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The response of an individual vortex to local mechanical contact

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Abstract: Recently we reported a new way to manipulate vortices in thin superconducting films by local mechanical contact without magnetic field, current or altering the pinning landscape [1]. We use scanning superconducting interference device (SQUID) microscopy to image the vortices, and a piezo element to push the tip of a silicon chip into contact with the sample. As a result of the stress applied at the contact point, vortices in the proximity of the contact point change their location. Here we study the characteristics of this vortex manipulation, by following the response of individual vortices to single contact events. Mechanical manipulation of vortices provides local view of the interaction between strain and nanomagnetic objects, as well as controllable, effective, localized, and reproducible manipulation technique.

Keywords: superconductivity, Superconducting vortices, scanning SQUID microscopy, single vortex manipulation

1 Introduction

Vortices in superconductor have been extensively studied as a way to understand fundamental issues in superconductivity, and as a model system for interacting particles [2, 3]. Practicing control over vortex position is needed in order to study how vortices interact with each other, with the lattice, and with other magnetic objects. Furthermore, understanding vortex motion or lack of it is a key area in research for developing better superconducting devices [4, 5]. Vortices can be controlled by electrical currents (Lorentz force) [2, 6], by altering the pinning landscape [7, 8] or by magnetic field [9, 10]. Recently we found that vortices also respond to local mechanical contact [1]. Strain is known to affect electronic properties in various materials. Specifically, in superconductors, it was shown that strain by mechanical stress can change parameters such as the critical temperature, critical current and critical field, yet the local interaction between vortices and strain fields was not studied until recently.

Local mechanical deformation by a tip of a silicon chip can move individual vortices without causing damage to the sample [1]. We observed this behavior in two samples of Niobium (Nb) (50 and 100 nm) and nine samples of Niobium Nitride (NbN) (30 nm) and confirmed for thousands of individual, well-separated vortices. Here we examine the response of an isolated vortex to contact events in the vicinity of its location.

2 Experimental

We image vortices using scanning SQUID microscopy, with high sensitivity to changes in magnetic flux [11]. The SQUID converts magnetic flux to measurable electric signal with voltage-flux characteristics that are periodic in the flux quantum Φ_0 and with the ability to resolve small fractions (10^{-6}) of Φ_0 [12]. The sensing area of the SQUID is a loop with diameter of 1 μm, called the pickup loop [13] (Figure 1a). The SQUID is mounted on a flexible cantilever and aligned with a small angle relative to the sample surface in order to bring the pickup loop as close as possible to the sample (Figure 1b). In order to probe the response to local stress, we increased the angle between the SQUID and sample which puts the pickup loop farther from the sample but allows the tip of the SQUID to contact the surface (Figure 1c). By pushing the cantilever into the sample we can apply forces up to 2 μN. We estimate that this force is equivalent to stress of 10^8 Pa, which is well within the mechanically elastic regime of Nb and NbN thin films [14, 15].

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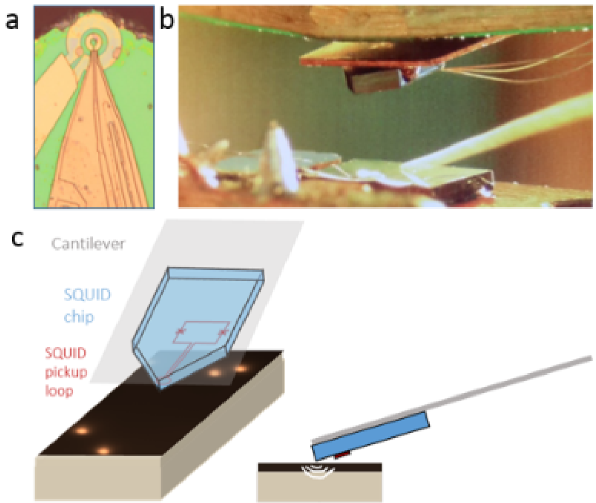

Figure 1: a. An optical image of the SQUID's pickup loop and field coil. b. A photograph of the SQUID as it approaches the sample. c. A sketch of the experimental configuration - the SQUID is mounted on a cantilever and its tip makes the first contact with the sample. At contact, the location of the pickup loop is slightly higher and further from the contact point with the sample.

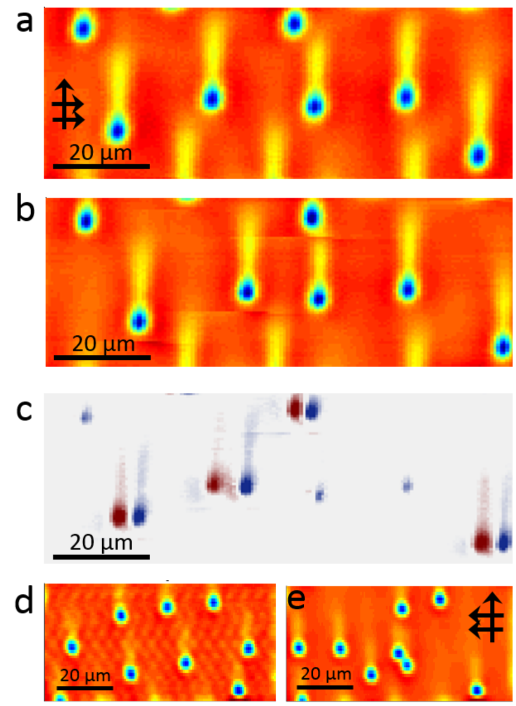

Figure 2: Vortex configuration imaged without contact by the SQUID at 4K. The arrows mark the direction of the scan, double arrow for fast axis. b. The same area imaged again, this time in contact. Vortices move during the scan to a new location. c. The difference between the two images (a, b), shows the displacement of the vortices. Blue (red) marks the new (old) location of the vortex. Vortices that did not move appear in the differential image as weak blue dots due to a small difference in the height at which each image was taken. The vortices moved up to 6 µm in this picture. d. Vortex configuration imaged without contact. e. The same area imaged in d imaged without contact after three scans in contact while the SQUID was turned off. The arrows mark the direction of the contact scans, double arrow for fast axis.

3 Results and discussion

Using this technique, we imaged vortices in two modes; imaging above the surface, without contacting the sample, or imaging while the tip of the chip is in contact with the sample. Figure 2a shows isolated vortices imaged about 200 nm above the surface by rastering the SQUID at a constant distance from the sample. Each vortex, carrying one flux quantum (1 Φ_0), has a keyhole shape which results from the convolution between the magnetic field lines of the vortex and the shape of the SQUID's pickup loop. The pickup loop is a circle of 1 µm diameter with leads connecting it to the rest of the device. Vortex configuration in Figure 2a was achieved by cooling the sample in the presence of 0.1 mG. Since the vortices were scanned without contact, their position did not change during this scan. The direction of the scan is from left to right (fast axis) and bottom to top (slow axis), as marked by the arrows. Next, we scan the same area, while continuously dragging the SQUID's tip in contact with the sample (Figure 2b). Figure 2b shows that 4 out of 7 vortices moved to a new location in the direction of the scan (from left to right). We subtract the two images to compare vortex locations. The differential image obtained shows the distance and direction of each displacement (Figure 2c).

Manipulation of vortices by Scanning SQUID was demonstrated before by applying local magnetic field using a single turn loop, fabricated around the pickup loop (field coil) [9, 16]. In the current work we do not flow any current in the field coil and therefore no local field was generated. The bias current through the pickup loop is around 10 µA, generating field of 50 mG. The force induced on the vortex by this field is smaller than the pinning force [16], which is several pN in Nb [17] and NbN [18]. Nevertheless, we repeated the experiment shown in Figures 2a-c with the SQUID disconnected from any current source. Figure 2d shows a configuration of vortices scanned without contact. After acquiring this image, we disconnected all leads from the sensor and preformed three scans in contact with no current flowing in the SQUID. Next, we retracted from the surface, and imaged the surface without contact, with current in the SQUID (Figure 2e). Vortices moved in the direction of the scan, similar to their response to contact with the SQUID turned on. A possible magnetic influence caused by distortion of field lines by the superconducting field coil and pickup loop, was ruled out experimentally [1]. The motion of vortices in our contact experiments is visually different than vortex motion by local magnetic field. The contact point is located about 8 μm away from the measured location, in the y+ direction, such that in the scan described in Figure 2b the contact is made prior to recording the magnetic signal. As a result, a displacement event appears as a faint step in the signal, and the vortex, imaged at its new location, appears intact. Vortices that are manipulated by local magnetic field, localized at the sensor, move during the imaging process ('shaking') [10, 16].

In order to understand the nature of vortex displacement as a result of physical contact, we performed tap experiment near a certain vortex. We define a tap experiment as the process of lowering the chip until contact with the surface, pressing the surface with force of 1 μN for about 2 s and then retracting the chip out of contact. An individual tapping event is shown in Figure 3.

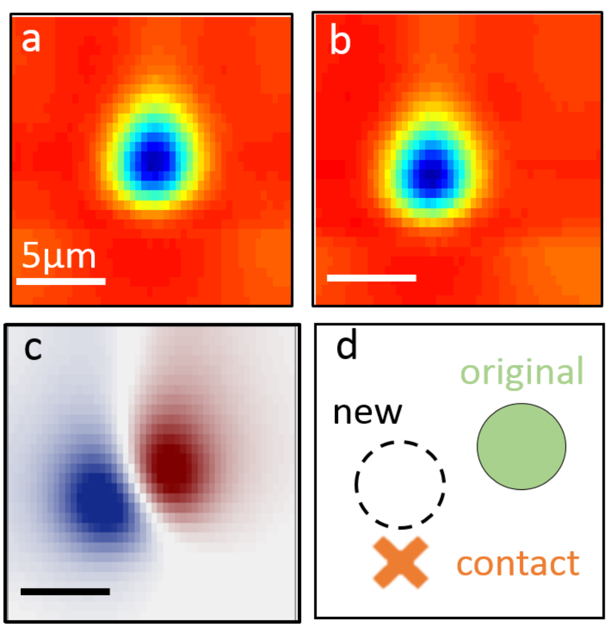

Figure 3: Displacement of an individual vortex due to a single contact event. a. An isolated vortex imaged out of contact. b. The same vortex imaged out of contact after a single contact event in the proximity of the vortex. c. A differential image (subtracting a and b). The differential image shows the direction of vortex displacement and the position of the vortex before (red) and after (blue) the contact event. d. An illustration of the location of the contact point (X) with respect to the vortex position prior to contact (green circle) and after the contact (dashed circle). The vortex was displaced by 1.95 μm.

We repeated this experiment while tapping around the vortex at different locations relative to its position. We start the sequence of tapping events away from the location of the vortex. The tapping order is from left to right and then again from left to right of the next line up. One tapping sequence is illustrated in Figure 4a, where the tap location is plotted relative to the location of the vortex at the beginning of the sequence. The vortex changes its position during the sequence multiple times due to the stress applied by the tip. Figure 4b shows the same taping sequence, where the location of each tap event is presented relatively to the position of the vortex before the tap. This presentation also emphasizes the effective radius of the tap. The tap locations in the map are color coded for the result of the tapping event. Taps which resulted in vortex movement are marked in red and taps that did not change the vortex position are marked in black.

Figure 4d shows the data for this entire tapping sequence; a set of differential images which are the result of subtracting two successive vortex images taken without contact before and after each tap. The taps which resulted in vortex movement are numbered, and the location of the tap relative to the vortex is shown with the same numbers in Figure 4c. Small movements of the vortex result in weaker signal in the differential image due to the overlap between the vortex signal in its previous and current positions. Following the results of this tapping sequence, and 21 more, we found that if the vortex moved, the motion was always in the direction of the contact point. For example, we take movement 3-6 of the sequence in Figure 4c. The contact point approached the vortex from left, and at first, no change was observed. When we tapped closer the vortex jumped to a new location, in the direction of the contact point (left from its original location). The next tap was to the right of the vortex, which then moved to the right. The vortex followed this pattern for a few more tapping events, after which the contact point was too far from the vortex and it ceased to move. Although the general vortex displacement is always towards the contact point, the exact vortex location seemed to be determined by the random pinning landscape surrounding the contact point.

Figure 5 show a combination of 5 tapping sequences. By combining the results of several sequences, we found that the effectiveness of the tap is limited to a radius of response which is smaller than 2 microns from the vortex center. Clearly, the radius depends on various factors, such as the strength of the mechanical contact, as well as the period of the contact [16]. In addition, not every contact results in vortex movement even if it is close to the vortex and within the radius of response. Local stress may cause vortex movement, yet the effectiveness of the stress and the final location of the vortex is determined by the local pinning landscape. Weakly pinned vortices will be more

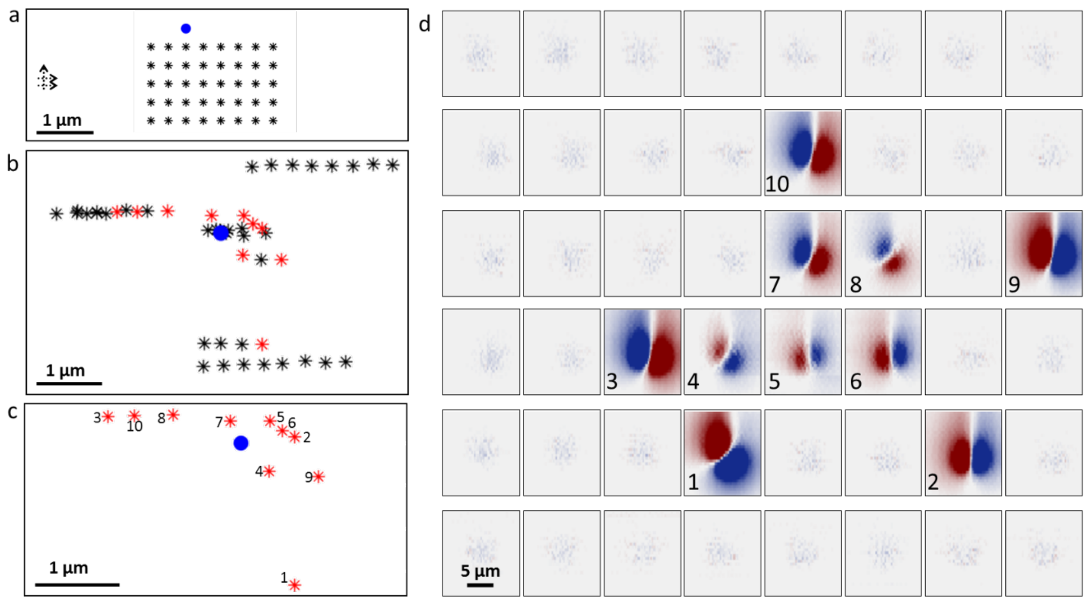

Figure 4: A sequence of contacts was made by tapping the SQUID tip at points spaced by 300 nm. a. The tapping sequence as it was designed relative to the original vortex position (marked in blue). b. The tapping sequence relative to vortex position (marked in blue) before each tap. This image marks the taps that caused the vortex to move (red) and the ones that had no effect on vortex position (black). c. The tapping sequence relative to vortex position (marked in blue), showing only the taps that caused the vortex to move. d. A sequence of differential images. Each image shows the position of a single vortex before (red) and after (blue) the tap. The tapping events that resulted in vortex displacement are numbered by their tapping positions, numbered in c.

responsive to tapping than vortices pinned at stronger pinning sites.

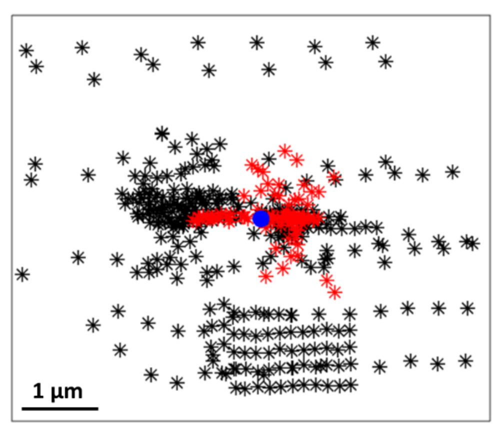

Figure 5: The results of 5 tapping sequences, each on a different vortex at a different location, overlapped. For each tapping sequence the taps are drawn relative to the vortex position before the tap. Red symbols represent taps which resulted in vortex movement and black symbols represent taps after which the vortex remained at the same position. The vortex is marked in blue.

4 Conclusion

In conclusion, we showed that the response of an isolated vortex to local mechanical stress is attractive and has a limited radius of response. There are several mechanisms which could explain the attractive interaction between vortices and local pressure. For example, the reduction of T_c due to pressure [15] or a local decrees in the film thickness [19], predict energetic gain in the location of the stress. However, the related force is few orders of magnitude smaller than the pinning force in Nb and NbN, and therefore, could not explain the motion. Further studies are needed in order to determine the exact mechanism.

Studying the interaction between vortices and local strain fields can lead to better understanding of local changes in the pinning potential and in the strength of superconductivity. The ability to control the location of vortices by local strain may help studies of vortex dynamics and may show usefulness for locally controlling other nanoscale magnetic objects. It may also assist novel applications at the nanoscale, such as logic elements [5], and spintronic applications [4].

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