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Manipulation of vortices by magnetic domain walls

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In a type-II superconductor, the magnetic field penetrates in the form of thin filaments called vortices. The controlled behavior of these vortices may provide the basis for a new generation of nanodevices. We present here a series of experiments showing simultaneous manipulation and imaging of individual vortices in a $NbSe_2$ single crystal. The magnetic field from a Bloch wall in a ferrite garnet film (FGF) is used to manipulate the vortices. High-resolution magneto-optical imaging enables real-time observation of the vortex positions using the Faraday effect in the same FGF. Depending on the thickness of the sample, the vortices are either swept away or merely bent with the Bloch wall. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1533120]

The vortices in a type-II superconductor consist of a normal core surrounded by supercurrents creating a magnetic field along the vortex. Recent developments in magnetic pinning by nanoengineered pinning arrays[1–7] suggest the possibility of developing a new generation of devices based on the controlled behavior of vortices. Creation and manipulation of single vortices were recently demonstrated using a miniature field coil mounted on a scanning superconducting quantum interference device microscope.[8] Magnetic domain walls produce an alternative magnetic pinning potential. These walls can be shaped and controlled by external stress patterns and magnetic fields. For low coercivity ferrite garnet films (FGFs) with in-plane magnetization, domain walls can be manipulated at frequencies in the GHz regime,[9] which makes them suitable for use in potential devices. Moreover, the strong Faraday rotation in FGFs can be used for direct real-time imaging of vortices, as recently demonstrated.[10] Such simultaneous manipulation and imaging of vortices without any external mechanical motion may provide a useful tool in the development of vortex based nanodevices.

In this work, we directly image pinning and manipulation of vortices in $NbSe_2$ by a movable magnetic Bloch wall in a bismuth-doped FGF. The Faraday effect in the same FGF is used simultaneously for imaging of vortex positions. We estimate the strength of the domain wall–vortex interaction and find that for sufficiently thin samples, the domain wall can sweep a region clear of vortices.

Figure 1 shows the principle of magneto-optical imaging (MOI). When passing through the FGF, linearly polarized light will have its polarization plane rotated an angle proportional to the strength of the magnetic field present. When using a crossed polarizer/analyzer setting, maxima in rotation will give maxima in recorded intensity, hence, a vortex will appear as a bright spot. The main improvements in our setup compared to conventional MOI[11] involves minimizing the gap between the superconductor surface and the FGF (only 0.14 μm), using a very thin and sensitive FGF, and building an open modular microscope optimized for polarization contrast.

In an FGF with in-plane magnetization, two domains with an opposite magnetization direction will be separated by a Bloch wall.[12] The domain wall will give rise to a stray localized field outside the film which will interact with vortices,[13] see Fig. 2. In the experiments described next, the position of the Bloch wall was controlled by applying a small horizontal field (~ 0.1 mT).

The first experiment was carried out on a cleaved $2H\text{–}NbSe_2$ single crystal[14] with $T_c = 7.2$ K, penetration depth $\lambda = 70$ nm, and thickness $d = 30$ μm. Upon cooling to $T = 4$ K in $B_z = 0.1$ mT, a disordered vortex lattice with lattice constant $a_0 = 4.5$ μm was formed, see Fig. 3(a). At this large inter vortex spacing, vortex–vortex interactions are negligible. We then moved a Bloch wall across the image area and looked for changes in the vortex positions. As Fig. 3(b) shows, the upper ends of the vortices were displaced a

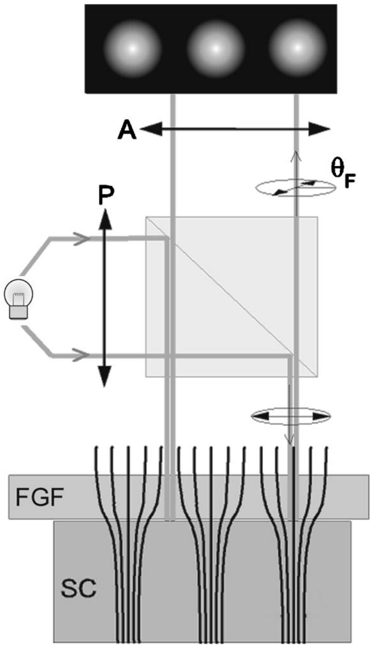

FIG. 1. Principle of MOI. The maxima of the magnetic field from vortices in a superconducting sample give maxima in the Faraday rotation θ_F of incoming plane polarized light in a FGF near the sample. Vortices appear as bright spots when imaged using a crossed polarizer(P)/analyzer(A) setting.

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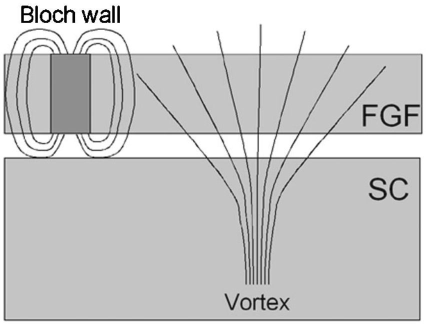

FIG. 2. Experimental procedure: A magnetic domain wall in a FGF is passed above a vortex in a superconducting sample. The interaction between the two can cause the vortex to move if the interaction force is large enough.

few microns, but the overall vortex distribution was preserved. In conclusion, we see that for this sample, the force from the moving domain wall f_w is smaller than the single vortex pinning force f_p, and we were not able to freely manipulate the vortices.

Since the total pinning force on each vortex is proportional to the sample thickness, we chose a new sample for the second experiment (cleaved from the same initial crystal) with $d = 10\ \mu\text{m}$. We applied the same external field before cooling, see Fig. 3(c). When we passed the domain wall across the image area, the vortices followed the motion of the wall and were swept out of the field of view, see Fig. 3(d). Hence, in this sample, f_w is larger than f_p.

In order to give a lower and upper estimate for f_w, we determined f_p for the two samples from an independent measurement. The remaining part of the crystal with $d = 0.3$ mm was mounted for global MOI at $T = 4$ K. By measuring the position of the penetrating field edge at a certain applied field, we found the critical current density for the crystal: $j_c = 4 \times 10^3$ A/cm^2. From this, we calculated the single vortex pinning force for the two first samples using the relation $f_p = j_c \Phi_0 d$, where $\Phi_0 = 2.07 \times 10^{-15}$ Wb is the flux quantum:

$$f_p(d = 10\ \mu\text{m}) = 0.8\ \text{pN},$$

$$f_p(d = 30\ \mu\text{m}) = 2.5\ \text{pN}.$$

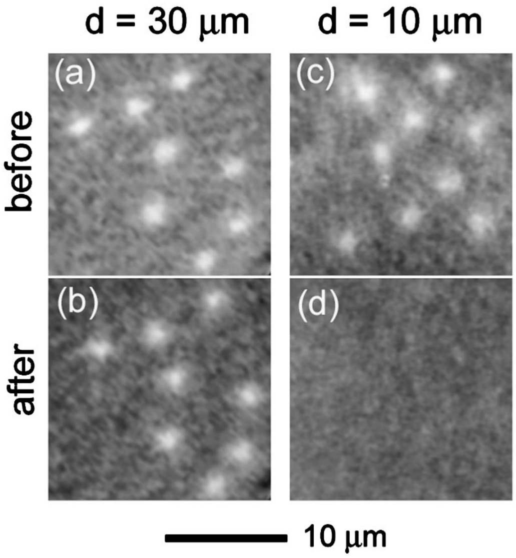

FIG. 3. Results for two samples with different thicknesses. In the $d = 30\ \mu\text{m}$ sample, only small changes in the vortex positions are observed from before (a) and after (b) a pass of the domain wall. In the $d = 10\ \mu\text{m}$ sample, all initial vortices (c) are swept away with one pass of the domain wall (d).

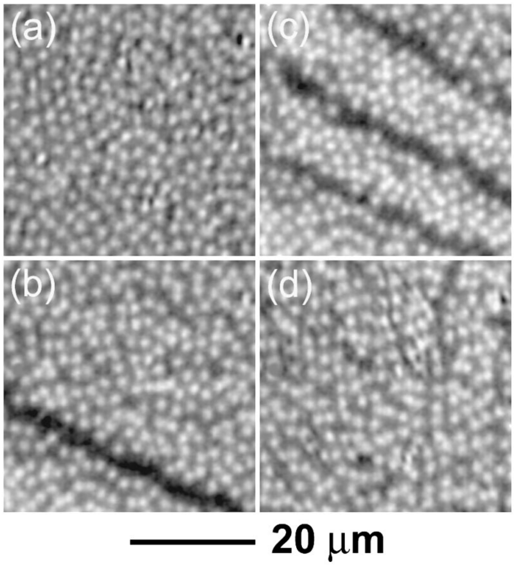

FIG. 4. Results for the $d = 0.3$ mm sample. Starting from the initial field-cooled vortex lattice (a), we can create vortex free channels at the turning point of the domain wall (b and c). The domain wall has been moved down from the upper right-hand side corner of the image area and turned at different positions. The channels can be subsequently erased by passing the domain wall across the whole field of view (d).

Hence, the interaction force between the Bloch wall and a single vortex is on the order of 1 pN.

In a final experiment, the Bloch wall–vortex interaction was examined in the $d = 0.3$ mm sample. We cooled the sample in a 0.5 mT applied field, which gave $a_0 = 2\ \mu\text{m}$, see Fig. 4(a). Using the obtained value for j_c, this sample has a single vortex pinning force $f_p = 25$ pN, which is one order of magnitude larger than f_w. By passing the domain wall back and forth across the image area, a vortex free channel was created at the turning point of the wall, Fig. 4(b). We were able to create more such channels by turning the domain wall at different positions at the sample, see Fig. 4(c). The channels were easily erased by passing the domain wall over the whole field of view as shown in Fig. 4(d).

These observations clearly show that vortices can be moved even in a sample where the applied force f_w is much smaller than the single vortex pinning force f_p. A plausible explanation is that only the upper part of the vortex is bent under the application of f_w, leaving the rest of the vortex undisturbed. Support for this is found by calculating the elastic force f_{el} on a bent vortex:[15]

$$f_{\text{el}} = 2 \varepsilon_0 \frac{u}{L} \approx 0.5\ \text{pN}.$$

Here u is the transverse distortion, L is the vortex length, and $\varepsilon_0 = \Phi_0^2 / 4\pi\mu_0\lambda^2 \approx 30$ pN is the vortex line tension at $T = 4$ K. We see that f_{el} is much lower than $f_p = 25$ pN, which means it is easier for the vortex to bend than to move as a rigid rod. So, in the case of this thick sample, the domain wall is analogous to a hairbrush. One’s hairstyle can be changed without moving the hair roots.

To summarize, we have demonstrated that a magnetic domain wall can be used to manipulate vortices. Depending on the thickness of the sample, the vortices are either swept entirely away or merely bent. The vortex–wall interaction force has been estimated to 1 pN. Magnetic pinning of vortices is an active field of study, and our work demonstrates the power of the MOI method in studying features of vortex behavior.

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