Origin of Broadband Noise in Charge-Density-Wave Conductors

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(Received 31 August 1984)

We report experimental results on the broadband noise in the sliding–charge-density-wave conductor, orthorhombic TaS_3. We propose that the noise has its origin in the interaction of a deformable condensate with random impurities. The experimental results are in excellent agreement with a phenomenological model based on fluctuations in the impurity pinning force due to deformations of the sliding condensate. The amplitude of the noise is directly related to the dynamic coherence volume of these deformations.

PACS numbers: 72.15.Nj, 72.15.Jf, 72.70.+m

Broadband "$1/f$ noise" is a generic phenomenon found in a wide variety of electronic systems. Current interest is focused on determining the origin of this noise and the information about conduction processes which can be obtained from it.[1] A new conduction mechanism has been observed in quasi-one-dimensional conductors[2] such as $NbSe_3$ and TaS_3. Above a threshold field E_T, current is carried by a sliding–charge-density-wave (CDW) condensate. Below E_T the condensate is pinned by impurities. The onset of sliding is accompanied by large-amplitude broadband noise of $1/f$ type.[3–6] Despite several experimental studies the origin of this noise remains elusive.

In this Letter we demonstrate that the noise has its origin in the interaction of the deformable condensate with random impurities. The central experimental features are in excellent quantitative agreement with a model where the noise is caused by pinning-force fluctuations associated with thermally activated transitions between "metastable" steady states of the condensate. Moreover, the model allows noise measurements to be used as a probe of the dynamic coherence length, a crucial, but until now inaccessible, quantity.

The results reported here were obtained with samples of orthorhombic TaS_3 grown by one of us (R.A.K.) using the standard I_2 vapor-transport technique. Contacts were made with platinum paint.[7] Noise measurements were performed at constant current in a two-probe configuration. A PAR model 124A lock-in amplifier measured the rms noise voltage.

Our measurements confirm the following major characteristics of the broadband noise. (1) *Field dependence.*—The onset of noise is sharp and coincident with the onset of CDW motion at E_T as evidenced by a comparison with the differential resistance measurement.[3] (2) *Frequency dependence.*—The noise power has an $f^{-\alpha}$ spectrum[4] which is field independent except near the threshold voltage V_T.[8] However, we find that the spectrum is strongly temperature dependent. (3) *Sample size dependence.*—The rms noise voltage δV scales as $[l/A]^{1/2}$ where l is the length and A is the cross-sectional area or, equivalently, $\delta V^2/V^2$ scales as the inverse volume.[4] This implies that the noise is generated throughout the sample volume and not at the surface or contacts.

The dependence of the noise on field, frequency, and temperature is inconsistent with a generalized form of Nyquist noise.[6] Instead, we show that it is consistent with a phenomenological model of resistance fluctuations at constant current, analogous to $f^{-\alpha}$ excess noise in normal conductors.[1]

A variety of experiments have shown the existence of metastable states of the CDW condensate which have different resistivities.[9,10] These are believed to correspond to long-wavelength deformations of the phase of the CDW order parameter. Such deformations alter the distribution of phases at impurity sites and therefore the pinning force exerted by the impurities on the sliding condensate.[11] We propose that thermally activated fluctuations between metastable states with different pinning forces produce the $1/f$ noise.

At constant total current, the fluctuations in the effective pinning force or threshold voltage V_T of the sample cause fluctuations in the chordal resistance $R\,(=V/I)$ which is explicitly threshold-voltage dependent. Within this model, therefore, the noise voltage δV is given by

$$\langle \delta V^2\rangle = I^2\langle \delta R^2\rangle = I^2(\partial R/\partial V_T)^2\langle \delta V_T^2\rangle . \qquad (1)$$

Direct measurement of $\partial R/\partial V_T$ is not possible; so we assume that R is a function of $V-V_T$ only, implying that $\partial R/\partial V_T = -\partial R/\partial V$. The latter is evaluated numerically from the I-V characteristics.[12] Since $\partial R/\partial V$ is only weakly frequency dependent below 100 kHz, the frequency dependence is entirely contained in $\langle \delta V_T^2\rangle$, i.e., $\delta V^2(\omega) = I^2(\partial R/\partial V_T)^2 \delta V_T^2(\omega)$.

Figures 1(a) and 1(b) show plots of the field dependence at two temperatures of the noise voltage measured at one frequency ($\omega = 330$ Hz, $Q=10$) and of the numerically evaluated value of $I\,\partial R/\partial V$. Clearly, except very near V_T, they track each other accurately.[8] The magnitude of $I\,\partial R/\partial V$ is of the order of unity,

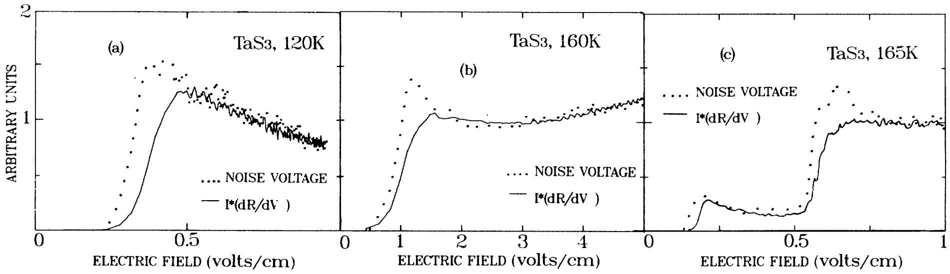

FIG. 1. Field dependence of the broadband noise (δV) measured at 330 Hz. The solid line represents the quantity $I\,\partial R/\partial V$ evaluated from the I-V characteristics. (a) $T=120$ K, (b) $T=160$ K, and (c) $T=165$ K for a sample with two distinct threshold fields (see text).

i.e., δV_T is of the same order as the noise which is small compared to the threshold voltage V_T. This is consistent with the sharp threshold field seen in experiments. For certain long ($l \sim 5$ mm) samples we have seen two distinct threshold fields, each associated with a sharp drop in the differential resistance and a step in the noise voltage. Figure 1(c) shows the field dependence, for such a sample, of the same two quantities as in Figs. 1(a) and 1(b). Not only does $I\,\partial R/\partial V$ show the same features as the noise voltage, but it also accurately reproduces the relative step heights *with no adjustable parameters.* We have also tested this field dependence for $NbSe_3$ below both the upper and lower T_c's and the agreement is excellent.

The threshold-fluctuation model thus provides the first explanation, to our knowledge, of the field dependence of the broadband noise. This model is analogous to the critical-current fluctuation model for Josephson tunnel junctions,[13] where temperature fluctuations were considered to be the source of the critical-current fluctuations. However, direct measurement of the field dependence of the voltage modulation caused by an imposed temperature modulation[14] rules out temperature fluctuations as the primary source of noise in CDW systems. Rather, the threshold fluctuations are associated with thermally activated transitions between metastable states.

The volume dependence of the noise described above, $\delta V^2 \propto l/A$, implies[1] that it is an incoherent addition of fluctuations generated in coherent volumes λ^3 (with anisotropy ignored). This coherence volume corresponds to the typical volume over which the CDW phase is deformed in going from one metastable steady state to another. The fluctuation of the effective pinning force δE_T in each region should be proportional to E_T itself which is a measure of the pinning force. The total noise voltage measured across the sample at constant current is then

$$\langle \delta V^2(\omega) \rangle = I^2 \left(\frac{\partial R}{\partial V_T} \right)^2 E_T^2 \lambda^3(T) \frac{l}{A} S(\omega, T), \qquad (2)$$

where $S(\omega, T)$ is the spectral weight function which reflects the rate of transitions between different metastable states.

The volume dependence of Eq. (2) is analogous to the usual $1/N$ dependence of the noise power $[\delta V^2/V^2]$ in normal metals where N is the number of electrons.[1] In CDW systems the number of independent entities generating the noise is lA/λ^3 which is small compared to the number of electrons in a metal. This factor is responsible for the large magnitude of the noise. An important feature of Eq. (2) is that information about the usually inaccessible quantity λ^3 can be obtained from noise measurements. By integrating the noise voltage over all frequencies we obtain an estimate of $\lambda^3 \approx 1\mu^3$ at 100 K.

In Fig. 2(a) we plot the temperature dependence, for $V = 2V_T$, of $\delta V^2(\omega)$ measured at 330 Hz. It grows rapidly below T_c and has a pronounced peak near 150 K where an incommensurate-commensurate transition is thought to occur.[15] This behavior contradicts earlier interpretations[5] of the temperature dependence of the noise as reflecting directly the order parameter which does not show the structure,[16] specifically the peak, seen in the noise voltage.[17] Figure 2(b) shows the temperature dependence of $I^2(\partial R/\partial V)^2 V_T^2$ measured directly. This quantity also grows rapidly below T_c and shows a pronounced peak at 150 K.

While the functions plotted in Figs. 2(a) and 2(b) appear qualitatively the same, quantitatively they are not identical. In Fig. 2(c) we plot the temperature dependence of their ratio which, according to Eq. (2), reflects the temperature dependence of $\lambda^3 S$. This grows below T_c and saturates gradually. The peak disappears and $\lambda^3 S$ changes relatively little near 150 K. This is consistent with the fact that x-ray measurements reveal no apparent structure in the CDW order parameter in this temperature range.[2]

Measurements of the noise spectrum $S(w, T)$ indicate that the temperature dependence of $\lambda^3 S$ near T_c is dominated by changes in the CDW order parameter. We expect that λ scales with the Lee-Rice[11] correlation

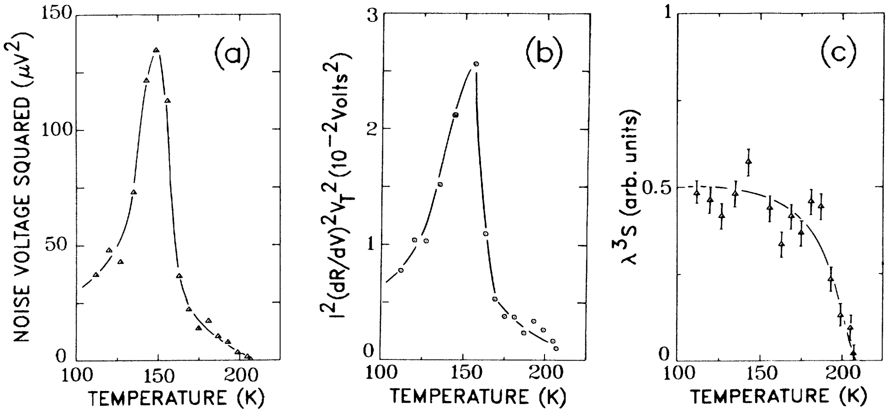

FIG. 2. Temperature dependence of (a) δV^2(330 Hz), (b) $I^2(\partial R/\partial V)^2 V_T^2$, and (c) $\lambda^3 S(\omega,T)$ obtained from Eq. (2). $V = 2V_T$ for all three quantities. The solid lines are guides to the eye.

length λ_{LR}. A mean-field calculation shows that $\lambda_{LR} \to 0$ as $T \to T_c$, suggesting that the observed behavior of $\lambda^3 S$ near T_c reflects a decrease of λ^3 to zero. Note that λ is distinct from the coherence length for CDW amplitude fluctuations which must diverge at T_c.[18] A microscopic theory is needed to understand the relation of λ to λ_{LR} and the dynamic coherence length of Fisher.[19]

We now consider the frequency dependence of the noise. Dutta and Horn have shown that thermally activated processes which alter the resistance produce a broad distribution of relaxation times provided the distribution of barrier heights is broad compared to $k_B T$. This leads to an $f^{-\alpha}$ spectrum which is both frequency and temperature dependent. We have made detailed measurements of the temperature dependence of the noise spectrum in TaS_3 which are consistent with this model. These results will be presented elsewhere. Independent evidence of a thermally activated distribution of relaxation times in CDW systems has been observed in the frequency dependence of the conductivity.[10,20,21]

An important feature of our model for the origin of broadband noise is that other properties can be inferred from noise measurements. One example, the coherent volume, was mentioned above. The model further suggests the following: (1) $S(\omega,T)$ is strongly related to $\sigma(\omega,T)$, the low-frequency relaxational conductivity[10]; (2) the onset of metastability and glassy behavior[9] occurs as the time scales of thermally activated processes become long relative to measurement times; (3) very low-frequency fluctuations near V_T account for "switching"[2]; (4) introduction of strong impurities that enhance dc metastability[9] would also enhance the low-frequency noise. These implications are being tested experimentally.

To summarize, we have presented a detailed explanation for the origin of $1/f$ noise in CDW systems. Analogous models should be applicable to other systems, in particular to flux motion in type-II superconductors[22] where $1/f$ noise is also observed at the onset of flux motion.

We acknowledge helpful discussions with A. N. Bloch, P. M. Chaikin, P. Dutta, D. C. Johnston, R. Koch, and J. R. Schrieffer.

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