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Physica C 341–348 (2000) 1023–1026

PHYSICA C

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Vortex dynamics in thin superconducting strips observed by Scanning SQUID Microscopy

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We have studied the flux dynamics in superconducting strips patterned from both Nb and weak-pinning amorphous MoGe films using a Scanning SQUID Microscope (SSM). The unparalleled flux sensitivity of the SSM allows us to image the vortices in the strip under a variety of field and cooling conditions with single vortex resolution for low flux density. We are able to apply transport currents while imaging the strip and observe the shift of the vortex distributions due to the Lorentz force. Surface steps etched into the strips significantly alter the flux patterns and introduce asymmetry in the vortex motion under applied transport currents. Both the change in vortex line energy across the step and the screening currents which flow along the step influence the vortex distributions and flux dynamics. We are studying the relationship between the vortex distributions from the SSM images and the transport characteristics of the strips.

1. INTRODUCTION

The dynamics of vortices in thin superconducting strips in a perpendicular magnetic field is a complex problem due to the large demagnetizing effects and sensitivity to strip edge structure and surface defects. The resulting geometrical barriers are frequently encountered in transport and magnetization measurements on both low-T_c and high-T_c superconductors. [1]

Simulations of the vortex behavior in type-II superconducting strips with no bulk pinning show the formation of a dome-like flux distribution in the center of the strip with vortex-free regions near the strip edges for applied fields above a critical entry field. As the field is reduced, the geometrical barrier maintains the flux in the strip. Thus the response is hysteretic despite the absence of bulk pinning. Transport currents shift the dome to one side due to the Lorentz force, widening the vortex-free region on one side, while shrinking it on the other side. This model has been used to calculate the field dependence of the critical current for these strips. [2]

Surface steps on a superconductor affect the local vortex dynamics due to the change in vortex length across a step. Vortex motion from a thinner to a thicker part of the sample is impeded because of the vortex line tension, while motion in the opposite direction can occur freely. Flux flow due to field gradients can produce inhomogeneous flux distributions around surface steps, as observed in $NbSe_2$ crystals both by Bitter decoration [3] and by Scanning SQUID Microscopy (SSM) [4]. Surface steps can also influence the static distribution of vortices due to the extra screening currents which flow along the edge of the step, as seen in Bitter decoration imaging. [5]

By patterning surface steps on thin film superconducting strips, we have observed the influence of a step on static field-cooled vortex patterns with SSM. We have also imaged the shift in the vortex distributions in the strips under applied transport currents. Surface steps on the strip cause the vortex dynamics to be asymmetric. In order to study the influence of bulk pinning on this behavior, we have made strips from films with different pinning strengths. These measurements are directly relevant to the emerging field of study of controlling vortex behavior with microfabricated structures. Modulated pinning configurations have been used to create narrow weak pinning channels [6], resulting in commensurability peaks in the vortex response. Asymmetric ratchet potentials based on patterned pinning distributions have been proposed as a way to rectify vortex motion under an oscillatory Lorentz force. [7]

PII S0921-4534(00)00768-1

2. EXPERIMENTAL TECHNIQUE

2.1 Strip fabrication

Nb films, with a T_c of 9 K, and amorphous MoGe films, with a T_c of 7 K were sputtered onto Si substrates. Using conventional photolithographic techniques, we have patterned 150μm wide thin-film strips in the geometry shown in figure 1. With this layout, we are able to apply transport currents to the strips during imaging. The pattern is etched into the film using either Reactive Ion Etching (RIE) or Ar ion milling. A second lithography step is used to expose a window on the surface of the strip, which is then partially etched, producing the cross section shown in figure 1(b).

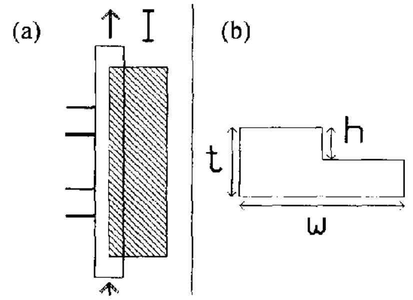

Figure 1. (a) Schematic of strip: voltage leads at left, hatched region partially etched to define surface step. (b) Cross-section across width of strip.

2.2 Microscope

Our SSM uses a custom thin film Nb trilayer dc SQUID which we fabricate in our cleanroom facilities. The spatial resolution of the SSM is determined by the size of the pickup loop and its height above the sample surface. Our current SSM uses a Nb pickup loop with a 10μm diameter fabricated near the edge of a quartz substrate (within 100μm). During scanning, the substrate is held at a shallow angle on a hinge with the edge of the substrate in contact with the surface, thus keeping the loop on the order of 2μm above the sample surface. The pickup loop is inductively-coupled to the SQUID via a superconducting dc flux transformer, consisting of a magnetically-screened low inductance transmission line connecting the loop to an input coil placed directly over the SQUID loop. The SQUID assembly is scanned over the surface at the end of a long pivot arm by stepper motors at the top of the insert. Magnetic features on the sample surface generate currents in the pickup loop which are read-out by the SQUID. Figure 2 demonstrates the ability of the SSM to resolve individual vortices at low fields, where the vortex images do not overlap. The SQUID, pickup loop, and sample are enclosed in a vacuum can, which is immersed in a liquid helium bath. This maintains the SQUID and pickup loop well below the transition temperature of Nb (9K), while the sample, mounted on a heater block, can be temperature-regulated from 2K to 20K.

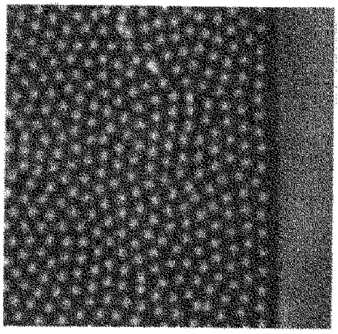

Figure 2. SSM image of vortices in MoGe sample, cooled to 4.2K in 39mOe. The edge of the film is near the right side of the image which is $(508\mu m)^2$.

3. MEASUREMENTS

3.1 Images of Nb strips

We have imaged flux distributions in Nb strips by cooling the samples to 4.2K in small magnetic fields (<0.1 Oe) and scanning with the field on. In regions with no step, such as figure 3(a), the vortices are uniformly distributed across the width of the strip. Because the intervortex spacing is much greater than the penetration length, each vortex can find a local pinning site, thus no long-range order is observed in the vortex distribution. These field-cooled vortex patterns are significantly altered in the vicinity of the patterned surface steps, as shown in figures 3(b) and (c). For the smallest cooling fields, the vortices order into a single row along the low side of the step. As the strips are cooled in larger fields, the density of vortices pinned along the step increases, as displayed in the averaged vortex distributions in figure 3(d). Additional vortices freeze away from the step in broad rows which are parallel to the step, generally avoiding the thick region of the strip adjacent to the step. This ordering around the step is most likely due to an extra screening current which

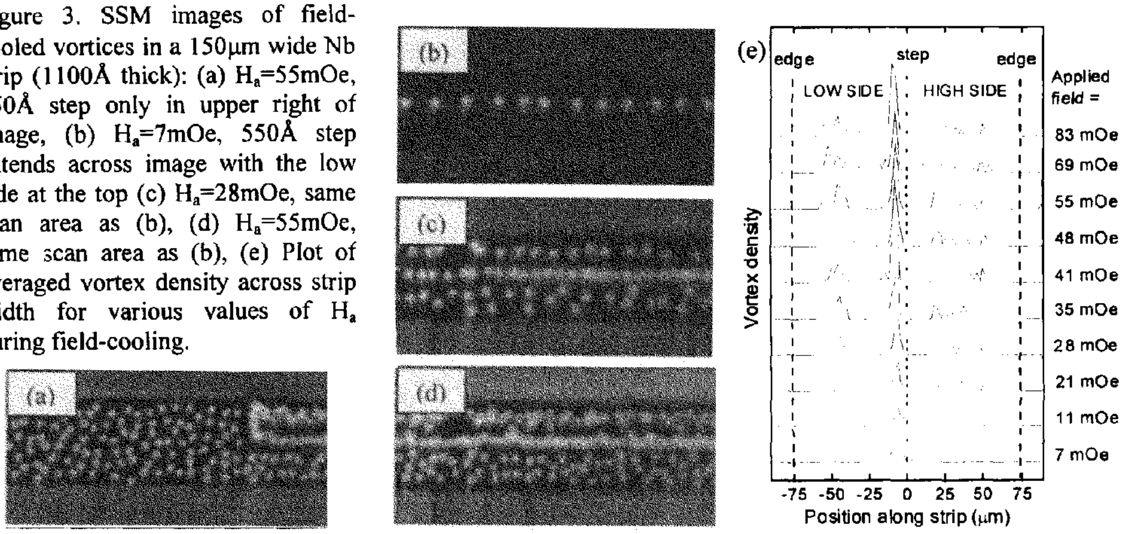

Figure 3. SSM images of field-cooled vortices in a 150μm wide Nb strip (1100Å thick): (a) H_a=55mOe, 550Å step only in upper right of image, (b) H_a=7mOe, 550Å step extends across image with the low side at the top (c) H_a=28mOe, same scan area as (b), (d) H_a=55mOe, same scan area as (b), (e) Plot of averaged vortex density across strip width for various values of H_a during field-cooling.

flows along the edge of the step. As the strip passes through T_c, this step current attracts vortices from the low side of the step and repels flux from the high side before the vortices quench in nearby pinning sites, forming the patterns we observe.

Moderate transport currents applied along the Nb strips do not shift the vortices, due to the strong pinning of the Nb films. For large enough currents, we observe flux entry into the strip due to the self-field of the transport current, as shown in figure 4. This produces a highly nonuniform distribution of flux which depends on the speed with which the current was increased, indicating some sort of thermomagnetic instability.

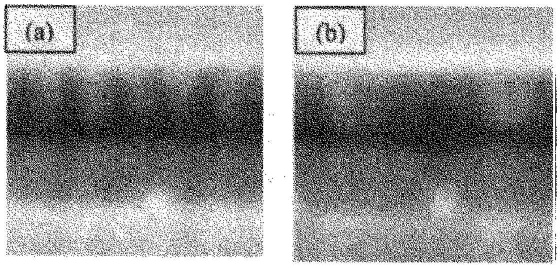

Figure 4. SSM images of flux instabilities in a 150μm Nb strip with a 550Å step with large transport currents in zero external field: (a) I=99.1mA, (b) I=50.4mA. Dark regions consist of many vortices which have entered the thin side of the strip due to the strip self-field.

3.2 Images of a-MoGe strips

Strips patterned from MoGe films exhibit a much different behavior due to the weaker pinning and the lower value of H_{c1}. Upon increasing the field after zero-field cooling the strip, vortices first enter the strip at a small field (around 0.1 Oe) and are swept towards the center of the strip by the Meissner screening currents. For larger fields, this vortex distribution widens, eventually filling most of the strip width. As shown in figure 5(a), we are able to shift these vortices to one side of the strip by applying a small transport current, which exerts a Lorentz force (F_L), J x Φ_0/c, on the flux. The streaks in some of the images are caused by a weak interaction between the scanning process and the weakly-pinned vortices in these MoGe films.

Flux entry into the MoGe strip with a surface step is asymmetric, as the local magnetic field exceeds H_{c1} on the thin side of the strip first. As the entering vortices are pushed towards the center of the strip, the step impedes their motion, resulting in a ridge of flux along the low side of the step. Such a distribution is shown in figure 5(b). The application of transport currents with F_L directed towards the step increases the vortex density along the low side of the step. The opposite polarity of current pushes the flux away from the step and toward the strip edge on the thin side.

3.3 Transport measurements on strips

We have measured the field dependence of the critical current for 20μm wide MoGe strips which

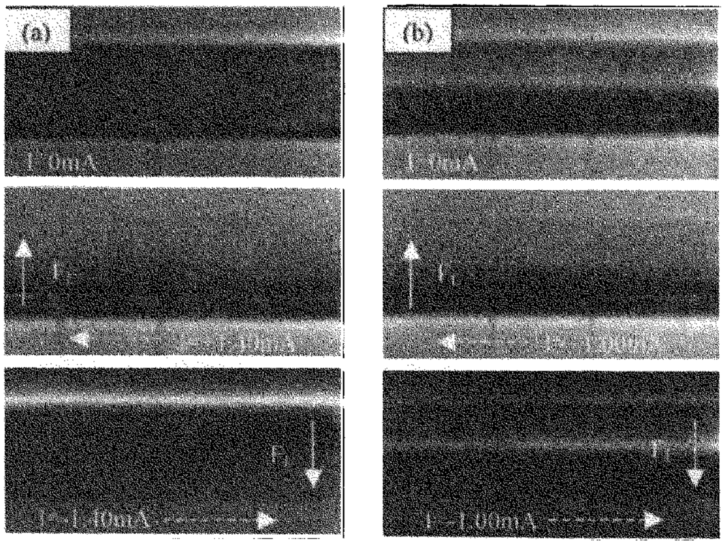

Figure 5. SSM images of vortices in 150μm MoGe strips (1000Å thick): *Column a*: no step; *Column b*: 400Å step extends across images with the low side at the top, T=4.2 K.

First row: flux entry upon increasing field after zero-field cooling strips: (a) H_a=166mOe, (b) H_a=138mOe.

Second row: F_L due to transport current toward top edge of strips (solid arrows indicate F_L, dashed arrows show direction of current).

Third row: F_L toward bottom edge of strips, note flux pinned along the step in (b).

were immersed in liquid Helium. The transport current was slowly increased until the voltage along the strip exceeded 2μV, with voltage probes separated by 200μm. The critical current for a strip without a surface step, displayed in figure 6, decreases linearly at low fields, while obeying an inverse power-law at larger fields. This behavior is consistent with the geometrical barrier calculations of ref. [2].

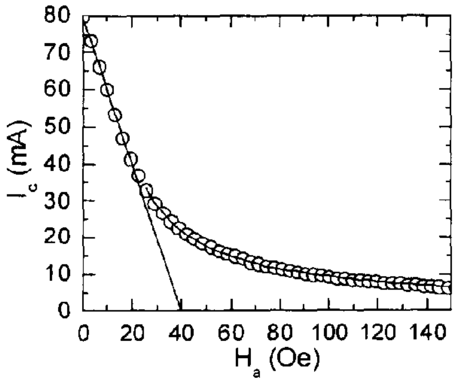

Figure 6. Critical current of 20μm MoGe strip with no step (open circles) at 4.2 K. Solid lines represent field dependence predicted by ref. [2].

4. CONCLUSIONS

The SSM is a useful tool for studying the rich low-field vortex dynamics in thin superconducting strips related to geometrical barriers. Steps etched into the strip surface introduce order into the field cooled flux patterns and make the vortex dynamics asymmetric. We are presently measuring the critical current of strips with steps, where preliminary data also show an asymmetry with current and field polarity. The influence of the step is probably related to extra screening currents which flow along the edge of the step. We are improving the resolution of our SSM in an attempt to measure the magnetic field associated with these step currents.

We acknowledge useful discussions with John R. Clem and F. Nori, and technical assistance from M.S. Wistrom. This work is supported by NSF(STC)-DMR91-20000 and NSF-DMR97-05695. We also acknowledge use of the Microfabrication Facilities of the Frederick Seitz Materials Research Laboratory of the University of Illinois.

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