Journal of the Physical Society of Japan
Vol. 69, No. 4, April, 2000, pp. 1251-1252

Quantum Collective Dynamics of Charge-Density Waves in Quasi-One-Dimensional Orthorhombic TaS_3

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(Received December 24, 1999)

KEYWORDS: charge-density waves, o-TaS_3, macroscopic quantum tunneling, phase slip

For more than 20 years, several aspects of the dynamics of the broken symmetry ground state, called charge-density waves[1)] (CDWs), have been widely explored. One of the most interesting properties is the nonlinear conduction associated with sliding CDWs. At relatively high temperatures, the general properties of this nonlinearity have been investigated in detail,[1)] and the dynamics of CDWs are well described by the classical model,[2-4)] in which CDWs are regarded as a classical deformable object.

At low temperatures, however, the transport properties of CDWs are radically different from those at higher temperatures.[5)] At such temperatures, the quantum nature of CDWs becomes pronounced. Recently, Zaitsev-Zotov observed *a temperature-independent* nonlinear current of orthorhombic TaS_3(o-TaS_3) crystals at low temperatures,[6,7)] which indicates a quantum-mechanical effect in CDW systems. He also found that the current-voltage (I-V) curves can partly be fitted by a scaling form

$$I \sim \exp(-\mathrm{const.}/E^{\beta}) \qquad (1)$$

with the scaling factor $\beta \sim 2$. Several theories have been proposed to explain his experimental results.[8-12)] Although Zaitsev-Zotov's results are beyond question, there is room for discussion concerning the scaling factor. We have a different interpretation:[13)] the factor may change as a function of external electric fields. In this paper, we investigate nonlinear conduction of o-TaS_3 at low temperatures, in order to determine the scaling factor related to quantum nucleation processes leading to CDW phase slips.

We have measured the nonlinear conductivity of pure o-TaS_3 at various temperatures ranging down to 50 mK. The samples were prepared using the chemical vapor transport method. Typical sample dimensions were $5\,\mathrm{mm}\times 10\,\mu\mathrm{m}\times 1\,\mu\mathrm{m}$. Special care was taken to eliminate the Joule-heating effect; the samples were prepared on a sapphire substrate and installed directly on a ^{3}He-^{4}He mixing chamber. The typical resistance ratio $R_{4.2K}/R_{300K}$ was $\sim 3\times 10^6$ and the linear resistance was typically $\sim 5\times 10^8\,\Omega$ at 4.2 K. The I-V characteristics were measured by the two-probe configuration, which is particularly suitable for high-resistance measurement. Electrical contacts were prepared by evaporating gold (Au) in a vacuum. To ensure accurate high-resistance measurements, we used triaxial cables to reduce the effects of both noise coupling and leakage currents. The noise level of our setup was $\leq 10^{-14}$ A. The shape of the measured I-V curves was reproducible and independent of the direction of the voltage sweep.

Figure 1 shows I-V characteristics in the temperature range of 50 mK–6 K. The dashed line represents ohmic behavior. Above 4 K, an ohmic contribution was observed below the threshold electric field V_T. When the electric field exceeded V_T, nonlinear current carried by CDWs became apparent. Qualitatively, this behavior corresponds to conventional I-V curves.[14)] Upon lowering the temperature to 3 K, the ohmic contribution fell below the resolution of the measurement and the weak nonlinearity which develops below V_T became more pronounced. Further reducing the temperature stopped the temperature variation of current at the largest fields first, and then at smaller fields.

Figure 2 shows the temperature dependence of the current $I(T)$ measured at various electric fields. Above 1 K, $I(T)$ can be approximated by the activation low $I(T) = I_0\exp[-\Delta(E)/k_{\mathrm{B}}T]$, where $\Delta(E)$ is an energy barrier which is a function of the electric field E. Below 0.1 K, temperature variation of nonlinear current vanished and $I(T\to 0)$ approached a nonzero value depending on the electric field. This is attributed to a novel type of collective transport, presumably due to macroscopic quantum tunneling.

Now let us explore novel features of nonlinear collective transport. Suppose that the I-V curve observed at 50mK can be roughly approximated by the scaling form $I = I_0\exp[-(V_0/V)^{\beta}]$. We transform this scaling form into

$$\log\left[-\frac{\mathrm{d}(\ln I)}{\mathrm{d}(1/V)}\right] = (1-\beta)\log(V) + \log(\beta V_0^{\beta}) \qquad (2)$$

to determine the precise value of β. The inset in Fig. 3 shows the plot of $-\mathrm{d}(\ln I)/\mathrm{d}(1/V)$ vs V on log-log scale for the limiting I-V curve. The straight lines represent least-square fitting to the data. The slope P is related to β by the relation $P = 1-\beta$. Figure 3 clearly shows that the limiting I-V curve consist of two branches: It can be fitted by $I \sim \exp(-\mathrm{const.}/V^{\beta})$ with $\beta = 0.23\pm 0.03$ for smaller electric fields, while $\beta = 0.31\pm 0.03$ for larger ones. These results are completely different from those by Zaitsev-Zotov. βs obtained in this study are clearly less than 1.

Within the existing theoretical frameworks, scaling factor β can be determined by the type of nucleation processes. For instance, $\beta = 2$ for a homogeneous phase slips based on vortex-ring creation,[10)] while $\beta = 1$ for vortex-pair creation.[9)] Anyhow β is an integer basically. In contrast, our experimental results suggest that β be a fraction: $\beta = 0.23\pm 0.03 \sim 1/4$ for smaller electric fields, while $\beta = 0.31\pm 0.03 \sim 1/3$ for larger ones. This requires new models for nonlinear conduction of CDWs

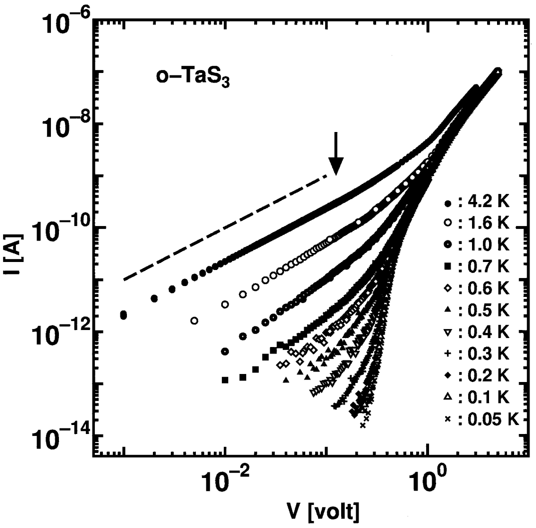

Fig. 1. *I-V* characteristics of *o*-TaS_3 in the temperature range of 50 mK–6 K. The dashed line corresponds to ohmic behavior. The threshold field is indicated by the arrow.

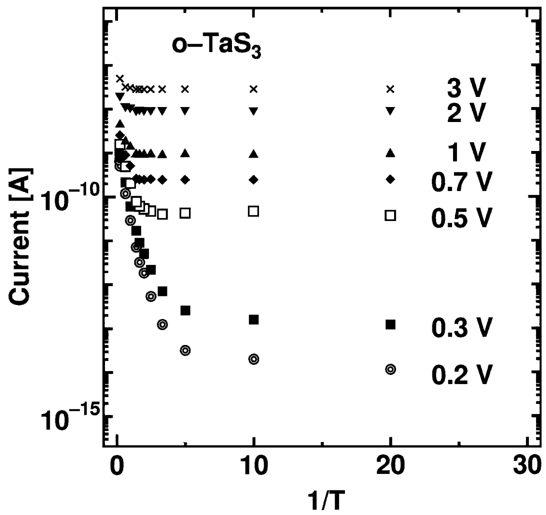

Fig. 2. The temperature dependence of the current $I(T)$ measured at various electric fields.

at low temperatures. One can image that *I-V* curves can be represented by the form $I \sim \exp(-\mathrm{const.}/E^{1/(d+1)})$ where d is an integer. This form is reminiscent of the expression for variable-range-hopping in electron conduction of disordered systems. In addition, if d is regarded as a system dimension index, it seems that dimensionality changes from $d = 3$ ($\beta = 1/4$) to $d = 2$ ($\beta = 1/3$) as the electric field increases. Further investigations for clarify our speculations should be done in the future.

In summary, we have found novel quantum-mechanical features of the nonlinear conduction of *o*-TaS_3 at low temperatures. There are two branches of *I-V* characteristics with different scaling factors β in the expression

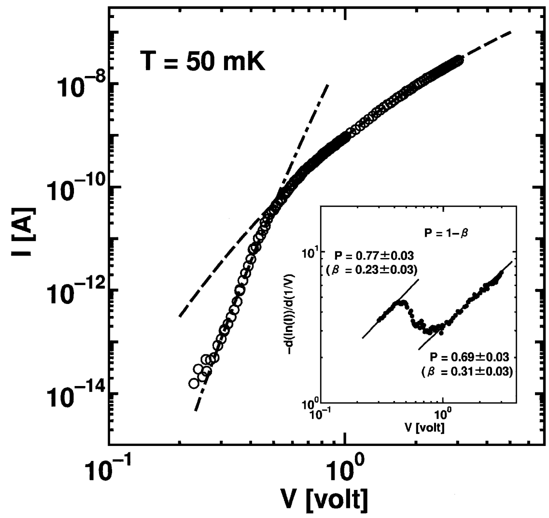

Fig. 3. The bias dependence of the nonlinear current observed at 50 mK. The dashed line is a scaling form $I = I_0 \exp[-(V_0/V)^{\beta}]$ with $\beta = 0.31$, $I_0 = 1.23 \times 10^{-4}$ A, $V_0 = 2.84 \times 10^{3}$ V. The dashed-and-dotted line is the same form with $\beta_2 = 0.23$, $I_0 = 1.27 \times 10^{11}$ A, and $V_0 = 1.14 \times 10^{7}$ V. The inset shows the plot of $-\mathrm{d}(\ln I)/\mathrm{d}(1/V)$ vs V on a log-log scale.

$I \sim \exp(-\mathrm{const.}/E^{\beta})$: $\beta = 0.23 \pm 0.03$ for smaller electric fields while $\beta = 0.31 \pm 0.03$ for larger ones. These "*fractional*" βs are quite different from the *integer* βs in previous studies. These results imply that quantum nucleation processes leading to phase slips differ from the existing ones.

We are indebted to K. Inagaki and Y. Kasai for the preliminary measurement. We would like to thank H. Matsukawa and M. Yumoto for stimulating discussions.

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