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Depinning and anisotropic order in flowing and static vortex lattices in $NbSe_2$ studied with magnetic decoration

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Vortex lattice dynamics is studied by magnetic decoration experiments on $NbSe_2$ at fields of 20–70 G. At depinning the motion begins along the principal lattice directions which are nearest to the direction of the driving force. The periodicity in the direction transverse to the motion is preserved. Along the flow channels, however, large variations of the intervortex spacing are observed. When the vortex lattice comes to a stop, the static structure partially preserves the displacement characteristics of the moving lattice, as follows from the anisotropy of the angular dependence of the vortex displacement correlator. [S0163-1829(99)07341-5]

Recently a lot of theoretical and experimental attention has been paid to the problem of depinning and flow of vortices in type II superconductors under the applied driving current. The developments of the last years were the prediction by Koshelev and Vinokur[1] of the dynamic recrystallization of the vortex lattice in motion and, later on, the theory of the moving vortex glass proposed by Giamarchi and LeDoussal (GLD).[2] The GLD theory predicts that a static vortex glass phase should transform to a moving glass with growing correlation lengths as the external force is applied. In contrast, some recent theory and numerical simulations predict the existence of a plastic flow regime between the static and dynamic glassy phases.[3,4] The most recent theoretical results by Balentz *et al.*[5] suggest that the dynamic phase diagram may also include a novel vortex phase—a transverse smectic, which is intermediate between the low drive moving liquid and the high drive moving glass phases. The novel dynamic behavior of the vortex matter predicted by these theoretical models remains, however, to be tested experimentally. Among the problems to be tackled is the evolution from the static lattice to the coherently moving lattice (or glass) under application of the driving current and possible intermediate flow regimes. Another side of the problem is to determine if the static structure of the vortex lattice and the way the lattice was created do affect depinning threshold and critical currents, as well as how fingerprints of the motion can be quenched in the static structure. The latter transport experiments,[6,7] strongly suggest that the history effects play important role in lattice depinning and motion.

Below we show experimental data, obtained with magnetic decoration technique. The experiments were done on single crystals of $NbSe_2$, a type II superconductor with T_c of 7.1 K and moderate anisotropy ($\gamma^2=9$). In order to visualize the depinning of the vortex lattice, the following procedure was used. The samples were cooled in an external magnetic field of 1 kOe, to a temperature of 1.3 K, after which the external field was removed. This resulted in the formation of the critical state in the entire sample. We determined the critical current density J_c (1.3 K) from resistivity measurements on similar samples and computed the flux profile $B(r)$ from the sample geometry.[8] The typical remanent induction in the middle of the sample was approx. 100–150 G. Finally, the decoration filament was switched on for about 1 sec. Due to sample heating during the decoration procedure with about 1.5 K, the critical current density decreases with 20%, giving rise to relaxation to a new critical state with lower induction $B(r)-\Delta B(r)$. In the course of this relaxation vortices move from the sample center towards the edges. Since the heat pulse and deposition of the magnetic particles are intrinsically synchronized with each other, self-synchronization of the decoration procedure with the vortex relaxation is achieved and the very onset of vortex motion can be imaged. This technique builds on a method,[9] implemented earlier by us to visualize the dynamics of the flux penetration.

The velocity of the moving vortices can be estimated by using the critical state model for a thin strip (or disk).[8] Substituting the sample dimensions (a long crystal of width ~ 300 μm) and the change in the local induction $\Delta B(x)$ induced by, as explained above, the short time ($\Delta t=0.5$ s) heating, the velocity of vortices passing through a line at a distance D from the sample center can be calculated and is given by

$$v(D)=\frac{1}{2D\Delta t B(D)}\int_{D}^{-D}\Delta B(x)x\,dx.$$

For the region shown in Fig. 1 taken at approx. 50 μm from the sample geometrical center we obtained $v\approx 0.67$ μm/s. The linear traces of the moving vortices are clearly seen. Assuming that the actual vortex structure resembles a triangular lattice flowing along one of its principal directions, we estimate $a_0\sim 0.55$ μm corresponding to an induction of ~ 65 G. It is intriguing that even at this small velocity of ~ 1 lattice spacing per second the periodicity of the moving structure in the direction transverse to the flow is preserved. Similar observations have been recently reported by Pardo *et al.*[10] The smearing of the structure inside the flow channels due to motion does not allow us to draw a distinctive conclusion from a Fourier analysis, i.e., we cannot decide whether a lattice (Bragg glass) or smectic flow is observed. By looking at the pattern inside the flow channels one can see the significant modulation of the amount of particles along the channels and sometimes distinctively sepa-

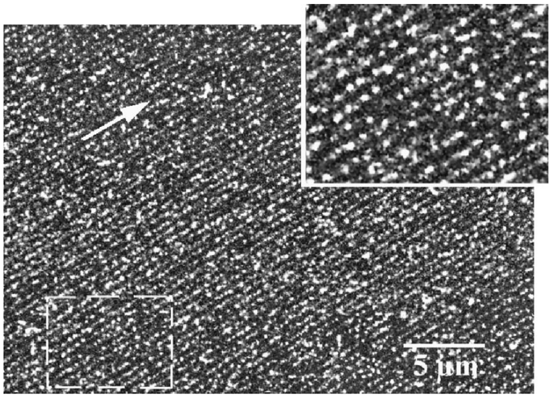

FIG. 1. Decoration picture of a flowing vortex lattice, $B \approx 65$ G, $v \approx 1.2 a_0\ \mathrm{s}^{-1}$. The structure retains its periodicity in the direction transverse to the flow (denoted by the arrow). Inset: the blow up of the outlined part in the bottom of the main image. Inside the flow channels the intervortex distance between the bright spots (which are presumably almost nonmoving vortices) varies considerably, suggesting an overall smectic order in the moving structure.

rated bright spots. Because the velocity of the moving vortices is small, one can imagine that some of the vortices hardly move during decoration and they are seen as bright spots rather then smeared lines in the decoration pattern. Clearly the distance between the neighboring ''quasi-immobile'' vortices varies strongly, as can be seen from the blowup image in Fig. 1. We therefore conclude in agreement with[10] that the overall flowing structure shows all the characteristics of the theoretically predicted vortex smectic phase.

In Fig. 2 the depinning of a vortex ''single crystal'' is shown. Here, at the left the vortices are not moving and a well-ordered static lattice is seen, while at the right the lattice begins to move. This situation occurs close to the geometrical center of the sample. A substantial ''smearing'' of the two lattice directions non-parallel to the direction of the motion (denoted by the arrows in the figure) at the very right of the image indicates that a velocity larger than 0.5 a_0/s is achieved. It is clear that there is a gradual transition between the static and moving phases. We do not observe an intermediate region of liquid flow preceding the moving ordered phase (The liquid flow would be seen as disordered pattern without channels). Instead, the transverse periodicity of the moving structure is well preserved in the depinning process. The correspondent deformation is highly anisotropic; meaning that vortex lattice ''elongate'' along the direction of motion, the vortices are moving from high to low flux densities, while the transverse metrics is preserved. This result may be considered as indirect evidence for the existence of the transverse critical current, predicted by the GLD theory and supported by recent numerical simulations.[11]

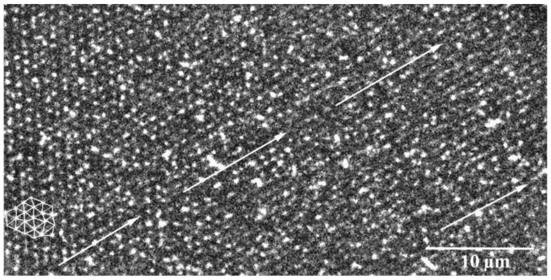

FIG. 2. Depinning of a vortex ''single crystal.'' Flow direction is denoted by arrows. A transition from the static lattice (left) to the flowing lattice (right) occurs without loss of structural periodicity in the transverse direction.

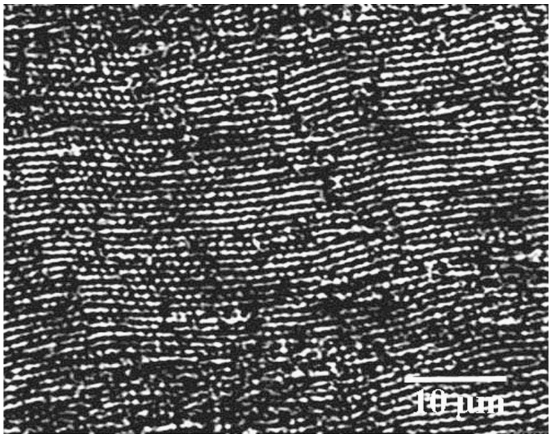

FIG. 3. Depinning of a polycrystalline vortex structure, $B \approx 25$ G. Individual lattice grains are depinned in those principal lattice directions which is nearest to the direction of the driving force. The image has been Fourier filtered to enhance the contrast between moving and static lattice parts.

At lower inductions (20–30 G) the static vortex structure consists of many misoriented grains. In view of the persistent long range order within the individual lattice grains, such structures can be called a polycrystal, as has been discussed earlier.[12] We believe the granular structure arises as a result of nucleation and growth processes near the superconducting transition. When the driving force is applied to such an orientationally frustrated structure, the motion begins in the directions of local lattice orientation in the grains which are nearest to the direction of the driving force. The preferential flow of the vortex lattice along its principal axis is consistent with the earlier theoretical predictions by Schmid and Hauger.[14] In our case, this phenomenon gives rise to preferential motion of the ''correctly'' oriented grains with respect to the ''misoriented'' ones. The pattern illustrating this behavior is shown in Fig. 3. This image has been Fourier-filtered to enhance the contrast between the static and moving lattice parts. One sees ''zig-zag'' channels of vortex flow embedded in a structure of static grains. Once again, the lattice tends to flow in the direction of its local orientation thus preserving its transverse periodicity, rather than following the mean direction of the driving force (which would smear the decoration image of the flowing lattice). One can imagine that the critical force needed to set the lattice into motion is anisotropic as well, depending on the direction of the driving force with respect to the local lattice orientation. Similar flow patterns were observed in numerical simulations[13] of the depinning process. Our experiments show that the misoriented grains play the role of intrinsic, large-scale inhomogeneities in the course of lattice depinning. The presence of these large immobile patches naturally suggests that the current distribution at the depinning is very inhomogeneous, with most of the current flowing through the static patches. The net vortex (and current) flow becomes more homogeneous, however, when most of the individual grains are set into motion and gradually anneal to a more

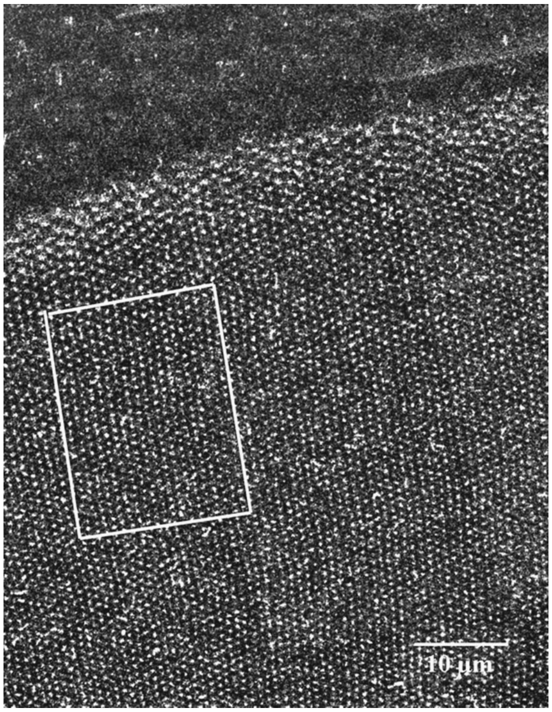

FIG. 4. Decoration pattern of a large flux front that penetrated a $NbSe_2$ single crystal. A field of 50 G was applied at 1.3 K to the zero field cooled sample. The pattern taken for further analysis is outlined with the frame.

unidirectional flow pattern. The results lead to the conclusion that initial static vortex configuration can actually define whether liquid or smectic flow regime will be established at depinning. This may be even more important at higher fields, and, especially in the peak-effect region where actual configuration and size of the defect free vortex ''grains'' might not only define the dynamics but also dimensions of the correlated regions for pinning and thus the local pinning strength.

Our observations of the flowing vortex smectic poses a question if the large relative displacements of the vortices along the flow channel directions can de traced back from the static vortex structure, after the driving force has been removed. Below we analyze the VL decoration pattern of a $NbSe_2$ sample after a field of 50 G was applied to a zero field cooled crystal at $T=1.3$ K. This field ramp gives rise to the penetration of a large vortex front towards the middle of the $NbSe_2$ crystal. The entire pattern is shown in Fig. 4. A section without topological defects consisting of 890 vortices (as outlined in Fig. 4) was triangulated and taken for analysis. The induction is 22 G. We calculate the VL displacement correlator. Instead of averaging over all directions we projected the relative displacements onto a certain axis defined by the unit vector $\mathbf{e}_\varphi$ making an angle φ with the x axis. The angular dependent displacement correlator $\langle u_\varphi^2(\mathbf{r})\rangle \equiv\langle[(\mathbf{u}(\mathbf{r})-\mathbf{u}(\mathbf{0}))\cdot\mathbf{e}_\varphi]^2\rangle$ obtained with this calculation revealed a substantial φ dependence for all $\mathbf{r}$. To illustrate the angular dependence, we calculate the correlator $\langle u_\varphi^2(\mathbf{r})\rangle$ for fixed r with angular steps of $5°$ and then average it over r. The angular plot of $(1/10a_0)\int_0^{10a_0}\langle u_\varphi^2(\mathbf{r})\rangle^{1/2}dr$ is shown in Fig. 5. One sees that the maximum amplitude of vortex displacements is in the previous flow direction. This result can be understood from the fact that at low fields at temperatures well below T_c pinning is individual and after the driving force is removed each vortex retains its position within the range of the pinning force $(\approx\xi\ll a_0)$. The large fluctuations of the intervortex distance inside the flow channels in the slowly moving vortex lattice are therefore partially preserved in the static structure and can be measured from the decoration pattern. This suggests an interesting possibility to study the motion history of the vortex lattice by imaging static structures.

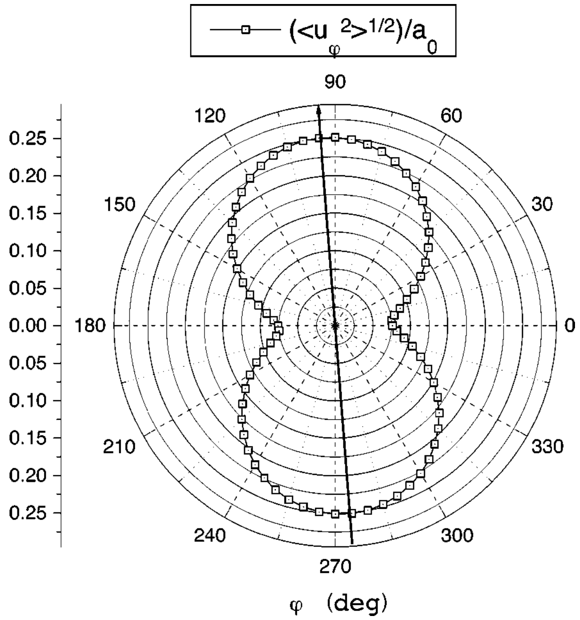

FIG. 5. Angular dependence of the vortex lattice displacement correlator (averaged over $10a_0$) for the flux front pattern of Fig. 4. The largest displacements occur in the direction of the previous flow.

In conclusion, we performed decoration imaging of the depinning process in the vortex lattice and found evidence for smectic flow for the vortex crystals set into motion. The picture of the depinning in ''perfect'' crystal suggest the persistence of the transverse periodicity, large longitudinal deformations of the lattice and formation of the flowing vortex smectic at low drive, with no preceding regime of the liquid flow. Misoriented grains and defects of the static lattice cause, however, an overall disorder in the flow, with the local flow matching the vortex lattice orientation closest to the direction of the driving force. The initial static vortex configuration defines the degree of plasticity and flow disorder at the depinning as well as the inhomogeneities in the current distribution. After stopping, vortex lattice retains fingerprints of the moving structure in the form of anisotropic displacement correlation, with maximal displacement in the direction of the previous flow.

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[1] A. E. Koshelev and V. M. Vinokur, Phys. Rev. Lett. **73**, 3580 (1994).

[2] T. Giamarchi and P. Le Doussal, Phys. Rev. Lett. **76**, 3408 (1996).

[3] K. Moon, R. Scalettar, and G. T. Zymani, Phys. Rev. Lett. **77**, 2778 (1996).

[4] S. Scheidl and V. M. Vinokur, Phys. Rev. B **57**, 13 800 (1998); Phys. Rev. E **57**, 2574 (1998).

[5] L. Balents *et al.*, Phys. Rev. B **57**, 7705 (1998).

[6] W. Henderson, E. Y. Andrei, M. J. Higgins, and S. Bhattacharya, Phys. Rev. Lett. **77**, 2077 (1996).

[7] M. J. Higgins and S. Bhattacharya, Physica C **257**, 232 (1996).

[8] E. H. Brandt, Phys. Rev. B **46**, 8628 (1992).

[9] M. Marchevsky, J. Aarts, P. H. Kes, and M. V. Indenbom, Phys. Rev. Lett. **78**, 531 (1997).

[10] F. Pardo, F. de la Cruz, P. L. Gammel, E. Bucher, and D. J. Bishop, Nature (London) **396**, 348 (1998).

[11] A. van Otterlo, R. T. Scalettar, and G. T. Zimanyi, Phys. Rev. Lett. **81**, 1497 (1998).

[12] M. Marchevsky, Ph.D. thesis, Leiden University, 1996.

[13] Min-Chul Cha and H. A. Fertig, Phys. Rev. B **50**, 14 368 (1994); Phys. Rev. Lett. **80**, 3851 (1998).

[14] A. Schmid and W. Hauger, J. Low Temp. Phys. **11**, 667 (1973).