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 NbSe2 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.

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 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. 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, domain walls can be manipulated at frequencies in the GHz regime, 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. 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 NbSe2 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.

In an FGF with in-plane magnetization, two domains with an opposite magnetization direction will be separated by a Bloch wall. The domain wall will give rise to a stray localized field outside the film which will interact with vortices, 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–NbSe2 single crystal with Tc = 7.2 K, penetration depth λ = 70 nm, and thickness d = 30 μm. Upon cooling to T = 4 K in Bz = 0.1 mT, a disordered vortex lattice with lattice constant a0 = 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 \( \theta_f \) 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.](image-url)
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 \( d=10 \mu m \). We applied the same external field before cooling, see Fig. 3(a). 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: \( j_c=4\times10^3 \) A/cm\(^2\). From this, we calculated the single vortex pinning force for the first two samples using the relation \( f_p=j_c\Phi_0d \), where \( \Phi_0=2.07\times10^{-15} \) Wb is the flux quantum:

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

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

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 \( a_0=2 \mu m \), 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:

\[
f_{el}=2\varepsilon_0\frac{\mu}{L}\approx0.5 \text{ pN}.
\]

Here \( \mu \) is the transverse distortion, \( L \) is the vortex length, and \( \varepsilon_0=\Phi_0^2/4\pi\mu_0\lambda^2\approx30 \) 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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