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ASYMMETRY IN THE STATIC AND DYNAMIC CHARGE DENSITY WAVE STATES OF $NbSe_3$: HEAT AND ELECTRICAL CURRENT FLOW

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ABSTRACT

The dynamic and static states of the charge density wave (CDW) in $NbSe_3$ have been measured by narrow band noise and differential resistance measurements, in the presence of a symmetry-breaking temperature gradient. In the dynamic state, the CDW velocity is sensitive to the relative direction of heat and electrical current flow. In the pinned state, metastable state structure with dramatic hysteresis is observed. Our results are consistent with predictions of a phase strain model of CDW motion in the presence of a temperature gradient.

INTRODUCTION

A frequently observed but rarely reported phenomenon in sliding charge density wave (CDW) conductors is a definite bias current polarity dependence of the narrow band noise spectrum. This "problem" is usually attributed to non-symetrically rectifying contacts, or some other "built-in" directionality in the sample (such as impurity distribution). A related observation is low-field hysteresis in dV/dI curves.

We here explore the dynamic and static CDW states of $NbSe_3$ by noise and differential resistance measurements, in the presence of an externally applied temperature gradient which introduces controlled symmetry breaking within the crystal. Unusual asymmetries are observed depending on the relative directions of heat and electrical current through the specimen. In the sliding CDW state, our results are consistent with a phase strain model of CDW transport; the same model has implications for metastable states in the pinned regime. Our findings

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also have implications for transport under isothermal conditions in (typical) crystals with slightly inhomogeneous impurity distributions, where forward and reverse current bias are non-equivalent.

EXPERIMENT AND RESULTS

The experimental configuration consists of a $NbSe_3$ crystal suspended between two copper blocks (labeled 1 and 2) whose temperatures T_1, T_2 are independently controlled. We define $T_2=T_1+\Delta T$. A dc bias current I is applied through the sample, and the rf voltage response (narrow band noise) detected with a spectrum analyzer. Positive electrical dc bias current is defined as positive charge flowing through the crystal from block 1 to block 2. Conventional lock-in detection (~100Hz) also allows for differential resistance measurements.

With a finite temperature gradient and bias current applied, there exist four different current flow-heat flow configurations: two configurations have I and ∇T pointing in the same direction, i.e. "parallel", while the other two configurations are "antiparallel". There is an asymmetry between parallel and antiparallel configurations in both the dynamic and static CDW state.

Asymmetry in CDW velocity

The CDW velocity (or velocities, if multiple subdomains are present) is reflected in the noise spectrum. For a given magnitude of the bias current $|I|$, the fundamental noise frequency f_{NBN} depends on the relative direction of heat and electrical current flow. For small temperature differences $|\Delta T|$, there is only one velocity domain and f_{NBN} is well-defined. For larger $|\Delta T|$ the noise spectrum splits, with N fundamental frequencies present. In this case we define an average frequency $\langle f_{NBN}\rangle=\Sigma_i f_{NBNi}/N$. Fig. 1 shows the average noise frequency versus ΔT for $NbSe_3$ in the lower CDW state, near 30K. There is a striking asymmetry between negative and positive bias current. For a given value of ΔT, the CDW on the average moves faster for the "parallel" configuration (where temperature gradient and electrical current are parallel). If the temperature gradient direction is reversed for this sample, the negative and positive current data points of Fig. 1 roughly interchange.

CDW velocities in the presence of a temperature gradient have been examined within a phase strain model of CDW dynamics [1]. For a subdomain of length L_D in a crystal of length L the CDW phase velocity is

$$v_o = (\rho_o E/\gamma)\{1-[L_D E'\Delta T\xi(\nu)/2EL]\}/\{1-[L_D\gamma'\Delta T\xi(\nu)/2\gamma L]\} \qquad (1)$$

where E is the applied electric field, ρ_o is the average CDW charge density, γ is CDW damping, $\xi(\nu)=\coth(\nu)-1/\nu$ with ν a parameter that depends linearly on

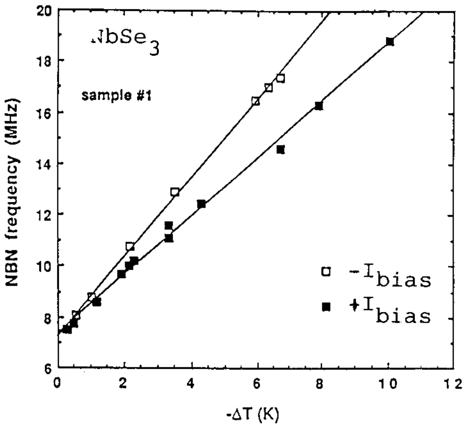

Fig. 1. Average narrow band noise frequency $<f_{NBN}>$ vs ΔT in NbSe$_3$ near 30K, for forward and reverse bias current. The CDW moves faster in the "parallel" configuration.

electric field [1], and the primes denote temperature derivatives. Eq. (1) is unchanged if both E and ΔT are reversed in sign, but is not invarient if either E or ΔT is changed alone. Physically, what happens is that the total charge attributable to the CDW in the crystal is different for different relative directions of heat and current flow. If the CDW damping were not strain dependent, the velocity asymmetry would arise simply because of the change in coupling between the CDW and the electric field. In a more general description where the damping is also strain dependent, part of the velocity asymmetry arises from a change in electric field coupling and part to a change in the average damping. Variation in the relative amount of normal and condensed carriers in the crystal also affects the low-field resistance, which we now explore.

Low-field hysteresis

Fig. 2a shows differential resistance curves for NbSe$_3$ in the lower CDW state with a temperature gradient applied to the sample. The sense of the hysteresis loops is reversed if the direction of the temperature gradient is reversed. The low-field differential resistance is a measure of the concentration of normal carriers in the CDW crystal. As discussed above, this concentration can be altered (in the sliding CDW state) by reversing the relative direction of heat and CDW current flow. If we assume that below the threshold field impurities within the sample freeze in the CDW distortions (i.e. internal strain) acquired in the sliding state, then the change in the respective carrier densities (normal versus condensed) is also frozen into place in the pinned regime. The distortions are relieved only when the applied field exceeds

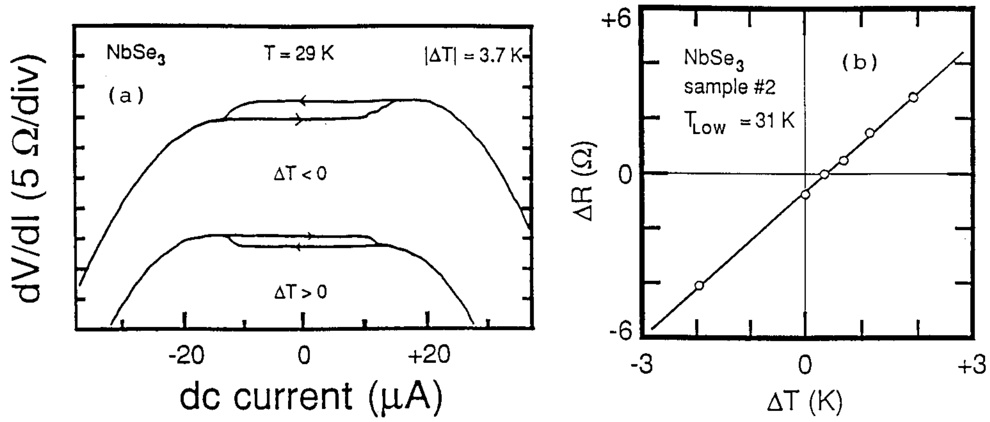

Fig. 2. a) dV/dI in $NbSe_3$ near 30K in the presence of a temperature gradient. Note the reversal of the sense of the hysteresis loop between $\Delta T>0$ and $\Delta T<0$. b) Magnitude of low field hysteresis in $NbSe_3$ vs. ΔT, near 30K. The intrinsic asymmetry can be nulled with an applied ΔT.

threshold on the opposite bias side, similar to the well-known pulse memory effect [2]. At this bias value, the sign of the strain is reversed resulting in surplus carriers decreasing in number, and minority carriers increasing in number. The hysteresis loop in Fig. 2a records this change. In principle, the hysteresis loop, taken together with the asymmetry in the narrow band noise spectrum (Fig. 1) can be used to determine the sign of the condensed carriers (i.e. hole-like or electron-like).

It is interesting to note that even under isothermal conditions, some CDW crystals [3] show low field hysteresis in the resistance (the crystal used for Fig. 2a had such a small isothermal hysteresis). In a sense, this looks like a "built-in" temperature gradient, perhaps due to an asymmetric impurity distribution within the crystal. In fact, it is often possible to null-out this intrinsic asymmetry by applying a small external temperature gradient. Fig. 2b shows the magnitude in the resistance hysteresis for such a situation. Note the vertical offset at $\Delta T=0$, which is removed at $\Delta T \sim 0.3K$.

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