Synthetic Metals, *19* (1987) 813–818

A RF-INDUCED DYNAMIC COHERENCE LENGTH IN $NbSe_3$

R.P. HALL**, M.F. HUNDLEY and A. ZETTL***
Physics Department, University of California, Berkeley, CA 94720 (U.S.A.)

ABSTRACT

We have investigated Shapiro step mode-locking in $NbSe_3$ as a function of sample dimension, using both a series of samples with different total length, and individual samples with a variable spacing between voltage sensing probes. The rf-induced dynamic coherence length is orders of magnitude larger than the Fukuyama-Lee-Rice length.

INTRODUCTION

In charge-density wave (CDW) transport, an electron-phonon condensate slides and carries a current I_{CDW} when an applied electric field E exceeds a critical threshold field E_T. Because a CDW is spatially periodic, interactions of a sliding CDW with its host lattice are temporally periodic. CDW motion is characterized by a washboard frequency [2]

$$\omega_B/2\pi = v/\bar{\lambda} = I_{CDW}/(n_c eA\bar{\lambda})$$

where v is the CDW velocity, n_c the number of condensed electrons, A the conductor cross-sectional area, and $\bar{\lambda}$ the interaction wavelength. A striking manifestation of the washboard frequency occurs when an rf signal of frequency ω_{ac} interferes with dc motion of a CDW [4]. This interference is observed directly in dc IV curves and is analogous to Shapiro step phenomena in superconducting junctions [5]. Subharmonic steps are observed [5-7] corresponding to interference between har-

*Research supported under NSF Grant DMR 84-00041.
**IBM Predoctoral Fellow.
***NSF PYI and Sloan Foundation Fellow.

0379-6779/87/$3.50

monics of both the washboard and external frequency. In some samples, complete or nearly complete [6] locking of CDW motion is evident: despite increasing dc bias, a CDW's velocity remains fixed by the requirement that $\omega_B = (p/q)\omega_{ac}$. When complete locking occurs, broadband noise is frozen out, suggesting the divergence of a correlation length [8]. Temperature gradient experiments show that an applied rf signal may completely lock a CDW over an entire sample length despite the presence of strong local inhomogeneities [9].

We have investigated CDW locking as a function of sample size, by either cutting crystals to successively smaller dimensions or measuring the response of uncut crystals over variable distances. We find that complete locking occurs in all crystals, but only over sufficiently short distances. When the measurement length exceeds a frequency-dependent correlation length, complete locking is lost. The correlation length measured by our experiments is a mean distance between phase slips [10] in the presence of an rf field.

MEASUREMENTS

Single crystals of $NbSe_3$ were grown in our laboratory by standard vapor-transport techniques. Typical threshold fields were between 10 and 30 mV/cm at 48 K. Current injection contacts were applied to the ends of samples by silver paint. Figure 1a shows Shapiro steps from a crystal of $NbSe_3$ measured at 48 K using a two-terminal configuration. The sample length was 2.5 mm and its cross-sectional

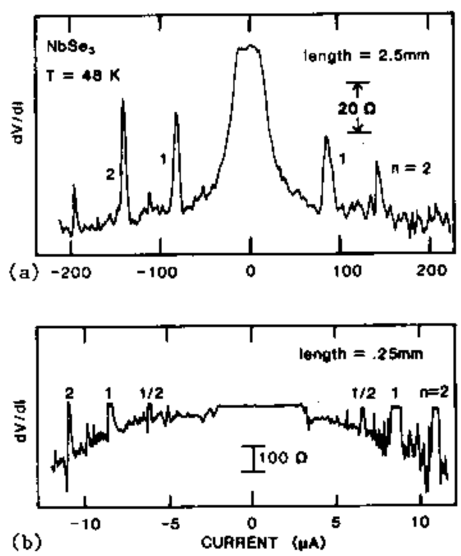

Fig. 1. a. Shapiro step spectrum of an $NbSe_3$ crystal. rf frequency is 5 MHz and rf amplitude has been adjusted to maximize the n=1 step height.
b. Shapiro step spectrum of a segment cleaved from the above crystal. Sample length and cross-section have both been reduced by a factor of 10.

area was about 28 $(\mu m)^2$. The rf frequency was 5 MHz and the rf amplitude was adjusted to maximize the step height. The sample was very far from locking, and remained so for all values of the rf amplitude. Figure 1b shows the effect of reducing the sample dimensions by a factor of 10 in both cross-sectional area and length. Complete locking occurs for the n=1/2, 1, and 2 Shapiro steps at ±6, 8, and 11 μA respectively.

Reducing both the sample cross-section and length is not always necessary to induce complete locking. In most samples we have achieved complete locking by shortening just the longitudinal dimension. For 5 MHz rf signals, we find that $NbSe_3$ samples must be roughly 0.5 mm or less for complete locking.

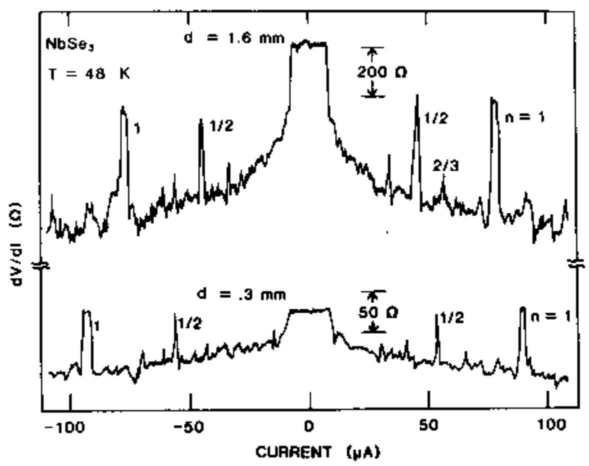

Fig. 2. Four-terminal measurement of Shapiro step sptctrum. Top trace: voltage-sensing probes 1.6 mm apart. Bottom trace: probes .3 mm apart. (rf frequency is 5 MHz and rf amplitude is chosen to maximize the n=1 step height.)

Cutting samples can cause crystal damage and suprious length dependences, and to avoid these problems we have made four-terminal measurements of uncut samples in which the distance d between voltage sensing probes was varied. Figure 2 shows Shapiro step spectra on the same crystal for two different values of d. When d was 1.6 mm, mode-locking did not occur, whereas when d was reduced to 0.3 mm, complete locking appeared. Our technique was non-invasive, as evidenced by the strong correlation between peaks in the lower and upper traces. For example, the n = 1/2 peak in the lower trace appears as part of the n = 2/3 peak in the top trace. The ambiguity of this n = 2/3 peak shows the difficulty of interpreting incompletely locked steps, which may be artificially broadened or easily mislabeled because of nonuniform velocity distributions within a sample.

Figure 3 shows the dependence of locking on the probe spacing d. The degree of locking may be quantified by measuring the ratio h/h_{max}, where h is the height of the interference peak and h_{max} is difference of the low-field and dynamic impedances. For complete locking, $h/h_{max} = 1$. Complete locking in Fig. 3 disappears when d exceeds 400 μm, which defines an rf-induced dynamic correlation length ξ_{PS}. We find that ξ_{PS} depends on the frequency and amplitude of the applied rf, as well as the probe *position* within a sample.

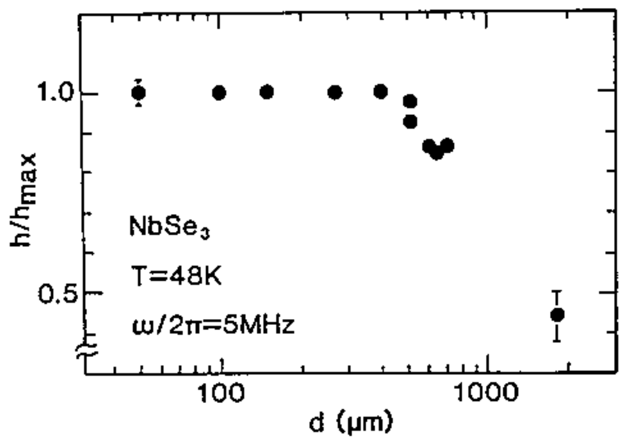

Fig. 3. Locking vs. probe separation for a fixed rf frequency of 5 MHz.

Figure 4 shows Shapiro step spectra at 3 different rf freqencies for a single crystal and fixed probe spacing. At 0.5 MHz, locking occurs over the entire sample and the interference peak shape suggests a very uniform CDW velocity throughout the sample. Locking over the entire sample persists up to 1.5 MHz but the peak shape becomes less square, suggesting that CDW motion is less uniform for higher rf frequencies. At 2 MHz, complete locking no longer occurs. By moving the voltage sensing probes along the sample, we mapped out the longest regions at 2 and 3 MHz. Figure 5 shows the length of these maximal regions vs. the rf frequency. The rf-induced correlation length ξ_{PS} decreases very quickly as the rf frequency increases. We also found that the position of the maximal regions changed as the rf frequency changed. For example, between 2 and 3 MHz the maximal region moved from one end of the sample to the other.

ANALYSIS

In order for locking to be existent but incomplete, the time-averaged velocity of a CDW must vary within a crystal. Discontinuity of the time-averaged velocity,

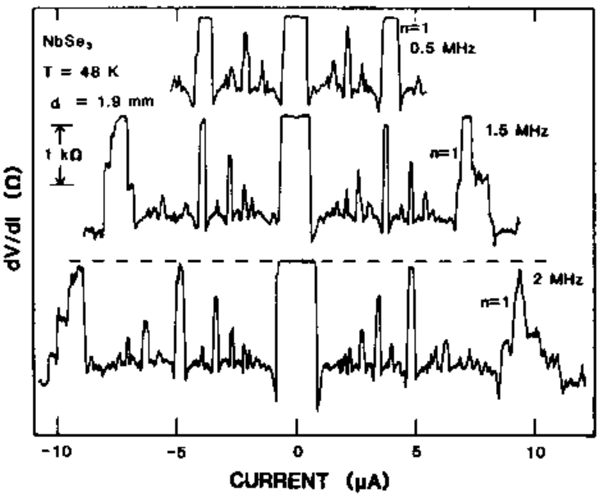

Fig. 4. Shapiro step spectra vs. rf frequency for fixed probe separation. (rf amplitude at each frequency chosen to maximize the n=1 step height.)

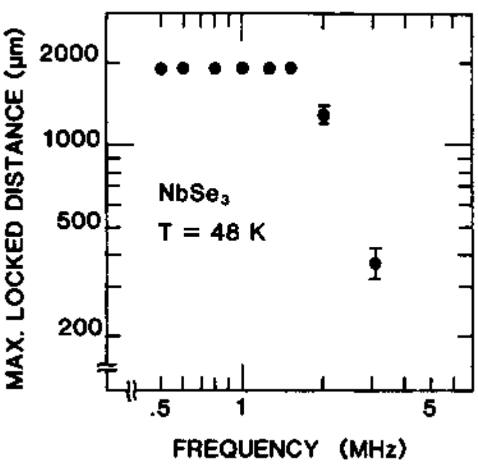

Fig. 5. Length of the largest locked segment in a crystal vs. rf frequency. (rf amplitude at each frequency chosen to maximize locking of the n=1 step.)

however, implies the existence of bulk phase-slips within a crystal. Hence the correlation length measured in our experiments is the distance between phase-slips in the crystalline bulk, as might arise from nominal inhomogeneities in impurity distribution or sample cross-sectional area. The strong frequency dependence of ξ_{PS} suggests that high frequency ac fields are less effective in overcoming such distributions and homogenizing the CDW phase velocity. Alternatively, the frequency dependence of ξ_{PS} may reflect an intrinsic susceptibility of the

CDW condensate to phase-slip and amplitude fluctuations at high velocity.

The dynamic correlation length here discussed is distinct from other correlations lengths discussed in the literature. Fukuyama, Lee, and Rice [11] proposed a *static* coherence set by the strength and concentration of impurities within a crystal. Fisher [12] has discussed a *dynamical* correlation length over which the *instantaneous* CDW velocity maintains coherence. Fisher has shown that this dynamical length is generally longer than the Fukuyama-Lee-Rice length, although far above threshold the dynamical length approaches the static length. Our definition of *time-averaged* correlation is less stringent than Fisher's, hence for low ac frequencies (and hence low velocities)

$$\xi_{PS} \geq \xi_{FISHER} \geq \xi_{FLR}$$

The strong frequency dependence of ξ_{PS} suggests that equality may hold far above threshold.

REFERENCES

1 For a review of CDW transport, see G. Grüner and A. Zettl, Phys. Reports, 119 (1985) 117.
2 R.M. Fleming and C.C. Grimes, Phys. Rev., Lett., 42 (1979) 1423.
3 Most theories of CDW transport predict that $\overline{\lambda}$ is equal to the CDW wavelength.
4 J. Richard, P. Monceau, and M. Renard, Phys. Rev., B25 (1982) 948.
5 A. Zettl and G. Grüner, Solid State Comm., 46 (1983) 501.
6 R.P. Hall and A. Zettl, Phys. Rev., B30 (1984) 2279.
7 S.E. Brown, G. Mozurkewich and G. Grüner, Phys. Rev. Lett., 54 (1984) 2272.
8 M.S. Sherwin and A. Zettl, Phys. Rev., B32 (1985) 5536.
9 M.F. Hundley and A. Zettl, Phys. Rev., B33 (1986) 2883.
10 N.P. Ong et al., Phys. Rev. Lett., 52 (1984) 663, and L.P. Gorkov, JETP Lett., 38 (1983) 87.
11 H. Fukuyama and P.A. Lee, Phys. Rev., B17 (1977) 535; P.A. Lee and T.M. Rice, Phys. Rev., B19 (1979) 3970.
12 Daniel S. Fisher, Phys. Rev. Lett., 50 (1983) 1486.