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14. ABSTRACT
The relevance of high-temperature superconductors (HTS) for the Air Force lies in their enormous potential for high-power microwave sources and high-energy magnet technology. HTS are complicated materials whose utility is limited by several factors, most fundamentally by the motion of quantum whirlpools of electrons, called vortices. Vortex motion is induced by current flow and causes dissipation, thereby destroying the utility of the superconductor. Understanding the microscopic mechanisms may enable improved current-carrying capability of HTS and achievement of Air Force objectives. The overarching objective of this research is to understand the dynamics of individual vortices,and to understand how vortex motion – and hence dissipation – is influenced by materials structure, by currents, and by other vortices. We used a Magnetic Force Microscope (MFM) to image and manipulate single vortices in YBCO thin films and crystals and quantitatively determine the local depinning force or single-vortex critical current. Thin films and thick single crystals show dramatically different behavior.

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nanomagnets, magnetic nanocrystals, cantilever torque magnetometry, magnetic force microscopy, scanning Hall probe microscopy, superconductors, high-temperature superconductors, coated conductors

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The relevance of high-temperature superconductors (HTS) for the Air Force lies in their enormous potential for high-power microwave sources and high-energy magnet technology. HTS are complicated materials whose utility is limited by several factors, most fundamentally by the motion of quantum whirlpools of electrons, called vortices. Vortex motion is induced by current flow and causes dissipation, thereby destroying the utility of the superconductor. Understanding the microscopic mechanisms may enable improved current-carrying capability of HTS and achievement of Air Force objectives. The overarching objective of this research was to understand the dynamics of individual vortices, and to understand how vortex motion – and hence dissipation – is influenced by materials structure, by currents, and by other vortices. We used a Magnetic Force Microscope (MFM) to image and manipulate single vortices in several samples: Nb thin films, Nb thin films that were nanoengineered to have an array of artificial pinning centers, YBCO thin films, and YBCO single crystals. In each case, we quantitatively determine the local single-vortex depinning force, which is equivalent to the single-vortex critical current. Thin films and thick single crystals show dramatically different behavior.

Initially, we demonstrated controlled local manipulation of single vortices by low temperature magnetic force microscopy in a thin film of superconducting Nb. We were able to position the vortices in arbitrary configurations and to measure the distribution of local depinning forces (Figure 1). This technique opened up possibilities for the characterization and use of vortices in superconductors. The technique was reported in E. W. J. Straver, J. E. Hoffman, O. M. Auslaender, D. Rugar, and Kathryn A. Moler, "Controlled manipulation of individual vortices in a superconductor," *Applied Physics Letters* **93**, 172514 (2008).

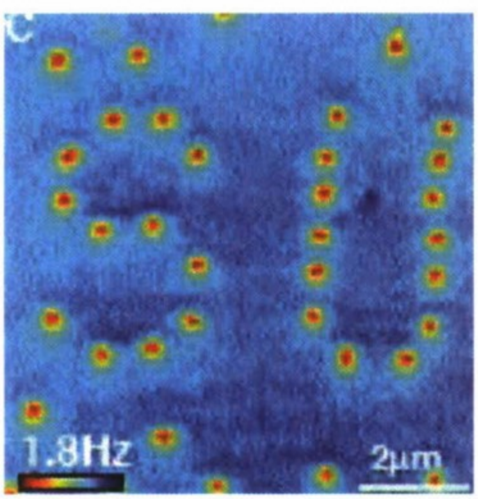

Figure 1. We demonstrated the ability to manipulate individual vortices in Nb films with sub-10-nm resolution for detecting the motion of individual vortices. This figure shows an MFM image of a region of a niobium film after the vortices have been manipulated to spell "SU".

We next studied c-axis oriented YBCO thin films deposited by pulsed laser deposition (PLD) on $LaAlO_3$ substrates by R.A. Hughes and J.S. Preston in McMaster University.

These samples showed a broad distribution of pinning forces. The data are so far unpublished.

Our next sample set was slightly overdoped YBCO thick single crystal grown by Ruixing Liang and Doug Bonn of UBC. The single-crystal sample was grown from flux in a $BaZrO_3$ crucible to give high purity and crystallinity. The particular sample on which we took our published data was selected for its clean [001] surfaces, which also means that it was rather free of strains. The sample was mechanically detwinned and subsequently taken through an annealing sequence in oxygen, finishing at 350C for an oxygen content near 6.991. This gives a slight overdoping, with T_c=87.8K (*11*), and very few defects on the Cu-O chains. We chose this sample because we believe it is the lowest pinning sample that is available today, with well-characterized defects, and therefore serves a benchmark. The transition temperature for the film was determined from a measurement of the resistivity to be 89.8K, with a width of about 0.5K. The film had a relatively smooth surface and lacked pinholes.

We imaged and manipulated individual vortices in detwinned YBa2Cu3O6:991 single crystal, directly measuring the interaction of a moving vortex with the local disorder potential. We found an unexpected and marked enhancement of the response of a vortex to pulling when we wiggle it transversely. In addition, we find enhanced vortex pinning anisotropy that suggests clustering of oxygen vacancies in our sample and demonstrated the power of MFM to probe vortex structure and microscopic defects that cause pinning. This work was published as Ophir M. Auslaender, Lan Luan, Eric W. J. Straver, Jennifer E. Hoffman Nicholas C. Koshnick, Eli Zeldov, Douglas A. Bonn, Ruixing Liang, Walter N. Hardy and Kathryn A. Moler, "Mechanics of individual isolated vortices in a cuprate superconductor" Nature Physics 5, 35 - 39 (2009). Several theory papers followed up on our work to describe the stochastic and average behavior of the vortices.

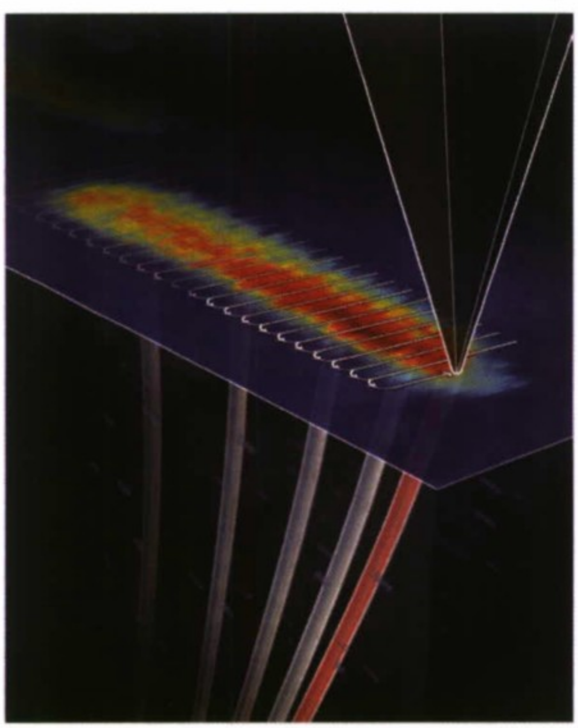

Figure 2. Measurements of single-vortex nanomechanics. Illustration of an MFM tip (pyramid) manipulating a vortex (elastic cylinder) to pull it through a sample with point pinning sites (small spheres). The data that shows the resulting vortex motion is from Nature Physics 5, 35 - 39 (2009). The quantitative analysis of complete data sets revealed the anisotropy of the pinning sites, which we attribute to oxygen vacancy clustering.

The last type of sample studied under this 3-year effort was an array of artificial pinning centers. The array consisted of nanoscale holes etched in a niobium film by Ar-ion sputtering an anodic aluminum-oxide template. Variable-temperature magnetometry showed a transition temperature of 7.1 K and enhancement of the magnetization up to the third matching field at 5 K. Using MFM with both attractive and repulsive tip-vortex interaction, we measured the vortex pinning strengh and investigated the motion of individual vortices in the nano-hole array. The depinning force for individual vortices at low field ranged from 0.7 to 1.2 pN, less than theoretical value for isolated holes. The motion of individual vortices was reproducible and consistent with individual vortex hops between adjacent holes in the film. The movements were repeatable but the sequency of hops depended on the scan direction. This assymetry indicated nonuniform local pinnin, a consequence of array disorder and hole-size variation. The work was published as J. C. Keay, P. R. Larson, K. L. Hobbs, M. B. Johnson, J. R. Kirtley, O. M. Auslaender and K. A. Moler, "Sequential vortex hopping in an array of artificial pinning centers" *Physical Review B* **80** 165421 (2009).

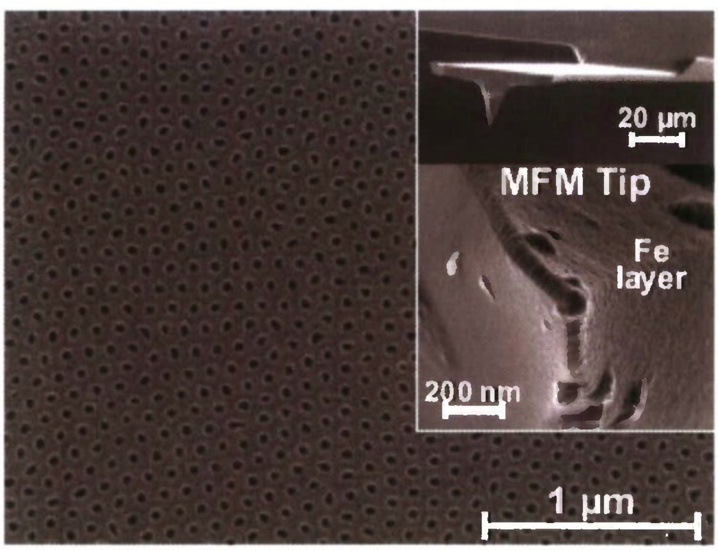

Figure 3. Plan-view SEM image of a 75-nm-thick Nb nanohole array. Insets are SEM images of the MFM cantilever (top) and MFM probe tip (bottom) used for this work. The probe was coated on one side (right) with about a 60 nm Fe layer.