Jumps between metastable states of the quasi-1*D* conductor TaS_3 with submicron transverse dimensions

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Experiments on small samples of the quasi-1D conductor TaS_3 reveal that the resistance is a discontinuous function of the temperature and the electric field. The results are explained in terms of an abrupt change in the deformation of a space-charge wave.

In a real quasi-1*D* conductor, the phase coherence of a space-charge wave is retained over a finite distance, usually much smaller than the dimensions of the samples which have been studied.[1] In orthorhombic TaS_3, a typical quasi-1*D* conductor, the length of the phase-coherence region along the principal-conductivity axis, $l_{\parallel}$, is on the order of 10 μm, while the transverse dimension of the coherence region, $l_{\perp}$, is one or two orders of magnitude smaller.[2–4] The dimensions of the TaS_3 samples which are usually studied are ~ 1 mm in the longitudinal direction and ~ 10 μm in the transverse direction, much larger than $l_{\parallel}$ and $l_{\perp}$, respectively. The effects which stem from a local change in phase in the individual phase-coherence regions are averaged out, and the temperature and field dependences of the resistance are found to be smooth. It can be expected that in samples with small dimensions, $\sim l_{\parallel}$ and $l_{\perp}$, the effects associated with the deformation of the space-charge wave in the individual phase-coherence regions will be much more obvious.

In the present experiments we measured the resistance as a function of the temperature, $R(T)$, and of the electric field in samples of orthorhombic TaS_3 with lengths $10 \lesssim L \lesssim 100$ μm and a cross-sectional area $s \sim 10^{-2}$–10^{-3} μm^2. In other words, the dimensions of these samples are close to the corresponding dimensions of the phase-coherence region. The technique for synthesizing the samples and contacts to the samples are similar to those described in Ref. 3. The initial samples, of large cross-

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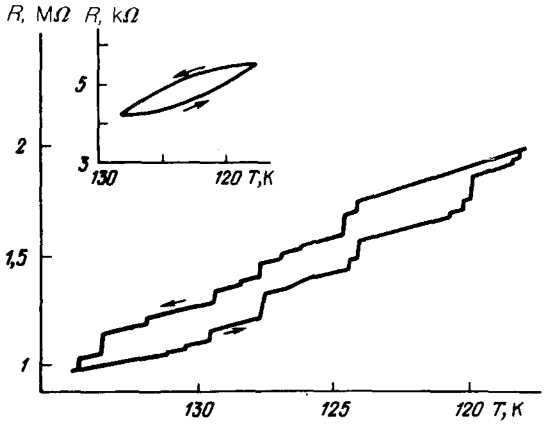

FIG. 1. Resistance versus the temperature in the interval 120–135 K for a sample of small cross-sectional area (sample #1, $L \approx 20$ μm, $s \simeq 10^{-2}$ μm^2). The insert shows the corresponding dependence for a large sample (#2, $L \simeq 1$ mm, $s \simeq 40$ μm^2). The amplitude of the current modulation is $\tilde{I} = 10^{-2} I_T$.

sectional area ($\sim$10–100 μm^2), from which the thin samples are obtained are quite pure and have threshold fields $E_T \simeq 0.25$ V/cm ($T = 120$ K) and a transition temperature $T_p = 225$ K.

The overall $R(T)$ behavior of the samples of small cross section is qualitatively the same as the usual $R(T)$ of thick samples. The Peierls transition, however, is more diffuse; T_p is slightly lower, and the region of an "activation" dependence of the conductivity (200–100 K) is nonlinear.[5] Figure 1 shows part of the $R(T)$ dependence for a sample with a cross-sectional area $\sim 10^{-2}$ μm^2 and the corresponding region for a sample with a cross-sectional area $\simeq 40$ μm^2 (the inset). The key qualitative difference between these $R(T)$ curves in thick and thin samples is the abrupt, rather than smooth, change in the resistance. The jumps occur in a time shorter than the time constant of the measurement apparatus (0.3–1 s). The change in resistance at a jump always occurs within the hysteresis loop, and the relative size of this change is $\sim 10\%$ in the samples $L \simeq 10$–20 μm long. The $R(T)$ curves found as the temperature is lowered and raised are qualitatively the same. When the $R(T)$ curves are recorded repeatedly, the value of the temperature at which the jumps occur fluctuates, but the regions of a smooth change in $R(T)$ between the jumps are reproduced and exhibit no hysteresis.

An electric field also causes an abrupt change in resistance. Figure 2 shows the differential resistance of a sample, R_d, as a function of the current I. We see that during the first increase in the current the elimination of metastable states occurs abruptly (region α), rather than smoothly, as in large samples.[6,7] During repeated recordings, with a current raised above the threshold ($I > 1.5 I_T$), the $R_d(I)$ curves exhibit a reproducible hysteresis (Fig. 2), with slight fluctuations in the switching times at $I \approx I_T$. The R_d curves are qualitatively like the corresponding curves found[3] for samples with a cross-sectional area of 0.1-1 μm^2. At $I < I_T$ the sample is in one of two states, determined by the direction in which the current is varied, by analogy with the results found[8] for $NbSe_3$. As I_T is approached, we observe abrupt changes in R_d. In samples of small cross-sectional area ($s \lesssim 10^{-2}$ μm^2), the threshold field E_T is more than an order of magnitude greater than E_T for samples with ordinary dimensions

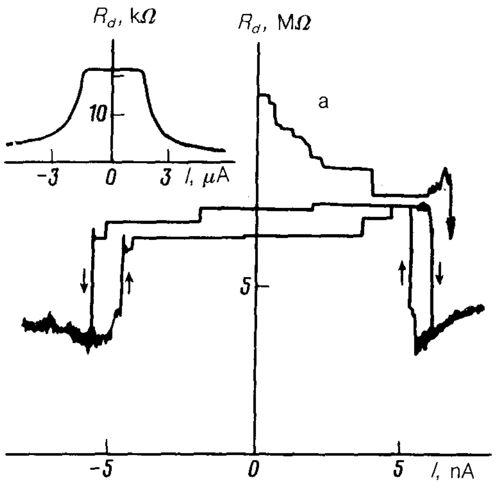

FIG. 2. Differential resistance of a sample of small cross-sectional area (sample #1) versus the current. The inset shows the corresponding behavior for sample #2 ($T = 98$ K).

(Fig. 3) and about an order of magnitude greater than E_T for samples $s \sim 0.1$–$1\ \mu m^2$ (Ref. 3).

In orthorhombic TaS_3 at $T \lesssim T_p$, a space-charge wave is incommensurable with the original lattice and gradually undergoes a transition to commensurability at $T \simeq 100$ K. In the course of this process, the component of the wave vector (q) of the space-charge wave along the principal-conductivity axis decreases by 2% (Ref. 9). Impurities in the sample retard these changes in q and give rise to metastable states and a hysteresis on the $R(T)$ curve. In each phase-coherence region (in a domain) the lifting of the metastability and of the phase deformation occurs through an abrupt change in the phase in a part of the phase-coherence region by an amount which is a multiple of $\sim 2\pi$ (Ref. 10). This process is equivalent to the creation (or annihilation) of a phase soliton.[5,11] In samples with dimensions close to the dimensions of the phase-

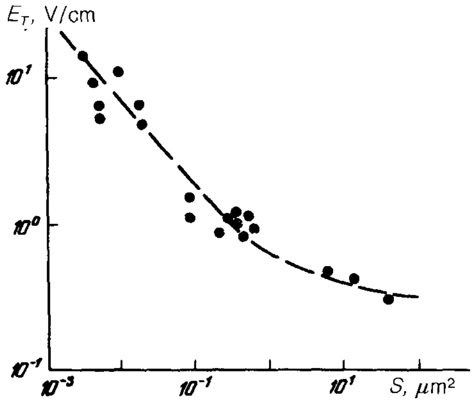

FIG. 3. Threshold field of the TaS_3 samples versus their cross-sectional area ($T \simeq 120$ K).

coherence region, these single, abrupt changes in phase should lead to abrupt changes in the resistance of the sample.

A change δq in q corresponds to the appearance in the sample of an additional charge $\delta\rho \sim d\varphi/dx \simeq \delta q$ and to a shift of the level of the chemical potential of the quasiparticles,[11,12] $\delta\zeta \sim \delta q$. These effects have been used to construct an explanation for the changes in the thermal emf of a TaS_3 sample upon changes in T and E (Ref. 11). The shift of the level of the chemical potential changes the concentration of quasiparticles and thus their contributions to the conductivity for a fixed space-charge wave ($E \ll E_T$).

Let us calculate the change in the resistance of a sample with dimensions on the order of the dimensions of the phase-coherence region. Upon a deviation of q from some value $q(T)$ in the simplest case, the one-dimensional case, an additional charge $\Delta\rho = en_0\,(q - q(T))/q_0$ arises in the sample, where n_0 is the number of states determining the value $k_F = q_0/2$. The equation of electrical neutrality[12] can then be written

$$en_0(q-q_0)/q_0 + eN_n \exp\left(-\frac{\Delta-\zeta}{T}\right) = eN_p \exp\left(-\frac{\Delta+\zeta}{T}\right), \tag{1}$$

where ζ is the level of the chemical potential, reckoned from the middle of the Peierls gap, 2Δ, and N_n and N_p are the effective state densities of the corresponding quasiparticles. The conductivity is

$$\sigma = eN_n\mu_n \exp\left(-\frac{\Delta-\zeta}{T}\right) + eN_p\mu_p \exp\left(-\frac{\Delta+\zeta}{T}\right), \tag{2}$$

when μ_n and μ_p are the mobilities of the quasiparticles. Assuming $N_n = N_p = N$ and $\mu_n = \mu_p = \mu$, for simplicity, we find from (1) and (2)

$$\sigma = en_0\mu \frac{q-q_0}{q_0} \operatorname{cth}\left(-\frac{\zeta}{T}\right), \tag{3}$$

where the dependence of ζ on $q - q_0$ is determined by expression (1). In orthorhombic TaS_3 we have[9] $(q - q_0) > 0$, so that we would have a p-type conductivity according to (3). This result agrees with experimental studies of the thermal emf (Refs. 11 and 13), the Hall effect,[14] and the fact that the equilibrium values of R lie inside the hysteresis loop[6,7] [see (2)].

In this case we find $\sigma = en_0\mu(q - q_0)/q$ from (1) and (2); this result is equivalent to $\coth(-\zeta/T) \simeq 1$ in (3). The appearance of a phase shift of 2π in a phase-coherence region of length l changes the electrical conductivity by $\delta\sigma = en_0\mu\delta q/q_0 = en_0\mu\lambda_0/l$, where $\delta q = 2\pi/l$, $\lambda_0 = 2\pi/q_0$ is the period of the commensurable space-charge wave. The corresponding change in resistance is $\delta R = (\sigma_0/s\sigma^2) \times (\mu(T)/\mu)\lambda_0$, where $\sigma = en_0\mu_0$ is the conductivity, and μ_0 is the mobility at $T > T_p$. The value of δR does not depend on the length of the phase-coherence region. The relative change in the resistance of a sample of length L, in one of whose phase-coherence regions there is phase shift of 2π, is $\delta R/R = \sigma_0\mu(T)\lambda_0/\sigma(T)\mu_0 L$. The use of our experimental data, $\sigma_0/\sigma(120\ \mathrm{K} \simeq 10^2$ and $\lambda_0/L \sim 10^{-4}$ ($L \simeq 10$–$20\ \mu$m), and the value[14] $\mu(T)/\mu_0 \simeq 10$ yields $\delta R/R \sim 10\%$, in good agreement with experiment (Fig. 1). Consequently, the appearance (or disappearance) of a phase shift of $\sim 2\pi$ in a phase-coherence region—an effect equivalent to the creation (or disappearance) of a phase soliton and corresponding to the appearance of a charge $\sim 2e$ on each chain—can be detected from the change in the resistance of a small sample by $\sim 10\%$, an easily measurable value. In samples with a small but nonzero number of defects, the nature of the jumps on the $R(T)$ curve reflects the individual features of the pinning forces and their spatial distribution. At a fixed temperature, the conductivity is determined by the specific realization of the spatial distribution of the phase of the space-charge wave in the sample. In a sense, the effect is analogous to the change in the conductivity of a mesoscopic sample upon a change in the spatial distribution of impurities.[15]

The dependence $R_d(I)$ is explained in a similar way. The application of a field eliminates the residual temperature deformation of the space-charge wave, and R_d discontinuously approaches a value close to equilibrium (Fig. 2). The jumps on the $R_d(I)$ curve at $I<I_T$ stem from the deforming effect of the field even at $I<I_T$. The hysteresis on the $R_d(I)$ curve and the bistability are consequences of a residual deformation of the space-charge wave after the application of a field.[11,16]

In addition to the impurities and contacts, in samples of small dimensions $\sqrt{s} \sim l_\perp$ a space-charge wave can apparently be strongly pinned by the surface of the sample also. This event probably explains the observed increase in the threshold field[16] (Fig. 3).

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