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SUB-DOMAIN SCALING AND ASYMMETRY IN $NbSe_3$

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In the presence of a uniform temperature gradient, the charge density wave (CDW) conductor $NbSe_3$ breaks into a series of N "sub-domains" with independent CDW phase velocities. We experimentally find a scaling relation $N \sim (\Delta T)^{2/3}$ where ΔT is the temperature difference between the ends of the sample. Changing the relative directions of the temperature gradient and the electrical current through the sample leads to the same N - ΔT scaling relation but results in unusual transport asymmetries in the dynamic and static CDW configurations. Many of our observations are in accord with a simple phase strain model of CDW dynamics in a temperature gradient.

Charge density waves (CDWs) have been the subject of great theoretical and experimental interest for nearly two decades.[1] The CDW is a collective mode with characteristic (per electron) electric field and frequency energies typically much smaller than the thermal energy k_BT. The strong correlation effects between "condensed" carriers can lead to unusual static and dynamic CDW configurations especially in the case of nonuniform impurity distributions or applied temperature gradients. For example, if a temperature gradient is applied to a CDW crystal of sufficient length, the sliding CDW condensate will break up into a series of velocity "sub-domains."[2]

A phase strain model has been proposed which treats CDW dynamics in the presence of a uniform temperature gradient.[3] The model predicts that the number of velocity subdomains N should scale directly with ΔT, the temperature difference between the ends of the CDW crystal:

$$N \sim \Omega(\Delta T)^p \qquad (1)$$

where Ω is a function only weakly dependent on ΔT and the electric field E. The scaling exponent p is either 2/3 or 2/5 depending on parameter limits. In addition, it is predicted that certain dynamic asymmetries should exist for the velocity sub-domains depending on the relative direction of heat and electrical current flow through the crystal. If the model results are extrapolated to the pinned CDW regime, one might expect unusual transport asymmetries for the static CDW as well.

We report here measurements on the CDW conductor $NbSe_3$ subjected to a uniform temperature gradient applied along the crystal chain axis. In the sliding CDW state, we infer the CDW velocity distribution from the narrow band noise spectrum and find that the scaling relation $N \sim (\Delta T)^{2/3}$ is obeyed. The details of the N and sub-domain velocity v_0 versus ΔT relationships demonstrate striking asymmetries between "parallel" and "antiparallel" temperature gradient and electrical current directions through the crystal. In the pinned CDW regime, differential resistance measurements display strong hysteresis effects, again sensitive to the relative directions of the temperature gradient ∇T and the electrical current I. Fine structure in the hysteresis loops reflects metastable states similar to the high-field velocity sub-domian structure.

The experimental configuration consists of a $NbSe_3$ crystal suspended (in vacuum) between two copper blocks whose temperatures T_1, T_2 are independently controlled. A dc bias current I can be applied through the sample, and the rf voltage response (narrow band noise) detected with a spectrum analyzer. In addition, conventional lock-in techniques allow differential resistance measurements. The inset to Fig. 1 shows schematically the sample mount and defines the directions of +I and $+\nabla T$. (+I is defined in the conventional positive carrier sense, and $T_2 = T_1 + \Delta T$.) We present data for three $NbSe_3$ crystals with lengths ranging from 0.9 mm to 1.6 mm. The samples were carefully selected to give clean and single narrow band noise spectra under isothermal conditions for a wide range of dc bias.

Consistent with previous observations,[2] in the present study the number of independent fundamental noise frequencies in the response spectrum is found to increase with increasing ΔT. If we associate each new fundamental frequency with the formation of an independent velocity sub-domain, the number of sub-domains N is simply the number of fundamental noise peaks in the response spectrum. Figure 1(a) shows N plotted versus ΔT for a particular $NbSe_3$ sample in the lower CDW state with a fixed dc bias I = -80 mA. (This corresponds to approximately two times the threshold field for depinning the CDW at the cold sample end maintained at T = 30 K.) Figure 1(a) shows the results for (-I,+ΔT) and (-I,-ΔT). Although N increases with increasing $|\Delta T|$ in each case, there is a clear asymmetry for parallel (-I,-ΔT) and antiparallel (-I,+ΔT) electrical current and temperature gradient. (We remark that, to avoid any undesirable memory effects before the reversal of either ΔT or I for a particular measurement, the entire crystal was warmed above the Peierls transition temperature and recooled with no bias current or temperature gradient. This

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insured that each measurement reflects the response of the virgin CDW state.) Figure 1(b) again shows N versus ΔT for the two parallel configurations (+I,+ΔT) and (-I,-ΔT). In this case, the N versus ΔT relation appears symmetric with respect to ΔT except for a small offset δT along the ΔT axis. This offset (which, in a sense, looks like a "built-in" temperature gradient) is sample dependent (in one sample it was fully absent), and we attribute it to a nonuniform impurity distribution within the crystal, that is, an impurity gradient. Except very close to the depinning threshold, the N versus ΔT relationships in Fig. 1(a) and (b) are found to be rather insensitive to the absolute value of the bias current I, which indicates that the velocity sub-domain configuration is independent of the velocity magnitudes.

To test for scaling of the form $N \sim \Omega(\Delta T)^p$ (see Eq. (1)), the data of Fig. 1(a),(b) can be plotted as log(N) versus $\log(\Delta T)^2$ as shown in Fig. 2(a). Both parallel (-I,-ΔT) and antiparallel (+I,-ΔT) data sets are shown (the shifts δT present in some samples have been subtracted for these scaling plots). The open circles indicate the middles of the constant N plateaus (the log scale makes these appear off center). The solid lines are least squares fits to the data (midpoint circles). The quality of the fits indicates that, indeed, there is a scaling between N and ΔT of the form suggested by Eq. (1) with p close to 2/3 for both parallel and antiparallel I and ΔT. The offset of the two fits in Fig. 2(a) suggests that Ω is not invariant to the relative directions of I and ΔT.

The number of data points in Fig. 2(a) is rather limited. This is related to the experimental difficulty of obtaining a large N for a given sample (and still keeping the hot sample end below the Peierls transition temperature and in the CDW state). To improve the statistical reliability of p, we have repeated the experiments and analysis shown in Figs. 1 and 2 multiple times for different $NbSe_3$ samples. Figure 2(b) shows a histogram of the exponents p thus obtained. Although some scatter is apparent, a dominant peak occurs near 0.6 to 0.7. The experimentally determined median value of p is $\langle p \rangle = 0.66$ in excellent agreement with the value p = 2/3 predicted by the phase strain model in a particular limit.[4]

Figure 1(a) shows that, although N scales with ΔT, the actual value of N for a given |ΔT| depends on the relative directions of I and ΔT. We have observed a similar directional dependence for the CDW sub-domain velocity as a function of ΔT. In a very general model,[5] f_{NBN} is directly proportional to v_0. For fixed bias current |I|, we have measured f_{NBN} as a function of ΔT using parallel and antiparallel (I,ΔT) configurations. A consistent asymmetry is observed in that the slope of the (nearly linear) *average* f_{NBN} versus ΔT relationship is larger for parallel (I,ΔT) configurations. Within a phase strain model,[3] this observation implies that (for a given sub-domain and per unit volume) the total charge in the CDW depends on the relative directions of I and ΔT. This has strong implications for the *static* CDW state as well which we now explore.

To test for possible ΔT dependent metastable state structure for the static (that is, pinned) CDW condensate, we have the measured dV/dI characteristics of $NbSe_3$ in a uniform temperature gradient. Figure 3(a) shows dV/dI versus I measured for |ΔT| fixed at 3.7 K. A striking hysteresis effect is observed in the low-field

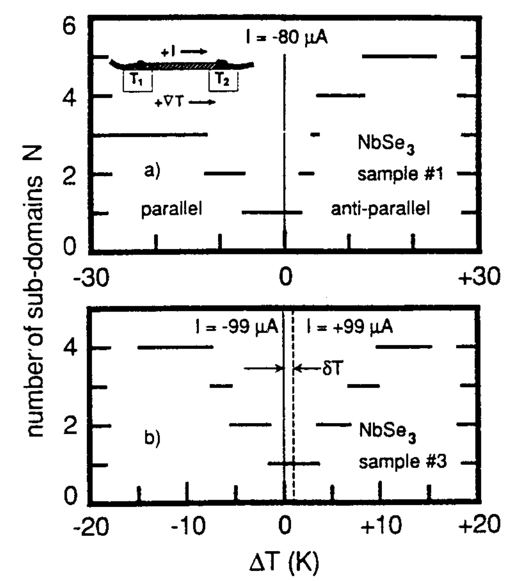

Fig. 1. N vs. ΔT in $NbSe_3$ for (a) "parallel" (-I,-ΔT) and "antiparallel" (-I,+ΔT) current-temperature gradient configurations, and (b) for the two "parallel" (-I,-ΔT), (+I,+ΔT) configurations. The data of (b) suggest an intrinsic sample asymmetry or "shift" of dT (see text). In all cases, the temperature of the colder end of the sample was held at 30 K; +ΔT means that $T_2 > T_1 = 30$ K, -ΔT means that $T_1 > T_2 = 30$ K.

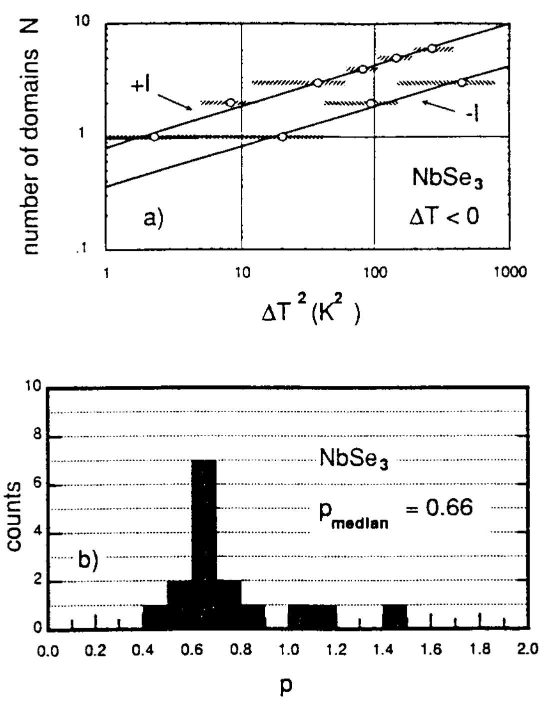

Fig. 2 (a) N vs. ΔT in $NbSe_3$. The circles show the center of each constant-N step, and the solid lines are the least-squares fit to the data assuming the form Eq. (1) (see text). (b) Histogram of the scaling exponent p. The median value is p = 0.66 (see Ref. 4).

resistance (which represents the resistance of the *uncondensed* electrons). The sense of the hysteresis loop is reversed if the direction of ΔT in the sample is reversed. In addition, the upper curve in Fig. 3(a) shows, for increasing +I, small "steps" in the dV/dI curve. This step-like structure is enhanced with increasing ΔT as shown in Fig. 3(b) which is for the same $NbSe_3$ sample with ΔT = +12.4 K. The number of dominant steps (identified with vertical arrows) in the dV/dI characteristics is roughly equal to five which is comparable to the number of sub-domains N in the sliding CDW state for ΔT = +12.4 K and +I. This suggests that the static metastable state CDW structure directly reflects an *intrinsic* sub-domain configuration.

We associate the temperature-gradient-induced hysteresis to a change in local CDW charge density with a resultant change in local normal carrier charge density. Below the threshold electric field, the nominal impurities present in the crystal prevent distortions in the CDW (acquired in the sliding state) from relaxing. Any change in the carrier density is then frozen in until an electric field is directed in the opposite direction with a magnitude characteristic of the local pinning energy of particular region (sub-domain). In Fig. 3(b), the prominent step-like structure on the lower curve (|I| increasing in the -I direction) corresponds to "erasing" one by one the metastable state structures in serially arranged *static phase* sub-domains; these static sub-domains may have a one-to-one mapping onto the *dynamic velocity* sub-domains present in the sliding CDW state.

In Fig. 3(a), the larger (low field) differential resistance occurs under (|ΔT|) conditions that lead to a *reduced* CDW velocity in the sliding regime (as discussed above in the f_{NBN} measurements versus ΔT). This reduction in velocity is consistent with the phase strain model where the mapping of the CDW is directly coupled to the normal carrier resistivity.[3] The sense of the hysteresis loops in Fig. 3(a) suggest that the CDW carriers in $NbSe_3$ in the lower CDW state are behaving as "hole-like" rather than "electron-like" in the sense that the CDW moves in the direction of the electric field (as a positive test charge does).

It is important to note that low-field hysteresis loops very similar to those observed in Fig. 3(a) have been observed in $NbSe_3$ crystals under isothermal conditions but with variations in impurity concentrations.[6] Indeed, in samples with ultrastrong impurity pinning sites which lead to switching and dramatic velocity sub-domain formation, the hysteresis is especially pronounced.[7] Our results here suggest that, in $NbSe_3$ samples with isothermal low-field hysteresis, the fundamental narrow

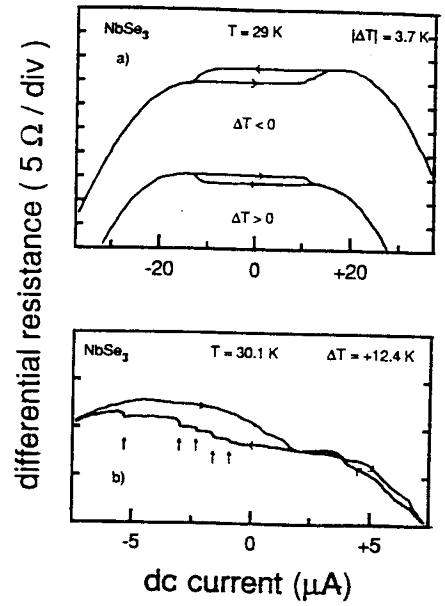

Fig. 3 (a) dV/dI in $NbSe_3$ with |ΔT| = 3.7 K. The sense of the hysteresis loop is reversed as ΔT is reversed. The curves for positive and negative ΔT are vertically offset for clarity. (b) dV/dI for large |ΔT|. The arrows mark "steps" which may reflect static CDW sub-domain structure. In (a), the colder end of the sample was held at 29 K while in (b) the colder end was held at 30 K. ΔT means that $T_2 > T_1$; $-\Delta T$ means that $T_1 > T_2$ (see inset to Fig. 1(a)).

band noise frequency in the sliding regime should shift if the bias current is reversed in polarity (while maintaining the same magnitude). Such shifts are often observed experimentally, but no attempt has been made to correlate them to possible low field hysteresis.

Finally, we note that the phase stain model leading to Eq. (1) also predicts a scaling of N with sample length L, $N \sim L^{(1-p)}$. In the present study, the sample lengths were not varied to test this prediction quantitatively (a qualitative increase of N with L can be inferred from previous studies).[2]

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