Progress report for DOE Award Number SC0008482, Colorado State University

Title: High-Bandwidth Scanning Hall Probe Imaging of Driven Vortices in Periodic Potentials
Principal Investigator: Stuart B. Field
Report Date: 1/26/17
Period Covered: 5/1/2012 (project start date) through 8/31/16

I. ACCOMPLISHMENTS DURING THE REPORT PERIOD

In this project we proposed to study the real-time dynamics of driven superconducting vortices moving in a periodic potential, using the technique of high-bandwidth scanning Hall probe microscopy to understand the local spatial and temporal characteristics of vortex motion in periodic potentials.

During the term of the project we made significant progress towards these goals, but the overall project goal was unfortunately not met. Nonetheless, certain intermediate goals were met, and we believe that even though the project has officially ended we will be able to finish the proposed experiments.

I.1. Sample Fabrication

A key requirement of the experiments was the fabrication of superconducting films with a smooth, periodic thickness modulation; this modulation leads to a corresponding modulation of the vortex potential. Smooth vortex potentials are critical to understanding the subtleties of vortex dynamics in the low-driving-force regime. It is in this regime that the vortices move slowly enough ($\approx$ 0.1–5 MHz frequencies) that their motion can be studied using high-bandwidth scanning Hall probe microscopy. We have proposed a novel method to construct smooth and reproducible thickness modulations by angle-evaporating (or angle-sputtering) the superconducting film onto a substrate which itself has a modulation in its surface profile.

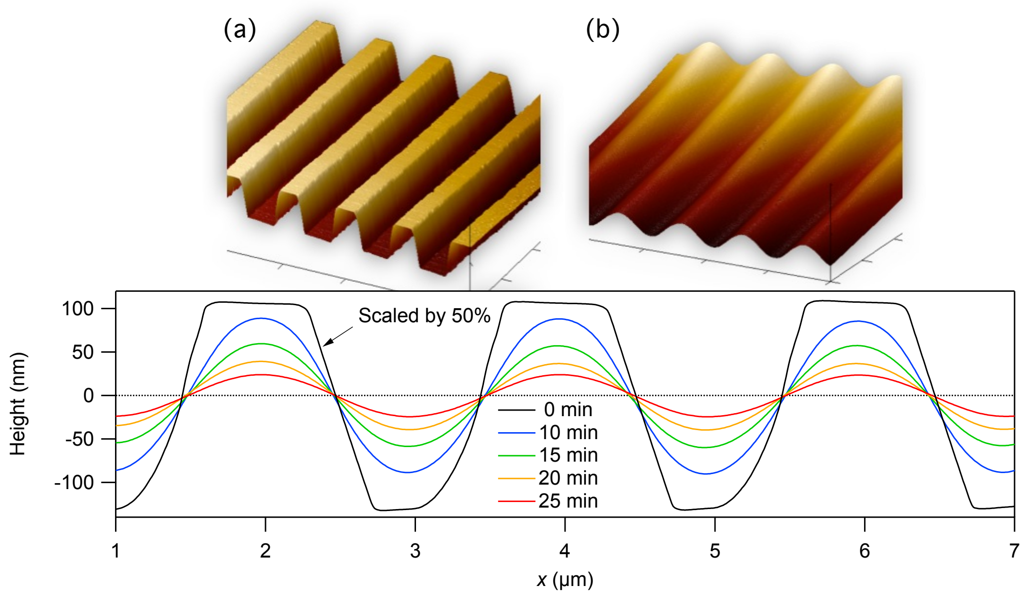

Figure 1: AFM images of the surface of an etched glass substrate (a) before annealing and (b) after annealing for 25 minutes at 650°. (c) AFM scans showing the progression of the substrate profile from a quasi-square wave to a sinusoidal wave as the annealing time is increased.

This method has been shown to work, and we have succeeded in fabricating superconducting films with a periodic thickness modulation, and have made the first measurements of their properties. To fabricate these substrates, we use electron-beam lithography to create a grating pattern in chrome-on-glass wafers. The chrome serves as a mask for a subsequent HF wet etch. When the chromium is removed, we are left with a glass substrate with a square-wave profile, as shown in the AFM image of Fig. 1a. Subsequent thermal annealing near the glass transition temperature then smooths this square wave into the required sinusoidal profile, as Figs. 1b–c show.

It can be shown that the thickness of a film evaporated onto a substrate with surface profile $h(x)$ is given approximately by

$$t(x) = t_0 \left[1 + \frac{dh}{dx} \tan \gamma \right] ,$$

where t_0 is the average film thickness and γ is the angle of evaporation measured from the normal. In other words, the *film* thickness is proportional to the slope of the *substrate*. Thus, evaporation of a film on a substrate with a sinusoidal surface modulation is results in a film with a smooth sinusoidal thickness modulation.

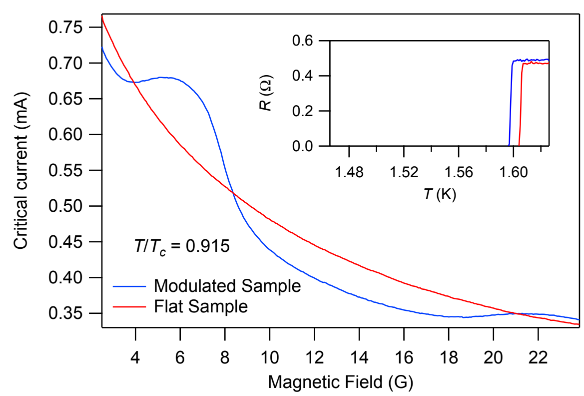

Figure 2: The critical current vs. field for a flat film (red) and one with a periodic thickness modulation (blue). Clear signatures of vortex matching effects are seen in the thickness-modulated film. (Inset) Resistance-vs.-temperature curves starting at $T = 1.464$ K, the temperature at which the data in the main panel was taken. The transition widths of ≈ 2 mK are negligible on this scale.

Currently, we are able to grow low-pinning films of granular aluminum, both evaporated and sputtered, and sputtered amorphous MoSi. Granular aluminum generally has lower inherent pinning than MoSi, but it more difficult to grow uniform films because of the very strong dependence of film parameters on the evaporation rate. Figure 2 shows the critical current for a flat granular aluminum film and on one with a sinusoidal film thickness. The modulated film shows clear signatures of matching effects and commensurability as the magnetic field, and hence the vortex density, is increased.

I.2. Hall Probe Fabrication

A critical aspect of this project is the application of submicron Hall sensors for real-time imaging of vortex dynamics. We are now able to fabricate high-quality probes in GaAs/AlGaAs heterostructures. Figure 3 shows a recent probe fabricated using electron-beam lithography and wet etching.

One issue that is always present in Hall-probe microscopy is that of probe noise. Currently, we are testing the scheme of Li *et al.*[1], who found that a small voltage applied to an insulated gate above the Hall probe channel could very substantially reduce the voltage noise of the probes. Also, at the 2013 BES Experimental Condensed Matter Physics PI Meeting in Gaitherburg I met fellow DOE awardee Gabor Csathy, an expert in

[1] Yongqing Li *et al.*, Phys. Rev. Lett. **93**, 246601 (2004).

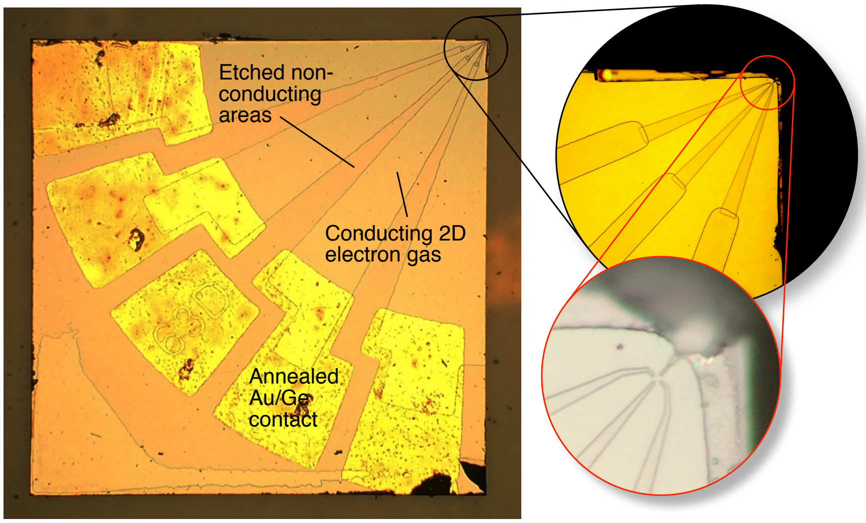

Figure 3: A Hall probe fabricated using electron-beam lithography. The left image shows an entire 5 mm $\times$ 5 mm chip, including the four annealed Au/Ge contacts and a gate contact. The magnified portions show the active area of the probe, fabricated using electron-beam lithography very close to the corner of the chip.

the fractional quantum Hall effect. I learned that his wafers are grown by Prof. Michael Manfra at Purdue, and Gabor was kind enough to introduce me to Prof. Manfra. Prof. Manfra has just recently provided us with some material that he things will be especially well suited to the fabrication of Hall probes, and we will soon be fabricating probes from this high-quality material and testing their noise properties.

I.3. Cryocooler Development

Figure 4 shows the specialized cryocooler that we have completed during the proposal period.[**?**] Helium gas from an external tank is precooled to 50 K, further cooled in a heat exchanger attached to the cryocooler's regenerator tube, then liquefied in a condenser attached to the second stage. After flowing through a capillary impedance, the liquid helium enters and fills the copper pot. The pot is externally pumped, cooling the helium down to 1.2 K just as in a conventional helium refrigerator. However, because the pot contains only a few cm^3 of liquid helium, the total helium used during a run is very small, only a few dollars' worth.

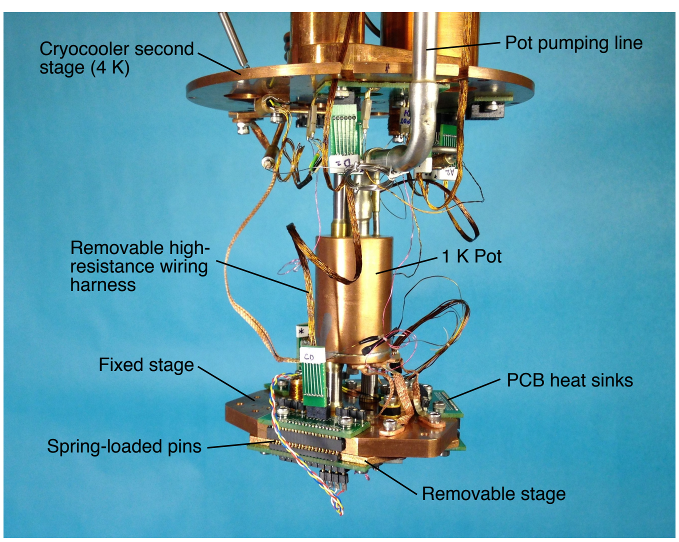

Figure 4: Cryomech PT403 pulse-tube cryocooler with pumped helium pot.

This cryocooler has proven to be a reliable and inexpensive way of reaching temperatures as low as 1.4 K at the sample stage. Some features of the instrument are highlighted in the figure. The wiring is completely modular, and the phosphor-bronze wiring harnesses can be removed for repair if necessary. All heat sinking of wires is done through printed-circuit boards whose traces are in excellent thermal contact with copper parts of the cryocooler. A very useful aspect of the design is that the lower copper stage is easily removable from the cryocooler. We have made three such stages: One for for measuring samples, one for testing Hall probes, and one to which the scanning Hall probe microscope is mounted. In this way, samples or probes can be mounted on the workbench under a microscope, and then easily reattached to the cryocooler. There are three sets of 20 spring-loaded pins that make immediate and reliable electrical contact. We have found the process of mounting samples and cooling them to base temperature to be simple, rapid, and reliable with this setup.

A downside of closed-cycle cryocoolers is that they have relatively high levels of vibration compared to conventional helium cryostats. Because scanning Hall probe microscopy is sensitive to vibration, we have designed a spring-based vibration isolation stage for mounting the microscope to the cryocooler. Recent tests have shown that the level of vibration of this stage are entirely adequate for quality Hall probe microscopy imaging.

I.4. Understanding the Role of Edge Pinning

The project goal was to understand the dynamics of vortices moving across superconducting films. In the course of our investigations, it became clear that the samples edges played a profound role in determining these dynamics, and that this role would need to be understood in depth. To this end, we have performed experiments on samples in which the edge of the samples have been deliberately fabricated into a tapered geometry. It was expected that the edge barrier for vortex entry, which depends on the precise geometry of the edge, could be strongly modified by the presence of such tapers.

Figure 5 shows the sample, fabricated in a 460-nm-thick granular aluminum film with a critical temperature of 1.72 K. The long edge of the sample is untapered; the five edges between the voltage leads have tapers ranging from 1 to 4 μm. AFM scans of these 5 tapered edges, plus the untapered opposite edge, are shown in Fig. 6. The expectation was that the edge barrier for vortex entry, and hence the corresponding critical current, would be suppressed for the longer tapers.

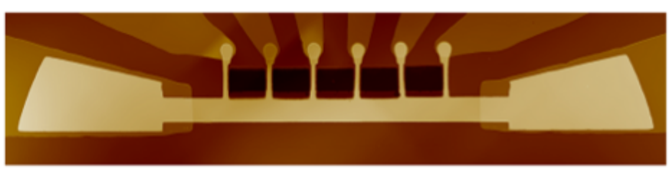

Figure 5: Sample used in the taper-edge experiments. Visible are the five segments, each with a different tapered edge. The tapers are difficult to see at this scale. The sample width is 110 μm.

The tapers were fabricated using a novel method. Photoresist was used to coat the sample, which was at this point wider than the final sample width. Then the resist was exposed near the edge in a *linearly sloping* fashion, using a motorized mask in the optical train. When developed, the resist takes on the same shape as the exposure density. Finally, the resist pattern is transferred in to the underlying aluminum by ion etching.

A strong suppression in the critical current with increasing taper width was in fact observed, as shown in Fig. 7. The purple trace shows the critical current for the 4-μm taper; the red curve is that of the 1-μm taper. For comparison, the back curve shows the critical current in the direction of the untapered edge. Overall, our experiments show that artificially nanostructured edges can profoundly change the barrier for vortex entry, and that a significant lowering of the edge-barrier induced critical current is possible by using tapered edges.

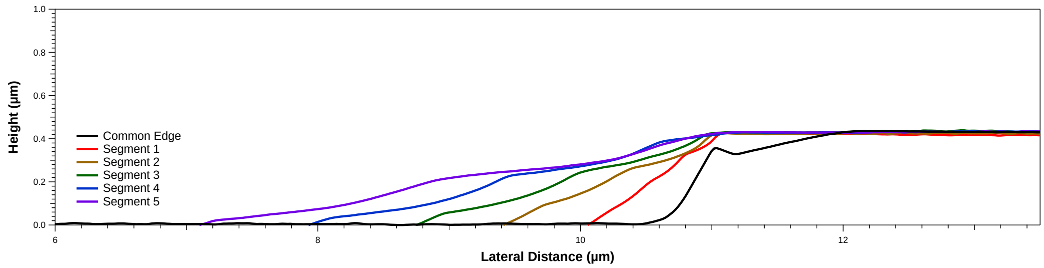

Figure 6: AFM scans of the 5 tapered edges, plus the untapered common edge. The slight modulation in the thickness is due to interference effects in the photoresist used to fabricate the edges.

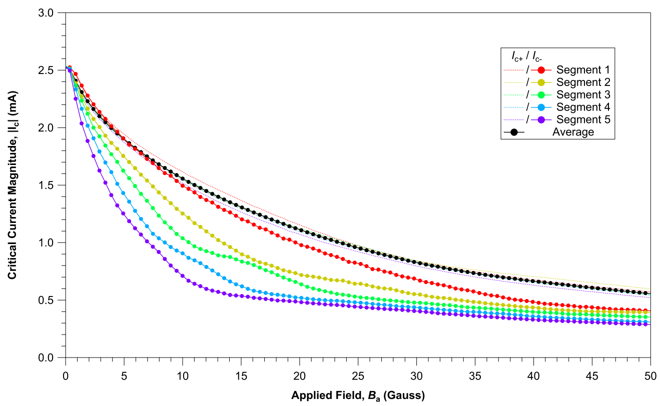

Figure 7: Critical current-versus-magnetic field graphs for the five tapered edges (colored traces), plus the untapered edge (black traces). A clear lowering of the critical current with increasing taper is observed.

II. PAPERS PUBLISHED

We published one paper during the proposal period: A. DeMann, S. Mueller, and S.B. Field, *Cryogenics* **73**, 60 (2016). We are currently in the process of writing up our results on the taper experiments.

III. PERSONNEL

During the current period, a number of people have participated in the project. The two main graduate students were Gus DeMann and Weston Maughan.

Gus Demann: Since the summer of 2013 he was fully supported by the project. Gus has become an expert in electron-beam lithography and other microfabrication techniques, and has been instrumental in overcoming the many technical issues involved with fabricating the thickness-modulated superconducting samples, as well as developing the full process for fabricating our latest-generation Hall probes.

Weston Maughan: Weston was supported by the project since the summer of 2014. He has taken the lead on fabricating the samples for the taper experiments.

Sara Mueller: Sara was a 2012 graduate of the CSU physics program. After graduation, she worked full time in my lab until August 2013, when she left to enter the graduate program in physics at the Ohio State University. At CSU, she worked on sample and Hall probe fabrication, gaining a particular expertise in optical and electron-beam lithography. She was fully supported by the project during her time at CSU.

Dan Illenberger: Dan is also a graduate of the CSU physics program. In my lab he worked mainly on thin-film deposition. He was fully supported on the project from March 2013 until January 2014, when he accepted a job at Bechtel Marine Propulsion Corporation/Knolls Atomic Power Laboratory.

Zack Robinson: Zack was an undergraduate in the CSU physics department who is now a graduate student at the University of Minnesota. He worked on the project from June 2012 until December 2013. He worked on a number of projects, including refurbishing our thermal evaporation system, and developing code for

data acquisition. Zack worked in the lab for credit, and was not funded by the project.
Paul Greife: Paul was an undergraduate in the CSU physics department. He is now a graduate student in Germany. He worked on the project from August 2013 until December 2013. Paul worked on several electronics projects. Paul worked in the lab for credit, and was not funded by the project.
Jake Walker Jake was a 2014 graduate of the CSU physics program; he is now a graduate student in our program. Jake did his honors thesis work in our lab, and designed and built a low-noise preamplifier for high-speed Hall probe experiments.