Observation of narrow-band charge-density-wave noise in TaS_3

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We report the observation of narrow-band noise in the linear-chain compound TaS_3. The noise frequency is proportional to the charge-density-wave (CDW) current, providing direct evidence for CDW motion in TaS_3.

It has recently been reported[1] that below the transition temperature to a charge-density-wave (CDW) state, the linear-chain compound TaS_3 exhibits a giant dielectric constant and, above a threshold field E_T, a nonohmic electrical conductivity. Both observations are closely analogous to those made in $NbSe_3$. They indicate the presence of a pinned collective mode, the charge-density wave (CDW), which is depinned at a high electric field.

In $NbSe_3$, the existence of broad- and narrow-band noise in the nonohmic regime is also direct evidence of a sliding CDW. Following the original work on this subject by Fleming and Grimes,[2] other groups[3–5] have measured and interpreted various aspects of the narrow-band noise. Several explanations have been proposed to account for it,[6] including solid-state turbulence and current oscillations due to a negative differential resistance.

In this Communication we report the observation of narrow-band noise in TaS_3 in the nonlinear conductivity regime, and compare the observed properties of the noise with those found in $NbSe_3$. We interpret the noise in TaS_3 as due to sliding CDW's. Its observation in a second material whose CDW transition exhibits properties which differ substantially from those of $NbSe_3$ may signal that sliding CDW noise is not an isolated phenomenon to be found only in $NbSe_3$, but that it can be expected to occur widely in materials which exhibit a nonlinear electrical conductivity associated with a CDW transition.

The main quantity measured in our experiments is the noise spectrum as a function of applied voltage (V) at a temperature ($T = 140$ K) which corresponds approximately to the minimum E_T in the CDW state. We detected the noise voltage V_n with a spectrum analyzer. A substantial improvement in the data was obtained by averaging 512 frequency (f) sweeps of the spectrum analyzer with a multichannel signal averager. A two-probe configuration with contact resistances two orders of magnitude smaller than the sample resistance was used. The noise spectrum was measured and dc current was applied along the needle direction, which corresponds to the chain direction in TaS_3.

The frequency spectrum of the noise is shown in Fig. 1 for various values of V at 140 K. The nominal threshold field, obtained from Fig. 2, is $E_T = 3.75$ V/cm. Below E_T, no evidence is seen for broad- or narrow-band noise, as indicated by the power spectrum at the top of the figure. Above E_T, however, sharp peaks with several harmonics appear, which move to higher f with increasing V. One such peak is identified by the arrows. It is clear that the spectrum is rather complicated. Measurements on other samples from the same batch demonstrate properties which are qualitatively similar, but quantitatively different from Fig. 1. We believe the spectral complexity and differences between samples are due to an inhomogeneous current density within TaS_3. Such inhomogeneities are probably responsible also for the rounding near E_T in Fig. 2. There are at least two reasons why these features should be more pronounced in TaS_3 than in $NbSe_3$, where some measurements[7] have shown a particularly simple spectrum and a very sharp threshold for nonlinearity. First, the crystal morphology of TaS_3 is much more fibrous than that of $NbSe_3$, which probably reflects a higher anisotropy of the former. As a consequence, different fibers can have a somewhat different current density, and therefore a different noise spectrum. Another contrast occurs because the homogenizing effect on the internal electric field by the remaining normal electrons in $NbSe_3$ is absent for TaS_3, which has a much more complete CDW transition.

We have observed another property of the noise which is also characteristic of CDW noise in $NbSe_3$. The noise amplitude rapidly decreases with increasing temperature and becomes unobservable somewhat below the metal-insulator transition temperature $T_{MI} = 215$ K.

In order to relate the noise frequencies to the total

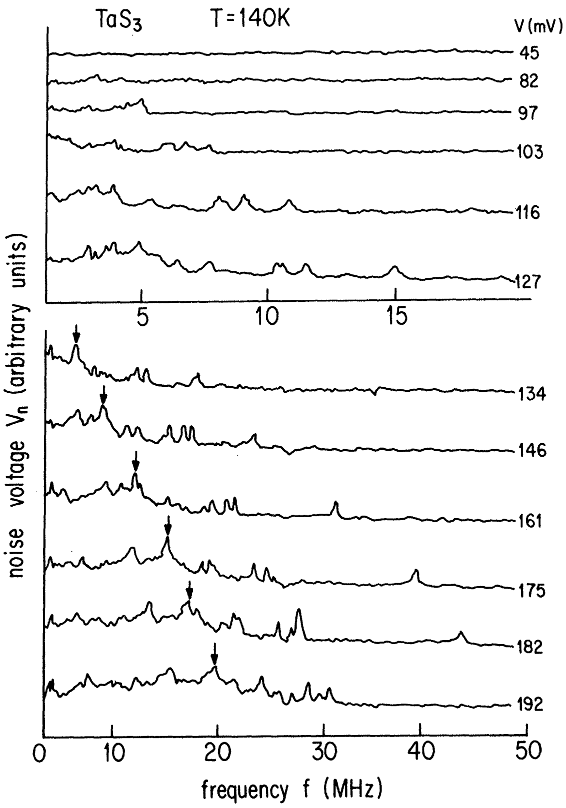

FIG. 1. Noise voltage as a function of frequency for different values of the bias voltage. Note the different frequency scale for the curves with $V < 130$ mV. The baseline $V_n = 0$ is established at the right-hand side of each trace. The nominal lead spacing is 0.2 mm. No noise is observed below E_T (Fig. 2), but it does appear above E_T. The peak identified with the arrow is used for Fig. 3. Its increase in f with higher V is characteristic of sliding CDW's.

dc current (I), we have measured the nonlinear conductivity (shown in Fig. 2) concurrently with the frequency spectra of Fig. 1, and have evaluated the excess current ($I_{\rm CDW}$) by using

$$I_{\rm CDW} = I - I_N \quad , \tag{1}$$

where I_N represents the current due to the ohmic behavior. I_N is established for measurements below threshold, and is extrapolated for field values above the threshold using the relation $I_N = G_N E$, where G_N is the conductance below threshold.

The observed variation of f as a function of $I_{\rm CDW}$ for the series of peaks identified by the arrows in Fig. 1 is shown in Fig. 3. An approximately linear relation is obtained. This was first proposed by Monceau *et al.*[3] for measurements on $NbSe_3$ and confirmed by other measurements[8] up to $f = 100$ MHz. This linear relation can be explained with the simple assumption that f is proportional to the CDW drift velocity v_d, i.e., $f = v_d/\lambda$, where λ is a characteristic distance. Since $v_d = I_{\rm CDW}/neA$, where n is the density of carriers, e is the electronic charge, and A is the cross-sectional area of the sample, it follows that

$$f = I_{\rm CDW}/ne\lambda A \quad . \tag{2}$$

A phenomenological model[9] for CDW depinning in a periodic potential also leads to Eq. (2).

A key element in the understanding of CDW conduction is the evaluation of λ. Although n is not known for TaS_3, we assume for the present that it is the same as for $NbSe_3$, $n = 1 \times 10^{21}$ cm^{-3} (see Refs. 8 and 9 for a discussion of this assignment). The sample cross section, obtained indirectly from its resistance, the spacing between the contacts, and the room-temperature conductivity $\sigma_{\rm RT} = 2 \times 10^3$ Ω^{-1} cm^{-1}, is $A = 3.3 \times 10^{-7}$ cm^2, which leads to $\lambda = 19$ Å. We note that a different choice of peaks in the noise spectrum would lead to a slightly different relation between f and $I_{\rm CDW}$, and consequently to a

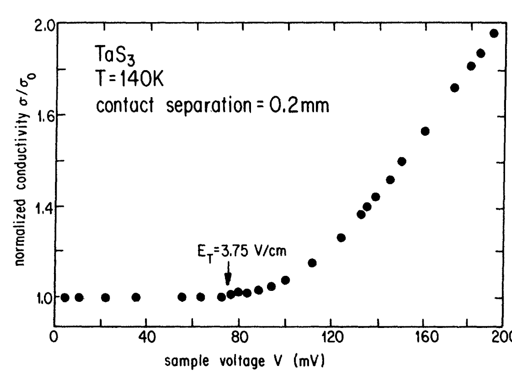

FIG. 2. Normalized conductivity as a function of bias voltage. The nominal assignment $E_T = 3.75$ V/cm is indicated by the arrow. The slowness of the increase in the data above E_T is attributed to an inhomogeneous current density.

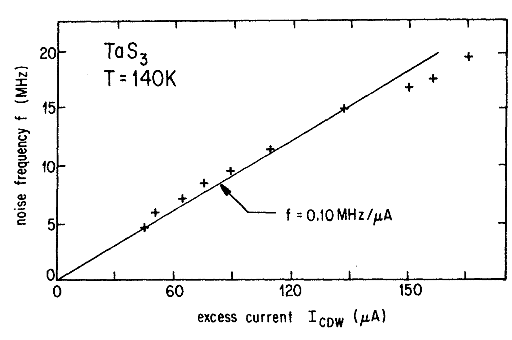

FIG. 3. Noise frequency as a function of excess (CDW) current for the peak identified in Fig. 1. The linear increase is characteristic of two models for CDW noise (Refs. 3 and 9).

somewhat different period λ. Independent measurements on a different sample with a well-defined dominant noise peak resulted in $\lambda = 14$ Å. Nevertheless, we conclude that the characteristic distance associated with the narrow-band noise is approximately one CDW period $4a_0 = 13.3$ Å.[10]

In conclusion, we have observed narrow-band noise characteristics of coherent voltage fluctuations in the linear-chain compound TaS_3. The noise frequency is proportional to the CDW current, which provides direct evidence that it arises from sliding CDW's. This, and related measurements, show that TaS_3 exhibits unusual CDW transport properties qualitatively similar to those seen previously only in $NbSe_3$. Since TaS_3 is a semiconductor below the CDW transition, these similarities may indicate that the uncondensed electrons in $NbSe_3$ play a minor role in the CDW transport properties.

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