Effects of charge-density-wave depinning on the elastic properties of $NbSe_3$

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Detailed measurements on the dc-voltage dependence of the Young's modulus E, shear modulus G, and their associated internal friction, in $NbSe_3$ below both charge-density-wave (CDW) transitions, are reported. As for TaS_3 [Phys. Rev. B **36**, 2969 (1987)], the moduli decrease when the CDW becomes depinned, with the relative change in G an order of magnitude greater than that in E. However, the changes, which are typically 2 orders of magnitude smaller for $NbSe_3$, are much sharper functions of voltage. Most surprisingly, the total magnitudes of the modulus changes are correlated with the threshold depinning field, and the internal friction associated with G (and with E in the lower CDW state) is less when the CDW is depinned than pinned. ac-induced softening of G, but not E, for voltages well below threshold is also observed. The implications of these results on various models of CDW depinning are discussed.

I. INTRODUCTION

During the past decade, the physics of charge-density-wave (CDW) depinning and motion has been extensively studied.[1,2] When a voltage $V > V_T$, the threshold for CDW depinning,[1] is applied to the sample, the resistance drops as the CDW contributes to the conductivity. Most experiments and theories have concentrated on the unusual electronic transport properties exhibited in this depinned state, and most observed phenomena have been explained in the context of both a quantum-tunneling model[3] and models treating the CDW as a classical deformable medium.[4]

In the last few years, there have also been a number of experiments showing that the elastic properties of CDW conductors are also affected by CDW depinning;[5-11] in particular, the elastic moduli decrease for voltages above threshold. Modeling these results has proven difficult due to the need to couple the CDW and lattice many-body systems. Recently, a few theories,[12-15] based on the classical deformable model, have been successful in describing results for the Young's modulus of TaS_3, the most extensively studied mode.[5,8,9]

$NbSe_3$ is a filamentary quasi-one-dimensional conductor (with high conductivity along the crystallographic $\hat{\mathbf{b}}$ axis); it has two independent CDW transitions, at $T_1 = 142$ K and $T_2 = 58$ K, and is the only CDW conductor which remains metallic below the CDW transitions.[1] The observed Young's modulus anomalies in $NbSe_3$ are two orders of magnitude smaller than that in TaS_3,[6,8] which, coupled with the more formidable Joule heating problems encountered due to the metallic conductivity, have made this compound more difficult to study quantitatively; however, the small observed anomalies are difficult to understand in the context of "conventional" classical models based on the decoupling of the CDW elastic response from that of the lattice,[12-14] as discussed below. Furthermore, we recently observed that the anomaly in the shear modulus of TaS_3 ($\sim 20\%$) is an order of magnitude larger than that in the Young's modulus,[11] implying that interchain coupling is greatly affected by CDW motion, an issue not addressed by such models, which consider the change in elastic constant of single chains. The large size of the shear anomaly in TaS_3 also poses a problem for an alternative "screening" model, recently proposed by Maki and Virosztek (MV).[15]

We have now quantitatively studied both the shear and Young's moduli of $NbSe_3$, and their associated internal friction, as functions of voltage below both transitions. In addition to large quantitative differences with TaS_3 (the anomalies for both moduli are two orders of magnitude smaller), there are interesting qualitative differences, to be described below. Most surprisingly, the magnitudes of the anomalies are strongly sample dependent, seemingly correlated to the threshold electric field, which may be explainable in terms of the MV model.[15]

II. EXPERIMENTAL METHODS

The Young's modulus and shear modulus were measured using the vibrating reed techniques described in Refs. 5(b) and 11. Flexural and torsional vibrations were excited and detected in long crystalline samples (typical dimensions 4 mm$\times$20 μm$\times$5 μm) using capacitively coupled electrodes. The Young's modulus along the chain ($\hat{\mathbf{b}}$) direction E is related to the fundamental flexural resonant frequency by[5]

$$E = A_1 \rho f_E^2 , \quad (1)$$

where A_1 is a constant that depends on the sample geometry and ρ is the density. Typically, $f_E \sim 1$ kHz. For measurements of the shear modulus, G (an unknown weighted function of c_{44} and c_{66}),[11] a stiff wire "flag" is attached to the center of the sample (with silver paint) and torsional vibrations were excited; G is related to the fundamental torsional resonant frequency by[11]

$$G = A_2 I f_G^2 , \quad (2)$$

where A_2 depends on the sample geometry and I is the moment of inertia of the flag. Typically, f_G was between 20 and 200 Hz. Thus relative changes in both moduli can be measured very precisely as functions of temperature or electric field (i.e., voltage across the sample). The quality factor Q of each resonance can also be precisely measured;[5(b)] changes in internal friction for the two modes, i.e., $\Delta(1/Q)$,[16] with voltage can be found by monitoring the amplitude of the resonances.

Of course, studying the voltage dependence of these properties necessitates putting leads on both ends. This complicates measurements of the Young's modulus because Eq. (1) only applies if negligible uniaxial stress (e.g., from differential thermal contraction) is present,[5]

$$\sigma < (t/L)^2 E \ , \tag{3}$$

where t is the sample thickness and L the length. For typical sample dimensions, this implies differential thermal contraction $\Delta L < 100$ Å. In past work,[5(b)] σ was kept small by having one end of the sample inertially, but not rigidly, clamped to a lead. In the present set of experiments, we attempted to measure changes in E and G on the same samples; since the flag would excessively bend a sample not rigidly clamped on both ends, it was necessary to mount the sample in a rigid, but "stress-free" configuration. This was accomplished by gluing the sample's ends down, with conducting silver paint, in a rigid composite sample holder with portions made of different materials chosen to roughly match the thermal contraction of $NbSe_3$ (above 100 K).[17] Such successful mounting, needed for *quantitative* measurements of the change in Young's modulus, was achieved in several samples, and was determined by comparing the measured temperature dependence of the flexural resonant frequency ($\Delta f_E/f_E = 0.5\,\Delta E/E$) with previous measurements on samples clamped on only one end.[18] The temperature dependence of E of one such clamped-clamped sample near T_1 is shown in Fig. 1; it agrees fairly well with the "clamped-free" data of Ref. 18; e.g., the minima at T_1 are similar in magnitude (i.e., they agree within 50%).

The typical experimental procedure was therefore to first mount a clamped-clamped sample, without a flag, and measure the temperature dependence of the Young's modulus to verify the absence of large uniaxial stress. The voltage dependence of the sample's dc resistance R (to determine the CDW depinning threshold), resonant flexural frequency, and quality factor would then be (simultaneously) measured below the two CDW phase transitions, typically at 102 and 50 K. Although two-probe dc measurements of the resistance were usually adequate to determine the CDW threshold voltage (to a few percent), in some cases measurements were checked with pulsed I/V measurements.[1] The flag would then be mounted, at which time both flexural and torsional modes could be observed, and distinguished by their different phase shifts.[11] To avoid measurement on "mixed" modes, however, the sample would be pulled slightly; the uniaxial stress would cause the flexural resonant frequency to increase drastically (e.g., by an order of magnitude), but have a very small effect on the torsional mode (see below). The temperature dependence of G and voltage dependence of R, G, and $1/Q$ would then be measured.

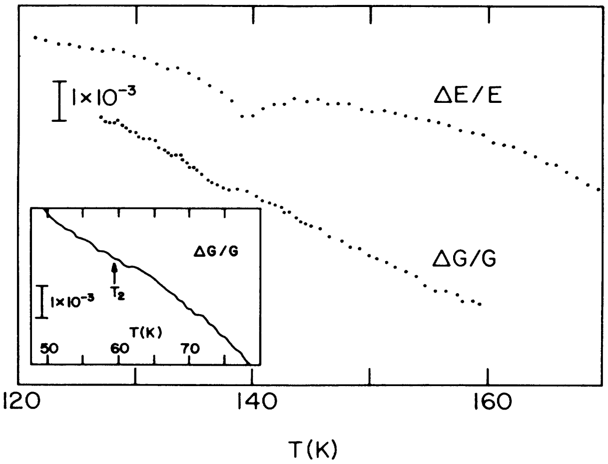

FIG. 1. Temperature dependence of the shear modulus G and Young's modulus E for a clamped-clamped sample near $T_1 = 142$ K. Inset: The temperature dependence of G near $T_2 = 58$ K.

The ability to use stress to avoid "mode mixing," and to separate the flexural from the torsional modes is demonstrated in Fig. 2. The voltage dependence of G and its internal friction, for an "unstressed" sample at 102 K, are shown. The sample was then stressed, which caused its flexural resonant frequency to increase by more than an order of magnitude; the threshold field increases by 50%, corresponding to a uniaxial stress of $\sigma \sim 1$ GPa (Ref. 19) and a length change of $\Delta L \sim 20$ μm. In this case, f_E depends predominantly only on the uniaxial

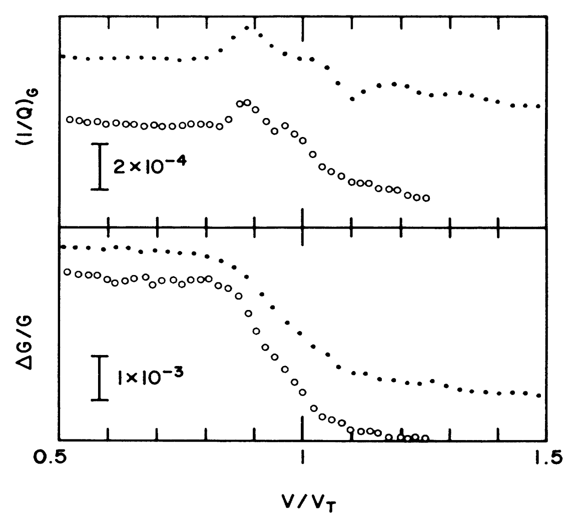

FIG. 2. Voltage dependence of shear modulus and internal friction for a sample (no. 1) at 102 K with no applied stress (closed circles, $V_T = 110$ mV) and ~ 1 GPa applied stress (open circles, $V_T = 155$ mV). The vertical offsets are arbitrary.

stress and, as shown in Fig. 5 of Ref. 5(b), no flexural anomalies can be observed. On the other hand, as shown in Fig. 2, the torsional anomalies, when the voltage is scaled to the new threshold value, are unaffected by the stress. Due to the insensitivity to thermal contraction, results on the absolute magnitude of the shear modulus anomaly are considered quantitatively more reliable than those of the Young's modulus.

Due to the metallic conductivity of $NbSe_3$, Joule heating of the sample can be a significant problem, even at voltages near threshold, and the true voltage dependence of the moduli and internal friction can be totally masked by their temperature dependences. The correction technique used for TaS_3, i.e., treating the temperature- and voltage-dependent shifts as independent perturbations, therefore did not work for $NbSe_3$. However, we found that if the measurements were taken in a sufficiently high pressure of helium gas, sample heating could be avoided. An example is shown in Fig. 3, in which the measured change in Young's modulus with voltage at 102 K is compared for pressures of 5 and 250 torr. At the low pressure, the modulus decreases approximately quadratically with voltage (i.e., linearly with Joule power), with no clear sign of a threshold. At high pressure, all the change is observed near threshold, indicating that it is due to the CDW depinning, and not heating. Unfortunately, using pressures this high greatly reduced the quality factors of flexural modes (to <200) and consequently our precision; the quality factors (~ 100) of the torsional modes were not strongly affected by these pressures. Quantitative differences between our results and those reported by others[6,8] may be due to significant Joule heating being present in their experiments.

Bourne, Sherwin, and Zettl[8] (BSZ) have reported that the Young's modulus has surprising effects from ac and joint ac and dc electric fields as well as dc alone. In some experiments, we therefore simultaneously applied ac (100 Hz–10 Mhz) or joint ac and dc voltages to the sample. The differential conductivity dI/dV could be measured in these experiments (see Fig. 7, below) by the lock-in detection of the current caused by an additional small (3 mV) low-frequency voltage. While these techniques are quite common,[1] we mention them to point out that, unlike most other work,[1] our experiments are voltage rather than current driven, i.e., we measured dI/dV, not dV/dI.

Experiments were done on crystals grown in a few growth tubes at the University of Kentucky and the University of Illinois, using conventional vapor-transport techniques,[1] starting from niobium metal of modest purity (i.e., 100 to 2000 ppm impurity levels).

III. DISCUSSION OF RESULTS

The temperature dependence of the shear moduli at the two transitions, together with that for the Young's modulus at T_1, are shown in Fig. 1. No changes in shear modulus, either a fluctuation-driven minimum[20] or an increase due to decreased screening,[18,21] as discussed below, are observed at either transition, $|\Delta G/G| < 2\times 10^{-4}$. The much stronger temperature dependence observed for TaS_3,[11] $\Delta G/G \sim 5\%$, is analogous to the results for the Young's modulus.[18]

Complete sets of data on the voltage dependence of the moduli, internal friction, and resistance for two (University of Kentucky) samples are shown in Figs. 4 and 5. The voltages are normalized to the thresholds as determined (within a few percent) from the resistance measurements. At 102 K, below the upper transition, both moduli start to decrease at a voltage $V_{on} \sim (0.8-0.9)V_T$, and saturate at a voltage $V_{sat} \sim (1.1-1.3)V_T$. The shear modulus drops are always a factor of 2–10 times larger than those of the Young's modulus, but similar in shape, as for TaS_3.[11] Similar results are obtained at 50 K, below T_2, with a somewhat broader distribution in V_{on} and V_{sat} ($V_{on} > 0.7V_T$ and $V_{sat} < 1.6V_T$). For a given sample and mode, the magnitude of the anomaly below T_2 is 15–30% of that below T_1. It is important to note that the changes in shear modulus with voltage greatly exceed any possible anomalies at the transition temperatures (Fig. 1).

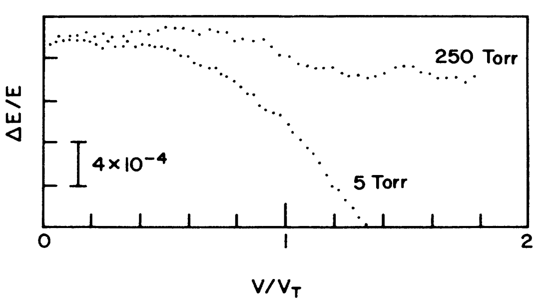

FIG. 3. Measured voltage dependence of the Young's modulus at 102 K for sample no. 1 in two different pressures of helium gas.

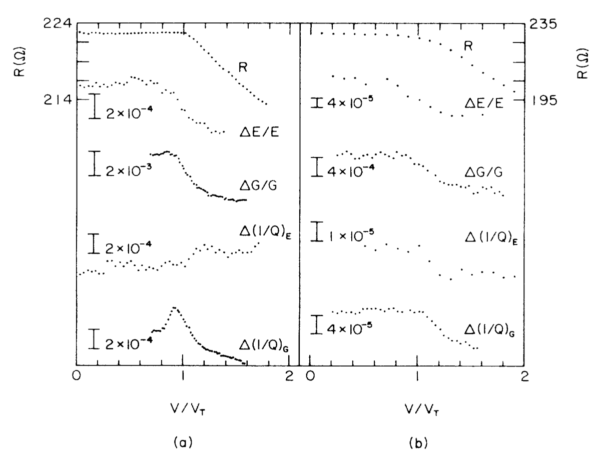

FIG. 4. Voltage dependence at (a) 102 K and (b) 50 K of the resistance R, the shear modulus G, its internal friction $\Delta(1/Q)_G$, the Young's modulus E, and its internal friction $\Delta(1/Q)_E$ for sample no. 1. Vertical offsets for moduli and internal friction are arbitrary.

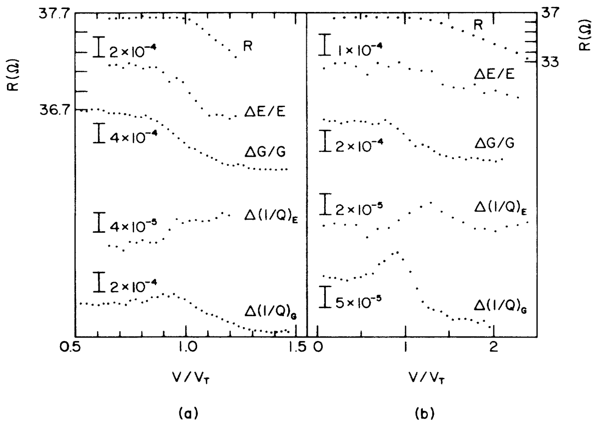

FIG. 5. Voltage dependence at (a) 102 K and (b) 50 K of the resistance R, the shear modulus G, its internal friction $\Delta(1/Q)_G$, the Young's modulus E, and its internal friction $\Delta(1/Q)_E$ for sample no. 2. Vertical offsets for moduli and internal friction are arbitrary.

The modulus anomalies are much sharper than in TaS_3, for which saturation is only observed at $\sim 10V_T$.[5(b)] Also, in TaS_3, only very small changes in moduli ($<10^{-3}$ of the total changes[5(b),11]) were observed below threshold, whereas in $NbSe_3$ roughly half the softening occurs below threshold. Thus, in $NbSe_3$, the softening seems more associated with the CDW depinning that its subsequent motion, and, apparently, the CDW becomes depinned (and polarized[1,2]) in many domains before a conducting channel appears at V_T. In TaS_3, on the other hand, polarization forces are larger, due to the lack of metallic electron screening, so that a conducting channel appears quickly, but the slow saturation of modulus at voltages above threshold may reflect the fact that many domains stay pinned up to high voltages (i.e., poor transverse coherence of the CDW), as discussed by MV.[15]

Results for the internal friction are also shown in Figs. 4 and 5. Below T_1, the internal friction associated with the flexural mode behaves as for TaS_3, with $1/Q$ increasing abruptly by 10–30 % of $|\Delta E/E|$; this small value implies that at least two relaxation times, with one much less than the oscillation period, are needed to describe the internal friction.[5(b),9] On the other hand, the internal friction associated with the torsional mode, after reaching a peak $[(1-2)\times 10^{-4})]$ slightly below V_T, falls rapidly so that the internal friction in the depinned state is *less* than that in the pinned. The net decrease is again 10–30 % of the shear modulus anomaly. The peak in $1/Q$ seems to fall below V_T, as determined from resistance measurements, and it is not clear if it should be associated with critical damping;[22] it is more likely that it is a consequence of two competing mechanisms affecting the damping in opposite ways.

Below T_2, $(1/Q)_G$ also decreases, again an order of magnitude less than the shear modulus itself, at threshold; for most samples, no peak is observed (i.e., the behavior of sample no. 1 is more typical than that of no. 2). Changes in $1/Q$ for the flexural mode, where the relative change in quality factor is only $\sim 0.1\%$, are difficult to resolve due to drifts in the detection electronics and sample and electrode mounts (e.g., creep in the silver paint), but appear to be similar (but smaller) to those for the torsional mode; i.e., as shown for sample no. 1 (Fig. 4), the internal friction decreases monotonically with voltage. The peak shown in Fig. 5 for sample no. 2 was not reproducible, and the scatter may be taken as an upper limit to the anomaly for this sample;

$$|\Delta(1/Q)_E| < 2\times 10^{-5} \sim 0.15|\Delta E/E| \ .$$

In Ref. 8(b) it was reported that there are large ($\sim 5\times 10^{-3}$) *increases* in the internal friction for the flexural mode below T_2, but no threshold was observed, and it is possible that those results were dominated by Joule heating, as mentioned above. The net decreases in internal friction which we observe for the shear modulus when depinning both CDW's, and for the Young's modulus for the lower temperature CDW, are the first observations of less damping in the depinned CDW state than the pinned, and contradict general intuition (e.g., see the discussions in Refs. 13 and 14).[23]

As discussed above, it is generally easier to get quantitative measures of the total magnitude of the elastic anomaly for the shear modulus than for the Young's modulus, due to the effect of uniaxial strain in changing the flexural resonant frequency. In Fig. 6 we plot the total change in shear modulus (i.e., $[G(0)-G(\infty)]/G(0)$ versus the threshold electric field for several samples below both transitions). Although there is considerable scatter, it is seen that the size of the shear anomalies are roughly proportional to the threshold fields. (In view of

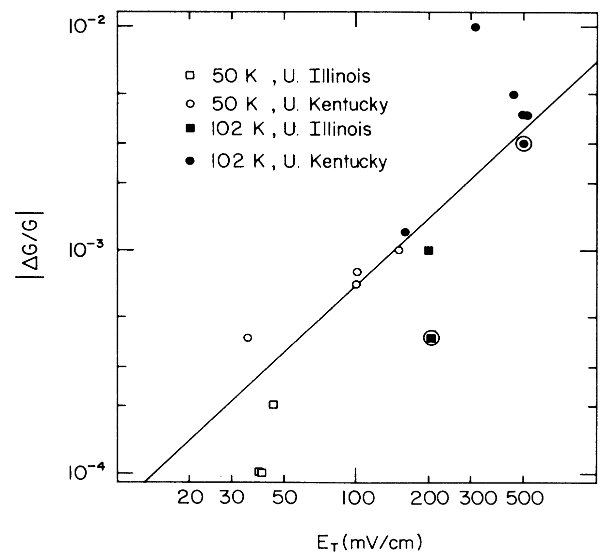

FIG. 6. Total shear anomaly $[G(0)-G(\infty)]/G(0)$ vs threshold electric field. The latter are not corrected for uniaxial stress or the presence of the conducting flag in the center of the sample, so E_T may be overestimated by up to 50%. The line of slope 1 is for reference only. Results for both CDWs are shown. Interference spectra for the circled samples are shown in Fig. 7.

the scatter, systematic errors in determining the threshold field due to the presence of the flag and uniaxial stress are not significant. Some scatter is, of course, expected because the dependence of G on c_{44} and c_{66} will vary with sample geometry.) It is also striking, although perhaps coincidental, that the data for the two transitions fall on the same line. Although we have quantitative data for fewer samples, a similar trend holds for the Young's modulus. While these results seem to support the intuitive idea that the same impurities and defects which pin the CDW couple the CDW to the phonon, "conventional" CDW decoupling models[12–14] find that the total anomaly in the (Young's) modulus is independent of the pinning field [see Eq. (4) below]. It would be interesting to continue these studies with doped or irradiated samples, having larger threshold fields,[1] although such experiments will be difficult due to the larger amount of Joule heating that will be encountered. (We note that recent studies of the effects of radiation damage on the Young's modulus of TaS_3 have indicated *no* increase in the elastic anomaly with damage.[24])

Given the considerable scatter in Fig. 6, it may be that the magnitude of the elastic anomalies are correlated with properties of the CDW other than threshold field, such as lack of velocity coherence in the depinned state.[5] The quality of the "Shapiro-step" interference spectrum, i.e. minima in the differential conductivity (dI/dV) as functions of dc bias in the presence of a fixed ac (at typically a few Mhz) field, is considered indicative of the velocity coherence of the CDW, with perfect mode locking

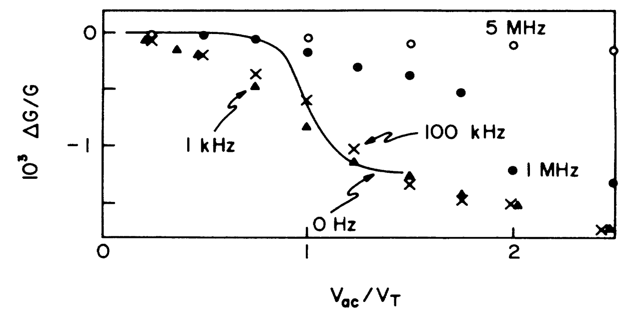

FIG. 8. Change in shear modulus (from its zero-voltage value) for sample no. 2 at 102 K as a function of ac voltage V_{ac}, normalized to the dc threshold, at different frequencies.

(i.e., dI/dV reaching its low-field value for finite intervals of V_{dc}) observed in coherent crystals.[1,25(a)] Indeed, the samples we obtained from the University of Illinois were from a growth tube from which unusually coherent samples, of several mm length, were found in the high-temperature CDW state,[25] although the samples we used were not specially handled or selected to insure this property.[25(b)] "Maximized" interference spectra for two samples (circled in Fig. 6) at 102 K are shown in Fig. 7; similar spectra were obtained for all samples in both CDW states. Although mode locking did not occur, large negative peaks, generally within a factor of 2 of the zero bias step, were observed. Although not of the quality of the spectra reported by Thorne *et al.*,[25(a)] these spectra are better than generally observed for samples greater than 1 mm long, especially at the upper CDW transition[1] and in view of the conducting "flag" in the center of the sample. All the samples are therefore considered as having reasonably coherent CDW states, and

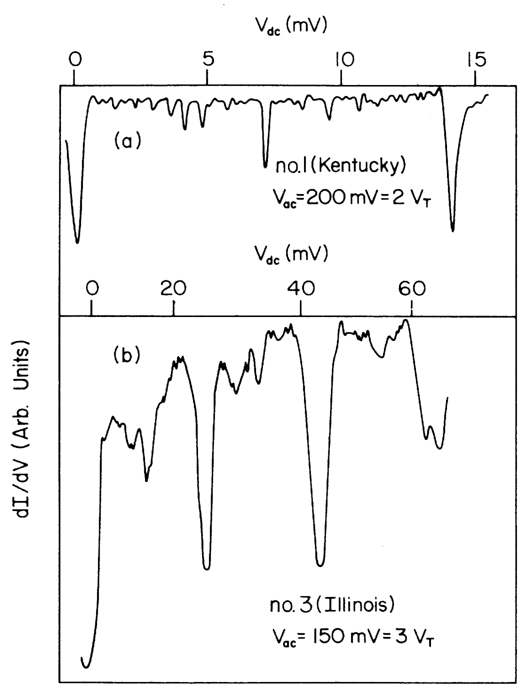

FIG. 7. Shapiro-step interference spectra, dI/dV vs V_{dc}, for the two samples circled in Fig. 6. Both spectra were taken at 102 K at a frequency of 2 MHz.

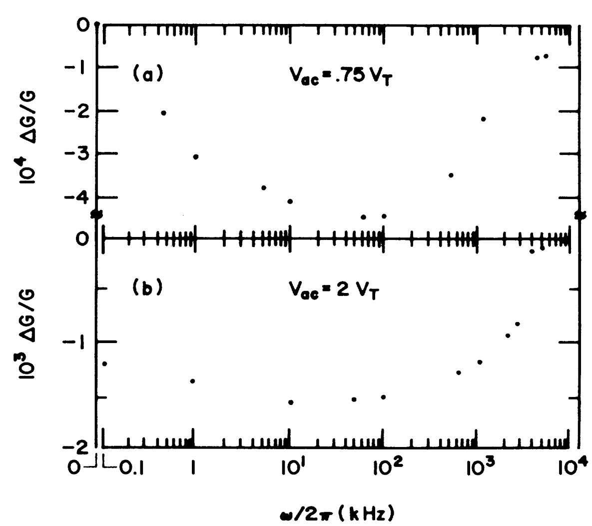

FIG. 9. Vertical cuts through Fig. 8 at (a) $V_{ac}=0.75V_T$ and (b) $2V_T$.

the presence of a larger number of domains, with strained boundaries giving rise to the elastic anomalies,[5] is now considered unlikely.[24] In particular, no correlation between the magnitude of the elastic anomalies and the quality of the interference spectra was found.

Bourne *et al.*[8] reported that, accompanying the interference features in the conductivity under the combined action of the dc and rf fields, interference features could be observed in the Young's modulus and internal friction of a few samples of TaS_3 and $NbSe_3$ (below T_1); in particular, on the Shapiro steps the Young's modulus and internal friction approached their low-voltage (i.e., pinned) values. We have looked for such features, without success, for both moduli in $NbSe_3$; it would have been especially interesting to see if the internal friction reverses itself at a Shapiro step for the torsional mode. We note that our samples were a few times longer, making observation of interference features more difficult, than those successfully observed by BSZ.[8]

Bourne *et al.*[8] also reported that ac fields alone affected the Young's modulus of TaS_3.[8] For applied voltages $V(t)=V_{ac}\sin(\omega t)$ with $V_{ac}>V_T$, the Young's modulus decreases from its zero field value, with $|\Delta E|$ a monotonically decreasing function of ω. However, decreases in modulus were also observed for $V_{ac}<V_T$, with $|\Delta E|$ having a maximum at a frequency <1 MHz.

We have repeated these measurements for both modes in $NbSe_3$ below T_1. In Figs. 8 and 9, results are shown for the shear modulus; the results are qualitatively similar to those of the Young's modulus of TaS_3 described above. For a given excitation frequency ω, G decreases with increasing voltage V_{ac} (Fig. 8). For $V_{ac}=0.75V_T$ [Fig. 9(a)], G has a pronounced minimum between 50 and 100 kHz, and goes to its zero voltage value for frequencies above 10 MHz and below ~ 100 Hz. For $V_{ac}=2V_T$ [Fig. 9(b)], the softening also decreases rapidly to zero for frequencies above 100 kHz; a weaker, partial decrease is also observed for frequencies below 10 kHz. Results for the Young's modulus are shown in Fig. 10. For ac voltages above threshold, the results are again similar; however, for voltages $V \lesssim 0.9V_T$, where the dc anomaly goes to zero [see Fig. 5(a)], *no* softening is observed for any frequency. Thus, as previously seen in the dc voltage dependence of the internal friction, there are qualitative differences in the behavior of the shear and Young's moduli. The *shear* modulus of $NbSe_3$ seems to behave in this regard like the *Young's* modulus of TaS_3.

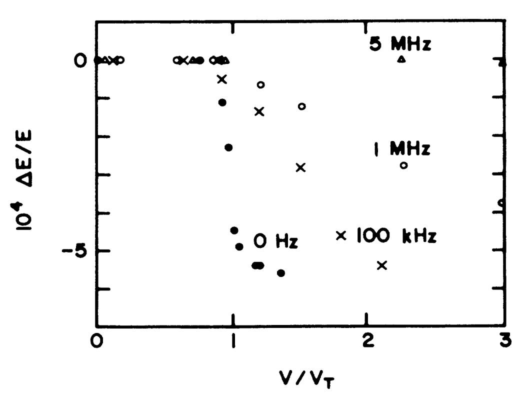

FIG. 10. Change in Young's modulus (from its zero-voltage value) for sample no. 2 at 102 K as a function of ac voltage V_{ac}, normalized to the dc threshold, at different frequencies.

IV. DISCUSSION OF MODELS

Most descriptions of CDW depinning[1,2,4] start from the Fukuyama-Lee-Rice[26] model of a classical, elastic CDW, with modulus K_{FLR}, deformed by the collective action of weakly pinning impurities. It has been argued that the change in Young's modulus with CDW depinning reflects the decoupling of the CDW elastic constant from that of the lattice.[6,12-14] This argument was supported by the fact that the calculated value[5] of the CDW elastic constant for TaS_3

$$K_{FLR}=hk_f^2 v_F/\pi^2 A \ , \tag{4}$$

where A is the area per chain, is comparable to the measured anomaly; later the various ac and interference features reported by BSZ (Ref. 8) could also be explained.[14] In these models,[13,14] the increase in internal friction in TaS_3 is a direct consequence of phenomenological "frictional" coupling between the CDW and the lattice vibration. The present results on $NbSe_3$, showing changes in internal friction of both signs for different temperatures and modes, indicate that, even for a qualitative description, the CDW-phonon coupling needs to be much more complicated. Furthermore, anomalies in E comparable to that for TaS_3 would be expected for $NbSe_3$, contrary to observation, and there is no way to accommodate the strong observed threshold field dependence in these models.

Moreover, as we previously discussed,[11] the "CDW decoupling" argument fails for a very fundamental reason. For one-dimensional conductors, the conduction-electron density is inversely proportional to the local (uniaxially strained) intrachain lattice constant, $n \sim (1+\varepsilon)^{-1}$. Therefore the CDW wavelength and the separation of pinning sites are both proportional to $(1+\varepsilon)$, and the same (average) energy is involved in straining the CDW, whether pinned or not,

$$U_{pin}(\varepsilon)-U_{pin}(0)=U_{depin}(\varepsilon)-U_{depin}(0) \ . \tag{5}$$

Hence one does not expect the lattice Young's modulus to change by K_{FLR} when the CDW becomes depinned, reflecting the fact that, in principle, the FLR elastic constant describes distortions of the CDW *with respect to* the lattice only. Interchain interactions can restore the depinning anomaly only to the extent that they affect the CDW wavelength.

On the other hand, the Young's modulus generally increases slightly on cooling through the Peierls transition, and this increase has been attributed to the decreased screening by the electrons of the long-wavelength acoustic phonons.[18,21] While Nakane and Takada[27] have shown that there will be no net decrease in the phonon screening by an unpinned CDW, MV (Ref. 15) have shown that the lack of screening will be largely restored by pinning, so that well below the transition

$$(E_{\text{pin}} - E_{\text{depin}})/E = \lambda f/(1-\lambda) , \qquad (6)$$

where f is the fraction of condensed electrons and λ is the electron-phonon coupling constant. In fact, the measured anomalies in Young's modulus at threshold[6] seem *roughly* consistent with the magnitudes of the stiffening observed below T_c. The latter are generally impossible to quantify, however, due to the difficulty in extrapolating the temperature dependence of E through the transitions, and are often further complicated by the presence of a fluctuation driven minimum at T_c.[18,20] It is important to note that unlike any changes in lattice moduli due to K_{FLR}, the MV result depends explicitly on the electron-phonon coupling constant.

The MV screening model should also hold in the quantum-tunneling theory of Bardeen,[3] since the ac conductivity, with dc biases above threshold, is similar to that of the classical theory.[1] It is interesting to note, on the other hand, that models involving softening by K_{FLR} cannot be consistently extended to the Bardeen theory, in which the CDW is depinned for a time t^* much shorter than the average drift period t_d (i.e., the classical "washboard" period[1]). Since the CDW is then only depinned for a fraction of the time[3] $t^*/t_d \sim 10^{-4}$, it is impossible to explain modulus anomalies $\Delta M/M > 10^{-4}$ without invoking an elastic catastrophy in the depinned state.

While the MV model can describe the Young's modulus anomaly in TaS_3, including the functional dependence of E on the CDW current,[15] its extension is problematic. For both $NbSe_3$ and TaS_3 (Ref. 11) the depinning anomalies in the shear modulus are much greater than the anomalous changes observed below T_c. The fact that in all cases the voltage dependence of $\Delta E/E$ is similar in shape, while an order of magnitude smaller, to that of $\Delta G/G$ suggests a common origin (i.e., interchain coupling) to the anomalies in both moduli. In this regard, it should be noted that Eq. (6) should more properly be written in terms of the longitudinal elastic constant (c_{22} for $NbSe_3$), rather than the Young's modulus ($E_2 = 1/s_{22}$), which depends on interchain as well as intrachain coupling through the Poisson contraction ($\nu \sim 0.34$).[19] Therefore, if dominated by changes in interchain coupling, it is reasonable that $\Delta E/E$ would have a similar sample dependence to $\Delta G/G$; thus it may be that the effects of screening on the Young's modulus anomalies [Eq. (6)] is much less than the effects of changes in the interchain coupling.

On the other hand, the sample dependence of the elastic anomalies shown in Fig. 6 has an intriguing possible explanation in terms of the MV screening model. In fact, Eq. (6) only holds if the CDW pinning frequency $\omega_P \gg qv_F$, where q is the phonon wave vector. For much smaller ω_P, Eq. (6) should be replaced by[15]

$$(E_{\text{pin}} - E_{\text{depin}})/E = (2+\lambda f)/(1-\lambda f)(\omega_P/qv_F)^2 , \qquad (7)$$

that is, the anomaly scales with $\omega_p^2 \propto E_T$.[1] For our experiments, q is very small, but *finite;* taking $q \sim 10\ \text{cm}^{-1}$ and $v_F \sim 5\times 10^8$ cm/sec [as for TaS_3 (Ref. 28)], this very-weak-pinning limit holds for $\omega_p/2\pi < 1$ GHz. While the average pinning frequency for $NbSe_3$ is a few times greater than this,[29] in fact a wide distribution of pinning frequencies is needed to explain the "low-frequency" conductivity;[29] such a distribution has not yet been incorporated in the MV model.[15]

In conclusion, we have found that, as for TaS_3,[11] interchain coupling, as manifested by the shear modulus, changes considerably in $NbSe_3$ when the CDW becomes depinned. As for TaS_3,[5(b),11] the changes in the shear modulus are several times larger than those for the Young's modulus, and the changes in both moduli, are also several times larger than the changes in the associated internal friction. However the modulus anomalies are much sharper in $NbSe_3$, with significant fractions of the changes occurring below threshold. For the shear modulus, and Young's modulus below T_2, the internal friction has a net *decrease* when the CDW becomes depinned. Most unexpectedly, the elastic anomalies seem proportional to the threshold field, perhaps reflecting the presence of very low CDW pinning frequencies in $NbSe_3$.

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