Flux-Line Shear through Narrow Constraints in Superconducting Films

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Flux-line-lattice flow has been studied in a novel superconducting device containing straight, nanometer-scale, weak-pinning channels in a strong-pinning environment. The shear strength of a two-dimensional, triangular lattice has been directly probed on length scales of order of the lattice parameter by variation of the magnetic field. Good agreement is found with a continuum-approximation model for shear flow. Unusual oscillations in shear strength and history effects were observed and explained by the (in)commensurability between flux-line lattice and channel.

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In this Letter we present novel experiments on an artificially structured, superconducting device[1] containing well-defined channels of weak flux pinning in a strong-pinning environment. In a magnetic field B this thin-film device contains a two-dimensional (2D) flux-line lattice (FLL) with a lattice parameter $a_0=1.075(\phi_0/B)^{1/2}$ (ϕ_0 is the flux quantum) that can be varied by our changing the field. Flux flow through the channels occurs as soon as the flow stress τ_{max} of the FLL is exceeded at the channels' edges. Using nanometer lithography, we have a means to investigate shear of this 2D lattice through constraints with widths W as small as a_0. Our measurements demonstrate flux-line shear (FLS) in our device. This is of special importance for the understanding of the high-field flux-pinning properties in technical superconductors. In addition, our data also display oscillations and hysteresis effects which have never been observed before and are related to the (in)commensurability of the well-defined channel width and the spacing of the lattice planes in the FLL. Since we are able to study the shear of a two-dimensional (2D) triangular lattice on an "atomic" scale, the relevance of our experiments is more general. In particular, our experiments open new possibilities for the investigation of the effect of dislocations on the shear modulus of a 2D lattice and allow a direct study of the anharmonicity of the lattice potential.

Our device, sketched in Fig. 1(a), consists of an array of 200 narrow channels parallel to the Lorentz force etched in a 50-nm-thick strongly pinning NbN layer ($T_c=12.7$ K) on top of a 550 nm-thick weakly pinning amorphous Nb_3Ge (a-Nb_3Ge) layer ($T_c=2.90$ K). In order to study FLS on single lattice planes, the channel width W should be of order a_0, which for reasonable fields (0.2 T) corresponds to $\simeq 100$ nm. As determined by scanning electron microscopy the actual channel width of our device is $W=90$ nm. The fabrication details are published in a conference report.[1]

Critical-current measurements were performed in a static and dynamic mode by a four-probe technique. In the static mode the critical current I_c was determined from the I-V curves measured after a field step with a criterion of 0.5 μV. In the dynamic mode the current was controlled in order to keep the voltage constant at 0.2 μV during the cycling of the field. The essential difference with the static experiments is that the flux lines in the channels are continuously flowing during field changes. In both modes I_c was determined as a function of B at several temperatures. As a result of the steep linear increase in the I-V curves above I_c, our results appeared to be insensitive to the choice of the voltage criterion. The results discussed below are obtained at the lowest temperature (1.74 K) and are typical for all observations.

Under the experimental conditions the critical current density J_c in NbN exceeds J_c in a-Nb_3Ge by at least a factor of 2×10^4. Because in sufficiently thin films in a

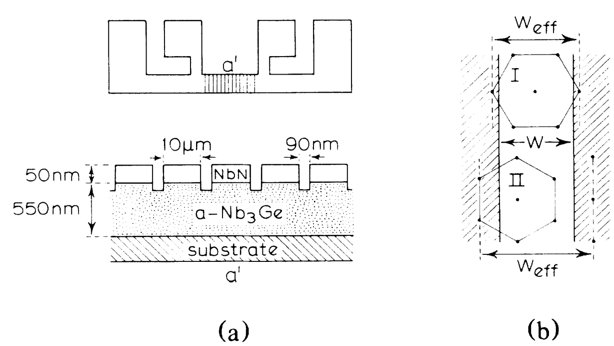

FIG. 1. Sketch of (a) the channel structure in a superconducting double layer and (b) of W_{eff} for two different orientations (denoted I and II) of the FLL. Note that the actual channel separation is a factor 100 times larger than the channel width.

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field normal to the surface flux lines essentially remain straight,[2] the position of the flux lines outside the channels is determined by their position in the NbN layer. In the channel, they adopt positions such as to minimize the deformation energy and to maintain the uniformity of B. The FLS is determined by the shear modulus c_{66} in the a-Nb_3Ge layer. If we invoke a continuum approximation for the FLL, the flow stress τ_{max} is exceeded when the Lorentz-force density BJ_c in the channels exceeds $2\tau_{max}/W$. Here $\tau_{max}=Ac_{66}$, where A lies between $(2\pi)^{-1}$ and $\frac{1}{30}$.[3] This model predicts a pinning force density for FLS of

$$F_p=2Ac_{66}/W \tag{1}$$

where, for large κ, c_{66} can be written as[4]

$$c_{66}=\frac{B_{c2}^2}{8\mu_0\kappa_1^2}\left[\frac{\kappa}{\kappa_2}\right]^2 b(1-0.29b)(1-b)^2, \tag{2}$$

and κ, $\kappa_1(T)$, and $\kappa_2(T)$ are the Ginzburg-Landau and Maki parameters, the latter for the dirty limit.

The recorded lines in Fig. 2 give the results of the dynamic measurements. The data lie well between the F_p values of a-Nb_3Ge and NbN indicating that they indeed result from FLS.[1] Salient features are the unusual oscillations and the differences between a field sweep up or down. The inset displays the effect of field reversals. It is seen that the crossovers occur in a very narrow field range. The solid line represents Eq. (1) with $A=0.047$, $W=90$ nm, and the experimental κ's and B_{c2} (Ref. 2) substituted. The choice for A originates from the criterion for the peak effect observed in 2D collective-pinning experiments.[5] It probably is smaller than $(2\pi)^{-1}$ because of the anharmonicity of the lattice potential and the dispersion of c_{66}.[6] Considering the approximations made, the general trend of the data is in satisfactory agreement with the solid line. Thus the FLS mechanism can be globally described by the simple continuum model. However, modifications related to the discrete nature of the FLL are needed to explain the observed deviations.

Because of the interaction with the surface,[7] flux lines cannot be located exactly at the channel edges. Accordingly, as indicated in Fig. 1(b) for the two energetically most favorable FLL orientations, the effective channel width W_{eff} is larger than W and a function of a_0. Secondly, the effect of flux-line dislocations on the flow stress has not been taken into account, although a reduction up to 50% has been shown experimentally[2,8] and by computer simulations.[9] Furthermore, we ignored in Eq. (2) the anisotropy and dispersion of c_{66}, which are especially important when only one lattice plane occupies the channel. We may account for these effects by defining an effective flow stress $\tilde{\tau}_{max}$ and replacing Eq. (1) by $F_p=2\tilde{\tau}_{max}/W_{eff}$. The quantity $(\tau_{max}/\tilde{\tau}_{max})W_{eff}/a_0$ $(=0.094c_{66}/F_pa_0)$ obtained from both our static and dynamic measurements is shown in Figs. 3(a) and 3(b) for

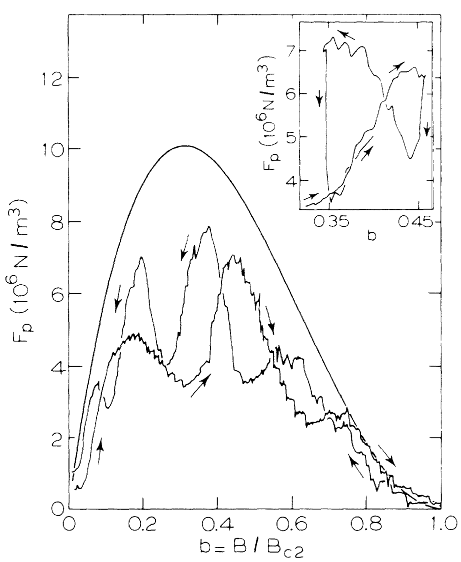

FIG. 2. Recording traces of F_p vs $b=B/B_{c2}$ at 1.74 K $(=0.6T_c)$ obtained from dynamic measurements. The solid line represents the continuum model.

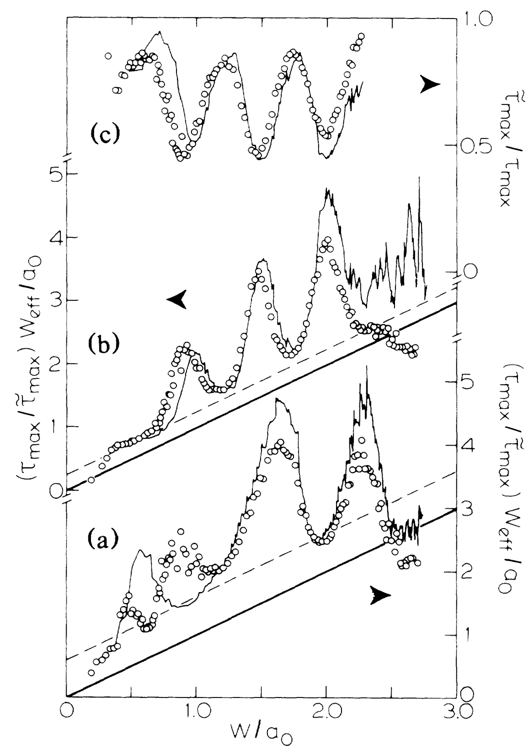

FIG. 3. $(\tau_{max}/\tilde{\tau}_{max})W_{eff}/a_0$ vs W/a_0 for static (circles) and dynamic (recording traces) measurements, (a) for increasing field and (b) for decreasing field. The solid and dashed lines represent the continuum model substituting W and the experimentally obtained W_{eff}, respectively. (c) $\tilde{\tau}_{max}/\tau_{max}$ vs W/a_0 obtained from the decreasing field-sweep measurements.

increasing and decreasing fields, respectively. The field dependence is expressed by the ordinate W/a_0 and the solid lines display the predictions of the continuum model.

Results for both the static and dynamic techniques in decreasing field are shown in Fig. 3(b) where peaks occur at $W/a_0 \simeq n/2$ and minima at $W/a_0 \simeq n/2+0.25$ ($n=1,2,3,4$). This periodicity corresponds to orientation I [Fig. 1(b)], since the lattice spacing normal to the channel in this case is $d_{\text{I}}=a_0/2$, whereas for orientation II it is $d_{\text{II}}=(a_0\sqrt{3})/2$. In addition, it has been experimentally established that during nucleation in a superconductor, flux lines remain at a fixed distance d_s from the surface. This distance is larger than that during denucleation.[10] As $d_{\text{II}} > d_{\text{I}}$, we assume that orientation II is favored for nucleation and orientation I for denucleation of flux lines at the NbN edge. Taking $d_s=\eta_1 a_0$ with η_1 a constant, we obtain $W_{\text{eff}}=W+2\eta_1 a_0$. We believe that the plane spacing at the minima is exactly commensurate with this W_{eff} leading to the condition $W+2\eta_1 a_0=nd_{\text{I}}$. From the positions of the minima (0.7, 1.3, 1.8, 2.3) we determine $\eta_1=0.12\pm0.02$. For other situations the flux-line density in the channels can only remain constant by the introduction of flux-line dislocations which will result in a decrease of $\tilde{\tau}_{\max}$. This effect is largest if the plane spacing is exactly commensurate with W giving rise to maxima at $W=nd_{\text{I}}$ as is indeed observed.

The effect of dislocations on $\tilde{\tau}_{\max}$ may be determined by the assumption that $W_{\text{eff}}=W+2\eta_1 a_0$ in the entire field regime. The continuum model with this W_{eff} is represented by the dashed line in Fig. 3(b). The deviation from this behavior, expressed as $\tilde{\tau}_{\max}/\tau_{\max}$, is plotted in Fig. 3(c). At $W/a_0=n/2$ the reduction of the shear stress amounts to about 50% which corresponds nicely with the results of Refs. 2 and 9. The disappearance of the periodicity for $W/a_0 \gtrsim 2.5$ can be ascribed to the fact that, close to B_{c2}, c_{66} becomes very small which results in an amorphous structure of the FLL in the channel. This effect is responsible for the peak effect in a-Nb_3Ge films.[5] It seems reasonable that this situation is better described by the continuum model.

In increasing field, orientation II would give rise to minima in Fig. 3(a) when $W_{\text{eff}}=W+2\eta_2 a_0=nd_{\text{II}}$. Determining η_2 from the minimum at $W/a_0=2.0$ ($n=3$), we obtain $\eta_2=0.30\pm0.03$ and predict for $n=2$ a minimum at $W/a_0=1.1$. This is indeed observed for the static data; however, not for the dynamic case. For an explanation of the low-field behavior (below $W/a_0=1$) one must realize that during field increase the flux lines enter the sample via the low-pinning channels and, therefore, these channels will always contain one lattice plane, even if $W/a_0 \ll 1$. As a result, orientation I will be most favorable in small increasing fields, as this orientation yields, for the neighboring rows of flux lines in the NbN, the smallest distance to the channel edge. Because orientation II is most favorable for large increasing fields, there has to occur a transition which may lead to unstable configurations. For decreasing fields having always orientation I as the most favorable, such anomalies are not expected.

Assuming an optimum distance $d_s \simeq 0.3a_0$, we obtain a reasonable explanation for the positions of the peaks and minima in Fig. 3(a). For the static measurements, the first peak results from a crossover from 1 to 2 lattice planes in the channels with orientation I maintained. At the second peak the FLL switches back to one plane but with orientation II. The significant scatter of the data indicates that the FLL configuration is unstable. Such instabilities are not observed for the dynamic case, probably because after a field increase a new FLL configuration is attained in a different way. In this mode the crossover from orientation I to II maintaining one plane in the channels presumably causes the first peak. At $W/a_0 \simeq 1.65$ the peaks indicate the switching from one to two planes with the same orientation. The peaks at 2.25 again mark the transition to the amorphous FLL. Comparing the peak height at 1.65 with the continuum model (dashed line) we again determine a reduction of $\tilde{\tau}_{\max}$ with 50%. Walton, Rosenblum, and Bridges[10] have shown that the transfer from nucleation to denucleation can take place in a very small field interval. This agrees very well with the dramatic effect we observe in the inset of Fig. 2 at the field reversals.

In conclusion, we have shown that in our device the FLS mechanism is operative and can be well described by a continuum approximation for the FLL. The orientation of the FLL with respect to the channels abruptly changes when the field-sweep direction is reversed leading to an unusual hysteresis behavior. For the first time oscillations were observed in F_p related to alternating configurations of order and disorder in the FLL. The flow stress, which was directly probed on a microscopic scale, exhibited a reduction of up to 50% due to dislocations. These nanometer-scale devices open new possibilities to study and simulate the mechanical and lattice properties of 2D lattices in general. Our work challenges the theory to further improve the microscopic description of lattice shear.

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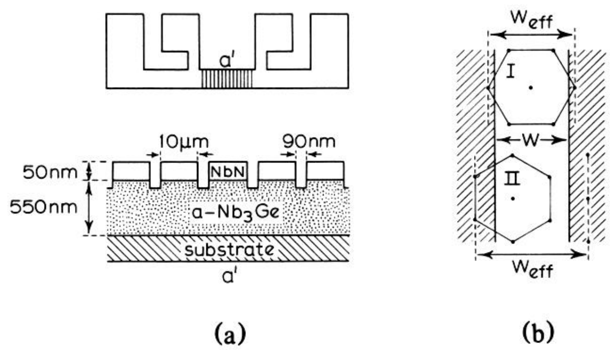
[1]E. van der Drift, S. Radelaar, A. Pruymboom, and P. H. Kes, J. Vac. Sci. Technol. (to be published).

[2]P. H. Kes and C. C. Tseui, Phys. Rev. B **28**, 5126 (1983).

[3]R. Schmucker, Philos. Mag. **35**, 431 (1977).
[4]E. H. Brandt, Phys. Status Solidi B **77**, 551 (1976).
[5]R. Wördenweber, P. H. Kes, and C. C. Tsuei, Phys. Rev. B **33**, 3172 (1986).
[6]E. H. Brandt, J. Low Temp. Phys. **26**, 709 (1977).
[7]C. P. Bean and J. D. Livingston, Phys. Rev. Lett. **12**, 14 (1964).
[8]R. Wördenweber, thesis, University of Leiden, 1987 (unpublished).
[9]E. H. Brandt, J. Low Temp. Phys. **53**, 4171 (1983).
[10]B. L. Walton, B. Rosenblum, and F. Bridges, Phys. Rev. Lett. **32**, 1047 (1974).



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