Solitary two-level fluctuations in extremely small samples of a quasi-one-dimensional TaS_3 conductor

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Reversible transitions between metastable states of a charge-density wave, which occur only in narrow ranges of temperatures and electric fields, have been observed.

Study of fluctuations in microscopic objects may yield completely new information not only on the origin of noise but also on the fine structure of states and the mechanisms responsible for the transitions between the states in various materials. In this sense, the two-level systems, which are a kind of elementary fluctuation media, are of interest. Such fluctuation media were observed in a wide variety of physical and biological objects (see Refs. 1 and 2, and the bibliography cited there).

Extremely small samples of quasi-one-dimensional conductors are studied because they help understand the general properties of a charge-density wave and because of their particular properties.[3–5] Study of samples with length scale $L = 20\ \mu\text{m}$ and $S \sim 10^{-2}\ \mu\text{m}^2$ showed that in them abrupt transitions occur between the metastable states, which are directed toward the center of the hysteresis loop: kind of "quantization" of the resistance. In thinner samples ($S \sim 10^{-3}\ \mu\text{m}^2$) the hysteresis on the temperature dependence of the resistance disappears.[4]

In the present letter we report the results of a first study of extremely small samples of orthorhombic TaS_3, with a cross-sectional area $S \lesssim 10^{-3}\ \mu\text{m}^2$ and spacing between contacts $L \sim 1\ \mu\text{m}$, which were synthesized for the first time. In these samples we hoped to see the reversible transitions between the metastable states, which were predicted in Ref. 6, and also a more detailed fine structure of the states of the charge-density wave and the transitions between them. We began our search for the reversible transitions by measuring the temperature dependence of the low-frequency noise in electric fields much smaller than the threshold field E_T which initiates the slipping of the charge-density wave. The noise in the sample was recorded in the given current mode. The resistance of the sample, averaged (over a time $\sim 10^{-2}$ s) as the temperature was varied, was automatically held constant. Upon cooling the sample, beginning with a temperature 10–20 K below the Peierls transition temperature, anomalously narrow peaks (of width $\Delta T \sim 1\text{K}$, $\Delta T/T < 10^{-2}$) of the rise in the noise voltage began to appear against the background of a constant noise level (Fig. 1). These peaks continued to appear as the sample was cooled down to liquid-nitrogen temperature, but at $T < 100$ K the frequency of their appearance diminished. Repeated measurements were generally able to reproduce the position and height of the peaks. When the temperature was held constant, the noise level at the noise peak remained constant during ~ 1-h measurement, i.e., the noise was steady. The plot of the noise vs the

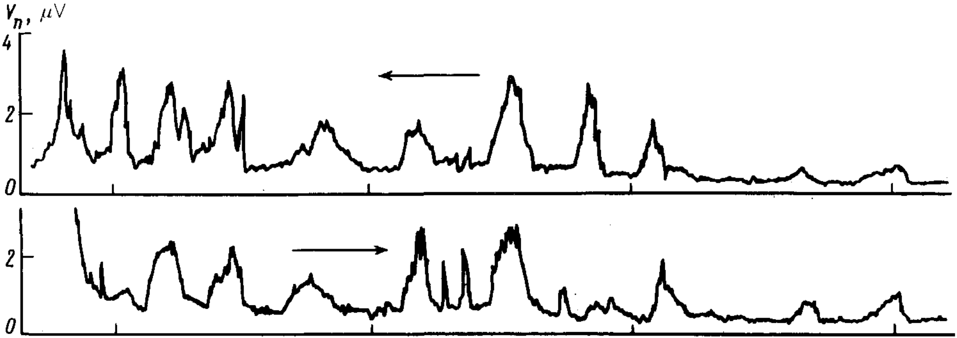

FIG. 1. Temperature dependence of the low-frequency noise of a TaS_3 samples ($S = 5\times 10^{-4}\ \mu\text{m}^2$, $L = 2\ \mu\text{m}$ with a voltage of 1–2 mV on the sample. The arrows indicate the direction of the temperature variation. The frequency band is 1–10 Hz.

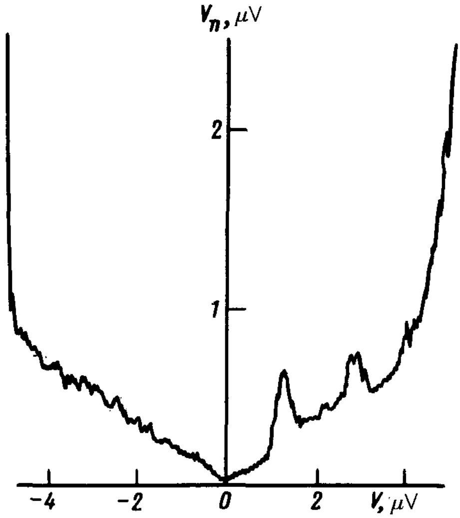

FIG. 2. Noise voltage vs the voltage applied to the TaS_3 sample ($S = 5\times 10^{-4}\,\mu m^2$, $L = 2\,\mu m$). The frequency band is 1–10 Hz, $T = 176$ K.

electric field was found to be similar (Fig. 2): the $V_n(V)$ curve also exhibits narrow noise peaks ($\Delta V \lesssim 1$ mV, $e\Delta V \ll T$). Upon varying the temperature, the peaks may shift toward zero field, approach the threshold field, appear, or disappear. We reached the conclusion that the regions in which the noise increases anomalously have the shape of an island in the T-V plane.

Oscilloscope studies of voltage oscillations have shown that noise voltage has the form of a random telegraph signal. The switching frequencies in various peaks were found to differ markedly: switching with a characteristic frequency ranged from several hundredths of a hertz to several tens of kilohertz. In some cases we saw switching directly on the $R(T)$ curve which was measured with a weak alternating current ($\widetilde{V} \sim 100\,\mu V$) (Fig. 3a). These measurements show that the fluctuating quantity is the resistance of the sample and that these fluctuations may occur even when no external electric field is applied to the sample; i.e., these measurements show that these fluctuations are not related to the threshold phenomena.[7] The temperature dependence of the fluctuations merits some attention (Fig. 3a): As the temperature is lowered, infrequent short transitions generally occur initially to a state with a higher resistance. The transitions subsequently increase in frequency and the sample spends equal time in each state at the peak noise level. The sample now remains progressively longer times in the high-resistance state, while the transitions to the preceding state become less frequent but do not cease yet. The shape of the oscilloscope traces changes in a similar manner as a result of the change in the voltage on the sample (Fig. 3b): As the voltage is raised (from V_1 to V_5), the sample remains progressively longer times in the new state until it finally stays in it permanently. In some cases we have observed two fluctuations operating simultaneously. Interactions similar to those recently detected in metallic intrusions were observed in this case.

In analyzing the results of the measurements we should bear in mind that a charge-density wave which is pinned to impurities may occupy a multiplicity of states

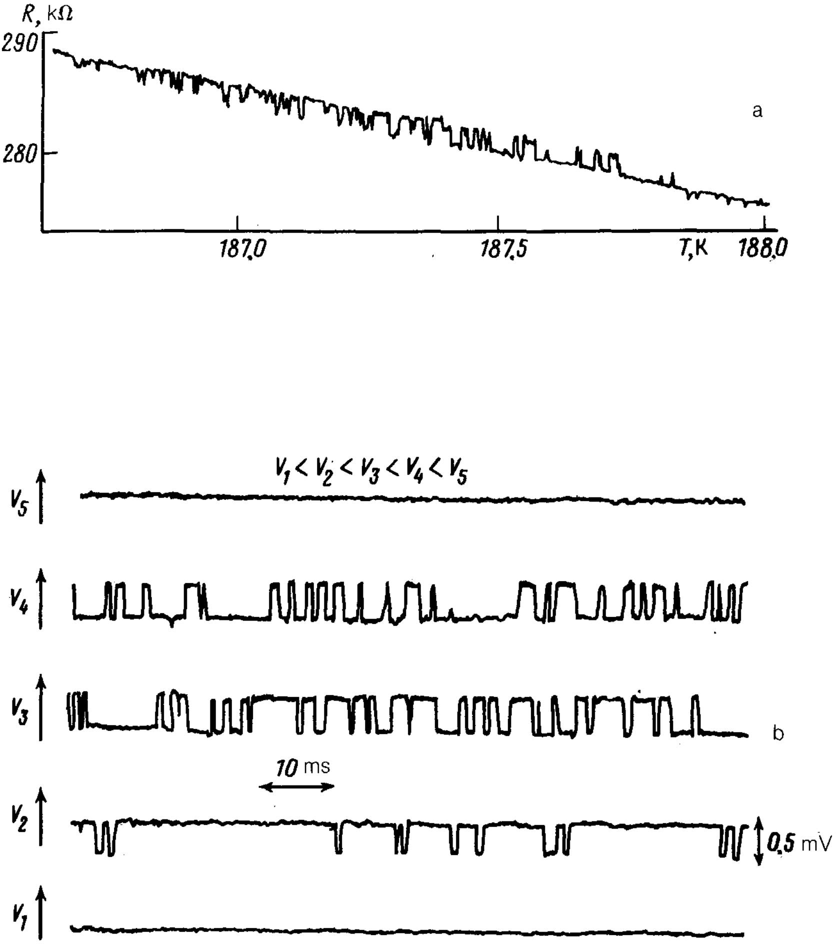

FIG. 3. Evolution of the resistance switching. a—Upon a change in the temperature ($dT/dt = 0.7$ K/min); b—upon an increase in the voltage from $V_1 = 4$ mV to V_5 mV, $S = 10^{-3}$ μm^2, $L = 2$ μm, $V_T = 10$ mV, $T = 189$ K.

of approximately equal energy which are distinguished by the spatial distribution of the phase of the charge-density wave.[8] It was shown in Ref. 4 that thin samples ~10 μm long, for example, have a discrete number of metastable states which are distinguished by the number of periods of the charge-density wave. A change in temperature changes the equilibrium configuration of the CDW. Conversion from one configuration to another can be accomplished by causing the phase of the CDW to slide,[9] which is seen as the motion of the vortices[10] (CDW dislocations). Conversion can also occur as a result of creep of the charge-density wave. An increase in the one-dimensional fluctuations in thin samples[4] and the spatial irregularity ζ of the chemical potential,[5] which stems from a large threshold field[3] ($E_t \sim 10^2$ V/cm), facilitate the transitions between the metastable states. Accordingly, upon convergence of the energies of the two nearest and lowest states, we see spontaneous transitions between them. Analysis of the abrupt changes occurring in extremely small samples led us to conclude that, in addition to the metastable states whose CDW differs by a whole period [the resistance changes typically by $\sim 10\%$ at $T = 100$ K (Refs. 3 and 4)], they also have metastable states corresponding to a partial entry of a new CDW period into the sample ($\Delta R/R \sim 0.1$–1%). We link these intermediate states with the vortex pinning in the sample and the noise surges which have been measured (Figs. 1 and 2) with the spontaneous transitions between these states. Any change in the external conditions (change in the electric field or the temperature) upsets the equilibrium and hence changes the probability of the sample being in a particular state (Fig. 3). We note that the transition frequencies which have been measured, $\omega = 10^{-2}$–10^4 s^{-1}, are small compared with the characteristic frequency, $\omega_0 \sim \omega_{ph,e-ph} = 10^9$–$10^{12}$ s^{-1}. This means that the high barrier W suppresses the frequency of transitions by about ten orders of magnitude in comparison with the number of attempts. In the case of thermal activation, the barrier height is estimated to be $W = T\ln(\omega_0/\omega) = 3$–$5\times 10^3$ K. This estimate of the barrier height is in reasonably good agreement with the predicted energy required to pin the vortex to a charged impurity, $W_p = (2\Delta/\pi)n^2$, where $2\Delta/\pi$ is the energy of the amplitude soliton per filament,[11] and n is the effective number of filaments in the vortex ($n = 3$ for $W_p = 4\times 10^3$ K). The number of electrons M that can be activated through the barrier W can be estimated from the width of the noise peaks on the curves $V_n(V) - M \geqslant T/e\Delta V$ and $V_n(T) - M = T/(d\zeta/dT\,\Delta T)$. Each estimate gives the value $M \sim 10^2$. The extremely narrow noise peaks are attributable to the collective nature of the transitions. The values of M and W are in good agreement with the corresponding parameters of the phase slip in the contact region[4,12] and the relaxation of the conductivity of metastable states.[6] Consequently, a thermally activated vortex motion can explain, in a consistent manner, the fluctuations which have been observed experimentally, the contact phenomena,[4,12] and the logarithmic relaxation of the metastable states.[6,12]

In summary, we have observed for the first time a reversible switching of a CDW in fields considerably lower than the threshold field. This switching, which is localized in narrow temperature and field intervals, is seen as single two-level fluctuations.

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[1] K. S. Ralls and R. A. Buhrman, Phys. Rev. Lett. **60**, 2434 (1988).
[2] B. Sakman (ed.), *Current Measurement in Single Channels*, Mir, Moscow, 1987.
[3] D. V. Borodin, S. V. Zaĭtsev-Zotov, and F. Ya. Nad', Pis'ma Zh. Eksp. Teor. Fiz. **43**, 485 (1986) [JETP Lett. **43**, 625 (1986)].
[4] D. V. Borodin, S. V. Zaĭtsev-Zotov, and F. Ya. Nad', Zh. Eksp. Teor. Fiz. **93**, 1394 (1987) [Sov. Phys. JETP **66**, 793 (1987)].
[5] V. Ya. Pokrovskii and S. V. Zaitsev-Zotov, Synthetic Metals **29**, F439 (1989).
[6] S. V. Zaĭtsev-Zotov and V. Ya. Pokrovskiĭ, *Proceedings of the XXV All-Union Conference on Low-Temperature Physics* Leningrad, 1988, Vol. 2, p. 112.
[7] N. P. Ong, C. B. Kalem, and J. C. Eckert, Phys. Rev. B **30**, 2902 (1984).
[8] P. B. Littlewood, Phys. Rev. B **36**, 480, 3108 (1987).
[9] L. P. Gor'kov, Pis'ma Zh. Eksp. Teor. Fiz. **38**, 76 (1983) [JETP Lett. **38**, 87 (1983)]; Zh. Eksp. Teor. Fiz. **86**, 1818 (1984) [Sov. Phys. JETP **56**, 1057 (1984)].
[10] N. P. Ong, G. Verma, and K. Maki, Phys. Rev. Lett. **52**, 663 (1984).
[11] S. A. Brazovskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **28**, 679 (1978) [JETP Lett. **28**, 631 (1978)].
[12] J. C. Gill, J. Phys. C: Solid State Phys. **19**, 6589 (1986).

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