

## Plastic Motion of a Vortex Lattice Driven by Alternating Current

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We have measured the response of the vortex system in the low  $T_c$  superconductor 2H-NbSe<sub>2</sub> to finite frequency drives. In a well-defined range of fields, temperatures, and driving amplitudes the system exhibits novel nonlinear phenomena. Most strikingly, the vortices can move easily in response to currents that are well below the dc critical current if the direction of the current is reversed periodically while the amplitude  $I$  is kept fixed, but they do not respond to a current that periodically switches between zero and  $I$ , while the direction is kept fixed. Pronounced memory effects associated with these phenomena indicate the presence of dynamically generated structural changes in the vortex array. [S0031-9007(98)07035-5]

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The physics of a vortex array (VA) in low  $T_c$  superconductors is governed by the competition between vortex interactions, which favor the formation of an ordered hexagonal lattice, and pinning by a random distribution of material defects, which favor a disordered VA. Recent work on dynamical transitions that occur when the VA is driven by a current [1–3] has shown that depinning is a complex process that can involve tearing and plastic flow [4–8]. However, while it was shown that the plastic flow is accompanied by an increase in signal noise [9] and that its low frequency response is anomalous [5], little else is known about the ac response in the plastic flow regime.

In this Letter we report the observation of a novel class of phenomena that occur when the VA is driven by alternating currents [10] with amplitudes below the dc critical current, in a region of the phase diagram which has been associated with plastic flow. We find that the vortices move easily when they are shaken back and forth by a current that periodically reverses direction while the amplitude,  $I$ , is kept fixed, but they do not respond to a current that periodically switches between zero and  $I$ , while the direction is kept fixed. Memory effects, which we attribute to dynamically generated changes in VA structure that remain when the drive is shut off, are associated with this behavior. The results appear to be related to plasticity effects in ordinary solids.

In most weak-pinning superconductors, the interplay between interactions and disorder leads to a peak in the critical current  $I_c$  which can be observed as a function of both field and temperature [5,8,11]: increasing  $T$  at fixed  $H$  leads to a sharp rise in  $I_c$  which sets in at  $T = T_m(H)$ , reaches its maximum value at  $T_p(H)$ , and finally goes to zero at the transition temperature  $T_c(H)$  (see Fig. 2). Studies of the dc current-voltage relation [5,8] and noise [9] have revealed that the variation of  $I_c$  in the  $H$ - $T$  plane is linked to the existence of three states of the VA with distinct dynamical properties. For  $T < T_m(H)$

[or equivalently for  $H < H_m(T)$ ], interactions dominate and the vortices form an ordered lattice that responds elastically when driven by a current,  $I > I_c$ . Above  $T_p(H)$ , the system is in a glassy state where the VA is highly disordered. Between  $T_m(H)$  and  $T_p(H)$ , the VA is in an intermediate state in which it behaves like a soft solid that tears when it is depinned. The vortex motion in this state is thought to involve the flow of channels of relatively weakly pinned vortices past more strongly pinned neighbors [5,7,8]. Such channels were also observed in numerical simulations [12]. The term plastic flow is used here to describe the motion in which different regions of the VA flow with different velocities.

The results shown here are for a single crystal sample ( $3 \times 0.6 \times 0.015$  mm) of the low  $T_c$  superconductor 2H-NbSe<sub>2</sub>. This sample was grown by vapor transport from a commercial NbSe<sub>2</sub> powder containing 200 ppm Fe impurities, which leads to a depressed value of the zero-field transition temperature,  $T_c$  of 5.8 K. The results reported here were also observed on two other samples of this material, one of which was grown from a high purity powder and had a  $T_c$  of 7.2 K, which is the nominal value for this material. We focus on results for an impure sample where the peak effect is more pronounced. Measurements were done by the standard four lead technique.

Figure 1 shows the response of the VA to alternating currents with amplitudes that are below the dc critical current ( $I_c = 45$  mA) at  $H = 0.5$  T and  $T = 4.59$  K. The data were taken with a digital oscilloscope and were averaged over many cycles to improve the signal-to-noise ratio. In Fig. 1a, we show the steady state response to a current that switched between  $-30$  and  $+30$  mA (bidirectional pulses). In this case the measured voltage, which is proportional to the velocity of the vortices (averaged over the entire system), is about 30% of what it would be in the free flux flow limit (i.e., in the

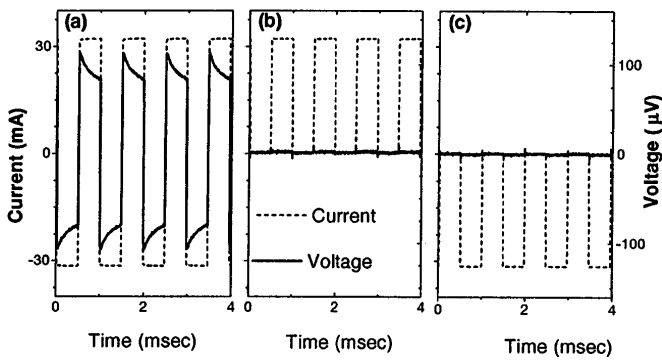


FIG. 1. Steady state response of the vortices at  $H = 0.5$  T and  $T = 4.59$  K to bidirectional pulses (a), positive unidirectional pulses (b), and negative unidirectional pulses (c).

complete absence of pinning). By contrast, when the driving current is switched between 0 and +30 mA or 0 and -30 mA (unidirectional pulses), the response is essentially zero (Figs. 1b and 1c). The tiny voltage spikes that coincide with the current switches are due to pickup between the leads and can be ignored.

A pronounced difference between the response to unidirectional and bidirectional drives is observed only at certain fields, temperatures, and driving currents. The insets of Fig. 2 compare the current-voltage characteristics for a dc drive to those of uni- and bidirectional pulses at 1 KHz for three values of  $T$ . The ac data were obtained with a lock-in voltmeter, which measured the response only at the fundamental frequency of the drive. The raw data for

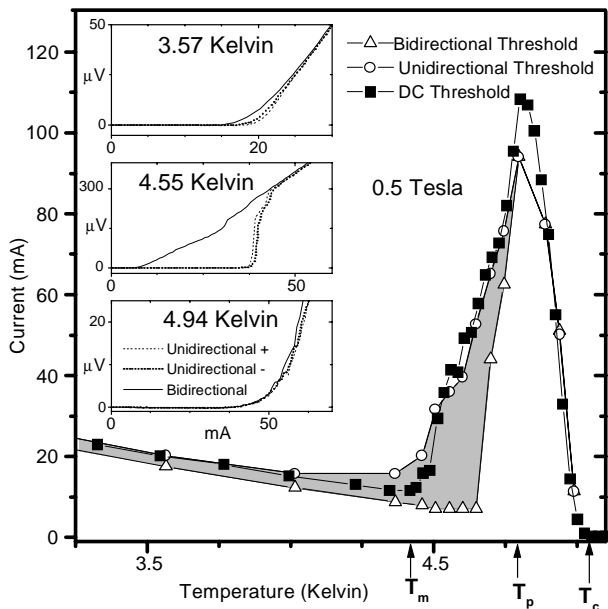


FIG. 2. Main panel: The temperature dependence of the threshold current for unidirectional and bidirectional pulses and for the dc currents. The lines are guides to the eye. The insets show the current-voltage characteristic at three temperatures for each type of pulsed drive.

unidirectional drives were multiplied by 2 to compensate for the fact that the time during which the current is applied is half as long as it is for the bidirectional case. We note that while the response to dc and unidirectional drives is almost the same, the response to bidirectional drives can differ significantly—at 4.55 K, the onset of motion for bidirectional pulses occurs at a current which is 5 times smaller than for the dc and unidirectional case. For the other two temperatures shown, there is little or no difference in the response to the different drives. The region where there is finite response to bidirectional pulses but no response to unidirectional ones is indicated by the shaded area in the main panel of Fig. 2. A large difference between the unidirectional and bidirectional thresholds occurs only between  $T_m(H)$  and  $T_p(H)$ .

We next studied the effects of varying the symmetry of the driving current. The response to changing the symmetry of the drive amplitude is shown in Figs. 3a–3c: an asymmetry in the amplitude (i.e., a larger driving current in one direction than in the other), even when it is small, causes a significant reduction in the response compared with that of the symmetric case. Remarkably, *increasing* the drive in either direction leads to a sharp *decrease* in the response (provided the drive is not too large). A similar reduction in the response is also seen if we add a small dc offset to a symmetric sinusoidal driving current. But simply increasing the amplitude of a symmetric bidirectional drive causes the response to increase.

In Figs. 3d–3f, the effects of varying the temporal symmetry of the pulse are studied while keeping the pulse amplitude symmetric. The pulse duration in each

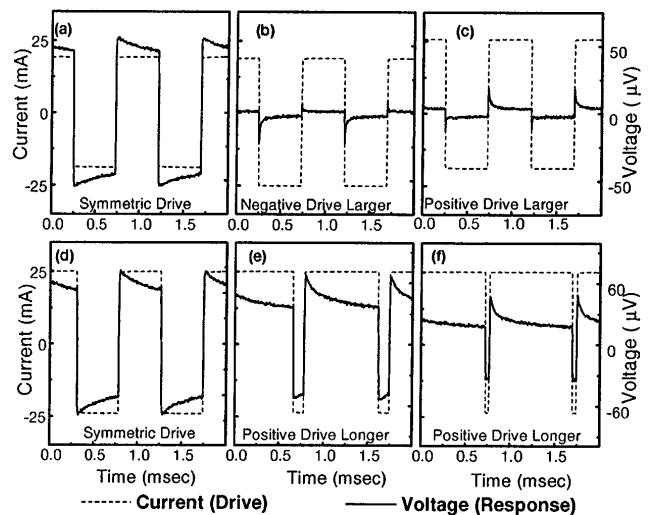


FIG. 3. The effect of changing the symmetry of the driving current. In (a) and (d) symmetric bidirectional pulses are applied. In (b) and (c) the amplitude in one direction is slightly larger. In (e) and (f), the amplitude is the same in both directions, but the positive pulses are longer. All data are for  $T = 4.59$  K and  $H = 0.5$  T.

direction is varied from symmetric (equal pulse lengths) to asymmetric (pulse duration in one direction up to 20 times longer than in the other) while keeping the repeat frequency of pulses fixed. In this case the response is only weakly affected: there is still a substantial voltage when the drive is positive (or negative) 95% of the time. In this case, there is a net flow of vortices, not just back and forth motion. This behavior is reminiscent of the flow of salt in a salt shaker, where the occasional reversal of the force is required to “unjam” the system and maintain the flow. However, this analogy does not work for the amplitude asymmetry effect.

The data shown so far were taken after the response settled to a steady state. If the drive is switched from the bidirectional pulses shown in Fig. 1a to the unidirectional pulses in Fig. 1b, the response takes some time to decay to zero. We studied such transient effects by observing how the response evolves when the drive is changed. For the data in Fig. 4, a +35 mA dc current was first applied for several seconds. Subsequently the current was switched back and forth between +35 and -35 mA several times, after which it was left at +35 mA. We see that initially the response is zero, consistent with the fact that  $I_c > 35$  mA. But a small voltage appears as soon as the direction of the current is reversed, and this voltage jumps up to a larger value on each subsequent reversal. If the bidirectional drive persists the response eventually saturates to the steady state shown in Fig. 1a. The voltage decays somewhat between each reversal. After the drive is switched back to dc the decay continues until the response goes back to zero. The entire pattern shown in the figure repeats exactly, if the current is cycled repeatedly through the sequence: dc, bidirectional pulses, dc.

It is important to note that if the current is set to zero after the vortices are shaken loose with bidirectional pulses, they remain in an “easy to move” state and give a large response as soon as the current is turned back on. (Waiting times of up to one hour were used.) However, when the current is shut off after applying a

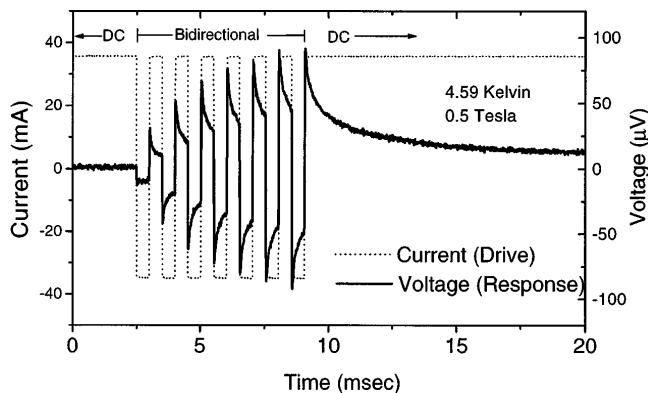


FIG. 4. In this measurement a dc current was first applied for several seconds. Then several bidirectional pulses were applied after which the current was set back to dc.

dc current long enough for the voltage to vanish, the vortices remain in a “hard to move” state and the transient effect shown in Fig. 4 will occur if bidirectional pulses are subsequently applied. The fact that the VA “remembers” how it was driven implies that the bidirectional and dc drives cause distinct changes in its structure that remain when the current is shut off. (Note that the response vanishes instantaneously when the current is set to zero.) Interestingly, the manner in which the response decays after the drive is switched from ac to dc, depends on the driving frequency, indicating that the frequency plays a role in determining the VA structure.

We also studied the frequency dependence of the response for symmetric bidirectional drives (both sinusoidal and square wave), in the range 3 Hz–100 kHz. In the region of the phase diagram bracketed by  $T_m(H)$  and  $T_p(H)$ , for driving amplitudes between the unidirectional and bidirectional thresholds, the response is strongly frequency dependent. The in-phase response exhibits a crossover between a low frequency regime where it is vanishingly small and a high frequency regime where it is a large fraction of the free flux flow value. At the same time the out-of-phase response is negligibly small [13]. The crossover frequency is in the range of  $\sim 1$ –10 kHz and varies with driving amplitude. One could attempt to attribute the crossover to the motion of weakly pinned vortices elastically coupled to more strongly pinned ones. However, in this case there would also be a large peak in the frequency dependence of the out-of-phase response which would be directly related to the storage and release of elastic energy during each cycle [14]. The lack of an out-of-phase response strongly suggests that the motion is plastic. The phenomena described here occur for relatively large currents ( $\geq 0.2I_c$ ) only, where the response is highly nonlinear. By contrast, when very small driving currents ( $I \ll I_c$ ) are used, our previous experiments have shown [15] that the system is linear and that it exhibits the behavior expected for the case of elastic coupling between vortices and pinning centers: a crossover in the in-phase response together with a large peak in the out-of-phase response at a characteristic pinning frequency,  $\omega_p$ .  $\omega_p$  was found to be in the range 1–100 MHz, which is orders of magnitude greater than the frequencies used here.

The results shown above closely resemble plasticity effects which occur in ordinary solids. When stresses greater than the “yield point” are applied to a solid, regions of the material slide past one another, creating permanent plastic deformations. As plastic flow proceeds, an initially soft material (e.g., annealed copper), becomes progressively more difficult to deform and the motion eventually stops (provided the applied stress is not too large). This phenomenon is known as “strain hardening” [16]. The material remains in a hardened state after the applied stress is removed. However, the yield point after strain hardening is typically somewhat anisotropic, i.e., less stress is required to cause plastic flow in the direction

opposite to which the object was deformed during the hardening process. When the stress on a heavily strained hardened material is repeatedly reversed, the material becomes progressively easier to deform: this process is known as “cyclic softening” [16]. Strain hardening is usually associated with an increase in the density of dislocations, whereas cyclic softening involves healing of dislocations and reordering of the lattice.

The behavior of the VA can be interpreted in terms of these plasticity effects. As noted above, there is mounting evidence that plastic flow in the VA involves the formation of channels in which the VA is more ordered and weakly pinned than in the surrounding areas. Since the motion of vortices in the channels requires slippage past the neighboring stationary vortices, the resulting dislocations and interactions between them will play a crucial role [17], just as in ordinary solids. Thus, our results suggest that symmetric back-and-forth shaking of vortices facilitates the formation and growth of easy-flow channels. However, when a unidirectional drive is applied, the response diminishes quickly, indicating that the channels become jammed. This decay of the response resembles the phenomenon of strain hardening in ordinary solids. Since the response is small the first time the direction of the current is reversed after a dc current is applied (Fig. 4), the strain hardening of the VA must be weakly anisotropic. This is consistent with the sensitivity to the symmetry of the driving amplitudes (Fig. 3). For asymmetric drives the larger amplitude pulses lead to jamming of the channels which cannot be completely unjammed by the smaller amplitude reverse drive.

We also note that as the VA moves, there can be substantial change in the degree to which the vortices' positions adjust to the pinning potential [6,8]. However, this alone does not explain the present results.

In summary, we have found that in a well-defined range of fields, temperatures, and driving amplitudes, the VA displays novel types of nonlinear response. In particular, the finite frequency current-voltage characteristics exhibit threshold currents that are much smaller than the dc thresholds. The finite frequency response is extremely sensitive to asymmetry in the driving amplitude. However, the response is insensitive to temporal asymmetry in the drive. The memory effects associated with these results show that dynamically generated changes in the structure of the vortex array are involved. As is the case with ordinary solids, it appears that unidirectional drives tend to disorder the system, while shaking tends to order it. More work is needed, both theoretical and experimental, in order to understand the mechanism leading to these unusual effects of jamming, softening, and plasticity and how they are related to the phase diagram of the vortex lattice.

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