Nonlinear conductivity anomalies of the quasi-one-dimensional compound *m*-TaS_3 near the Peierls transition temperature

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A new nonlinear conduction regime was discovered in the Peierls conductor m-TaS_3. This regime occurs in a narrow ($\cong 5$ K) temperature interval near the Peierls transition temperature $T_{P2}=157.5$ K and it is characterized by the appearance of a) two substantially different threshold voltages in the dependence of the differential conductance σ_d on the dc voltage V_{DC} and b) periodic steps in the function $\sigma_d(V_{DC})$ in the presence of a strong rf field. Here the magnitude of a step $(40\ \mathrm{k}\Omega)^{-1}$ is comparable to the conductance quantum. © *1995 American Institute of Physics.*

A three-dimensionally ordered state with a charge-density wave (CDW) forms in quasi-one-dimensional (quasi-1D) conductors below the Peierls transition temperature T_P.[1] The CDW starts to slide in a constant electric field with voltages V_{DC} greater than the threshold voltage V_t. As a result, a nonlinear contribution to the conductivity appears and an alternating field with frequency f_{CDW}, proportional to the current I_{CDW} in the charge density wave, is generated.[2] This is observed experimentally as dc CDW current steps ("Shapiro steps") on the $I-V$ curve in the presence of a rf field with frequency f such that $f_{\mathrm{CDW}}/f=p/q$ (where p and q are integers).[3] In the dependence of the differential conductance σ_d on V_{DC}, these steps correspond to sharp interference peaks. As the temperature T_P is approached from below, the contribution of the CDW to the total conductivity decreases, since the concentration, $n_s \propto I_{\mathrm{CDW}}/f$, of electrons condensed in the CDW drops sharply.[4,5] Moreover, the coherence of the sliding CDW is destroyed increasingly more strongly because of the increasing 1D fluctuations.[6] The mechanism of "melting" of the CDW has been studied inadequately.

The main objective of the present work was to investigate this mechanism. The function $\sigma_d(V_{DC})$ was measured in detail in the fluctuation temperature range near T_P. It was found that in some temperature interval the character of the functions $\sigma_d(V_{DC})$ changes qualitatively both with and without the rf field.

We chose the comparatively little-studied compound m-TaS_3. This compound is interesting because of its high degree of one-dimensionality (the ratio of the conductivities along and across the 1D chains reaches 2000 (Ref. 7) at $T\approx T_{P2}$). This compound exhibits two Peierls transitions: $T_{P1}=235$ K and $T_{P2}=157.5$ K. All measurements were performed near the temperature of the lower Peierls transition. The threshold field for depinning of a CDW was 1.8 V/cm at $T=139$ K. The differential conductance was

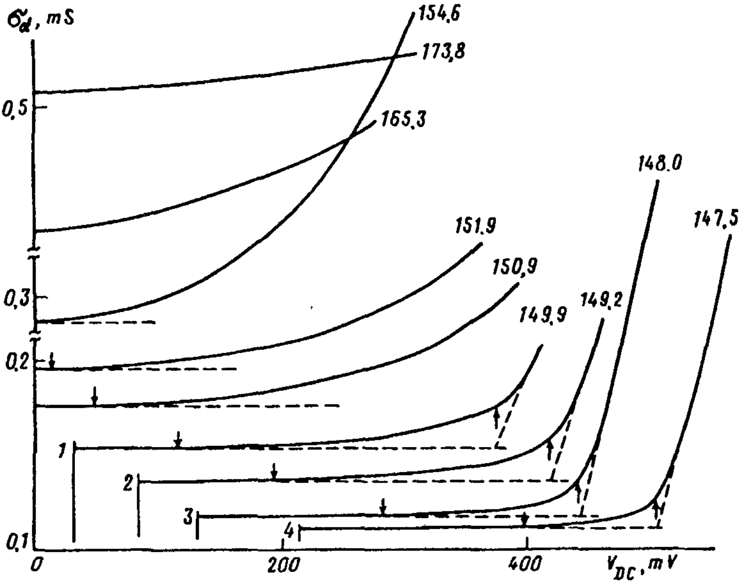

FIG. 1. Differential conductance $\sigma_d(V_{DC})$ versus the voltage at different temperatures above and below $T_{P2} = 157.5$ K. The upward arrows show the values of the upper threshold voltage V_{t1} and the downward arrows represent the values of the lower threshold voltage V_{t2}. Curves *1–4* are shifted to the right along the abscissa axis.

measured by the standard modulation technique at a frequency of 700 Hz with a modulation amplitude of 1 mV. Figures 1–5 show the experimental results obtained for $1 \times 0.01 \times 0.003$-mm m-TaS$_3$ sample.

We begin with a discussion of the results obtained in the absence of a rf field (Figs. 1 and 2). As the temperature approaches $T_0 = 146.8$ K, two threshold voltages with qualitatively different temperature behavior appear on the curve $\sigma_d(V_{DC})$ [the method for determining the upper (V_{t1}) and lower (V_{t2}) threshold voltages is clear from Fig. 1)]. A new mechanism of nonlinear conduction comes into play at voltages $V_{DC} > V_{t2}$. As the temperature T increases, the threshold voltage V_{t2} at which this mechanism is actuated drops sharply,[2)] reaching zero at $T = T^* = 152$ K. Above T^* the curve $\sigma_d(V_{DC})$ is nonlinear in the entire experimental voltage range. It is interesting that the curvature of this curve increases with T as long as $T < T_{PT}$, reaches a maximum at $T = T_{P2}$, and then decreases with increasing T in the range $T > T_{P2}$.

We now consider the behavior of $\sigma_d(V_{DC})$ in the temperature range $T_0 < T < T^*$ in the presence of a rf field. It turns out[5] that the function $n_s(T)$ starts to drop rapidly at temperatures $T \geqslant T_0$. Figure 3 shows the behavior of $\sigma_d(V_{DC})$ in the presence of a rf field with frequency $f = 5$ MHz and amplitude $F_{RF} = 1$ V. The rf field was applied on the same current contacts as the voltage V_{DC}. As the temperature increases, the character of the features changes qualitatively: Instead of the standard resonance dips (or together with them), a set of steps appears in the function $\sigma_d(V_{DC})$. These steps appear first in the

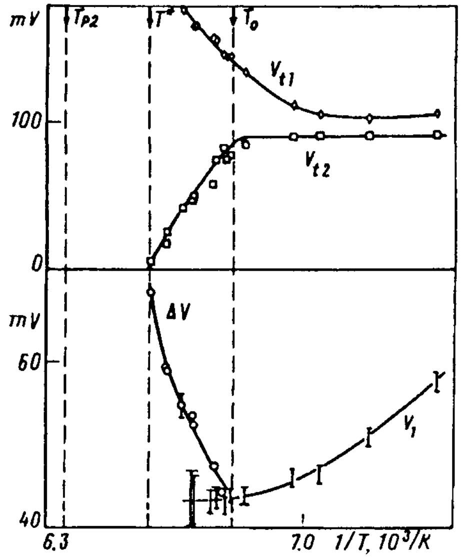

FIG. 2. Temperature dependences of the upper (V_{t1}) and lower (V_{t2}) threshold voltages, the period of the steps with respect to the voltage ΔV and the voltage V_1, corresponding to the position of the main interference peak with $p/q = 1/1$. The characteristic temperatures are: $T_{P2} = 157.5$ K — Peierls transition temperature; $T^* = 152$ K — the temperature at which the bottom threshold V_{t2} vanishes; and, $T_0 = 146.8$ K — the temperature above which V_{t2} and n_s start to decrease rapidly.

region of high voltages and they coexist with the resonance dips, which correspond to the Shapiro steps on the $I-V$ curve and which are observed for low values of V_{DC}. As the temperature T increases, the steps appear in the entire experimental range of voltages V_{DC}, and the resonance dips (interference peaks) vanish (at temperatures $T > 149.9$ K). We shall call the most pronounced steps "large." These steps lie approximately at the same equidistant (with respect to σ_d) levels. As T decreases, "small" steps appear between the large steps.

We now enumerate separately the large and small steps in order of their appearance in the function $\sigma_d(V_{DC})$. For some temperatures, up to five large and five small steps are observed in $\sigma_d(V_{DC})$. The width of the plateau decreases with increasing step number n and increasing temperature T.

For each temperature the plot of the position V_n of the centers of the large steps on the voltage axis as a function of the number n of the large step is a straight line whose slope is equal to that of a similar plot for small steps. We can therefore construct the single plot $V_n(n)$ on which the small steps correspond to fractional numbers on the n scale (Fig. 4). All functions $V_n(n)$ are linear, and the period ΔV of the appearance of the steps increases from 44 mV to 70 mV as T increases from 147.5 K to 151.9 K.

Plots of σ_d (V_n) constructed in the same manner as a function of the step number n, are shown in Fig. 5. These plots are also straight lines plotted as a function of n, but the slope does not depend on T. The change in $\sigma_d(V_n)$ on each step ($\Delta\sigma_d$) is equal to

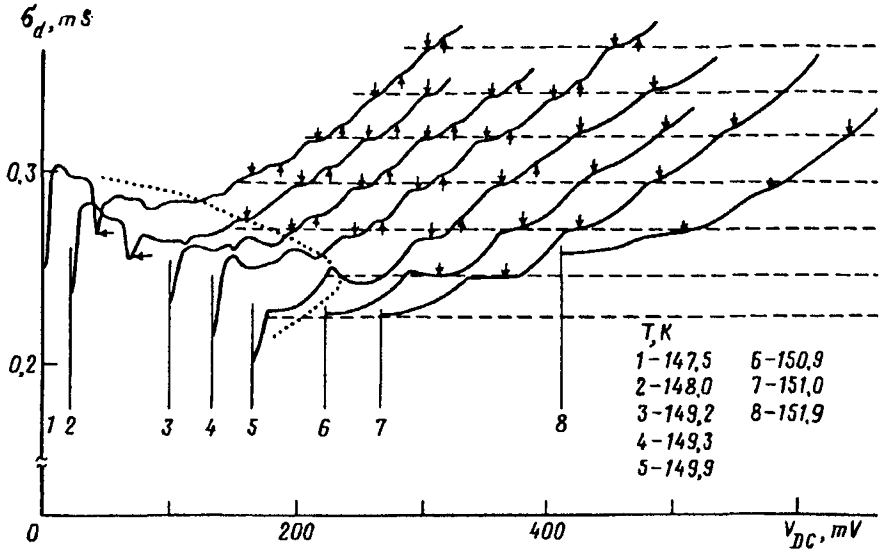

FIG. 3. Differential conductance σ_d as a function of the constant voltage V_{DC} for different temperatures in the presence of a rf field. Curves *2–8* are shifted to the right along the V_{DC} axis. The downward arrows represent the large steps and the upward arrows are the small steps. At low voltages (the region delineated by the dotted line) interference peaks corresponding to Shapiro steps in the $I-V$ curve are observed. The horizontal arrows denote the interference peak with $p/q = f_{\mathrm{CDW}}/f = 1/1$.

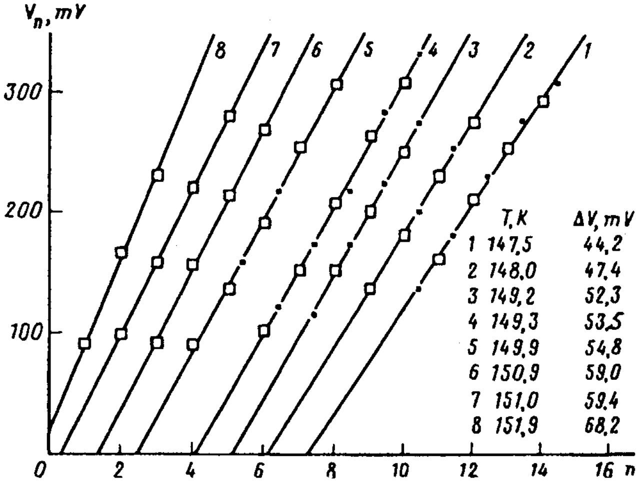

FIG. 4. Position of the center of the steps on the voltage axis as a function of the step number n for different values of T. The large squares correspond to the large steps and the small squares correspond to the small steps. The curves *1–7* are shifted along the n axis.

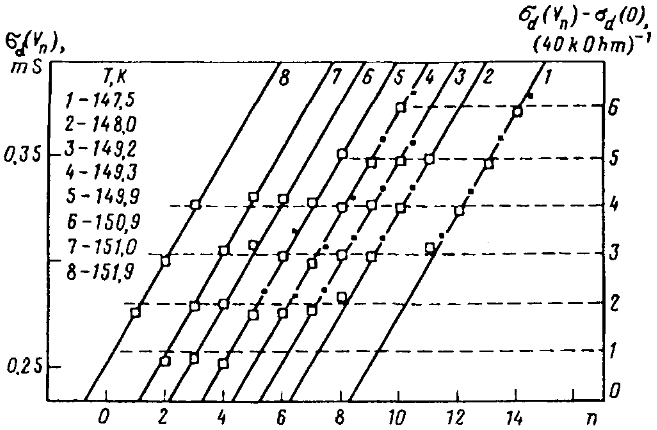

FIG. 5. Differential conductance σ_d with $V_{DC}=V_n$ as a function of the step number n in the same temperature range. Curves *1–7* are shifted along the n axis. The large squares correspond to the large steps and the small squares correspond to the small steps. The dashed horizontal lines correspond to equidistant levels with period $(40\ \mathrm{k}\Omega)^{-1}$.

$(40\ \mathrm{k}\Omega)^{-1}$. Moreover, as one can see from Figs. 3 and 5, the absolute positions of the plateau (on the σ_d axis), which correspond to the large steps, are virtually independent of T.

The steps observed by us differ from the weak interference peaks, which correspond to the Shapiro steps on the $I-V$ curves. First, the steps on $\sigma_d(V_{DC})$ are periodic with respect to the voltage, while the interference peaks are periodic with respect to the current in the CDW. Second, these two types of features on $\sigma_d(V_{DC})$ can coexist (see Figs. 2 and 3). Third, they depend completely differently on the temperature T (Fig. 2).

We note that the value of $\Delta V(T)$, which is normalized to the upper threshold voltage $V_{t1}(T)$, does not depend on T: $\Delta V/V_{t1}=0.15$ in the entire temperature range where steps could be observed simultaneously on $\sigma_d(V_{DC})$ in the presence of a rf field and V_{t1} in the absence of a rf field.[3)] This indicates that the observed steps are somehow associated with the motion of the CDW.

In summary, in the temperature range $T_0<T<T^*$ two threshold voltages appear near T_{P2} on the voltage dependences $\sigma_d(V_{DC})$ in the absence of a rf field. The higher voltage, V_{t1}, which increases with the temperature T, corresponds to depinning of a CDW and the lower voltage V_{t2}, which decreases rapidly with increasing temperature, corresponds to the actuation of a new conduction mechanism. In the presence of a rf field step-like behavior of $\sigma_d(V_{DC})$ was observed in the same temperature interval. The steps in $\sigma_d(V_{DC})$ are periodic with period ΔV with respect to the voltage and with period $\Delta\sigma_d$ with respect to the differential conductance. The quantity $\Delta\sigma_d$ does not depend on T and is almost three times smaller than the quantum $2e^2/h$, which is observed upon quantization of the ballistic conductance of quasi-1D constrictions in semiconductor structures with a 2D electron gas at liquid-helium temperatures.[9,10] The nature of the effect is not understood. It can nonetheless be assumed that some kind of CDW excita-

tions, which start to conduct at $V \geqslant V_{t2}$, appear at temperatures $T \geqslant T_0$. Apparently, their quantum properties are manifested with a synchronizing action of the rf field. To determine the nature of these excitations, additional experimental and theoretical investigations must be performed.

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(2) The appearance of two threshold voltages in m-TaS$_3$ at very low temperatures (below 80 K) was observed in Ref. 8, but the lower threshold field increased with T.

(3) In the experimental range of V_{DC}, we were able to determine V_{t1} only up to $T = 149.9$ K.

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