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BROAD BAND NOISE ASSOCIATED WITH THE CURRENT CARRYING CHARGE DENSITY WAVE STATE IN TaS_3

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We report the observation of low frequency broad band noise in the current carrying charge density wave (CDW) state of orthorhombic TaS_3. The noise amplitude is proportional to the number of condensed electrons, and we suggest that the broad band noise reflects the dynamics of the internal deformations of the CDW condensate.

It is by now well established that the remarkable transport properties of the transition metal trichalocogenides $NbSe_3$ and TaS_3 are due to the response of the charge density wave (CDW) condensate. The nonlinear conductivity observed[1] above a well-defined threshold field E_T together with current oscillation in the current carrying state[2] demonstrate the highly coherent response of the condensate to external driving fields.

The CDW order parameter is given by $Ae^{i\phi}$ where A is the amplitude and ϕ is the phase of the condensate. The current density due to the sliding CDW is related to the time derivative of the phase

$$j = \frac{e\lambda n}{2\pi}\frac{d\bar{\phi}}{dt} \qquad (1)$$

where $\bar{\phi}$ refers to the average phase in the sample, and it is assumed that the time derivative of the phase is independent of position; in other words the CDW condensate moves as a rigid entity with the internal dynamics of the condensate neglected. Recent phenomenological theories[3,4] of CDW transport describe the observed dc and ac response phenomena in terms of Eq. (1), with certain assumptions on the current carrying mechanism. In all cases observed so far, the CDW mode is pinned by impurities. In $NbSe_3$ the pinning energy increases linearly[5] or quadratically[6] with increasing impurity concentration c, and a concentration dependence proportional to c^2 has been found in TaS_3.[7] While the models which attempt to describe the highly coherent response of the CDW condensate treat the pinning in a phenomenological way (either as a periodic pinning potential[3] or a pinning gap[4]), they fail to account for the microscopic details of the pinning mechanism.

The observed concentration dependence of the pinning energy (and of the characteristic field E_T where depinning of the CDW occurs) can be accounted for by including local deformations of the phase around the impurities,[8,9] and the elastic term response for these deformations is given by

$$H = \frac{hV_F}{4\pi a^2}\int (\nabla\phi)^2 \, d\vec{r} \qquad (2)$$

where V_F is the Fermi velocity and a the lattice constant parallel to the chain direction.

With static local deformations playing an important role in the pinning mechanism, it is expected that the dynamics of these distortions will show up in the transport phenomena in the form of incoherent, broad band noise, in the current carrying CDW state.

In this communication we report our observations of the low frequency (0-25 KHz) in the charge density wave state of orthorhombic TaS_3. The onset of the current carrying state is accompanied by the sudden appearance of broad band (and weakly frequency dependent) noise. The temperature dependence of the noise amplitude reflects the temperature dependent carrier number n(T) condensed in the CDW mode.

The broad band noise was measured using an HP 3582A spectrum analyzer. The voltage drop across the sample was amplified by a broad band differential amplifier before the Fourier transform was taken. Figure 1 shows the rms value of the broad band noise for applied voltages V = 0 mV and V = 50 mV. The threshold voltage for the onset of nonlinear dc conduction is V_T = 20 mV, as determined by dc conductivity measurements as a function of applied voltage. The noise amplitude increases slightly with decreasing frequency showing that the noise is not completely white, but it is also not a 1/f noise. The functional dependence of the noise spectrum can be represented by an $f^{-0.4}$ behavior in the frequency range measured. Noise spectra, such as shown in Fig. 1, were taken at various applied dc voltages and at various temperatures. The functional dependence of the noise amplitude was found to be insensitive to both the variation of temperature and applied voltage. Both the overall amplitude and the frequency dependence of the broad band noise are in broad qualitative agreement with experiments performed on $NbSe_3$.[10,11] In those experiments, for the same frequency range, $V(\omega)$ was found to be approximately three orders of magnitude smaller than the threshold voltage V_T, and was a slowly decreasing function of increasing frequency.

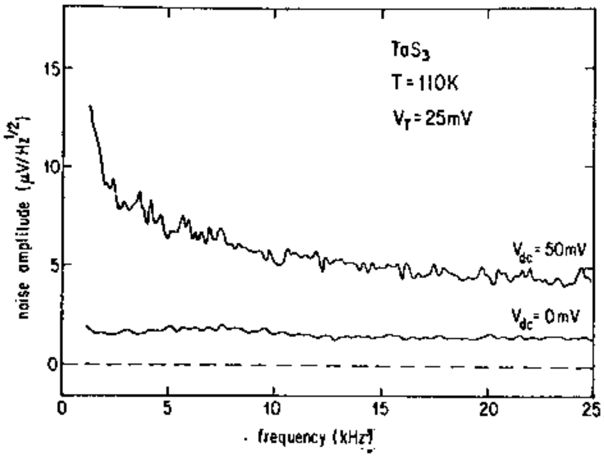

Fig. 1. Broad-band noise spectrum for orthorhombic TaS_3, expressed as noise voltage per root Hertz. The dashed line shows the absolute baseline for zero ac response. Because of amplifier noise, the effective baseline should be taken as the V_{dc} = 0 trace. V_T represents the threshold voltage for nonlinear dc conduction.

In Fig. 2 we show the field dependence of the dc conductivity $\sigma = I/V$ (measured using conventional voltmeters and standard resistances to measured V and I) together with the amplitude of the broad band noise at 15 KHz. It is apparent that the onset of the broad band noise coincides with the onset of nonlinear conduction, i.e., with the development of the current carrying CDW state.

We have shown before[1] that in the temperature range between 200 and 100 K, the threshold field for the onset of nonlinear conduction in TaS_3 is independent of temperature. We have measured the amplitude of the broad band noise at various temperatures at applied voltages V = 50 mV, corresponding to approximately $2V_T$ at all temperatures, and Fig. 3 shows the temperature dependence of the broad band noise amplitude (referenced to 15 KHz) at this applied voltage. The amplitude $V(\omega)$ decreases with increasing temperature, going smoothly to zero at the CDW transition temperature. In fact the temperature dependence of $V(\omega)$ is close to the temperature dependence of the number of carriers, as evaluated from X-ray,[12] low field transport[13] (conductivity and thermoelectric power), and current oscillation[2] studies. We conclude, therefore, that the broad band noise does not represent temperature driven excited states (such as solitons), but - aside from the temperature dependent carrier number in the condensate - is essentially a zero temperature phenomenon.

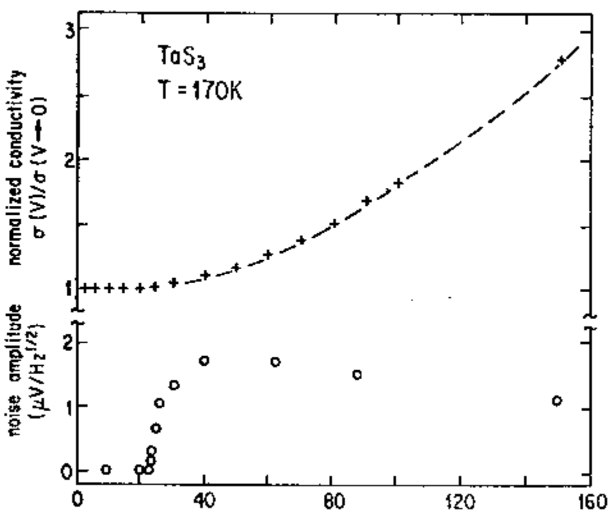

Fig. 2. dc conductivity and broad-band noise amplitude for orthorhombic TaS_3, as functions of the applied dc bias voltage V_{dc}. The noise amplitude is the noise voltage per root Hertz at 15 KHz. The onset of nonlinear dc conduction is at V_T = 25 mV. The dashed line is a guide to the eye for the conductivity data.

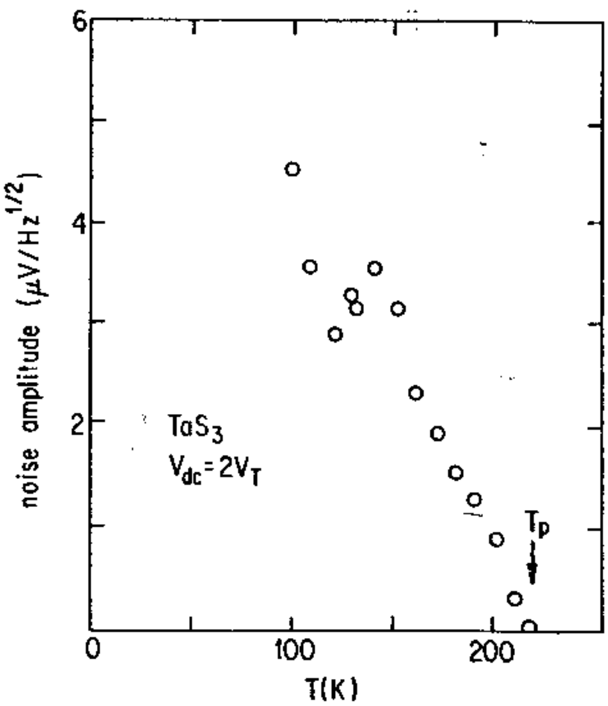

Fig. 3. Broad-band noise amplitude for orthorhombic TaS_3 as a function of temperature. The noise amplitude is expressed as noise voltage per root Hertz. The sample has been biased to twice the threshold field for the onset of nonlinear dc conduction. The CDW transition temperature T_P is identified in the Figure.

Several explanations have been advanced to interpret (on a qualitative basis) some features of broad band noise observed in $NbSe_3$. Monceau et al.[11] interpret their experimental data as due to coupling between various CDW segments in the current carrying state. It is, however, well established both in $NbSe_3$[14] and TaS_3[2] that a coherent current-carrying state develops at applied electric fields rather close to E_T, and at higher fields coupling between different regions of the specimen is already established. Another type of explanation is based on noise generated by solitons and antisolitons.[15] No evidence for solitons associated with th slight deviation from commensurability has been found in these compounds, and temperature generated soliton-antisoliton ($S-\bar{S}$) pair densities would strongly increase with increasing temperature, due to the gap in the S and $\bar{S}$ excitation spectrum, in contrast to the observed temperature dependence.

In the classical single particle description of the nonlinear and frequency dependence CDW response[3] the equation of motion of the average phase is given by

$$\frac{1}{\tau}\frac{d\bar{\phi}}{dl} + \omega_p^2 \sin\bar{\phi} = \frac{2k_F eE}{m} \quad (3)$$

where k_F is the Fermi wave vector, τ is a phenomenological damping constant, ω_0^2 is the pinning potential. $Q = 2\pi/\lambda$, where λ is the CDW period, and e and m refer to the effective charge and effective mass of CDW. Equation (3) leads to a coheret CDW response with no broad band noise in the current-carrying state. Equation (3) is formally analogous to the equation which describes the behavior of resistively coupled Josephson junctions.[16] Noise phenomena, which represent thermally assisted[17] or quantum[18] transitions between the minima of the periodic potential, are extensively studied in the Josephson literature. Temperature driven fluctuations, however, cannot play an important role in the dynamics of the collective CDW mode, where a large number of degrees of freedom are frozen out by the development of the condensate, and the depinning process is essentially a zero temperature phenomenon. We believe, therefore, that while the models which include a noise term to the right hand side of Eq. (3) give results qualitatively similar to those observed by us, the noise does not represent the random motion of the collective coordinate or average phase ϕ.

The most likely explanation for our findings is that the dynamics of the internal deformations of the CDW condensate, which is pinned by randomly distributed impurity potentials, is important in the dynamics of the current carrying state. A model, originally proposed by Fukuyama and Lee[8] and by Rice,[8] has recently been considered by Pietronero and Strässler.[19] A computer simulation leads in the current carrying state both broad band and arrow band noise, with $V(\omega)$ nearly frequency independent in the low frequency limit.

We note that Eq. (3) with a periodic potential leads to a threshold field E_T, to infinitely sharp narrow-band "noise" peaks with no associated broad band noise in the nonlinear region, and also to a spurious divergence of the differential conductance dI/dE near E_T.[20] A rigid CDW in the presence of randomly distributed impurity centers, however, does not lead to a periodic pinning potential.[21] The inclusion of the elastic term, Eq. (2), in the CDW dynamics does lead to impurity pinning,[9] with an appropriate concentration dependence of the threshold electric field. It also removes the divergence in the I-V characteristics and also gives low frequency broad band noise[19] in agreement with the experimental observations in TaS_3 and also $NbSe_3$. Whether a quantitative account of these observations is feasible with a consistent set of impurity potentials and elastic constants of the CDW remains to be seen. Computer simulations for various applied fields, stiffness parameters, and probably extensions of the model to three dimensions would be required for a detailed comparison between theory and experiment.

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Note added in proof: Recent broad band noise experiments on $NbSe_3$ [J. Richard, P. Monceau, M. Papoular, and M. Renard, J. Phys. C 15, 7157 (1982)] show the same qualitative features as those reported in this paper.

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