Anomalies in the phase slip of the charge-density wave in orthorhombic TaS_3 at liquid-nitrogen temperature

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In orthorhombic TaS_3 the appearance of phase-slip centers at the negative contact at a temperature below 100 K perturbs the motion of a charge-density wave at distances $\gtrsim 0.5$ mm from the contact and leads to an anomalously large increase in the voltage drop of the sample.

In a quasi-one-dimensional conductor the electric current transported by a charge-density wave becomes a quasiparticle current near the contacts. The process by which a current is converted occurs as a result of the phase slip of the charge-density wave[1–3] and is maintained by a boosting voltage $U_{\rm ps} \sim 1$ mV (Refs. 4–7) which decreases near the contact. Experiments have shown that at least at temperatures $T \gtrsim 0.5T_p$ (T_p is the Peierls transition temperature) the $U_{\rm ps}$ of $NbSe_3$ (Ref. 5) and orthorhombic TaS_3 (Ref. 7) is related to the current I_c of the charge-density wave by the relation $I_c \sim \exp(-F/T)\sinh(\eta U_{\rm ps}/T)$, where $F = 10^3$–10^4 K, and $\eta \sim 10^2 e$ (e is the electron charge), which allows us to regard the sliding phase as a thermal-activation process analogous to the formation of phase-slip centers in superconductors near the critical temperature.[8] The phase-slip voltage measured in Refs. 5 and 7 is a sum of the boosting voltages $U^+_{\rm ps}$ and $U^-_{\rm ps}$, produced at the positive and negative contacts, respectively. In the present letter we report the observation of the nonequivalence of $U^+_{\rm ps}$ and $U^-_{\rm ps}$ and their anomalous dependence on the current which arises in an orthorhombic TaS_3 near the temperature of the transition to commensurability.

We studied the nonlinear conductivity of single-crystalline filamentary samples of orthorhombic TaS_3. The results reported in this letter were obtained by using one of the four samples under study with similar properties. The inset in Fig. 1 shows the location of the contacts of one of the samples. Contacts 1 and 4 were established by cold indium soldering and contacts 2 and 3 were secured by using indium whiskers $\sim 10\ \mu$m in diameter. The phase-slip voltage $U_{\rm ps}$ is defined as the difference between the voltages U_a and U_b produced at a given current in section 3–4, respectively, in the presence of phase-slip centers in contact 3 [circuit diagram a in the inset in Fig. 1, $U_a(I) = U_{14}(I_{34})$] and in the case of a moving charge-density wave when no phase-slip centers formed in contact 3 [circuit diagram b, $U_b(I) = U_{34}(I_{14})$]. To reduce the errors due to the presence of metastable states, we carried out sequential measurements at each of the fixed values of the current, based on circuit diagrams a and b; the current was switched in section 3–4 without an interruption. In the measurements we used current sources with an output resistance of $>$ GΩ, which is much greater than the resistance of the test samples ($\sim$0.1–1 MΩ).

Figure 1 shows the results of the measurements of the $U_a(I)$ curve (curve a),

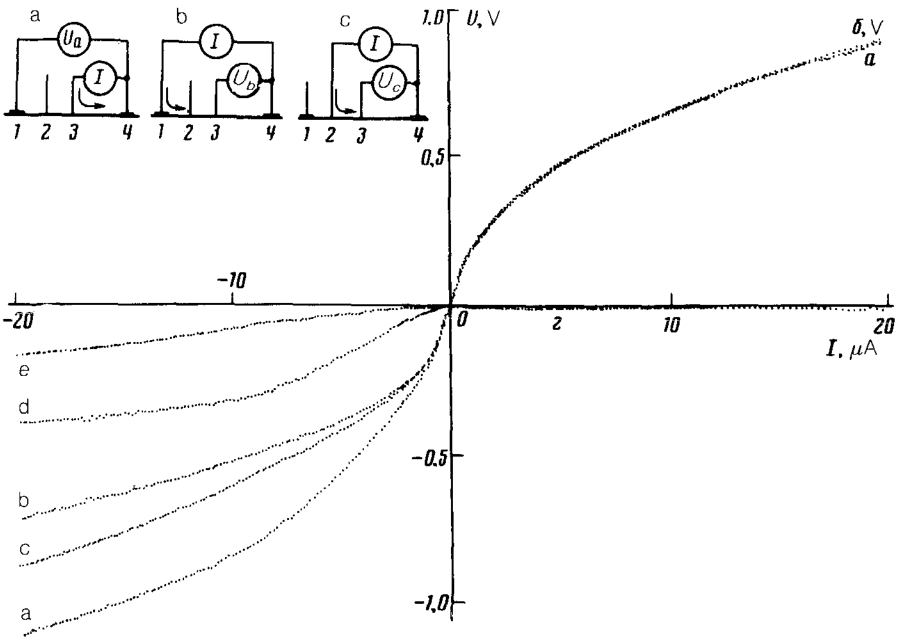

FIG. 1. The current-voltage characteristics of section 3–4 were obtained by using different measurement techniques. Curves a, b, and c, respectively, were obtained on the basis of circuit diagrams a, b, and c, shown in the inset. Curves d and e, respectively, were obtained from $U_a(I)-U_b(I)$ and $U_c(I)-U_b(I)$, $T=77$ K. The arrows indicate the positive direction of the current ($I>0$). The spacing between the contacts is $L_{12}=370$ μm, $L_{23}=470$ μm, and $L_{34}=870$ μm. Transverse dimensions of the sample—2×5 μm^2.

$U_b(I)$ curve (curve b), and the difference between them $U_{ps}(I)=U_a(I)-U_b(I)$ (curve d). At $|I|<I_n=0.3\,\mu$A (I_n is the current at which the current-voltage characteristic begins to behave nonlinearly) U_a and U_b are identical within the measurement error (10 μV) and at $|I|>I_n$ the value U_a begins to differ from U_b. At $I>0$ the formation of phase-slip centers in contact 3 reduces the voltage drop in section 3–4 and at $I<0$ it increases the voltage drop appreciably (by a factor of >1.5 at $I=-20$ μA). Since $|U_{ps}|$ in the last case is much greater than the Peierls gap, $2\Delta=125$ meV (Refs. 10 and 11), a question arises as to the spatial distribution of this additional voltage. Measurements based on circuits b and c, with use of the same current-contact switching procedure as was used in the measurement of U_{ps}, showed that narrowing the distance between the current contact and section 3–4 from 0.8 mm (circuit b) to 0.5 mm (circuit c) while holding the current constant leads to a significant change in the voltage in section 3–4 (curves b and c in Fig. 1). The functional dependence $\Delta U_{ps}(I)=U_c(I)-U_b(I)$ (curve e) and the dependence $U_{ps}(I)$ (curve d), which occur after the threshold is reached, depend on the current polarity. It can be seen from Fig. 1 that at $I<0$ a large fraction of U_{ps} decreases at a distance $\gtrsim 0.5$ mm from the current contact and with an increase in the velocity of the charge-density wave, this fraction increases, rather than decreases, because of the decrease in the length scale of the perturbation diffusion produced by the phase-slip centers.[1,3]

A study of the spectra of the narrow-band generation occurring in section 3–4 (contact 3 was grounded and the rf voltage was removed from contact 4) showed that at a given current, regardless of its direction, the generation frequency and hence the velocity of the charge-density wave in circuit b are 1–5% higher than those in circuit c. An increase in the voltage in section 3–4 can thus be accompanied by a decrease in the velocity of the charge-density wave.

The results described above show that a moving charge-density wave establishes a coupling between the electric field in one part of the sample and the current that flows in the other part. To determine the nature of this coupling, we studied the dependence of the voltage drop in section 3–4 on the current I_y flowing in section 1–2 (see the inset in Fig. 2). The measurements were carried out at several values of the current I_0 that flowed through section 2–4. At $I_0 > 0$, the voltage U_{34} changed by several percent due to the current I_y (see Fig. 2). At $I_0 < 0$, the value of U_{34} was found to depend more strongly on the current I_y that flowed in section 3–4, which was removed a distance of 0.5 mm: at $I_0 = -10\,\mu$A a change in I_y from $-10\,\mu$A to $+10\,\mu$A led to a 20% increase in U_{34}. The dependence of U_{34} on I_{12} is direct experimental proof that there is a nonlocal coupling between the distribution of the potential and the current in the various parts of the sample. The nonlocal-coupling hypothesis was frequently used previously in interpreting many experiments (see, e.g., Refs. 4 and 11).

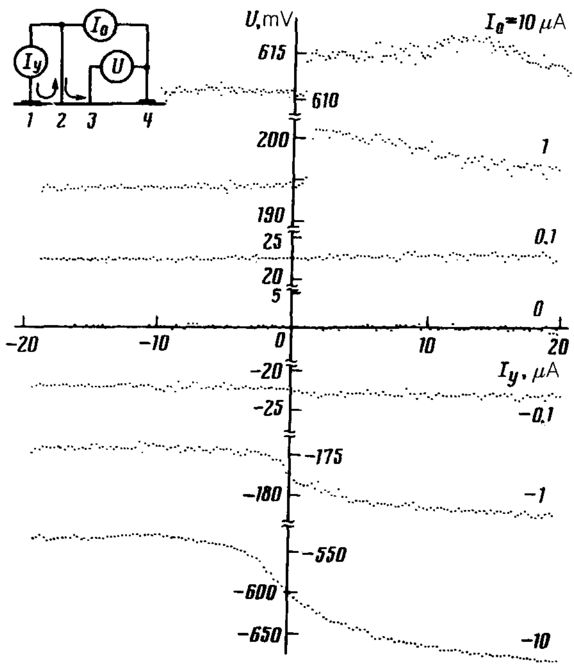

FIG. 2. The voltage U_{34} versus the control current $I_y = I_{12}$, $T = 77$ K. The curves are labelled with the value of the current $I_0 = I_{24}$ at which the measurements were conducted. Inset—measurement circuit. The arrows show the positive direction of the current.

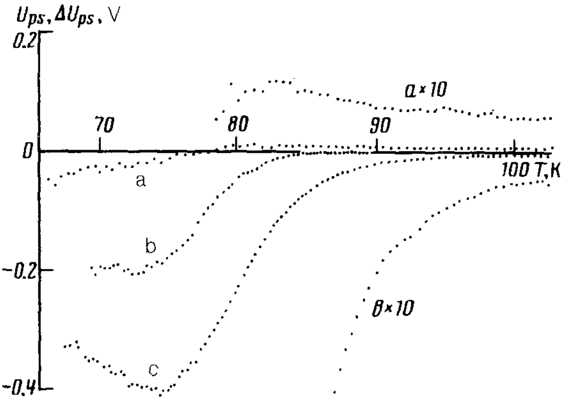

FIG. 3. Temperature dependences of U_{ps} for a current $+10\,\mu$A (curve a) and a current $-10\,\mu$A (curve c). Curve b—temperature dependence ΔU_{ps} ($-10\,\mu$A).

We found it also useful to study the temperature dependence of the effects which we have detected. With this goal in mind, we measured U_{ps} and ΔU_{ps} as functions of temperature for several fixed values of the current. It can be seen from the results in Fig. 3 that as the temperature is raised to 100 K, the value $U_{ps}(-10\,\mu\text{A})$ (curve c) decreases by almost two orders of magnitude, and a current-sign-reversal symmetry arises: $U_{ps}(I) = -U_{ps}(-I)$ (curves a and c). With an increase in the temperature, $\Delta U_{ps}(-10\,\mu\text{A})$ (curve b) approaches zero much quicker and at $T > 90$ K, we have $|\Delta U_{ps}| < 1$ mV.

At $I \gg I_T$ virtually all of the current is transported by the charge-density wave. We see from these results that in a given section of the sample a charge-density wave can move at a certain velocity at significantly different voltage drops U, differing by a factor of 1.2–1.5, where $\Delta U \gg \Delta$. A change in the voltage drop of this magnitude can be explained only by the change in the friction of the charge-density wave by approximately the same factor (1.2–1.5). In an orthorhombic TaS_3 the charge-density wave approaches commensurability as the temperature is lowered, and the longitudinal component of the wave vector q decreases.[12] At $I < 0$ the deforming action of the electric field on the charge-density wave near contact 3 should also lead to a decrease in q, i.e., to an approach of the charge-density wave to commensurability. According to Borodin *et al.*,[13] the quasiparticle conductivity σ_q should also decrease. The observed decrease in the conductivity σ_c of the charge-density wave can theoretically be linked with the fact that it is proportional to the quasiparticle conductivity.[14–16] However, a solution of the problem on the distribution of the potential U along the sample, which was found under the assumption that $\sigma_c \sim \sigma_q$ and on the basis of the relations[3,13] $\sigma_q = \sigma_0 \cosh(\zeta/T)$, $I_c = \sigma_c[-\nabla(U-\zeta)]$, and $I_q = \sigma_q(-\nabla U)$ (Ref. 3) and on the basis of the chemical-potential shifts specified at the boundaries, ζ^+ and ζ^-, yields, in the limit $I \gg I_T$, essentially symmetrical (with respect to the current) functional dependences $U_{ps}(I)$ $[U_{ps}(I) \approx U_{ps}(-I),\ U_{ps}(I) < 0]$, which are at variance with the results of the measurements (see Fig. 1). The results of the measurements, in fact, show that the charge-density wave decelerates extremely rapidly near the negative contact when the phase-slip centers are formed (and when the charge-density wave approaches commensurability), whereas σ_c increases only slightly near the positive contact. As the temperature is lowered and as it approaches the temperature of the transition to commensurability (~ 70 K; Ref. 15), the threshold field E_T at which the charge-density wave begins to slip increases in an orthorhombic TaS_3 by several orders of magnitude,[15,17] while the conductivity of the charge-density wave decreases sharply.[15] These effects, which are not related to the small quantitative change in the conductivity of the quasiparticles but rather to the qualitative change in the dynamics of the charge-density wave upon the transition to commensurability, apparently play the key role in stopping of the charge-density wave.

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