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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.

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), ~1 μm 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 μN, 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, ~10 μA, and the magnetic fields induced by this current are ~1 mGauss, much below the fields required to move vortices. Using an on chip field coil we can apply stronger fields (> 1 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 Tc in the presence of 68 mGauss. This configuration is rather uniform over the sample (1 mm^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 Tc (~15 K) the vortices are large and mobile,

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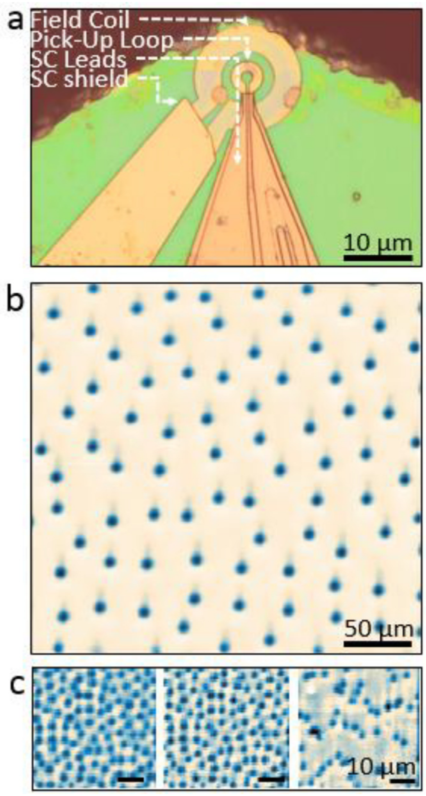

Fig. 1. Vortex configuration imaged by a scanning SQUID sensor. a, An optical image of the SQUID sensor, in scanning configuration, showing the field coil, pickup loop and leads. Image is flipped vertically. The SQUID is fabricated on a silicon chip and then polished into a corner. b, An undisturbed 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);

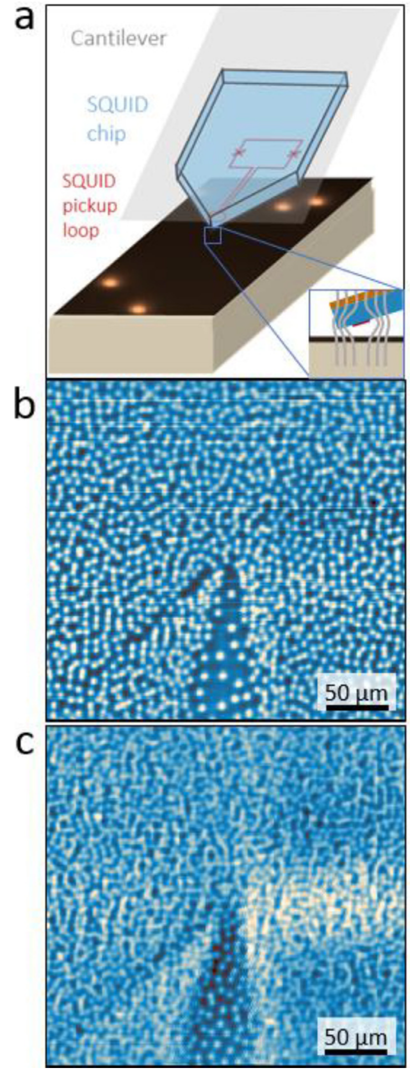

Fig. 2. The effect of proximity, while cooling, between the scanning SQUID chip and a type-II superconducting sample. a, A schematic representation of the chip near the sample, without contact. Inset, the magnetic field lines are distorted by the presence of the superconductor (the SQUID), eliminated from the leads area and concentrated near its edges. b-c, Vortex distribution, imaged at 4 K without contact, after cooling the sample through Tc~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/cm^2, while the density in the area outside is 205 vortices/cm^2. Here the vortices are positive. The signal or each vortex (white dot) is 1 Φ_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 ~9 µm 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 µN, 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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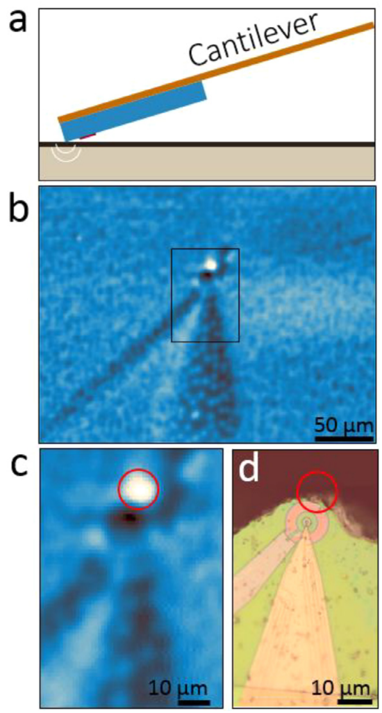

Fig. 3. Accumulation of vortices in response to contact. a, A sketch of the chip in contact with the sample while cooling. The tip of the chip is pushed into the sample by piezo element. b, Vortex distribution, imaged at 4.2 K without contact, after cooling the sample through Tc∼15 K in the presence of 745 mGauss with the tip of the chip pressing on the sample by 616 nN. The location of the contact point is bright white. The reduced vortex density that reflects the superconducting leads and pickup loop of the SQUID is similar to the result described in Fig. 2. However, vortices accumulate at the contact point. The density of the vortices in the shadow is 120 vortices/cm^2, and in the area outside is 360 vortices/cm^2. There was no current flowing in the field coil during this cooldown. c, Zoom-in on the area of the contact point marked by a square in b. d, an optical image of the SQUID, flipped vertically. The contact point is marked with red circle.

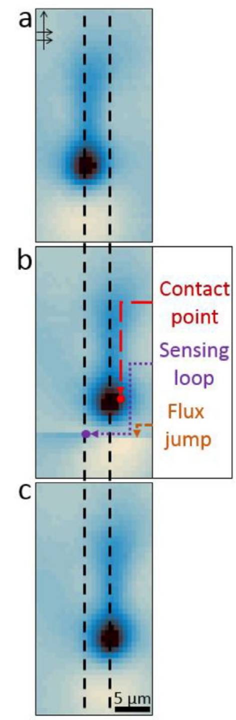

Fig. 4. The effect of scanning in contact a single vortex. a, A single vortex scanned without contact between the chip and the sample. b, The same area scanned in contact, pressing ∼0.1 μN into the sample. In this image, the sensing point (marked in yellow) is about 6 to 8 μm away from the contact point (marked in red). Slow axis is bottom to top, fast axis left to right, which is why we observe a change in the signal few rows before the sensing loop reaches the center of the vortex. Such line is typically observed when vortices move in our pictures. c, The same area scanned without contact, after manipulation. It is evident that the center of the vortex moved in the fast axis direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

chip. The details of this behavior of accumulation of vortices at the contact point is described in the work of Kremen et al. [13]

The contact point shown in Fig. 3(c) is 9.1 μm away from the SQUID's pickup loop. Next we demonstrate on an individual vortex how this difference between the contact point and the sensing point affects the manipulation (Fig. 4). The interaction between the contact point and the vortices in thin NbN films was observed as attractive [13]. The vortex shown in Fig. 4 has a keyhole shape, which is a result of the convolution of the field from an isolated vortex and the SQUID's pickup loop (see the pickup loop's shape in Fig. 1(a)). Fig. 4(a) and Fig. 4(c) demonstrate a vortex imaged without contact between the tip and the sample, before and after (accordingly) imaging in contact (Fig. 4(b)). By scanning the tip in contact, from left to right (fast axis) and bottom to top (slow axis), we moved an individual isolated vortex while simultaneously scanning the local magnetism (Fig. 4(b)). Therefore, when the slow scanning direction is from bottom to top, the contact with a vortex is made before that vortex is imaged. In the process of the scan, a discontinuity in the measured magnetism is observed due the movement of the vortex.

Finally, we demonstrate how we manipulated a single vortex, without affecting other vortices around it. Fig. 5(a) shows the initial, as cooled, configuration. We chose the vortex marked by a red circle and aimed to place it between the two vortices to the right. Since the interaction is attractive [13], we move the vortex by dragging the tip in front of it, so it will follow. After several dragging events the vortex moved to the new location (Fig. 5(b)), where it remained stable overnight.

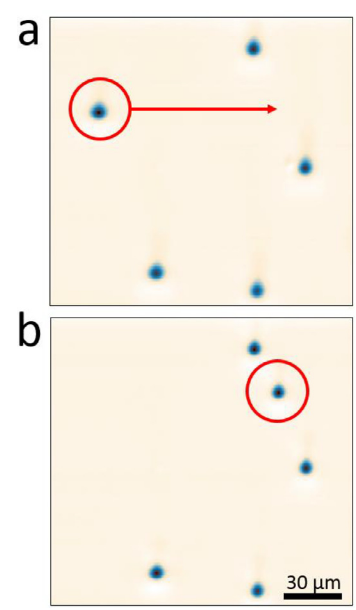

Fig. 5. Manipulation of a single vortex by applying stress with a scanning SQUID. a, An as-cooled vortex configuration. We planned to move the left-most vortex (circled in red) 90 μm to the right. b, The same area scanned after the movement. Only the circled vortex has moved, as desired. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Summary

To summarize, we showed how we can use scanning SQUID microscopy, a non-invasive technique, to determine vortex configuration by deliberately altering local magnetic fields or by mechanical contact.

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