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MAGNETO-OPTIC IMAGING OF SINGLE VORTEX DYNAMICS IN $NbSe_2$ CRYSTALS

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A new high sensitivity magneto-optical (MO) imaging system capable of resolving single vortices has been developed. Its ability to image areas containing a vast number of individually resolved vortices in real time was successfully demonstrated. The design of the system and its capabilities will be presented, as well as results from investigations of $NbSe_2$ crystals were we have observed the quasi-lattice arrangement of vortices, the details of vortex and anti-vortex annihilation, and avalanche-like flux creep.

1. INTRODUCTION

The study of vortex dynamics in type-II superconductors is of great interest from both scientific and engineering perspectives. In addition to determining the critical current of a material,[1] vortex motion can also serve as a model of condensed matter flow.[2] The current understanding of vortex dynamics is largely based on model assumptions and their indirect confirmation through experimental methods. These methods usually measure either on very few vortices, or on a very large number of vortices averaging over their individual contributions.[3-6] The exceptions are Lorentz microscopy[7] and our high sensitivity Magneto-Optic (MO) system. Our technique enables imaging of large areas containing many individually resolved vortices. It operates in real time, is applicable to samples of any thickness, and is completely non-destructive. We have demonstrated the potential of our MO system by successfully imaging different types of dynamic processes involving single vortices in a $NbSe_2$ crystal.

2. EXPERIMENTAL

The MO system is based on conventional MO microscope principles.[8,9] A plate of a Faraday active indicator is placed on top of a sample, and by employing the rotating capabilities of the indicator a polarization microscope can image the

magnetic flux density over the surface of the sample. The indicator used was a ferrite garnet film (FGF) grown by liquid phase epitaxy on a Gadolinium Gallium Garnet substrate. The chemical composition was $(Bi, Lu)_3(Fe,Ga)_5O_{12}$, and the FGF had a thickness of 0.8 μm. The main improvements of our system compared to the conventional set-ups are due to the thin indicator, the polarizers, the beamsplitter, and the connection between the objective and the cryostat. Figure 1. shows a schematic of our MO system. Light emitted from an Hg-lamp is collimated and made linearly polarized before entering the cryostat where the indicator is mounted on top of the sample. After being rotated by the FGF the light gets diverted by a Smith beamsplitter to the detector branch of the optical system. The Smith beamsplitter, having a mirror in its design, is preferable when minimum depolarisation is desired. The light then passes through a second polarizer (analyser) producing the contrast image on the CCD detector.

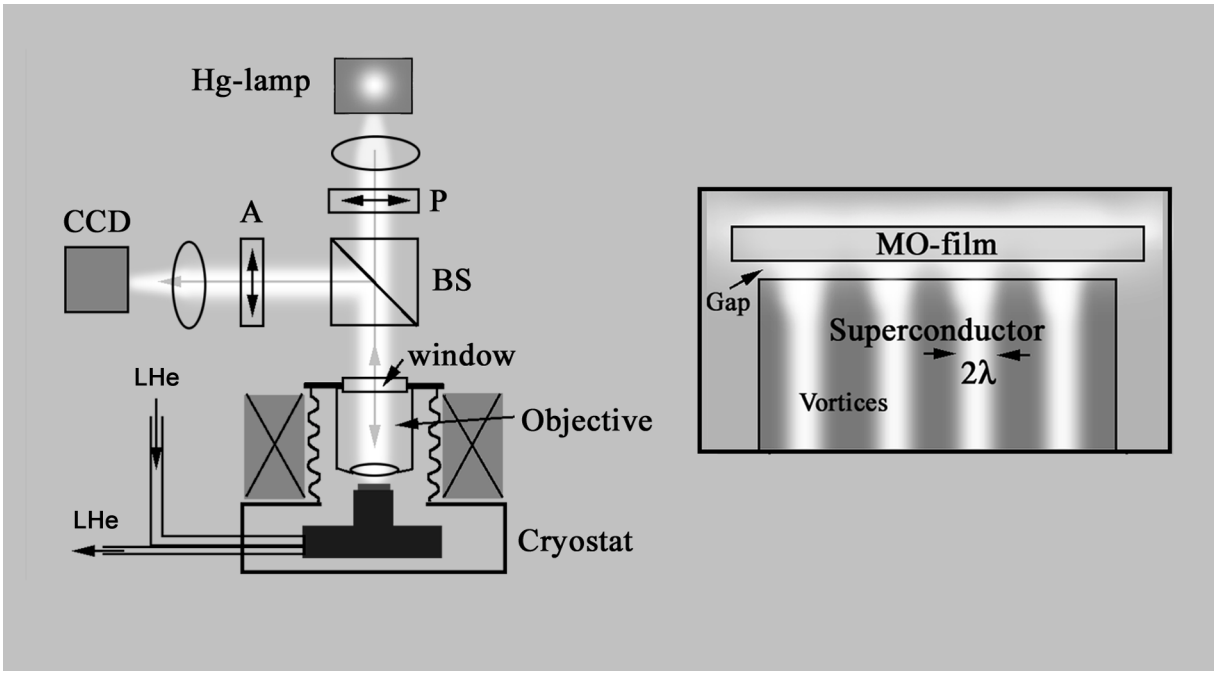


FIGURE 1
Schematic of the high sensitivity magneto–optic system. Insert: Diagram of the sample and indicator configuration including vortex geometry.

The polarizers are Glan-Taylor prisms, producing better extinction between the rotated and the incident polarization. Our open optical system offers the necessary

flexibility to permit the use of prism polarizers, which are generally lacking in commercial microscopes.

One mechanism reducing the polarization contrast is geometric depolarisation occurring whenever a polarized beam is transmitted at a broad range of angles through a window. In conventional systems the objective is located outside the window, which causes the focused polarized beam to be transmitted at high angles relative to the window surface. By mounting the objective inside the cryostat on a flexible baffle, the beam is parallel as it passes through the window. We also use a High-Res optical cryostat from Oxford Instruments, which has very little mechanical vibrations.

The MO system was used to study vortex dynamics in a cleaved $NbSe_2$ crystal[10] with Tc = 7.2 K and dimensions of 0.2 x 2 x 8 mm. The crystal was mounted onto the cryostat cold finger using vacuum grease. The FGF was placed over the sample and fixed in position using straps of aluminum tape. The insert in figure 1 indicates the exponentially rapid decay of field as one move away from the surface of the superconductor. With a gap distance corresponding to the intervortex distance, the field modulation due to the vortices at the position of the indicator decreases by a factor of 500. It is therefore a crucial step to minimize the gap distance. The use of an indicator without mirror layer ensures this while allowing us to monitor and control the gap size across the sample by observing Newton rings.

3. RESULTS AND DISCUSSION

Images of vortices trapped after field cooling to 4 K is shown in figure 2. Each bright spot corresponds to one vortex. Image (a) is taken after cooling in 3 G while image (b) shows the result after cooling in 6 G. The vortex patterns in both cases display a highly distorted hexagonal lattice with average inter vortex distances of 2.6 μm and 1.8 μm.

A sequence of images was recorded while keeping the sample in a constant applied field to investigate how the flux relaxation[11] develops on single vortex scale. The sample was FC in 1 G to 5.5 K and then the field was ramped to 20 G and kept constant for the rest of the experiment. A total of 42 images were taken during a period of 420 seconds.

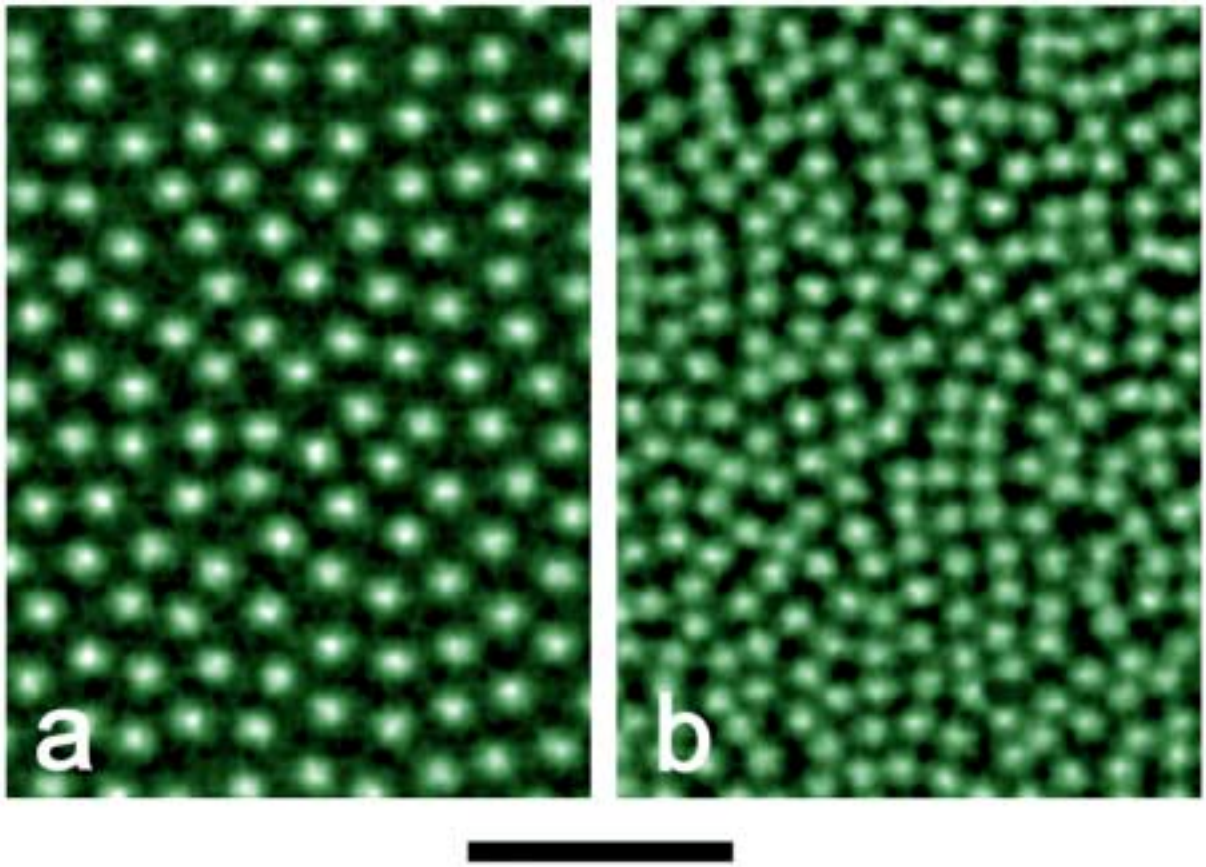


FIGURE 2
Images of the $NbSe_2$ crystal after FC to 4 K. a) Vortex image with 3 G applied field. b) Vortex image with 6 G applied field. Scale bar equals 10μm.

Figure 3 (a) shows a region of sparsely distributed vortices in front of a more dense area. The sample edge is located below the frames. The distribution remains largely undisturbed except occasional jumps involving very few vortices. However, sudden shifts of a significant portion of the vortex pattern take place three times during the experiment. The effect of this avalanche like motion can be seen in figure 3 (b), which is taken after the second large avalanche. The vortex front moves approximately 8 μm as a result of the avalanche, maintaining its angle relative to the sample.

By taking the difference between images recorded after and before the avalanches occur, we can visualize the shift in vortex distribution. The effect of the third avalanche is shown in figure 3 (c). The differential procedure is also useful to measure the number of vortices involved in the avalanches.

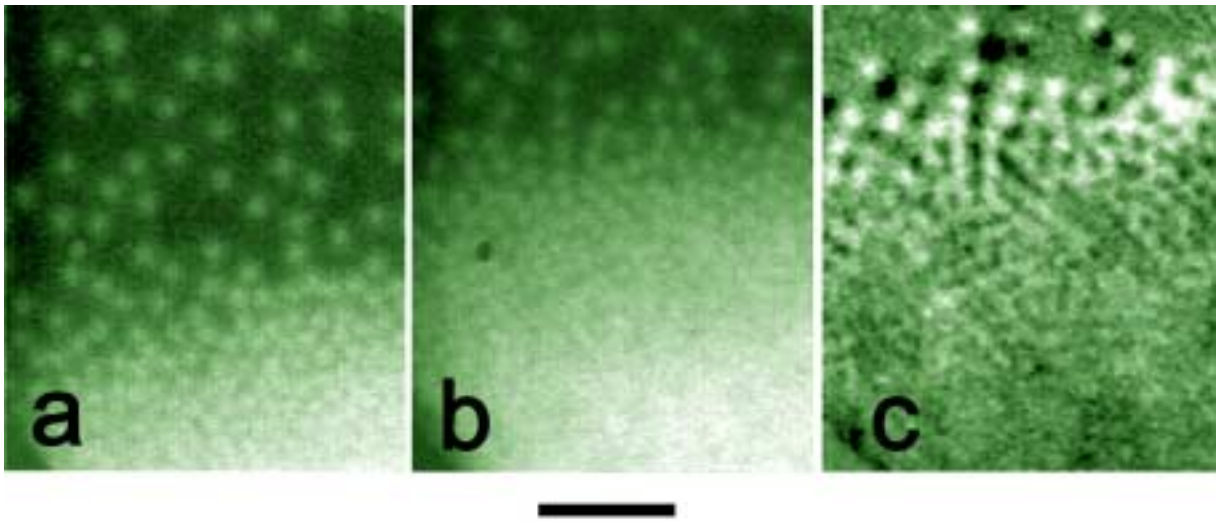


FIGURE 3
Images at 5.5 K, after FC to 1G, ramping the field to 20 G, and then keeping the field constant during the experiment. a) Vortex image before the second large avalanche. b) Vortex image after the avalanche. c) Differential image showing vortex movement in the third large avalanche. Scale bar equals 10 μm.

Figure 4 illustrates the statistics of the vortex jumps, where a histogram is made by counting the bright and dark pair of dots in the differences images running through the sequence. A dark dot indicates the old position of a vortex while the bright spot is located at the new position. The graph then shows how the relaxation behaves as a function of time, clearly demonstrating the statistical nature of jumps. Such behaviour has been seen only indirectly using Hall probes[12,13] and other techniques.

The three large avalanches have a cut off at 100 vortices. These avalanches probably affects the entire vortex filled region, but since we cannot resolve individual vortices in the dense regions the difference images produce a blur in those areas. The counting therefore gives a low limit on the number of vortices moving.

The relaxation experiment involves vortices of one polarity only. If the external field applied to the superconductor is reversed, vortices of opposite polarity, so called anti-vortices, will start to enter the sample. If vortices from the original field (before reversal) are pinned in the sample, they will meet the anti-vortices. A boundary will form where vortices and anti-vortices annihilate.

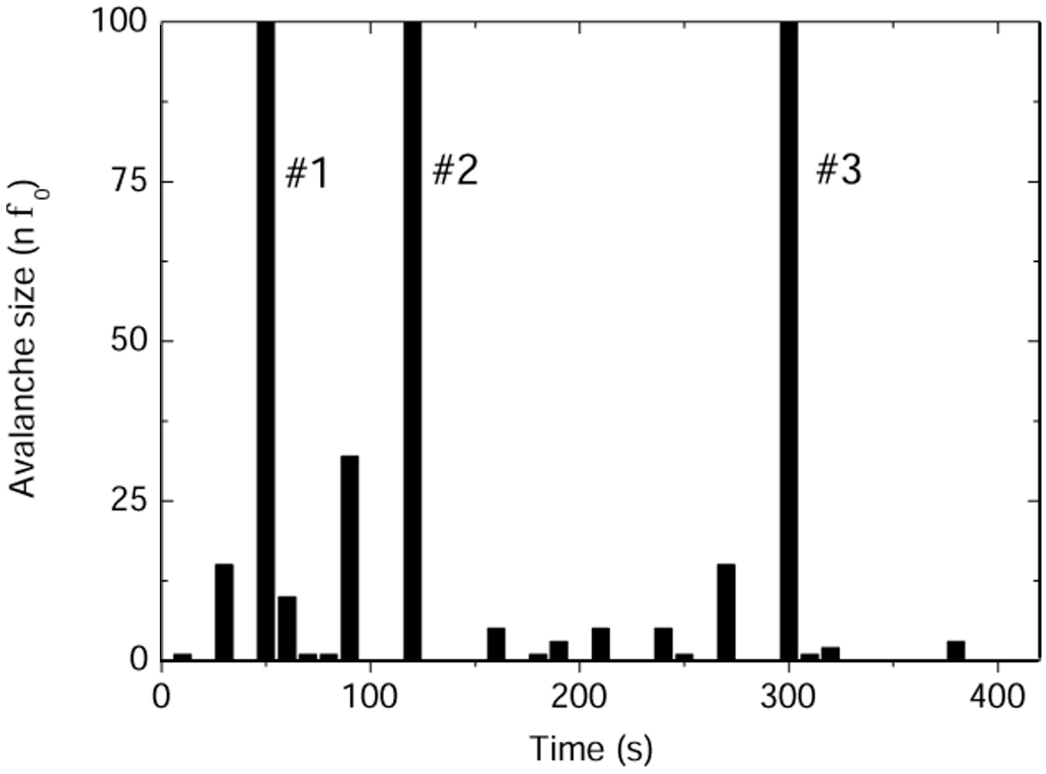


FIGURE 4
Vortex motion statistics at T= 5.5 K, Ba = const = 20 G. The three large avalanches are numbered.

In regular MO images the boundary appears as a dark band separating bright regions of opposite polarities. The mechanism of annihilation is well known, however, few studies reveal the details of the process.[14]

Figure 5 shows vortex and anti-vortex annihilation imaged in real time. The sample edge is outside the topside of the frames. An applied field in the range of 5-15 G generate anti-vortices, which move into the sample as bright dots. These meet with vortices trapped from a previous reverse field cool, appearing as dark dots. The images are extracted from a video section recorded during the experiment.

Our images show the behaviour of three isolated vortices. A vortex (dark spot) is located in the lower part of the first frame, moving upwards. Two anti-vortices (bright spots) move through the sample towards the vortex. The first bright spot pass by the vortex and continues to move on. There is no attraction observable between the two.

However, when the second anti-vortex start to approach, it fuses with the vortex and annihilation occurs, leaving behind an empty area. The second anti-vortex has a direction that takes it slightly closer to the vortex, permitting annihilation.

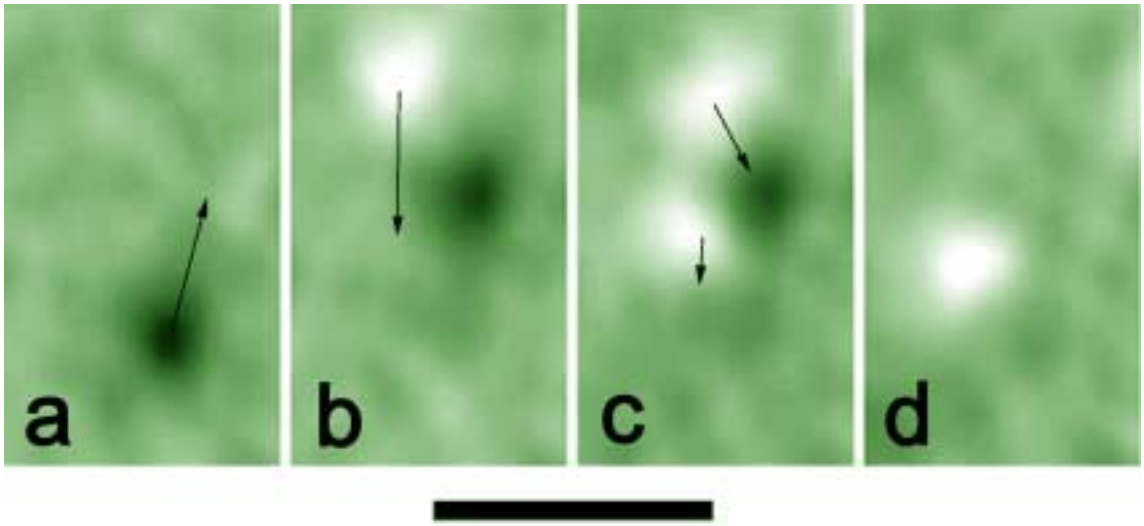


FIGURE 5
Images taken at 4 K after FC at -1 G and then applying a small ramping field (10 G). The images show how a vortex (dark) annihilates with an anti-vortex (bright). Scale bar is 5 μm.

4. CONCLUSION

We have developed a high sensitivity magneto-optic system capable of imaging distributions of vortices with single vortex resolution. The system, which works in real time, was used to observe vortex dynamics in a $NbSe_2$ crystal. We are able to se on a single vortex scale how flux relaxation occurs in an avalanche like fashion, and we also observe the annihilation process between a vortex and an anti-vortex.

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