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Vortex configuration in the presence of local magnetic field and locally applied stress

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ABSTRACT

Vortex configuration is determined by the repulsive interaction, which becomes dominant with increasing vortex density, by the pinning potential, and by other considerations such as the local magnetic fields, currents flowing in the sample, or as we showed recently, by local stress applied on the sample. In this work we describe different ways to control vortex configuration using scanning SQUID microscopy.

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1. Introduction

Vortices in thin films form an Abrikosov lattice [1], because of the repulsive vortex-vortex interaction. The lattice may be distorted due to the interaction of the vortex core with the disordered pinning landscape [2]. The final configuration is therefore determined by the pinning landscape and the vortex-vortex interaction. This configuration can be controlled in a number of ways, such as magnetic manipulation [3], or by altering the pinning landscape. In addition, manipulation of the position of an individual vortex can be done using Magnetic Force Microscope (MFM) [4], which can also image the vortex configuration. Additional methods of mapping vortex configuration are Hall Probe Microscopy [5], Scanning Tunneling Microscopy (STM) [6] and scanning SQUID microscopy [7,8]. Here we describe how we locally determine and control the vortex configuration and the position of individual vortices using scanning SQUID microscopy.

2. Experimental

Scanning SQUID is a powerful tool for highly sensitive detection of magnetic flux near surfaces. SQUIDS convert flux into measurable electric signal, with periodicity of one flux quantum, Φ_0 . A SQUID is a superconducting loop with two Josephson junctions. Our SQUIDS are designed for scanning, with an extended loop (the pickup loop), $\sim 1 \mu\text{m}$ in diameter. The main loop is covered with a superconductor, to shield it from magnetic fields, so that

the flux is measured only through the pickup loop. The SQUID excels in sensitivity and noninvasiveness. Here, we used scanning SQUID microscopy to image vortices in thin superconducting films of NbN. We can also measure the strength of the superconductor (the diamagnetic response) locally, using a field coil co-centered with the pickup loop to apply magnetic field near the sensing point (Fig. 1(a)). The SQUID is fabricated on a silicon chip that is polished into a corner and then mounted on a cantilever at an angle to the sample. By pushing the cantilever into the sample we can apply forces up to $2 \mu\text{N}$, which is well within the mechanically elastic regime of our samples.

3. Results and discussion

Local magnetic fields, for example the fields applied by MFM, can move vortices by magnetic force [4]. Applying current to the sample will also change the vortex position, as seen for example in Lorentz microscopy [9] and Hall Probe Microscopy [10]. In scanning SQUID microscopy the measurement itself does not affect vortex configuration, because the current through the pickup loop is rather small, $\sim 10 \mu\text{A}$, and the magnetic fields induced by this current are $\sim 1 \text{mGauss}$, much below the fields required to move vortices. Using an on chip field coil we can apply stronger fields ($> 1 \text{Gauss}$) and use them to push vortices [11].

Fig. 1(b) shows vortex configuration imaged by the SQUID. This is a typical configuration which was observed after we cooled the sample through T_c in the presence of 68mGauss . This configuration is rather uniform over the sample (1mm^2) and is not affected by the SQUID. The vortex density is determined by the local field present when the sample cools through the superconducting transition. Close to T_c ($\sim 15 \text{K}$) the vortices are large and mobile,

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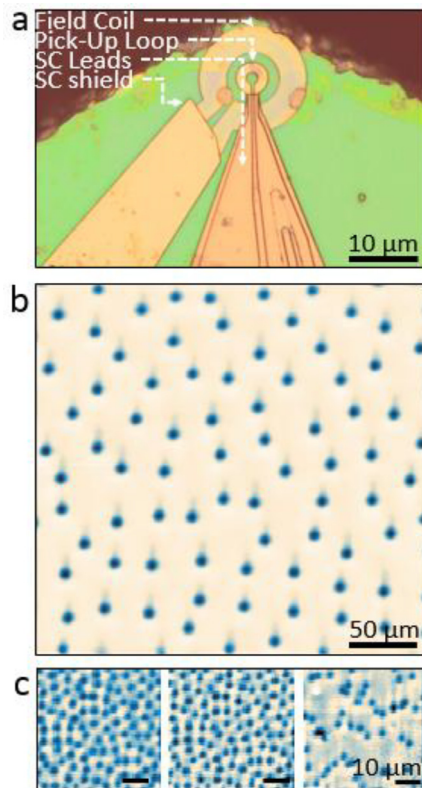


Fig. 1. Vortex configuration imaged by a scanning SQUID sensor. a, An optical image of the SQUID sensor, in scanning configuration, showing the field coil, pick-up loop and leads. Image is flipped vertically. The SQUID is fabricated on a silicon chip and then polished into a corner. b, An undisturbed vortex configuration imaged by the SQUID, as cooled in 68 mGauss. Here the vortices are negative (black), and the flux in each is $1\Phi_0$. Image was taken at temperature of ~ 4.2 K. c, Vortex configuration imaged at 4.2 K: As cooled (left), unchanged after cycling the temperature to 8 K (middle), and different after cycling the temperature to 9.4 K (right). At 9.4 K the vortices were mobile and after returning to 4.2 K we found them pinned at new locations.

and thus spread uniformly all over the area. At 4 K the vortices are pinned and by imaging vortex configuration after cycling the temperature around different temperatures we find that vortices stay pinned up to 8–9 K in the NbN samples we used for this study (Fig. 1(c)).

One way we can locally determine the vortex configuration is by applying local magnetic fields [12]. The on-chip field coil incorporated in the chip of our SQUID sensor allows application of local field of up to few dozen Gauss. This field penetrates the superconducting sample, allowing control of the position of vortices on the sample.

Another way to determine the local field during cooling is to place another SC close to the SC sample. The superconductor modifies the distribution of field lines and the vortex configuration is then determined by the non-uniform field. As opposed to the previous experiment, we now cool the sample in close proximity to the SQUID. If the sample becomes superconducting before the SQUID becomes superconducting (the sample's T_C is larger than the SQUID's T_C), no changes to the vortex density are evident. If the sample's critical temperature is lower than the SQUID's critical temperature, the SQUID prevents the magnetic field lines from passing through it (Meissner effect), distorting them. This, in turn, causes the magnetic fields penetrating the sample to concentrate outside the superconductor area of influence (see Fig. 2(a)). We observed this repulsion in a number of different densities, creating a mirror image of the SQUID parts on the sample (the shadow);

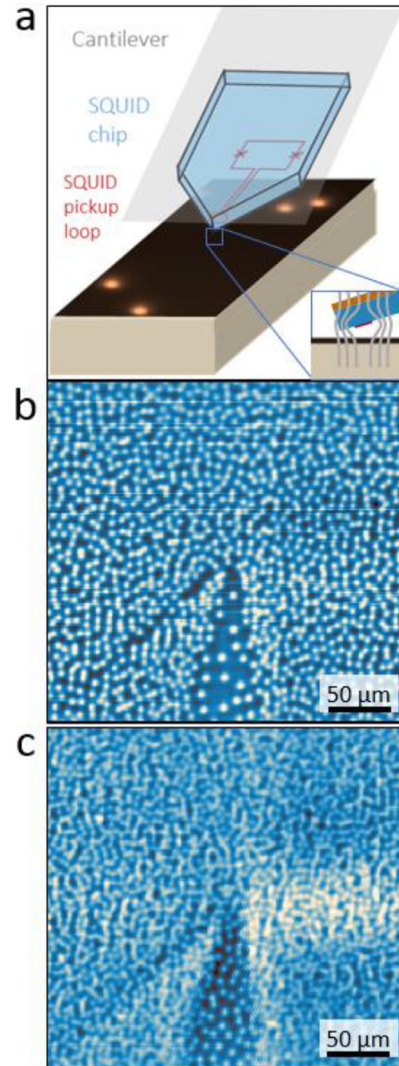


Fig. 2. The effect of proximity, while cooling, between the scanning SQUID chip and a type-II superconducting sample. a, A schematic representation of the chip near the sample, without contact. Inset, the magnetic field lines are distorted by the presence of the superconductor (the SQUID), eliminated from the leads area and concentrated near its edges. b–c, Vortex distribution, imaged at 4 K without contact, after cooling the sample through $T_C \sim 15$ K with the SQUID parked close to the surface of the sample, without contact, in the presence of 425 mGauss (b) and 660 mGauss (c). The vortex density reflects the local distortion of magnetic field lines caused by the SQUID. The density of the vortices in the shadow is 59 vortices/cm², while the density in the area outside is 205 vortices/cm². Here the vortices are positive. The signal of each vortex (white dot) is $1\Phi_0$.

see Fig. 2(b), 2(c)). Using the scanning SQUID, we can create this local change of densities, and tune it by controlling the distance between the chip and the sample.

The tip of the SQUID chip, which we polished into a corner, is $\sim 9 \mu\text{m}$ away from the center of the pickup loop. We mounted the SQUID at an angle of 4 degrees, and as a result the silicon corner touches the sample first, before the pickup loop. When we kept the tip of the chip in contact while cooling the sample (Fig. 3(a)) and pushing with $0.6 \mu\text{N}$, we saw an accumulation of vortices at a specific point (Fig. 3(b)). Using the known location of the chip during cooldown, and the shadow it casts on the vortex distribution (the reduced number of vortices under the leads) we identify the location of the accumulation as the location of the contact point. The SQUID and the sample are kept at the system's base T (4.2 K) and uniform temperature is maintained by the presence of exchange gas. We attribute this accumulation to contact with the tip of the

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