Nonlocal effects during current flow through orthorhombic TaS_3

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Experiments reveal that when the current exceeds a certain threshold for the motion of a charge-density wave an electric field of the opposite sense arises in the sample over a distance $\approx 100\ \mu m$ outside the current contacts, and the conductivity increases. These effects are linked with a deformation of the charge-density wave near the contacts.

Several recent papers have mentioned an effect of the measuring contacts on the conditions for the motion of charge-density waves in quasi-1-D conductors. Gill[1] reported a change in the $\sigma(E)$ characteristics upon a replacement of current contacts by potentiometric contacts; Ong and Verma[2] found that contacts affect the excitation of a narrow-band noise; and Mihaly *et al.*[3] showed that the depinning field for a charge-density wave increases with decreasing distance between potentiometric contacts. In the present letter we report the observation and study of some new nonlocal effects which accompany the motion of charge-density waves near the current contacts on *o*-TaS_3 samples: 1) the appearance of a nonuniform distribution of the electric field in the region between the current contacts and the appearance of an electric field of the opposite sense in the region outside the current contacts; 2) an increase in the conductivity in the region outside the current contacts. We attribute the observed effects to a deformation of a moving charge-density wave near the contacts and to the penetration of this motion over macroscopic distances in the region outside the current contacts.

The *o*-TaS_3 samples were synthesized in a heterogeneous gas-phase reaction between Ta and S, followed by crystallization in a temperature field with a small gradient (2 deg/cm).

In principle, a voltage could be produced in the region outside the current contacts by a "spreading" of the current near a contact. For a sufficiently small contact,

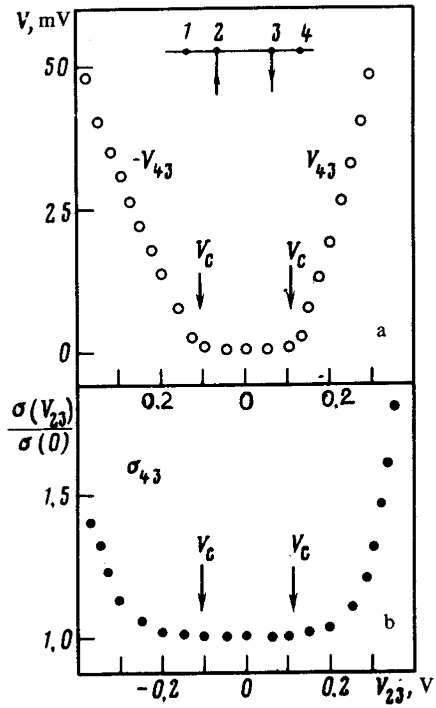

FIG. 1. The potential difference (V_{34}) outside the current contacts (part a) and the normalized conductivity (part b) versus the potential difference between the current contacts, V_{23}, on sample No. 5 with a transverse dimension of 1 μm ($T = 110$ K, $L_{23} = 1.8$ mm, $L_{34} = 1$ mm, $V_c = 0.12$ V).

the current lines would extend a distance $r \simeq a\sqrt{\sigma_\parallel/\sigma_\perp}$, into the region behind the current contacts, where a is the transverse dimension of the sample. To suppress this effect we selected samples with small transverse dimensions, $a = 0.5$–1.5 μm, and we used contacts with dimensions $\simeq 50$ μm$\gg r$. The contacts were fabricated by cold soldering with indium.

We found that when a current corresponding to the motion of a charge-density wave is passed through contacts 2 and 3 (see the inset in Fig. 1) a potential difference V_{12}, V_{34} arises in the region outside the current contacts (1, 2 and 3, 4). This potential difference $V_{12} \approx V_{34}$ is a substantial fraction (0.1–0.3) of V_{23} and has the sign opposite that of V_{23}. Figure 1a shows the $V_{34}(V_{23})$ dependence found for one of the samples at a temperature of 110 K. Regardless of the polarity of V_{23}, the voltage V_{34} arises under the condition $|V_{23}| > V_c$, where V_c is the voltage corresponding to the depinning of the charge-density wave in the region 2, 3 (this voltage was found at the same temperature from four-probe measurements of the current-voltage (IV) characteristic, with the current flowing between contacts 1 and 4, while contacts 2 and 3 were used as potentiometric contacts). This result is a direct indication that the observed effect is related to the motion of a charge-density wave. We also found that in regions 1, 2 and 3, 4 the conductivity increases if $|V_{23}| > V_c$ (Fig. 1b), implying that a charge-density wave is also moving in the regions outside the current contacts. The conductivities σ_{12} and σ_{34} were measured at a low alternating current ($\approx 10^{-7}$ A) with a frequency of 600 Hz.

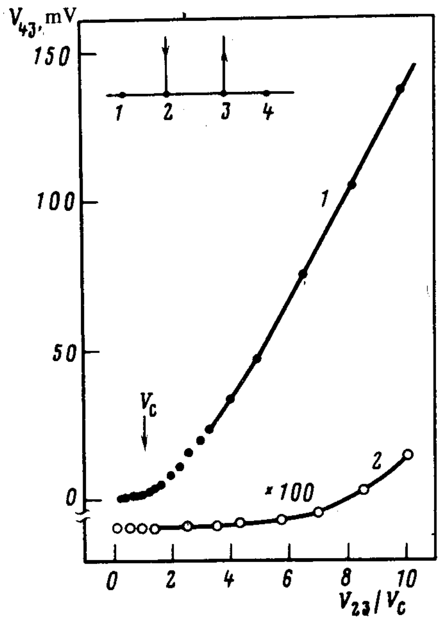

FIG. 2. Distribution of the field E near current contact 4 (sample No. 3, $T = 110$ K, $L_{12} = 2$ mm, $L_{23} = L_{34} = 500$ μm, $L_{45} = 450$ μm, and $L_{56} = 1$ mm).

Measurements taken at various temperatures showed that above the temperature corresponding to the Peierls transition, $T_P = 220$ K, both of the effects shown in Figs. 1a and 1b disappear.

To determine the distribution of the electric field E in the region between the current contacts, we used four probes separated by a distance ≈ 500 μm (Fig. 2). The electric field between two adjacent probes was taken to be the potential difference measured between these probes divided by the distance between them. From Fig. 2 we see that under the condition $V_{14} > V_c$ the field distribution between current contacts 1 and 4 also is very nonuniform: The field in the central region is weaker than it would be if the distribution were uniform (the dotted line). The field increases severalfold as current contact 4 is approached. Just beyond the contacts the field rapidly changes sign, remaining large in magnitude, and then drops rapidly to zero. At $V_{14} < V_c$, we do not observe a nonuniformity of the E distribution.

Further experiments were carried out to measure the field decay length in the region outside the current contacts, L_E. Direct measurements (carried out by bringing contacts 4 and 5 closer together; see Fig. 2) yielded an upper estimate $L_E < 200$ μm. From measurements in which we varied the size of the current contact we found $40 < L_E < 130$ μm, i.e., $L_E \approx 100$ μm. The results of these measurements are shown in Fig. 3. Curve 1 corresponds to a size $L_3 = 40$ μm of current contact 3 (in Fig. 3), while curve 2 corresponds to $L_3 = 130$ μm. When L_3 is increased by a factor of only three, the V_{34} signal disappears almost completely (at $V_{23} = 10V_c$, the V_{34} level has dropped by a factor of 600), indicating that the field decays very sharply.

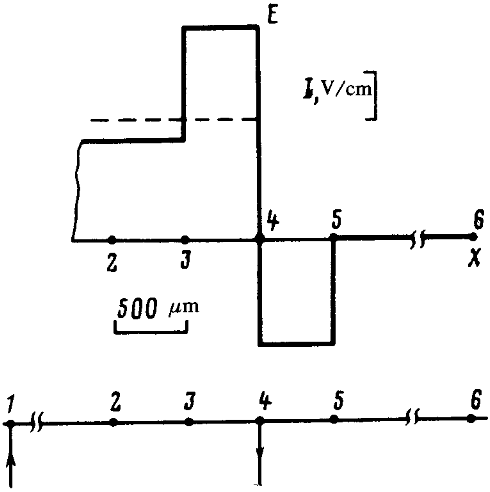

FIG. 3. Plot of $V_{34}(V_{23}/V_c)$ for two identical samples, Nos. 6 and 7, with current contacts of different sizes: 1—$L_3 = 40$ μm; 2—$L_3 = 130$ μm ($V_c = 60$ mV, $T = 118$ K).

These experimental results can be explained by the theory derived by Artemenko and Volkov (see the paper which follows immediately), in which a charge-density wave is treated as a moving medium that can be described by a phase which is a function of the coordinates and the time. At a current above the threshold level, the phase of the charge-density wave in region (2, 3) in Fig. 1 begins to increase over time. Since the phase is not perturbed far from region (2, 3), the charge-density wave becomes deformed near the current contacts $(\partial\chi/\partial x)\neq 0$, where χ is the phase of the charge-density wave). In the deformation region, the velocity of the charge-density wave, $U = (\dot{\chi}/Q)$, decreases (Q is the wave vector of the wave), vanishing over a macroscopic distance L_E in the region outside the current contacts.

The reason why the electric field is of the opposite sense in this region is that the current of a charge-density wave must be cancelled by a quasiparticle current here; i.e., the electric field must be applied in the direction opposite that of the field between the current contacts. Since there are few quasiparticles at low temperatures ($T \ll \Delta$), the cancelling field must be large in magnitude.

Under these experimental conditions, the distance $L_E \approx 100$ μm was shorter than the distance between the current contacts. It follows from the theory that in this case the mechanism limiting the propagation of the electric field in regions (1, 2) and (3, 4) is the appearance of phase-slippage centers[4,2] due to the large phase gradient near current contacts 2 and 3. According to a theoretical estimate, a phase-slippage center arises at a phase gradient such that the field propagates over a distance $L_E \sim (\sigma_N / I)\Delta\,(T/\Delta)^{3/2}$, where Δ is the energy gap, σ_N is the conductivity in the normal state at the given temperature, and I is the current between contacts 2 and 3. This distance is in reasonable order-of-magnitude agreement with experiment.

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