Local nature of charge-density-wave conduction noise in niobium triselenide

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In four-probe samples we show that the charge-density-wave noise spectrum fundamental in each of the three segments oscillates independently. Amplitude studies also show that the conduction noise originates at the contacts rather than in the bulk.

In the charge-density-wave (CDW) systems $NbSe_3$ and TaS_3, the clearest signature of CDW conduction is the appearance of well-defined frequency components and their harmonics in the power spectrum of the CDW current.[1,2] The fundamental frequency f increases monotonically with the electric field inside the sample. Soon after the original report by Fleming and Grimes,[1] the frequency f was shown to be linearly related to the CDW current I_{CDW} by Monceau, Richard, and Renard.[3] The slope of the plot of I_{CDW} vs f provides a measure of the condensed density participating in the CDW conduction. This has been used by several groups[2-6] to measure the condensed carrier density and to monitor the decrease in the condensed density as the temperature T approaches the transition point T_c.

Because such "noise" spectrum analyses may play a role in clarifying the physics of CDW conduction as significant as that of tunneling in superconductivity, it is important to determine the physical nature and origin of the noise spectrum. A major hypothesis that has emerged is that the noise is due to impurities interacting with the spatially periodic CDW condensate.[3,7] The periodic potential seen by the drifting CDW sets up oscillations in I_{CDW} which then appear as an ac voltage on the oscilloscope. This model faces both experimental and theoretical difficulties. In our data the *amplitude* of the ac noise appears to be independent of the impurity concentration c (Ref. 6) (and hence the height of the pinning barrier). Measurements on a clean sample (residual resistance ratio of 150) which are presented here show very sharp lines (Q exceeding 1000) of large amplitude. Further, the amplitude is independent of the length l of the sample. This observation indicates that the noise signal is not an extensive quantity. In fact, the noise amplitude for all samples we have examined is roughly 20 μV independent of c, l, f, and T (except near T_c). Theoretical attempts by a number of authors[8] to obtain a sharp noise spectrum by averaging over impurities have not survived passage to the thermodynamic limit. We report here the first of a series of experiments designed to address these problems.

By studying the relative contributions to the total "noise" intensity from various parts of the sample we have obtained evidence that the source of the "noise" is quite different from that postulated in these conventional theories. The physical evidence points to a property of the noise signal which we shall call local. In our experiment normal (uncondensed) electrons are injected into (or bled from) a segment of the sample, say, α. (See Fig. 1 inset.) This has the effect of reducing the electric field E in α while leaving E negligibly perturbed in β and γ. The effect of such an inhomogeneous field distribution on the noise spectrum is as follows. A side component splits off from the original fundamental spike and moves to lower frequencies as the shunt resistor (and E in the α segment) is decreased. We easily justify identifying this side component with the α segment because it alone is shifted and by an amount consistent with the calculated decrease in E. The rest of the original spike remains unperturbed. In Fig. 1 we show for

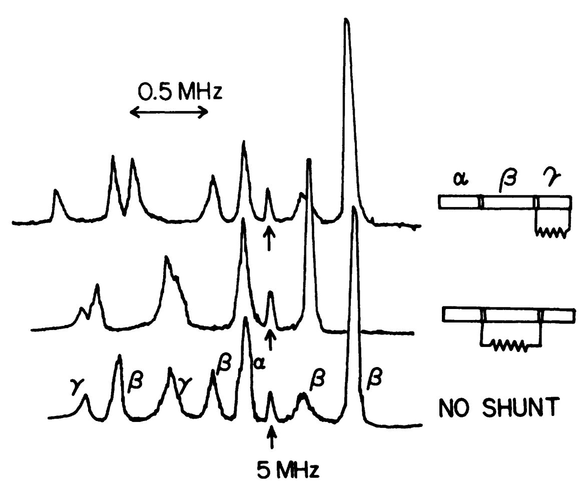

FIG. 1. Identification of components of the fundamental in the power spectrum of $NbSe_3$ at 50 K. By shunting each of the three segments α, β, γ, in turn, it is possible to identify that segment with the components that are shifted. The arrow indicates a frequency market.

clarity a much-recycled spectrum which displays several fine-structure components. By shunting each segment in turn, we can identify the source of each component. In the bottom trace of Fig. 1 the components have been labeled according to their origin. The ease with which the individual spikes can be moved (sometimes right through each other without any observable glitch) demonstrates that the three segments oscillate independently from the others and no locking mechanism or phase synchronization exists between the three segments.

To analyze these results we consider the effect of the silver paint contact pad on the CDW conduction. Because of the higher conductivity of the pad the component of the E field along the chain direction E_x is much reduced compared with the rest of the sample. Near threshold the CDW condensate is stationary in the region covered by the paint (see Fig. 2) while the drift velocity v_s is finite in the uncovered regions. The sample reconciles these differences in v_s by conversion of condensed carriers into free carriers in a region near the paint boundary of magnitude equal to a healing length ξ.[9] (This is analogous to the occurrence of phase-slip centers and hot spots in superconducting whiskers.) The occurrence of regions under the contact pads where v_s is zero effectively truncates the sample into three independent parts which may oscillate at three (or more) closely spaced frequencies. This explains the occurrence of the three fundamentals F_0, F_1, and F_2 in the data of Richard *et al.*[4] which are on four-probe samples. At high E fields the region under the pad starts to slide but at much lower velocity than the rest of the sample. This explains the appearance of low-frequency spikes[1,4,5] which lag (and are incommensurate with) the major fundamentals.

The second observation we report concerns the relative magnitudes of the fine-structure components. We find that the apparent oscillator strengths change dramatically in ranking as the noise probe (the lead connecting the sample to the spectrum analyzer) is moved to different parts of the sample. For example, the α lines appear weak when the noise probe is at the γ end of the sample while the γ lines appear strong. The situation is reversed if the noise probe is moved to the α end. In Figs. 3 and 4 we show this amplitude attenuation for the α and γ lines for various noise-probe and ground configurations (ij). (i indicates the position of the noise probe and j the ground.) Because of the fluctuating output of the spectrum analyzer, these lines represent averaged intensities over five sweeps. In both figures it is clear that the largest signals are obtained when the noise probe is in contact with one of the ends of the segment in question (e.g., 21, 13, and 23 in Fig. 3). Conversely, the signal is reduced by a factor of 5 to 10 when neither noise probe nor ground touches the relevant segment (e.g., 34 and 43 in Fig. 3, and 12 and 21 in Fig. 4). Configurations in which the

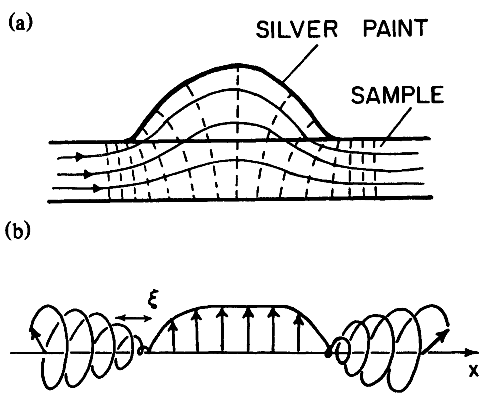

FIG. 2. (a) Schematic distribution of current flow lines and equipotential lines in the vicinity of a contact pad. The electric field component along the chains is inhomogeneous. (b) Representation of sliding conductivity near threshold field. In the middle secton the CDW is stationary, while in the uncovered regions the phase of the order parameter (indicated by arrows) rotates. Adjacent regions are separated by an interface where the order parameter is zero. ξ is the healing length.

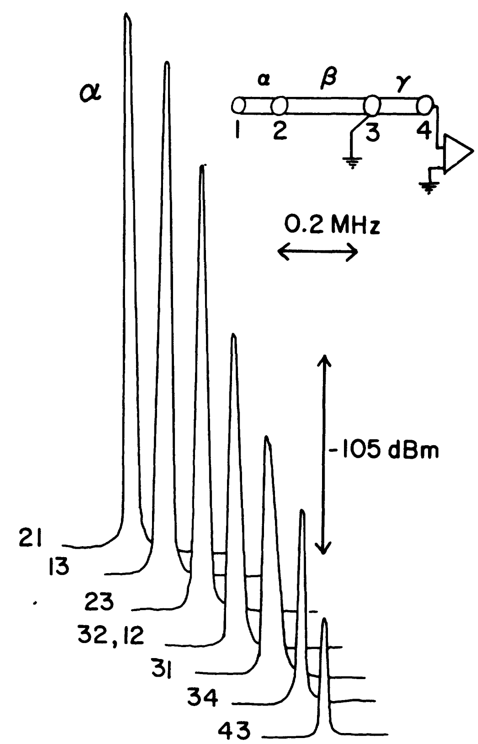

FIG. 3. Variation of the averaged amplitude of the α line in the power spectrum (linear scale) for different positions (ij) of the noise probe (i) and the circuit ground (j). The inset shows the configuration (43). The preamp consists of three ganged single-ended ANZAC AM-107 modules. The sample current is from a floating battery.

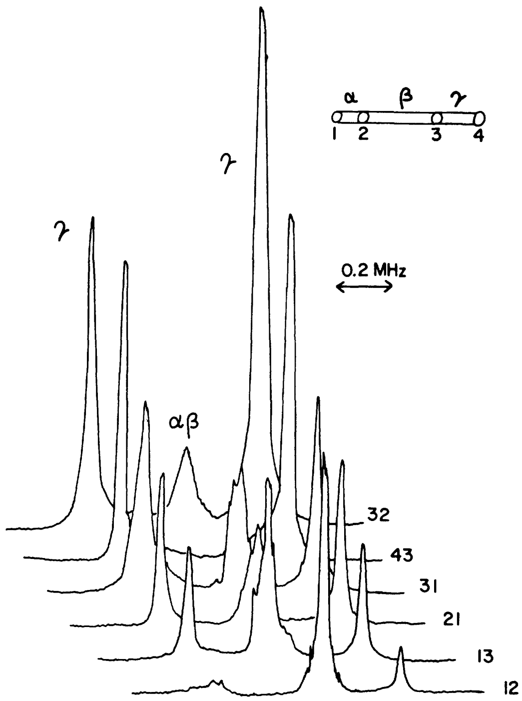

FIG. 4. Variation of the averaged amplitude of the γ line in the power spectrum (linear scale) for different positions of the detector (see Fig. 3 and text).

ground but not the noise probe touches the relevant segment produce intermediate intensities (31 and 32 in Fig. 3). Certain configurations (e.g., 12 in Fig. 3 and 43 in Fig. 4) violate these simple rules. More recent experiments[6] show that an interference effect exists between the two ends of a given segment which tends to diminish the observed signal. These are consistent with the observed violations.

Although the observation that the signal strength is diminished as the noise probe is moved away from the source is reasonable, the magnitude of the attenuation is surprising. (The attenuation of the γ lines in Fig. 4 is about 30 dB over a sample length of 1.5 mm.) This drastic attenuation is consistent with a model in which the source of the noise is highly localized at the site of the contacts rather than uniformly distributed throughout the length of the sample (as would be required in an impurity-driven model). Such a local model accounts for the absence of scaling of the noise amplitude with sample length. It is also consistent with the lack of dependence of the amplitude on the impurity level within the bulk since the latter would produce an ac voltage that scales with length. These results imply that CDW conduction noise arises because of the presence of discontinuities at the boundaries. In principle, if a continuous closed loop of $NbSe_3$ could be produced no noise should be observed. However, the technical problems of establishing this null result appear insurmountable.

In summary, the presence of probe contacts seriously perturbs the CDW conduction in these remarkable solids (over and above the usual Schottky barrier problems which are usually not serious). Four-probe samples are truncated into three independent segments. The persistent invariance of the noise amplitude with respect to changes in c, T, f, E, and l cannot be reconciled with the simple classical models[3,7] which assume that the bulk current has an additive ac component due to the impurity potential. Our data imply that the origin is highly localized at the sample-contact interface. However (in the simplest model), the contact surface has to be smooth on the nanometer scale (which is impossible) if the noise signal is to add coherently. In the model by Maki and Ong,[9] which examines the role of a transverse vortex sheet acting as the noise generator and phase sink, this stringent requirement is not needed. Recent experiments by Gill[10] and Saint Lager *et al.*[11] have demonstrated the existence of a 100-μm length scale in the non-Ohmicity. It is this length rather than ξ which is relevant to the noise generation problem. Theoretical studies on the boundary effects on the drifting CDW are particularly desirable.

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