Effects of transport current and columnar defects on the rf penetration depth of NbSe₂

M. Chung,⁎ Y.-K. Kuo, Zhigang Xu, L. E. DeLong, and J. W. Brill
Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055

R. C. Budhani
Materials Science Division, Brookhaven National Laboratory, Upton, New York 11973-5000
(Received 4 April 1994)

We report on simultaneous measurements of the dc critical current and rf penetration depth of superconducting 2H-NbSe₂. We observed that the large peak in the dc critical current (the "peak effect") occurs at the same applied magnetic field H(T) as a maximum in the rf penetration depth, indicating that the anomaly in flux-line dynamics is associated with a change in flux-line pinning strength. The anomalies in the critical current and rf penetration depth disappear in a sample with a high density of columnar defects produced by Ag-ion bombardment; both superconducting and charge-density-wave phase transitions are substantially broadened by the defects.

The study of the pinning and dynamics of magnetic flux lines (FL's) in type-II superconductors has been greatly stimulated by the discovery of high FL mobility in the high-transition-temperature (Tc) cuprates. The observation of reversible magnetization (i.e., unpinned FL's) at temperatures considerably below Tc in the cuprates motivated many of the early dynamic measurements, such as ac susceptibility and vibrating-reed experiments, in which loss peaks were associated with changes in FL pinning. A number of models, such as FL phase transitions and FL diffusion in different directions, were forwarded to explain multiple peaks in dissipation as a function of temperature. The subsequent observation of multiple peaks in other, "low-temperature" superconductors, brings into question explanations that are dependent on the high Tc and short coherence length of the cuprates.

We previously reported on double loss peaks of vibrating reeds (at ~1 kHz) of low-Tc (7.2 K) 2H-NbSe₂ (Refs. 6 and 7) in the mixed state. While this material is a layered conductor [with conducting (a,b) planes], its anisotropy (effective mass ratio mₐ/mₐ,b ~8) is much less than that of the cuprates. Moreover, the resonant frequency of the vibrating reed has an unusual, sharp minimum at a magnetic-field-dependent temperature, Tp(H), between two loss peaks. In subsequent work, we showed that the rf (~1 MHz) penetration depth also has an unusual peak at Tp(H). D'Anna et al.10 showed that these peaks could also be observed with a low-frequency (<1 Hz), large-amplitude torsional oscillator; in a Bean critical-state model,11 their results imply that the extra loss peak coincides with a peak in critical current. In fact 2H-NbSe₂ has been a model system for studying the critical current "peak effect," wherein a peak in Ic is observed as a function of H at a field slightly below Hc₂.12,13 Whereas for most materials, such a peak is only observed for very impure or work-hardened samples,14 the peak is observed readily even for nominally pure NbSe₂.12,13 The conventional model for the peak effect in bulk samples is that it is a consequence of the competing field dependences of the FL pinning strength and FL lattice shear modulus.15 However, as D'Anna et al.10 point out, one would therefore not expect to see the peak as a function of temperature at fixed field, and they suggest that the latter is a consequence of the anisotropy of NbSe₂.

On the other hand, similar anomalous features in the rf penetration depth and vibrating-reed response were not observed for crystals of 2H-NbSe₂,8 which is very similar in transition temperature [Tc = 6.5 K (Ref. 16)] and morphology to 2H-NbSe₂ but is even more anisotropic (mₐ/mₐ,b = 64);9,10 therefore, explanations of the peak effect in the selenide (and cuprates) which depend only on their anisotropy cannot be complete. We previously suggested that the differences in FL pinning between NbSe₂ and NbSe₂ may be a consequence of the existence of a charge density wave (CDW) in the former8,17 and its absence in the latter.8,16 The CDW charge oscillations (with wavelength ~10 Å) should be "invisible" to the superconducting vortices [with normal core radii, ξa,b ~ 80 Å (Ref. 9)]. However, the CDW in NbSe₂ is slightly incommensurate [1 - 3q/a* = 0.011 (Ref. 9)] with the lattice, and so is expected to have a domain structure with incommensurate regions of length a/0.011 = 310 Å separated by "discommensurations."16 These CDW defects may affect the pinning of FL's, especially if they are aligned on neighboring layers forming an extended defect, and indeed may explain why the peak effect is so prominently observed in NbSe₂.

In this paper, we report on measurements of the dc critical current and rf penetration depth of crystals of NbSe₂. Because of the sample and history dependence of anomalous effects,1 both quantities are measured on the same sample simultaneously. We establish that the peak in rf penetration depth (as a function of H) coincides with the peak in dc critical current, as suggested by D'Anna et al.10 We also present results on crystals of NbSe₂ that underwent heavy-ion (Ag⁺) bombardment, which produces columnar defects (~||c) that should strongly pin the FL's. In these crystals (i) no peak in rf penetration depth is observed, although there is unusual structure in the penetration depth at small H, and (ii) the superconducting and CDW phase transitions are substantially broadened, as determined by measurements of the specific heat.
$2H$-NbSe$_2$ powder was grown by heating stoichiometric mixtures of the elements in vacuum. Crystals were grown from the powder by iodine vapor transport. Crystals have a micaceous morphology and are easily cleaved along $c$, but for this study only as-grown (noncleaved) crystals with non-visible cracks or defoliations were used. Typical crystal sizes were 4 mm $\times$ 2 mm $\times$ 10 $\mu$m.

The penetration depth was measured by inductively coupling the sample to an 800-kHz tank circuit and measuring the change in resonant frequency, $\Delta f$. While the orientation of the crystal could be varied with respect to an applied dc magnetic field, the ac field of the tank circuit ($\sim$ 1 Oe) was always parallel to the $c$-axis. The change in penetration depth is proportional to $-\Delta f$. For resistance and critical-current measurements, four contacts were attached to the sample with silver paint, but the sample remained in the tank circuit. The criterion used for the critical current was that $V = 550 \pm 100$ nV ($\sim 500 \mu A \times R_{\text{normal}}(T_f)$), but the results were not sensitive to this choice.

Relative changes in the tank circuit resonant frequency, $\Delta f_{\text{rf}}/f$, for two crystals measured in field sweeps (increasing field) with zero current at 4.5 K are shown in Figs. 1(a) and 1(c). [Prior to studying the variation with dc current, we established that the maxima in $-\Delta f$ (i.e., in penetration depth) in field sweeps occur at the same $H(T_f)$ as measured in temperature sweeps, such as those shown in Ref. 8.] Also shown are the critical currents, $I_c$, measured immediately afterward and the changes in resonant frequency, $\Delta f_r$, measured in the presence of $I_c$. $|\Delta f_r| < |\Delta f_0|$, reflecting the weaker FL pinning in the presence of current. However, although broader and weaker, the maxima in $-\Delta f_r$ occur at the same fields as those in $-\Delta f_0$, indicating that the mechanism which causes the anomalous changes in the pinning of oscillating FL's still occurs when they are moving; e.g., during part of the rf period (1.25 $\mu$s) the FL's are effectively pinned (as is the case for flux creep). Furthermore, except for a small shift to lower field for sample II, consistent with estimates of Joule heating, the peaks in $I_c$ occur at the same field as the maxima in $-\Delta f_r$; i.e., the anomaly in FL dynamics indeed coincides with the change in FL pinning strength. This identification is a strong indication that these dynamic anomalies cannot be due to simple FL diffusion, for which $H(T)$ should be frequency dependent.

The peak effect in this material was also observed as a
function of magnetic field by other authors. Interestingly, our peak in $I_c$ is much sharper than that previously published and its magnitude is temperature independent [see Fig. 1(b)]. At low fields, we observe that the pinning force $F_p(\sim H)$ is roughly proportional to $H^{1/2}$ [see Fig. 1(d)], as suggested by the two-dimensional collective pinning theory. The critical-current peak effect is generally associated with a rapid change in the shear modulus ($C_{66}$) of the FL lattice, while the vibrating-reed response and rf penetration depth are usually assumed to depend on its compressional ($C_{11}$) and tilt ($C_{44}$) moduli. The fact that anomalies occur for all quantities at the same $H(T_F)$ indicates that all moduli are affected by the anomalous interaction (e.g., from the CDW discommensurations). We previously pointed out that $dH/dT_F \approx dH/dT_c$ (between 0.2 and 1.4 T); it is curious that an anomaly ($T_F$) presumed to be due to an extrinsic pinning mechanism so closely tracks an intrinsic thermodynamic phase boundary.

Of course, questions still remain regarding what kind of impurities or defects pin the FL's and why the peak effect occurs so prominently in NbSe$_2$. In order to understand the microscopic mechanism of the peak effect, it is desirable to examine samples with different types of defects. Unfortunately, our attempts to dope crystals (with tantalum or excess niobium) resulted in multiphase material. Instead, crystals were irradiated with 276-MeV Ag ions at Brookhaven National Laboratory. The ion beam was incident at 2° off the sample normal ($c$). Heavy-ion irradiation usually creates amorphous tracks (columnar defects with a radius $\approx 60 \, \text{Å}$) along the ion paths through the material. The expected ion range is $\approx 13 \, \mu\text{m}$, comparable to the sample thickness. The ion bombardment fluence $\approx 4 \times 10^{11} \, \text{cm}^{-2}$, corresponding to an average defect separation $\approx 160 \, \text{Å}$ and a matching field, for which the FL density would equal the defect density, $\approx 8 \, \text{T}$, much greater than the fields we investigated. The ion bombardment decreased the residual resistivity ratio of the NbSe$_2$ crystals from 30 to 19.

The dc critical current vs magnetic field at 4.5 K for an irradiated crystal is shown in Fig. 2(a); strikingly, no peak effect is observed. Similarly, there is no peak in RF penetration depth; in Fig. 2(b), we plot $\Delta \phi$ measured in temperature sweeps for several fields $\bf H$[c]. (Also, no peaks were observed for $\bf H \parallel c$.) The critical current density is an order of magnitude larger than for undamaged samples, indicating that there is no significant fraction of undamaged material. These results are consistent with strong pinning of the FL's by the defects, as recently observed with scanning tunneling microscopy. The critical current decreases monotonically with field, but with a negative curvature, similar to that observed for heavy-ion irradiated high-$T_c$ materials, and unlike the undamaged sample, as shown in Fig. 1.

Note [Fig. 2(b)] that two steps in the penetration depth are observed in zero field, but become unresolved with increasing field. These steps are also observed in the temperature dependence of the resistance and are under further investigation. The specific heat of the irradiated sample shown in Fig. 2 was subsequently measured using ac calorimetry. As shown in Fig. 3(b), there is a single, “structureless” broad maximum in specific heat, as compared to a sharp peak for a pristine crystal [Fig. 3(a)], indicating that the defect disorder greatly broadens the transition, as expected, but reveals no clear evidence for multiple superconducting phases (or a significant fraction of undamaged material).

We previously hypothesized that the anomalous penetration depth was caused by an interaction of the FL's with the discommensurations of the CDW. Because the discommensuration spacing is comparable to the defect spacing, we expect the CDW to be strongly perturbed by the radiation damage. Surprisingly, the resistance has a small peak near 30 K.
(the CDW transition temperature) similar in appearance to that of undamaged crystals, as shown in Fig. 4, indicating that the CDW still exists. Apparently, however, the interaction of the damage tracks with the FL's now dominates their pinning. Figures 3(c) and 3(d) show the temperature dependence of the specific heat near the CDW transition. While the undamaged sample has a mean-field-like peak near 30 K, such a peak is absent for the radiation-damaged sample. Instead, there is a small (history-dependent) drop in specific heat when cooling through the transition, suggesting that the CDW gap changes relatively slowly with temperature (i.e., it is broadened). This broadening may reflect large strains in the discommensuration structure caused by the dense columnar defects.

In summary, we measured the dc critical current, rf penetration depth, and specific heat of crystals of $2H$-NbSe$_2$ before and after inflicting heavy-ion radiation damage. In simultaneous measurements in the pristine samples, we found that peaks in the rf penetration depth coincide with peaks in critical current, as suggested by D'Anna et al. Both anomalies are gone for irradiated crystals, consistent with strong pinning of the flux lines by the columnar defects.

This research was supported in part by the National Science Foundation, Grant No. EHR-91-08764.

---

*Present address: Department of Physics and Astronomy, Kinard Laboratory of Physics, Clemson University, Clemson, SC 29634-1911.