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MAGNETO-ELASTIC PROPERTIES OF $NbSe_3$

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ABSTRACT

The Young's Modulus (Y) and internal friction (δ) have been measured in the charge density wave (CDW) conductor $NbSe_3$. Anomalies are clearly resolved in Y and δ at the upper CDW transition, T_1 (144K) and in Y at the lower CDW transition, T_2 (59K). Below 100K, Y has been measured in transverse magnetic fields up to 8T. Small field-induced stiffening effects are observed.

INTRODUCTION

$NbSe_3$, a quasi-one-dimensional CDW material, exhibits interesting magnetic and elastic properties. Numerous studies [1,2,3] have indicated carrier conversion induced by magnetic fields in the lower CDW state. From the mean field theory of Maki and Virosztek [4], we expect an increase in $\Delta Y/Y$ to occur with the application of a magnetic field. Recent studies [5] have suggested a magnetically induced phase transition at 30K which may couple to Y.

We clearly resolve the fluctuation anomalies in Y and δ at T_1 and in Y at T_2. We apply a reduced temperature analysis of the fluctuation region around T_1 to determine the dimensionality of this transition. For T<100K, we see some evidence for magnetically induced elastic stiffening, but no evidence of an additional phase transition at 30K.

EXPERIMENTAL METHOD

Y and δ for $NbSe_3$ crystals were determined as functions of temperature and magnetic field using a modified vibrating reed technique. Flexural vibrations were excited with a PZT transducer to which the sample was rigidly adhered with stycast. Though we examined several crystals, we obtained best results when the free end of the beam was the uncut, as grown end of a crystal.

Changes in the resonance frequency f_r were related to Y by $\Delta Y/Y = 2\Delta f_r/f_r$, and changes in δ were determined from the reciprocal of Q. Over small temperature ranges, Q was proportional to the resonance vibration amplitude since the amplitude of the PZT oscillation changed slowly with temperature.

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RESULTS

For our best sample, we find the ratios of the fundamental to the first four harmonics to lie within .1% of those for a perfect cantilever beam (1:6.267:17.55:34.39:56.84). Unless otherwise noted the results describe the magnetic and temperature dependence of the first harmonic (3521 Hz at 295K).

Figure 1a shows Y and δ near T_1. Fluctuation anomalies are clearly present in both quantities, and the reduced Young's modulus anomaly $(Y-Y_0(T))/Y_0$ is plotted against the reduced temperature $\tau = (T-T_p)/T_p$ in Figure 1b. A linear form for Y_0 does not give results independent of the range over which Y_0 was fit. We find consistent results using two quadratic fits extending from 10K to 50K above and below the transition respectively. The first and third harmonics show similar temperature dependences. In the range $\ln|\tau|=-3.5$ to -5, the curves have a slope $\cong-1.1$ for $\tau>0$ and $\cong-0.74$ for $\tau<0$.

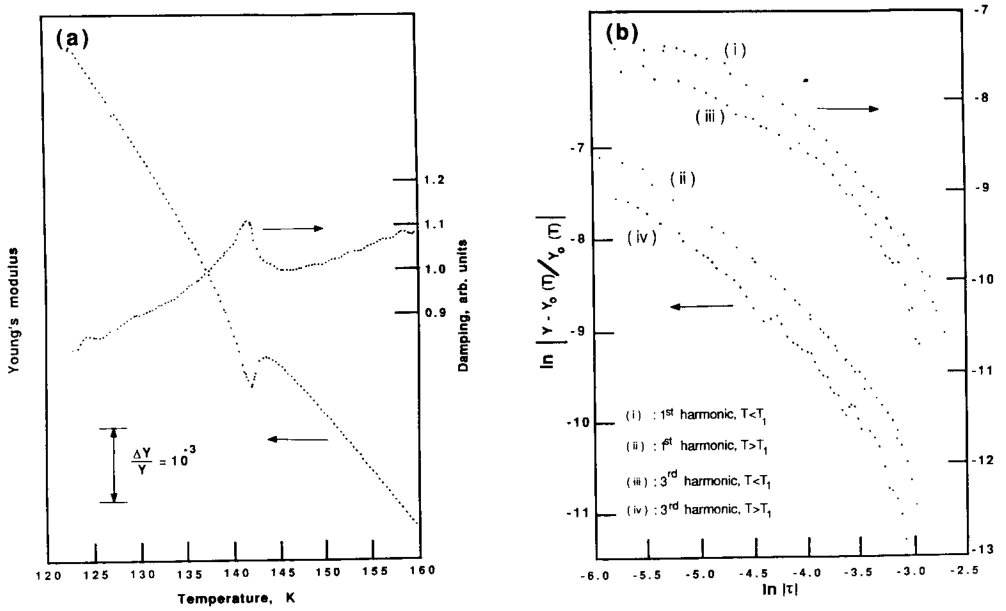

Figure 1. (a) Y and δ vs. Temperature near 144K, and (b) the logarithm of the reduced Young's modulus vs. the logarithm of the reduced temperature near 144K for the first and third fundamental frequencies.

A small softening in Y is also visible at T_2 (Figure 2). The anomaly has previously been described simply as an increase in $\partial Y/\partial T$ at T_2 but in our data it is clearly seen as an anomaly ($\Delta Y/Y\cong-1.3 \times 10^{-4}$) which disappears as T is decreased below T_2. To obtain the lower curve, we subtracted a quadratic best fit from 25K to 55K. Using a quadratic best fit above the transition, no softening was visible. No anomaly is observed in the damping within our experimental resolution.

Figure 3 shows $f_r(T)$ for magnetic fields of 0T and 7.7T. The 7.7T curve is shifted down by about .9 Hz nearly independent of temperature. This shift is unexplained and may be instrumental; it is presently being investigated.

To increase our sensitivity in the region from 5K to 40K several runs were averaged to cancel out spurious effects. Figure 4 depicts the 7.7T data with a baseline subtraction of the 0T data. From this data, it seems that additional softening occurs at 20K, but no feature is evident at 30K. In a temperature range which includes T_2,

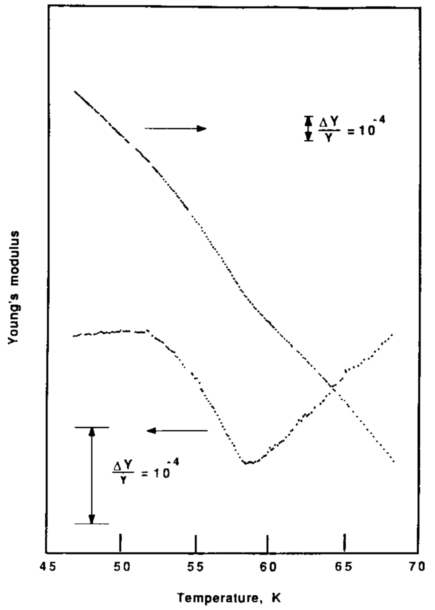

Figure 2. Y vs. T near 59K. The lower curve has been normalized by a quadratic best fit.

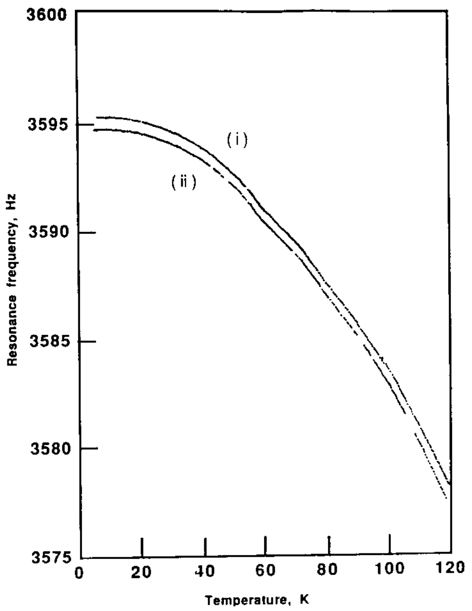

Figure 3. Y vs. T for (i)H=0T and (ii)H=7.7T.

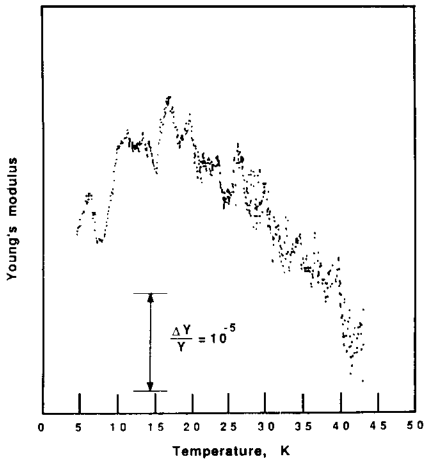

Figure 4. Y(H=7.7T)-Y(H=0T) vs. T. An average of three cooling runs.

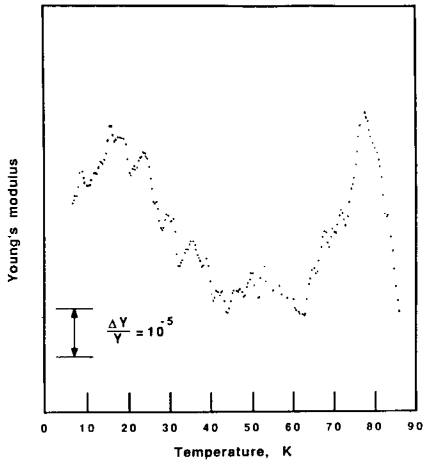

Figure 5. Y(H=7.7T)-Y(H=0T) vs. T.

Figure 5 shows no enhanced magneto-elastic effect at the transition. A peculiar anomaly occurs above the transition, and additional stiffening is evident as the sample is cooled below 45K.

DISCUSSION

The results of the reduced temperature plot, Fig.1b are inconclusive in demonstrating scaling behavior of Y at T_1. Using mean field theory with non-linear electron dispersion, Nakane [6] predicted that $\Delta Y/Y$ should scale as

$\tau^{-3/2}$ for $\tau >> \tau_1$ and $\tau^{-1/2}$ for $\tau < \tau_1$ where τ_1 is a crossover temperature between one-dimensional and three-dimensional fluctuations. We estimate τ_1 from the ratio of the transverse to parallel conductivity to be approximately 0.003. As seen previously in TaS_3 [7], the curves above and below T_p do not give similar temperature dependences. The slopes lie between the expected values of -3/2 and -1/2 and may demonstrate a region of intermediate dimensionality. The frequency independence of the slopes is expected since the anomaly arises from the interaction between phonons and the phason mode which exhibits no dispersion in this frequency range.

The stiffening observed below 45 K in 7.7T (Fig.4) is consistent with the theory of Maki and Virosztek [4] on the effect of sound velocity of a pinned CDW. The sound velocity should increase below the CDW transition because with pinning, the phason mode can no longer participate in screening the phonons. From their theory, $\Delta Y/Y \cong \lambda(0)g(T)/(1-\lambda(0))$ where $g(T)$ is the CDW carrier density as a function of temperature and $\lambda(0)$ is the electron-phonon coupling constant. From Fig.2, using a straight-line extrapolation from above T_2 to 15K below T_2, we find $\Delta Y/Y \cong 5.6 \times 10^{-5}$. At this transition approximately 40% of the Fermi surface is destroyed. Both NBN [2,3] and magnetoresistance [1] indicate carrier conversion into the CDW as the magnetic field is increased. At 8T, they predict increases of 5% and 30% respectively on the CDW carrier density with an onset of the conversion at 50K. In Fig. 4, we see an increase in $\Delta Y/Y$ of 2.8×10^{-5} with an onset of 45K. From the predicted behavior, this reflects an increase in carrier density of 20%. Because of the shape of the transition, the Young's modulus increase associated with the lower CDW transition may not be correctly reflected by a linear extrapolation.

The softening which sets in at 18K may be the signature of a magnetically induced phase transition. However, the work of Parker et al suggests that the phase transition occurs at higher temperatures, at which no elasticity anomaly is visible. Our experimental configuration is only sensitive to transitions which couple to strain in the b-direction. This phase transition may not couple to this strain and would thus not be observed.

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