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Transient voltage oscillation, narrow-band-noise and non-linear conductivity in SDW: $(\text{TMTSF})_2\text{AsF}_6$

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ABSTRACT

Transient voltage oscillation was observed in the spin-density wave phase of $(\text{TMTSF})_2\text{AsF}_6$. Its frequency is proportional to the non-ohmic current. In high electric field, current-field relation becomes irregular and transient oscillation diminishes. The bistability of the density-wave conductivity proposed by Littlewood is likely to be realized.

1. INTRODUCTION

In the spin-density-wave (SDW) phase of $(\text{TMTSF})_2\text{X}$ family, evidences for the SDW sliding have been accumulated [1-7]. Therefore, recent efforts are focused to find the characteristics of the SDW dynamics in contrast with the charge-density-wave (CDW). In insulating CDW systems, non-linear current shows a strong increase in narrow voltage range at lower temperature [8]. Littlewood [9] proposed that, as screening of fluctuating local electric field by normal carriers becomes incomplete at low temperature(T), density-wave (DW) sliding becomes less viscous when its velocity is high. While the main source of DW damping at low velocity is the screening by normal carriers, the damping at high electric (E) field is of residual non-electronic origin. As the result, the non-ohmic current is scaled by the ohmic current at low E and a bistable region appears in the current(I)-E characteristic, above which dI/dE is much smaller.

Mihaly et. al. [10] reported that the ordinary nonlinear conduction above the threshold field E_T in $(\text{TMTSF})_2\text{PF}_6$ becomes invisible with lowering T and non-linear current shows a strong increase at higher E-field. This phenomenon is similar to the switching observed in the CDW systems but they proposed that a new type of nonlinear conduction is realized in high field, not a crossover to the less viscous regime as proposed by Littlewood. Because it was found that the current density $j(E)$ in high E-field obeys the relation for the tunneling of the Zener type, $j(E) \propto \exp(-E_0/E)$, they suggested that the high field conduction might be rather connected to a tunneling mechanism as proposed by Bardeen [12]. Recently, Traetteberg et. al. [11] obtained a similar conclusion.

In this paper, we report on damped voltage oscillation superposed on dc component, NBN and anomalous current-voltage relation in high field, in $(\text{TMTSF})_2\text{AsF}_6$ below 3 K. The results are compared with the Littlewood theory.

2. EXPERIMENT

Though all the features discussed in this paper have been observed in several samples, experimental results obtained in a typical sample are presented below. Its cross-sectional area and distance between voltage contacts were $(9 \times 29) \mu\text{m}^2$.

and 1.12 mm, respectively. Current contacts covered the whole areas of both ends of the crystal for uniform current flow. The sample was slightly pressurized in a clamp-type bomb to avoid resistance jump. The actual pressure at low T was determined as ≈ 0.9 kb from indium manometer. The metal-insulator transition temperature T_C is 12.2 K. Pulse conductance was measured between 1.2 K and T_C . Pulse width was carefully selected between 1 μ sec to 10 msec with repetition rate ≈ 1 Hz. At low T and especially at low E , large width was selected because edges of the voltage response were rounded. At higher field, small width was chosen to avoid effect of self joule-heating. When necessary, voltage value was determined by extrapolating to the leading edge. Both voltage and current wave-forms were recorded repeatedly and averaged to calculate conductance values.

3. RESULTS AND DISCUSSION

Fig.1 shows the averaged voltage and current profiles above E_T . No serious effect of joule-heating was observed up to the highest wattage. Damped oscillation is found in the voltage wave-form. The amplitude of the voltage oscillation shows an exponential decay; $\Delta V(t) \propto \exp(-t/\tau)$. The damping factor ($1/\tau$) is proportional to the non-ohmic current I_{SDW} . Figure 2 shows the initial amplitude ΔV_0 at 1.2 K plotted against E . The maximum of ΔV_0 is located at ~ 200 mV/cm, near the knee in the current-voltage relation discussed below. Below 280 mV/cm the voltage oscillation was still observed in a reproducible manner at the leading edge of pulse excitation, but its amplitude decreased with increasing E .

Fig.1. Normalized wave-forms of voltage and current at 1.2K.

Fig.2. Initial amplitude of voltage oscillation vs. electric field.

Above 350 mV/cm we could not separate the oscillation from the background in the wave-form averaged for repetitive pulses. Figure 3 shows the frequency of the transient oscillation F_{TR} as the function of the SDW current density J_{SDW} . We have assumed that J_{SDW} is equal to I_{SDW} divided by the sample cross-sectional area. The ratio $F_{TR}/J_{SDW} \sim 300$ KHz·cm²/A is independent of T . Matsukawa and

Takayama [13] showed, from numerical simulation, that the large amplitude oscillation decays as the CDW configuration in random impurity potential changes from that favourable in the pinned state to other ones more stable under external field. The residual oscillation is observed as NBN.

NBN was observed in the same sample below ~ 2 K but not at higher T . It was gradually diminished with increasing J_{SDW} . Though not plotted in the figure, the NBN frequency, F_{NBN} , fits the same line shown in Fig.3; $F_{TR}/J_{SDW} = F_{NBN}/J_{SDW}$. The value of F_{TR}/J_{SDW} is 1/4 of that expected for an incommensurate SDW from the washboard model. The conventional explanation for it is that the SDW was pinned in three-quarter of the volume of the present sample even in high E-field.

In Fig. 4 the conductance at 1.2 K is plotted against the field. Below 200 mV/cm the conductance $\sigma(E)$ increases gradually, in a similar way as is observed above E_T at higher T . Between 200 mV/cm and 280 mV/cm, $\sigma(E)$ increases rapidly in a narrow range of field. Typically, the differential conductance is larger by three decades than the ohmic one. Such a rapid increase of $\sigma(E)$ has been observed in $(TMTSF)_2PF_6$ at lower temperature [11,12]. In this region, F_{TR}/J_{SDW} is approximately the same as that at low J_{SDW} . From the regular relation between

Fig.3. Frequency of transient oscillation F_{TR} plotted against the non-ohmic current density. Inset: in linear scales.

Fig.4. Conductance-field relation. Open circles indicate that the voltage oscillation was observed. Inset: low field. The threshold field E_T is indicated by the arrow.

F_{TR} and J_{SDW} it is inferred that the huge increase of $\sigma(E)$ is a property of the ordinarily process of depinning and sliding. On the other hand, from Fig. 2, the onset of rapid increase of $\sigma(E)$ corresponds to the maximum of the oscillation amplitude ΔV_0 . At higher T , the maximum of ΔV_0 shifts to higher field but the above correspondence was reproduced. It is probable that the maximum of ΔV_0 is an indication of some unresolved change in the ordinary sliding of the SDW. In addition, the huge increase of $\sigma(E)$ does not correspond to the ordinary

depinning process. The latter occurs above $E_T=43$ mV/cm at 1.2 K in this sample as shown in the inset of Fig.4.

Above 280 mV/cm $\sigma(E)$ is not a single-valued but is rather hysteretic. In this anomalous region F_{TR} shows a larger scatter as shown in the inset of Fig.3 and the voltage oscillation is missing in some data points. We have checked that the apparant irregularity of the voltage response is not correlated to joule-heating; both voltage and current wave-forms were regular. The transient oscillation vanishes with further increase of the field.

It is likely that the irregular increase of the conductivity above ~ 300 mV/cm corresponds to the transition to less viscous regime of DW motion, proposed by Littlewood [9]. The current-voltage relation calculated for the CDW weakly pinned by impurities is of S-shaped, therefore, Littlewood expected that the bulk sample is broken into inhomogeneous current paths. The hysteretic voltage response in the transition region suggests that low-velocity domains coexist with high-velocity domains and their distribution is not uniquely determined within the field range of S-shaped conductance. We expect that missing the transient voltage oscillation corresponds to enhanced rigidity of the DW in the high field regime; large change does not occur in the metastable SDW configuration as the sliding sets forth. It is expected that the transition field is scaled by E_T , in the sense that it is lower in samples of low E_T ; in another sample we observed the ordinarily E_T is ~ 10 mV/cm and the anomalies are located at ~ 100 mV/cm at 1.2 K.

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