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ON THE NONLINEAR CHARGE DENSITY WAVE CONDUCTIVITY OF TaS_3

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The conductivity of the charge-density-wave semiconductor TaS_3 is shown to consist of temperature dependent ohmic, and field dependent but temperature independent, contributions at temperatures below the Peierls transition $T_p = 215$ K. The field dependent conductivity can be described by a tunneling formalism proposed by Bardeen.

The linear chain compound TaS_3 (orthorhombic phase) undergoes a phase transition to a Peierls-Frölich semiconducting state[1,2] at T_p = 215 K. The superstructure[2] is at 0.5 a*, 0.125 b*, 0.25 c* where c is the chain direction, and thus the charge density wave (CDW) is commensurate with the underlying lattice. We have shown before that the conductivity is strongly nonlinear[3] and frequency dependent[4] below T_p, and is accompanied by a giant dielectric constant[3] in the CDW state. These observations, together with the appearance of narrow band noise[5] with fundamental frequency $f_n \sim I_{CDW}$, where I_{CDW} is the excess current due to the CDW, give conclusive evidence that the CDW's are pinned at low fields but can be depinned at high electric field strengths.

In this communication we report detailed field dependent conductivity studies in the CDW state. We demonstrate that the dc conductivity σ below T_p can be decomposed into two parts: an ohmic conductivity which depends strongly on the temperature, and a field dependent conductivity which is independent of temperature above 150 K. We conclude that finite temperature effects are unimportant to describe the CDW dynamics in TaS_3.

The low field dc conductivity is shown in Fig. 1. The Peierls transition, evidenced by the temperature derivative[3] of σ, is shown in the same figure by the arrow. Detailed field dependent conductivity measurements, using pulse widths as short as 100 nsec, were performed at selected temperatures both above and below T_p. Above T_p we have found ohmic behavior up to fields of approximately 1 V. Below T_p, σ is strongly non-ohmic at small electric fields. Down to about 130 K we observe a sharp threshold E_T for the onset of nonlinear conductivity. At low temperatures the sharp threshold disappears, most probably due to inhomogeneous electric field distributions. In this communication we focus on experiments performed in the temperature range where a sharp threshold is observed.

A typical $\sigma(E)$ curve measured in this temperature region is shown in the insert of Fig. 2. σ measured at 700 mV at various temperatures is also shown in Fig. 1, together with σ_{ac} measured at 2.4 GHz. It is evident from Fig. 1 that the conductivity is enhanced both at high electric fields and at high frequencies. This is indicative of a strong relation between

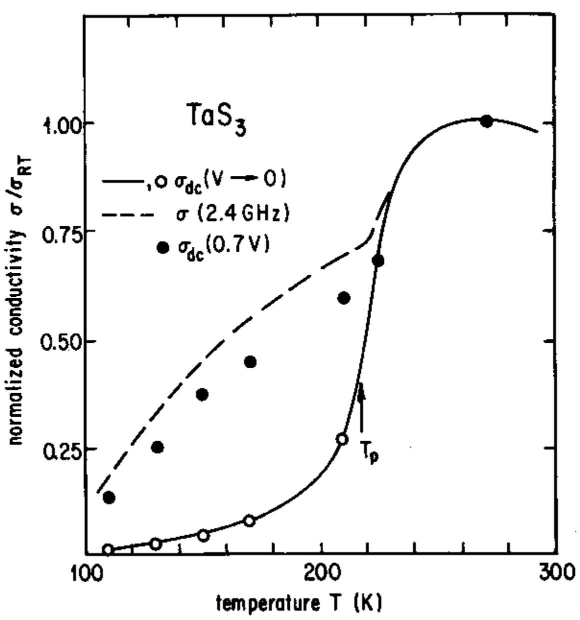

Fig. 1. Temperature dependence of the conductivity of TaS_3. σ(2.4 GHz) is from Ref. 4.

field and frequency dependent response of the CDW condensate.

In order to examine the field dependent part of the dc conductivity in detail, we have subtracted from $\sigma(T,E)$ the conductivity measured below the threshold field E_T, $\sigma(T,E \rightarrow 0)$. This is shown in Fig. 2, where $\sigma(T,E) - \sigma(T,E \rightarrow 0)$ has been normalized to the pretransition value $\sigma(T = 221\ K)$. It is evident from Fig. 2 that σ can be written as

$$\sigma(T,E) = \sigma(T) + \sigma(E) \quad (1)$$

where $\sigma(T)$ is the ohmic part of the conductivity. The field dependent part $\sigma(E)$, which represents the response of the CDW to a dc field, is independent of the temperature between 210 K and 150 K. The ohmic part changes by nearly one order of magnitude in this temperature region. I-V curves taken at temperatures below 150 K show deviations from those shown in the figure. At low temperatures independent evidence[3,4] suggests that a coherent response of the CDW does not apply, and that independent CDW segments, with a distribution of pinning energies, play an important role.

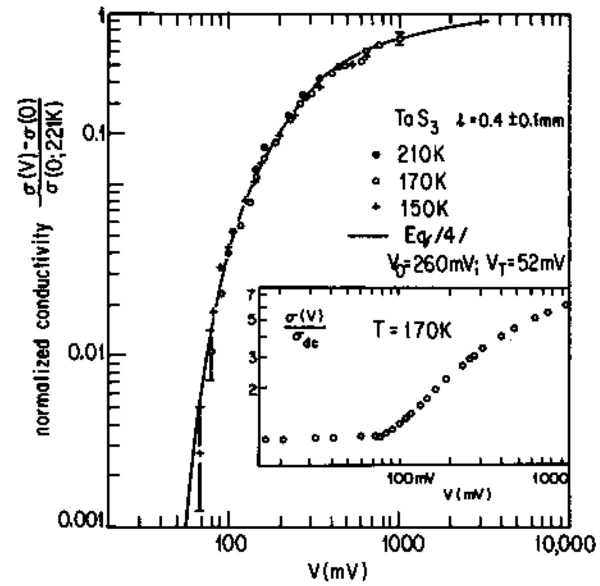

Fig. 2. Field dependence of the nonlinear part of the conductivity. The full line is Eq. (4), with parameters given on the figure. The insert shows $\sigma(E)$ measured on the same sample.

The ohmic and strongly temperature dependent contribution to the conductivity is most probably due to single particle excitations across the Peierls-Frölich gap. Indeed, $\sigma(T)$ can well be described by an activated conductivity $\sigma(T) = \sigma_0 \exp[-\Delta(T)/kT]$, where $\Delta(T)$ is temperature dependent. $\Delta(T \rightarrow 0) = 700$ K and goes to zero at the transition. From $\sigma(T)$ the temperature dependence of Δ can be evaluated.[6] Alternatively,[7] $\Delta(T)$, as given by the BCS form, accounts well for the observed $\sigma(T)$.

In describing nonlinear conductivity in $NbSe_3$, the prototype material for CDW conduction, various formulas have been proposed. The majority of these are modifications of a tunneling formula, accounting also for the finite threshold field for the onset of CDW conductivity.[8] It was suggested recently by Bardeen[9] that for a state where the CDW can be represented by a finite correlation length L, two characteristic fields play an important role. The characteristic field appearing in the tunneling probability is given by

$$E_o = \frac{\pi\varepsilon_g^2}{4\hbar e^* v_F} = \frac{\varepsilon_g}{2\xi_o e^*} \quad (2)$$

where ε_g is the pinning gap, $e^*/e = m/M$ is the ratio of the band mass to the Frölich mass, and $\xi_0 = 2\hbar v_F/\hbar\varepsilon_g$ is the coherence distance. The threshold field is given by the criterion that $e^* E_T L > \varepsilon_g$ for tunneling to occur. These assumptions lead to a tunneling probability

$$P(E) \sim [1 - (E_T/E)] \exp(-E_o/E) \quad (3)$$

and consequently to a conductivity given by

$$\sigma(T,E) - \sigma(T) = A[1 - (E_T/E)] \exp(-E_o/E). \quad (4)$$

The full line of Fig. 2 is Eq. (4) with parameters $E_T = 1.3$ V/cm, $E_0 = 6.5$ V/cm calculated from V_0 and V_T and ℓ as given on the figure, and $A = 0.8\ \sigma_{RT}$.

We have also measured the differential conductivity dI/dV in the presence of a dc bias voltage, using a lock-in technique. By comparing the conductivities measured by pulse and by dc technique, we have established that sample heating is not important up to fields approximately three to four times E_T. In Fig. 3 the full points are from a continuous dV/dI plot, and have been normalized to the same $\sigma(E \rightarrow \infty)$ as given in Fig. 2. The tunneling probability [Eq. (3)] leads to

$$\frac{dI}{dV}\frac{1}{\sigma(E\rightarrow\infty)} = \left[1 + \frac{E_o(E-E_T)}{E^2}\right] \exp(-E_o/E) \quad . \quad (5)$$

Equation (5), plotted as a function of V/V_T, is shown as a full line in Fig. 3. The only adjustable parameter in the figure is V_T, which is determined by the length of the sample. We note that the differential conductance is a very sensitive function of the nonlinear characteristics. Although $\sigma(E)$ derived on the basis of a classical description[10] leads to a conductivity which has the same overall behavior as the tunneling formula given by Eq. (4), dI/dV in the classical description diverges at E_T. This is in contrast to Eq. (5), which predicts an increasing differential conductance with increasing V in agreement with the experiment.

The measured characteristic fields E_0 and E_1 can be used to evaluate the parameters which characterize the CDW in the tunneling model.[9] From Eq. (2) and from the definition of the correlation length L it follows that $E_0/E_T = L/2\xi_0$. Then with $E_0 = 6.5$ V/cm and $E_T = 1.3$ V/cm, we obtain $L = 10\ \xi_0$, a correlation distance which is ten times larger than the coherence distance. Assuming that $e^*/e = m/M = 10^{-3}$, and $v_F = 10^7$ cm/sec, Eq. (2) leads to $\varepsilon_g = 1.1 \times 10^{-17}$ ergs, orders of magnitude smaller than kT, and to $\xi_0 = \varepsilon_g/2e^*E = 10^{-4}$ cm.

We also note that a formula, slightly dif-

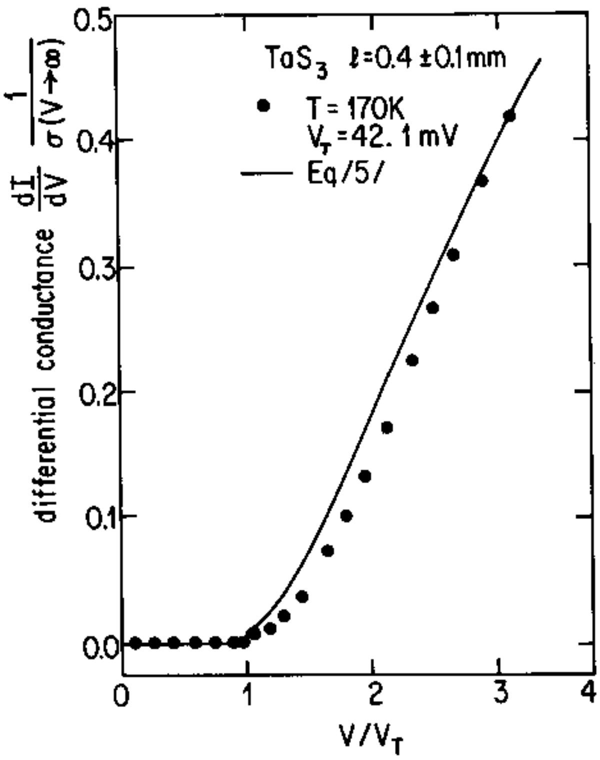

Fig. 3. Differential conductance dI/dV versus electric field. The full line is Eq. (5) with parameters given on the figure.

ferent from Eq. (4), was proposed to account for $\sigma(E)$ observed in $NbSe_3$. Fleming and Grimes[8] analyzed their experiments using an empirical expression

$$\sigma(E) = A[1 - (E_T/E)] \exp[- E_0/(E-E_T)] . \quad (6)$$

We also find good agreement between our experiments and Eq. (6).

In conclusion, we have shown that the dc conductivity $\sigma(T,E)$ of TaS_3 can be decomposed into a temperature dependent but ohmic part, and a field dependent part which does not appear to depend on the temperature. This observation suggests that the high field limit of the conductivity depends only slightly on the temperature somewhat below the Peierls transition. The analysis also suggests that σ, due to the sliding CDW, is close to the conductivity due to normal electrons observed above the transition temperature T_p.

The field dependent part of the conductivity can be described by the tunneling formula proposed by Bardeen, with parameters in agreement with those suggested by commensurability pinning.[9] The characteristic energy ε_g is orders of magnitude smaller than kT, and the characteristic length $L >> c_0$, where c_0 is the lattice constant, providing direct evidence for transport by the collective mode. The observation that E_0 and E_T are independent of the temperature is surprising. The coherence length is expected to decrease near T_p, leading to a divergent E_0 (and also E_T) at the transition temperature. While this has been observed in $NbSe_3$,[11] both E_T and E_0 are temperature independent up to $(T_p-T)T^{-1} = 4\times10^{-2}$.

We also note that the same analysis was previously applied by Bardeen[9] to account for the nonlinear conductivity of TaS_3 observed at low temperatures.[12] We have shown before[3,4] that at low temperatures randomness plays an important role and has a drastic influence on the I-V characteristics. We believe, therefore, that our evaluation of the CDW parameters is more relevant to the intrinsic coherent response of the charge density waves in TaS_3.

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