ON THE NONLINEAR CHARGE DENSITY WAVE CONDUCTIVITY OF TaS\textsubscript{3}

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The conductivity of the charge-density-wave semiconductor TaS\textsubscript{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\textsubscript{3} (orthorhombic phase) undergoes a phase transition to a Peierls-Pröflich semiconducting state\textsuperscript{1} at \(T_p = 215\) K. The superstructure\textsuperscript{2} is at \(0.5\) \(a\), \(0.125\) \(b\), \(0.25\) \(c\) where \(a\) 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\textsuperscript{3} and frequency dependent\textsuperscript{4}, below \(T_p\), and is accompanied by a giant dielectric constant\textsuperscript{5} in the CDW state. These observations, together with the appearance of narrow band noise\textsuperscript{6} with fundamental frequency \(\nu_{\text{CDW}}\) where \(\nu_{\text{CDW}}\) 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 \(\sigma\) below \(T_p\) can be decomposed into two parts: an ohmic \(\sigma\) conductivity which depends strongly on the temperature, and a field dependent conductivity which is independent of temperature above 120 K. We conclude that finite temperature effects are unimportant to describe the CDW dynamics in TaS\textsubscript{3}.

The low field dc conductivity is shown in Fig. 1. The Peierls transition, evidenced by the change in the temperature derivative\textsuperscript{3} of \(\sigma\), 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 the fields\textsuperscript{3} of approximately 1 V. Below \(T_p\), \(\sigma\) 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 \(\sigma(T)\) curve measured at 700 mV at various temperatures is also shown in Fig. 1, together with \(\sigma\) 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

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**Fig. 1.** Temperature dependence of the conductivity of TaS\textsubscript{3}. \(\sigma(2.4\) GHz) is from Ref. 4.

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 \( E_T \), \( \sigma(T, E = 0) \). This is shown in Fig. 2, where \( \sigma(T, E) - \sigma(T, E = 0) \) has been normalized to the pre-transition value \( \sigma(T = 221 K) \). It is evident from Fig. 2 that \( \sigma \) can be written as

\[
\sigma(T, E) = \sigma(T) + \sigma(E)
\]

(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\(^5\) 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.

\[E_0 = \frac{eE_0}{5}\hbar\pi v_{F}} = \frac{eE_0}{5\hbar\pi v_{F}}\]

(2)

where \( E_0 \) is the pinning gap, \( \sigma/\epsilon_0 = \pi/2 \) is the ratio \( \epsilon_0 \) of the band mass to the Fröhlich mass, and \( \epsilon_0 = 2m_F/\hbar^2 \) is the coherence distance. The threshold field is given by the criterion that \( \exp(-E_{0}/E) \). Similarly, assumptions lead to a tunneling probability

\[P(E) \sim [1 - (E_0/E)] \exp(-E_0/E)\]

(3)

and consequently to a conductivity given by

\[\sigma(T, E) - \sigma(T) = E_0 \exp(-E_0/E)\]

(4)

The full line of Fig. 2 is Eq. (4) with parameters \( E_0 = 1.3 \, V/cm, \epsilon_0 = 6.5 \, V/cm \) calculated from \( V_0 \) and \( V_{se} \) and \( E_0 \) given on the figure, and \( A = 0.8 \, \Omega^{-1} \).

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 \( E_0 \). In Fig. 3 the full points are from a continuous \( dV/dI \) plot, and have been normalized to the same \( \sigma(E = \infty) \) as given in Fig. 2. The tunneling probability [Eq. (3)] leads to

\[
dI/dV = \frac{1}{\sigma(E = \infty)} \left[ 1 + \frac{E_0 (E_0/E)}{E_0} \right] \exp(-E_0/E).
\]

(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\(^5\) 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 \( E_0 \). 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 \( E_0 \) can be used to evaluate the parameters which characterize the CDW in the tunneling model. From Eq. (2) and from the definition of the correlation length \( L \), it follows that \( E_0/L_0 = 1/L_0 \). Then with \( E_0 = 6.5 \, V/cm \) and \( E_0 = 1.3 \, V/cm \), we obtain \( L = 10 \, \xi_0 \), a correlation distance which is ten times larger than the coherence distance. Assuming that \( \epsilon_0 = \pi/2 \) is \( \pi/2 \), and \( v_F = 10^7 \, cm/sec \), Eq. (2) leads to \( E_0 = 1.1 \times 10^{-17} \, ergs \), orders of magnitude smaller than \( k_T \), and to \( \xi_0 = 2\pi\hbar v_F = 10^{-5} \, cm \).

We also note that a formula, slightly dif-
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 $\sigma$, due to the sliding CDW, is close to the conductivity due to normal electrons observed above the transition temperature $T_t$.

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. The characteristic energy $\epsilon_0$ is orders of magnitude smaller than $kT$, and the characteristic length $L > \epsilon_0$, where $\epsilon_0$ is the lattice constant, providing direct evidence for transport by the collective mode. The observation that $E_0$ and $E_0$ are independent of the temperature is surprising. The coherence length is expected to decrease near $T_t$, leading to a divergent $E_0$ (and also $E_0$) at the transition temperature. While this $T_t$ has been observed in NbSe$_2$, 11 both $E_0$ and $E_0$ are temperature independent up to $(T - T_t) = 4 \times 10^{-4}$.

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. We have shown before 9 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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