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TEMPERATURE-GRADIENT-INDUCED SUBDOMAIN SCALING IN $NbSe_3$

P. PARILLA*, M.F. HUNDLEY#, A. BEHROOZ**, W.N. CREAGER, and A. ZETTL
Department of Physics, University of California at Berkeley, Berkeley, California 94720 U.S.A.

ABSTRACT

In a temperature gradient, the charge density wave (CDW) in $NbSe_3$ breaks up into a series of N coexisting "subdomains" with independent CDW phase velocities. With ΔT the temperature difference applied across the ends of the sample, we find $N \sim (\Delta T)^{2/3}$. This scaling relation has been predicted by a phase-strain model of CDW dynamics.

INTRODUCTION

Previous experiments [1] have demonstrated that if a longitudinal temperature gradient is applied to a charge density wave (CDW) crystal of sufficient length supporting a sliding CDW condensate, the CDW phase velocity v_0 may assume different values in different parts of the crystal. Qualitatively, the number of independent velocity "subdomains", N, increases in a step-wise manner with increasing ΔT, where ΔT is the temperature difference across the ends of the crystal.

A recent phase strain model [2] of CDW dynamics in a temperature gradient has predicted an unusual scaling relation:

$$N = \Omega\,(\Delta T)^{2/m} \tag{1}$$

where Ω is a function only very weakly dependent on ΔT, and m=3 in one model limit and m=5 in another limit. We have tested experimentally this prediction for $NbSe_3$ in the lower CDW state, and find Eq. (1) to hold with m=3.

*Present address: Solar Energy Research Institute, Golden, CO 80401 U.S.A
#Present address: Los Alamos National Laboratory, Los Alamos, NM 87545 U.S.A.
**Present address: Middlebury College, Middlebury, VT 05753 U.S.A.

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EXPERIMENT AND RESULTS

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. 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 0.9mm to 1.6mm. The samples were carefully selected to give clean and single narrow band noise spectra under isothermal conditions, for a wide range of dc bias.

The number of velocity sub-domains N is simply the number of fundamental narrow-band noise peaks in the response spectrum. Fig. 1a shows N plotted versus ΔT for a particular $NbSe_3$ sample in the lower CDW state, with a fixed dc bias $I = -80\mu A$ (this corresponds to approximately 2 times the threshold field for depinning the CDW at the cold sample end kept at 30K). Results are shown for both forward and reversed temperature gradients. Although N increases with increasing $|\Delta T|$ in each case, there is a clear asymmetry for "parallel" ($-I,-\Delta T$) and "antiparallel" ($-I,+\Delta T$) 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 insured that each measurement reflects the response of the virgin CDW state). Fig. 1b shows N vs ΔT for a different sample, for the two parallel configurations ($+I,+\Delta T$) and ($-I,-\Delta T$). In this case the N vs 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, i.e. an impurity gradient. Except very close to the depinning threshold, the N vs ΔT relationships in Fig. 1a,b are found to be rather insensitive to the absolute value of the bias current I, i.e. the velocity sub-domain configuration is independent of the velocity magnitudes.

To test for scaling of the form $N \sim \Omega(\Delta T)^{2/m}$ (see Eq. (1)), the data of Fig. 1a,b can be plotted as log(N) vs $\log(\Delta T)^2$, as shown in Fig. 2a. Both parallel ($-I,-\Delta T$) and antiparallel ($+I,-\Delta T$) data sets are shown. 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 m close to 3 for both parallel and antiparallel I and ∇T. The offset of the two fits in

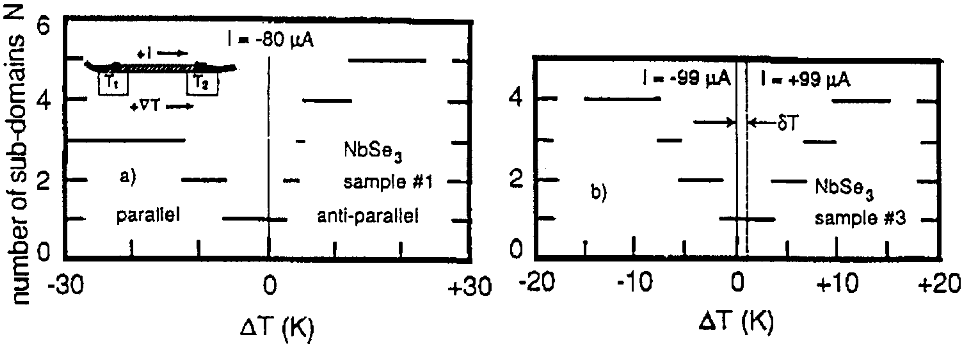

Fig. 1. N vs ΔT in $NbSe_3$ for a) "parallel" (-I,-ΔT) and "antiparallel" (-I,+ΔT) current-temperature gradient configurations, and b) for the two "parallel" (-I,-ΔT), (+I,+ΔT) configurations. The data of b) suggest an intrinsic sample asymmetry with effective "shift" of δT. In all cases the temperature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

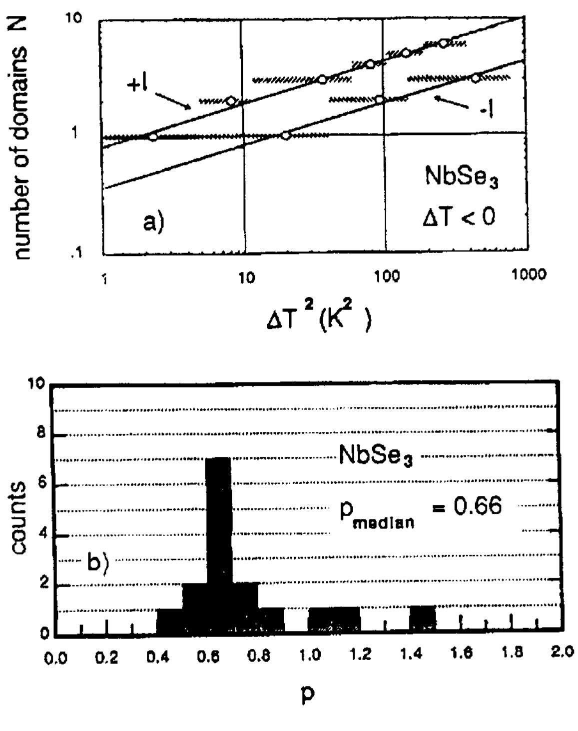

Fig. 2. a) N vs ΔT in $NbSe_3$. The circles show the center of each constant-N step, and the solid lines are the least-squares fit to the data assuming the form Eq. (1). b) Histogram of the scaling exponent. The median value is $2/m=p=0.66$.

Fig. 2a suggests that Ω is not invariant to the relative directions of I and ΔT.

The number of data points in Fig. 2a 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 m, we have repeated the experiments and analysis shown in Figs. 1 and 2 multiple times for the different $NbSe_3$ samples. Fig. 2b shows a histogram of the exponents $2/m = p$ thus obtained [3]. 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 the "large-$|\upsilon|$ limit" [2]. This limit means physically that the temperature gradient induced strain profile of the CDW condensate is dominated by carrier conversion rather than by the intrinsic CDW elasticity. The carrier conversion process thus plays a key role in determining CDW dynamics in the presence of a temperature gradient.

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3 Strictly speaking, Eq. (1) is valid only in the large N limit (see ref. 2), while experimental data reflect the small N limit. For large-$|v|$, this can be corrected for by replacing N with $N' = N\,(1 - 1/(4N^2))^{-1/3}$ in Eq. (1). The histogram in Fig. 2b results from this corrected expression.