Real Space Images of the Vortex Lattice Structure in a Type II Superconductor during Creep over a Barrier

F. Pardo and F. de la Cruz
Centro Atomico Bariloche and Instituto Balseiro, Comision Nacional de Energia Atomica, 8400 S. C. de Bariloche, R. N., Argentina

P. L. Gammel, E. Bucher, C. Ogelsby, and D. J. Bishop
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974
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We report on Bitter decoration studies of the magnetic flux line lattice in the type II superconductor $NbSe_2$ during flux creep experiments over barriers, a surface step. We find that these steps can act as "vortex diodes." By imaging the real space structures of the vortex lattices as they flow over these steps and measuring the change in vortex density, we are able to measure the energetic height of the barrier as well as the elastic correlation length of the vortices along their length. At low fields, we find that the vortices are correlated over distances of roughly 5 μm. [S0031-9007(97)03874-X]

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The response of a type II superconductor to an applied magnetic field is both technologically important as well as scientifically interesting. It is technologically important because all of the relevant superconductors, from an engineering point of view, are type II materials, and their response to fields and currents limits the kinds of applications which can be realized. They are scientifically interesting because their flux-line lattices (FLL) are excellent model systems for many important issues in condensed matter physics, such as the flow of pinned structures [1], self-organized criticality [2], and phase transitions in the presence of disorder [3]. When a magnetic field between H_{c1} and H_{c2} is applied to a type II material, a vortex lattice of magnetic flux lines can form. When this field is rapidly removed, material defects will pin the lattice, preventing it from being instantaneously expelled. How this FLL interacts with these defects and flows around them as the magnetization leaves the sample can tell us much about the pinning mechanism itself.

There have been many studies of both the temporal [4] and spatial responses [5] of the magnetization of a type II superconductor during flux creep. However, very little is known about the structures the vortices form as the FLL flows. In this paper we present real space images of how a vortex lattice interacts during creep with a particular type of defect, a surface step. Images of the kind presented here allow us to perform a number of quantitative measurements. By calculating the energy differences between the structures close to and far away from the step, we can calculate the energy height of the step. For step heights in the 40 to 250 nm range, we find a linear dependence of barrier energy with step height. This quantitative measurement then allows us to measure how well the vortices are elastically correlated along their length. This is an important issue in vortex physics as different regimes of anisotropy, temperature, and field can produce either two- or three-dimensional vortices. This paper then presents a new way to directly measure this correlation length.

Our experiments used the Bitter decoration technique [6] to directly visualize the vortex lattice structures. In the technique, iron clusters of roughly 50 Å diameter are evaporated onto the surface of a sample which has a vortex lattice present. The clusters are attracted to the field gradients arising from the vortex lines emerging from the surface of the sample and decorate the surface where vortices are located. Van der Waals forces hold the clusters quite strongly after they have landed on the surface, allowing one to warm up the sample and image the vortex locations at room temperature with a scanning electron microscopy (SEM). The technique can either image static vortex structures or dynamic ones if, for example, the vortex configuration changes during the approximately 1 sec needed for the evaporation to take place.

In the experiments described here, high quality $NbSe_2$ crystals with typical dimensions of 0.5 mm $\times$ 0.5 mm $\times$ 0.2 mm similar to those used in Ref. [7] were cleaved, and the resulting surface topographies were measured with a profilometer. Samples were then cooled down to 4.2 K with a field of 36 Oe applied in the **c** direction. At 4.2 K, the field was removed and after waiting 10 min, the sample was decorated. This resulted in "quasistatic" images of the vortex lattice. By quasistatic, we mean that the creep rate was less than one lattice constant per second, giving us the opportunity to resolve individual vortices in our images.

Shown in Fig. 1(a) is a Bitter pattern of a FLL taken at 4.2 K without the applied field having been removed. The continuous line highlighted with the arrow is a 0.3 μm surface step. Figure 1(b) is a Delaunay triangulation of the vortex patterns with the topological defects shaded. Despite the fact that the FLL is polycrystalline, there is not

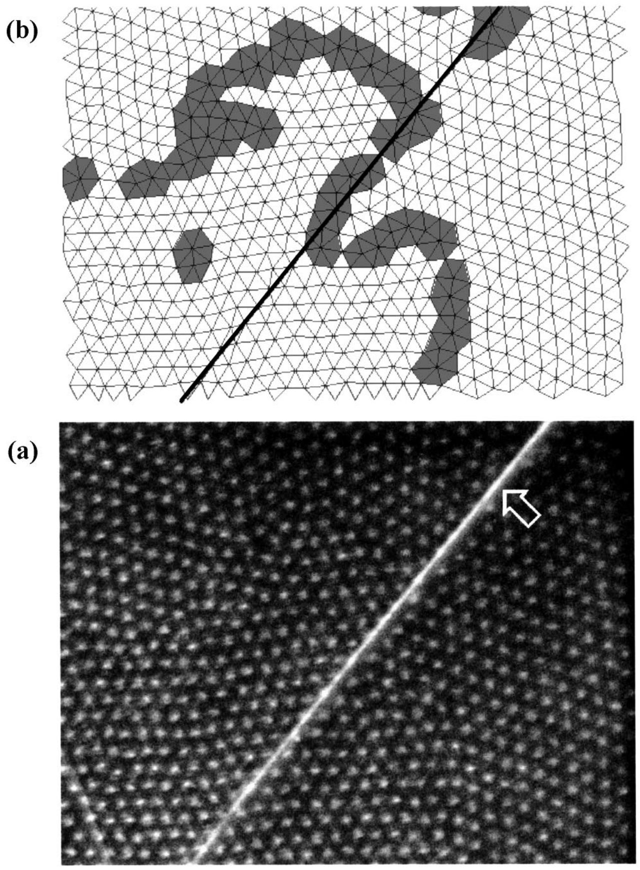

FIG. 1. Shown in the lower frame is a magnetic decoration image of a FLL on the surface of $NbSe_2$ taken at a temperature of 4.2 K and a field of 36 Oe with the field remaining static. The white diagonal line is a 0.35 μm surface step. The upper frame shows a Delaunay triangulation of the lower image with the topological defects shaded in. Well away from the step, the intervortex distance is 0.8 μm.

a strong correlation between grain boundaries and surface steps, in contrast to results in BSCCO [8]. We believe that this is due to the lower line energy in $NbSe_2$ due to a lower $\kappa \sim 20$. This then requires a larger step for the formation of grain boundaries. Furthermore, the large region of reversible behavior in BSCCO can favor the freezing of the vortex lattice at steps in a particular orientation. This is because with a large region of reversible magnetization, the vortex-vortex interactions are well pronounced and quite strong, comparatively speaking, when the lattice becomes pinned, at or below the irreversibility line. This can produce a well-ordered structure which will then pin in an orientation to minimize interaction energy with the step. However, the case with $NbSe_2$ with a very narrow region of irreversible magnetization is quite different. In this case, the pinning of the lattice sets in close to T_c with weak vortex-vortex interactions, and an amorphous solid is formed which takes little notice of the extended defect, the step. The extended defect does not greatly affect the long-ranged orientational order in the lattice because there is none yet present in the unpinned lattice as it starts to pin near T_c. One should note that in the absence of flow, the vortex density near the step is uniform and appears to be the same as that well away from the step. As we will show below, this is quite different from what is seen during creep experiments.

We now consider images taken near steps during flux creep. In particular, we will discuss images where vortices are forced to overcome a step height, σ, on their way to the sample edge. As the step requires a change in energy of $\sigma\varepsilon_L$, where ε_L is the energy per unit line length, it is clear that the step should modify the motion.

Shown in Fig. 2(b) is a typical result for a FLL imaged 10 min after the field was removed. The vortex flow is towards the left-hand side of the image. From the measured decay of the magnetization in a commercial SQUID magnetometer, we estimate the flow velocity to be $\sim$0.3 μm/sec. These SQUID results are in agreement with the average magnetization as calculated from several decoration images. The subject of this paper is not the observation of creep itself but the detailed spatial dependence of the vortex pattern during the creep. As the decoration time is of the order of 1 sec and the vortex lattice constant

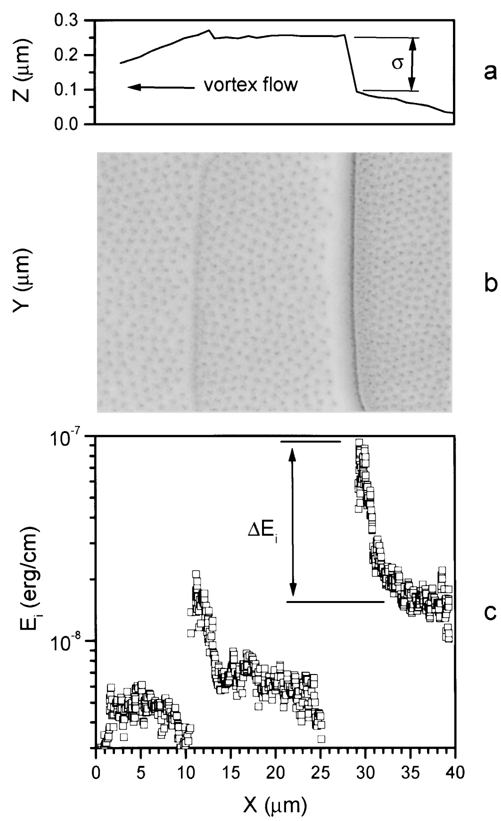

FIG. 2. Shown in the upper frame is the surface topology of our sample with two surface steps, the center frame shows the decoration image taken at 4.2 K, 10 min after a 36 Oe field was removed from the sample, and the lower image shows a calculation of the interaction energy using as input the location of the vortices determined from the decoration image. X, Y, and Z are the spatial coordinates.

is ~1.0 μm, this puts us safely into the quasistatic regime where we can still image individual vortices.

Figure 2(a) shows a surface profile recording done along the direction of flow. There are two well-defined steps in the surface, a small one on the left and a larger one on the right. The image in 2(b) clearly shows how the vortices "pile up" at the leading edge of a step with a larger density difference for a higher step. Shown in Fig. 2(c) is a calculation of the vortex-vortex interaction energy per unit length for the pattern we have observed. It is extracted from our data in the following way. After a decoration, we find the vortex locations by fitting their locations to Gaussians. We then use the pairwise interaction potential, $E_{12} = (\phi_0^2/8\pi^2\lambda^2)K_0(r_{12}/\lambda)$, calculated out to a distance of 20λ. The effects of the steps are clearly seen in a plot of a vertically integrated, sliding average of this interaction energy as we move across the sample. The vortex density increases on the right-hand side of the step and is rarified on the left-hand side. The interaction energy has two components near the step. There is the rapidly rising and falling part at the step due to the step, and there is an overall, gradually changing baseline shift away from the step. This overall baseline shift is due to the field gradients in the sample due to the creep and is also found in samples without steps. The rapidly changing part near the step represents a competition between the interaction energy of the vortices and the line energy difference on both sides of the step,

$$\sigma\varepsilon_L = t\Delta E_i\,, \tag{1}$$

where t is the sample thickness, ε_L is the line energy given by $(\phi_0/4\pi\lambda)^2 \ln\kappa$ and ΔE_i is the vortex-vortex energy increase per unit length due to the pileup of vortices. This quantity ΔE_i is labeled in Fig. 2(c).

This kind of picture would suggest that vortices should be able to flow into thinner regions without a pileup. This is clearly demonstrated in Fig. 3 where vortices have moved into a well without changing their density but have accumulated to a higher density at the far wall where the sample increases its thickness again. This indicates that the steps in this system are not just regions of localized disorder due to local strains, for example, which might be expected to pin the flow of vortices in either direction [9]. Instead they are rather ideal, clean regions where the thickness changes but the pinning appears to be only geometrically induced and not related to disorder. The steps appear to function as "vortex diodes" impeding flow in one direction but not the other. An interesting point is the "hydrodynamic" flow of vortices around the tip of the surface defect shown in Fig. 3. The vortices appear to line up and flow parallel to the tip in uniform channels.

The central result of this paper is obtained from a measurement of ΔE_i as a function of step height σ for thick samples ($t > 50$ μm). Shown in Fig. 4 is this dependence for a sample which was 200 μm thick (open symbols). Other thick samples show quantitatively the same behavior, but usually do not have steps which span such a wide range in height. As expected from Eq. (1), we find a linear behavior but we find that the slope, 4×10^{-7} erg/(cm μm), is roughly 40 times larger than ε_L/t. Also shown in Fig. 4 as the filled circles are results from a 60 μm thick sample which agree quantitatively with the 200 μm results. This argues that the vortex array seen at the surface is not propagated throughout the bulk of the sample but exists only for a thickness $t_{\rm eff} \ll t$. The surface pattern then merges with a more homogeneous, less energetically costly, bulk pattern roughly 5 μm below the surface with the step. That is, the increase of vortex density induced by the presence of the step is a maximum at

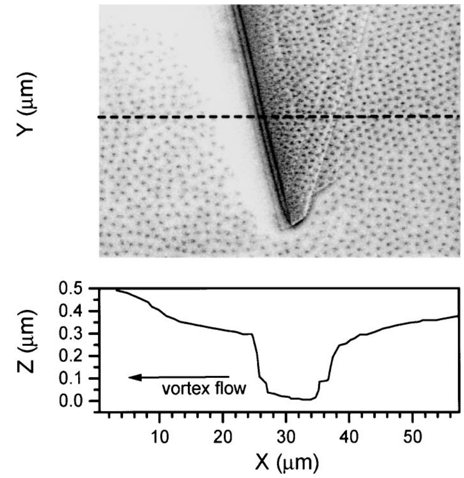

FIG. 3. The upper frame shows a magnetic decoration image on a sample with a triangular depression whose topology is shown in the bottom frame. For the decoration image, the sample was cooled to 4.2 K in a field of 36 Oe and the sample decorated 10 min after the field was removed at low temperatures and vortex creep was well under way.

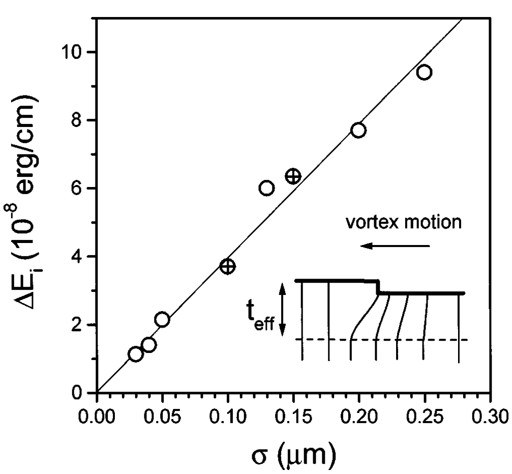

FIG. 4. Shown is a plot of the interaction energy versus step height σ for thick samples. The open circles are data for a 200 μm sample and the shaded circles are for a 60 μm thick sample. The inset shows our model for vortex flow over the barrier created by the surface step.

the surface and decays towards the uniform bulk distribution at around 5 μm below the surface.

To test this hypothesis, we have performed decorations under the same conditions as above but for samples which were much thinner ($t \sim 8\ \mu$m) and were comparable in thickness to t_{eff}. In this situation we find that $t\Delta E_i/\sigma$ equals 2.4×10^{-6} erg/cm, which agrees closely with $\varepsilon_L = 2.03 \times 10^{-6}$ erg/cm. This shows that the vortex lines are well correlated along their length for no more than 5 μm at these low fields. Our decoration results follow the trend as shown in small angle neutron scattering (SANS) data on the same system [10], but generally give somewhat larger values for the correlation length than we find for the extrapolated SANS data. This is consistent with the fact that our decoration probably gives an upper limit for the correlation length since the high vortex density very close to the step is hard to resolve with our technique and, if resolved, would increase the measured value of ΔE_i.

Finally, it is interesting to ask the question as to whether these surface steps can modify the creep rate. During the early stages of creep, the total vortex flow should be reduced because of the barrier $\sigma\varepsilon_L$. However, as the vortex-vortex interaction increases due to the pileup at the barrier, the stable configuration $\sigma\varepsilon_L = t_{\text{eff}}\Delta E_i$ is established and one might expect that the creep rate would then be governed by other kinds of material defects. However, something more subtle may happen. Because of the short correlation length along the lines, the tops may be pinned at the surface defect while the rest of them flow along with the bulk lattice flow as shown in the inset of Fig. 4. The vortex could then snap through the vortex free region seen at the surface in a short time scale. This situation would remain stable until $t_{\text{eff}}\Delta E_i < \sigma\varepsilon_L$ and then again one would be in a creep regime dominated by the barrier. Therefore, one could imagine a situation in which the steps have an impact on the creep even in the steady state. However, the relatively small step height in comparison with the average sample thickness might still make this effect hard to observe in a global magnetization measurement but a local probe, such as used in magnetization studies of YBCO [11] and BSCCO [12], might be able to see it directly.

In conclusion, we have observed a stable configuration for the FLL during creep over a barrier, a surface step. We find that the steps can act like "vortex diodes." From a calculation of the energetics of the structures, we are able to extract a longitudinal correlation length in a new way. We find values for this length which are in rough agreement with values obtained from SANS data at higher fields. Contrary to intuition, it may be possible for surface barriers to affect the creep rate of the FLL in the steady state.

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