3. Resonance frequency shift versus tip-sample separation at 7.9 K. Sharp discontinuities in the curve profiles (arrows) indicate the creation of vortices by the magnetic field of the tip. (a) Two vortices are created simultaneously, resulting in a change in the resonance frequency of 0.4 Hz. (b) Two vortices are created in succession, each contributing a 0.2 Hz change in the resonance frequency. The vertical axis of both curves has been offset for clarity. (Inset) A 5 x 5 μm^2 MFM image acquired at 6.0 K after (a), illustrating the two nucleated vortices. The 'x' denotes the tip position during the spectroscopy.

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