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CONDENSED MATTER

Magnetoresistance of a Two-Dimensional $TbTe_3$ Conductor in the Sliding Charge-Density Wave Regime

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The magnetoresistance of a $TbTe_3$ two-dimensional conductor with a charge-density wave (CDW) has been measured in a wide temperature range and in magnetic fields of up to 17 T. At temperatures well below the Peierls transition temperature and in high magnetic fields, the magnetoresistance exhibits a linear dependence on the magnetic field caused by the scattering of normal charge carriers by "hot" spots of the Fermi surface. In the sliding CDW regime in low magnetic fields, a qualitative change in the magnetoresistance has been observed associated with the strong scattering of carriers by the sliding CDW.

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Pair interaction between quasiparticles often leads to symmetry breaking of the ground state of solids and to the formation of superconductivity or states with charge-density waves (CDWs) or spin-density waves [1, 2]. A CDW ground state is characterized by a spatial modulation of the electron density ~cos($Qx + \varphi$), a periodic distortion of the lattice with the same wave vector $Q_{\mathrm{CDW}} = 2k_{\mathrm{F}}$, and opening of the energy gap Δ in the electron spectrum. The Peierls instability in quasi-one-dimensional compounds, as a rule, appears owing to the nesting of the Fermi surface with the wave vector $Q = 2k_{\mathrm{F}}$.

Both quasi-one-dimensional and, more recently, quasi-two-dimensional CDW compounds were actively investigated and many properties of this state are pretty well studied [2]. Much less attention was paid to studying the mechanisms of the influence of CDWs on the properties of conduction electrons remaining on the Fermi level. This problem is topical for the systems with incomplete dielectrilization of the electron spectrum in the Peierls state including all quasi-two-dimensional compounds, in which CDWs, as a rule, coexist/compete with other types of electron ordering: with superconductivity in high-T_c cuprate superconductors [3] and transition metal dichalcogenides [4], as well as with magnetic ordering in rare-earth tritellurides RTe_3 (R is a rare-earth element) [5].

As was recently found in [6], the magnetic-field dependence of the magnetoresistance of quasi-two-dimensional CDW compounds $TbTe_3$ and $HoTe_3$ exhibits a temperature-dependent crossover from an ordinary quadratic law at high temperatures and in weak magnetic fields to an unusual linear dependence at high temperatures and in high magnetic fields. To explain this observation, a theoretical model was proposed under the assumption of the existence of strong scattering of quasiparticles by CDW fluctuations near "hot spots" of the Fermi surface, where this surface is most strongly reconstructed. It was of interest to perform similar measurements under the conditions where the CDW state was somewhat modified. At a low temperature, when the effect of linear magnetoresistance appears, the CDW state can be modified only by driving the CDW state into the sliding mode. In this work, an experiment of this kind was carried out with $TbTe_3$. This compound exhibits a transition to a state

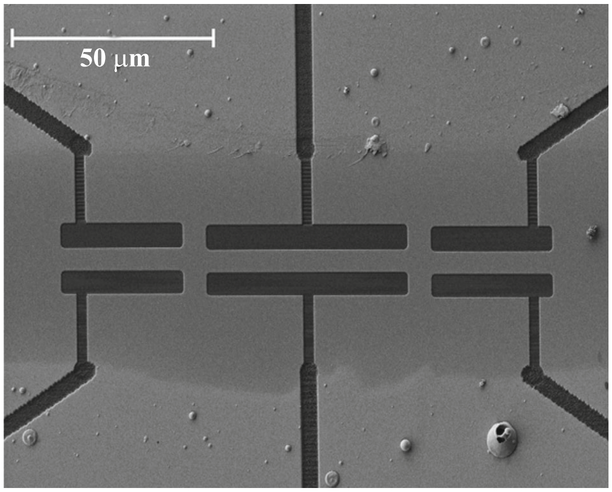

Fig. 1. Scanning electron microscope image of the typical bar structure based on a $TbTe_3$ single crystal.

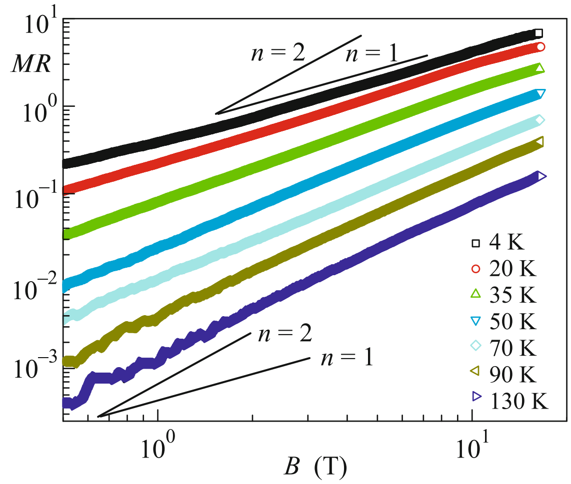

Fig. 2. (Color online) Magnetoresistance of $TbTe_3$ versus the magnetic field at various temperatures. Solid black straight lines correspond to the ($n = 1$) linear and ($n = 2$) quadratic dependences.

with an incommensurate CDW with the wave vector $\mathbf{Q}_{CDW1} = (0, 0, {\sim}2/7c^*)$ at the temperature $T = 330$ K [7]. Importantly, the compounds of the RTe_3 family are the only known quasi-two-dimensional compounds in which a collective motion of a CDW can be reliably observed [8, 9].

$TbTe_3$ single crystals were grown in a pure argon atmosphere by the technique described in our previous work [8]. Thin rectangular single-crystal samples thinner than 1 μm were prepared by the micromechanical thinning of relatively thick crystals preliminarily glued to a sapphire substrate. The quality of crystals and the spatial position of crystallographic axes were monitored by X-ray diffraction.

According to [9], the sliding of the CDW manifested as a sharp increase in the current on the current–voltage characteristics at a certain threshold electric field E_t could be observed in $TbTe_3$ only in the temperature range of 180–320 K. The E_t value increased linearly with a decrease in temperature and a simultaneous linear decrease in the electric resistance. Therefore, the observation of sliding at temperatures below 180 K appeared to be troublesome owing to the necessity of passing a high current and a considerable increase in Ohmic heating. In this work, to solve this problem, bar structures with a length of 70–150 μm and a width of 5–10 μm were prepared by etching with the use of a focused ion beam, which allowed increasing the resistance considerably and decreasing the current required for the achievement of E_t. The image of such a structure is shown in Fig. 1. The bars were oriented along the *c* crystallographic axis, the direction of which coincides with the wave vector of the CDW. As was shown in [8, 9], it is exactly the direction of a possible motion of the CDW in RTe_3 compounds.

The magnetic field produced by a superconducting solenoid was perpendicular to the structure plane (parallel to the crystallographic axis *b*). The magnetic-field dependences of the in-plane resistance, $R(B)$, and the current–voltage characteristics of the structures were measured by the four-terminal method in the magnetic field ranging from 0 to 17 T.

Figure 2 shows the field dependences of the magnetoresistance $MR = (R(B) - R(0))/R(0)$ of one of the structures on a log–log scale. As in [6], MR at low temperatures ($T < 50$ K) is a linear function of the magnetic field B in strong magnetic fields and is a quadratic function in weak fields ($B \ll 1$ T). With an increase in T, the field region corresponding to the quadratic dependence of MR expands monotonically. A visible nonlinearity of the dependence $R(B)$ at $T = 4.2$ K in the field region of 1–3 T is most probably caused by the suppression of antiferromagnetic ordering in $TbTe_3$ by the magnetic field [10].

Unfortunately, we could not achieve the state of sliding CDW at values of the transport current that would not lead to a considerable Ohmic heating of the structures at temperatures below 100 K. Hence, the comparative measurements of dependences $MR(B)$ were carried out at temperatures of 100, 120, and 140 K. As is seen in Fig. 2, a strict linear dependence was not observed at these temperatures. However, the deviation of $MR(B)$ from the quadratic law with an increase in B seems obvious.

Figure 3 shows the differential current–voltage characteristics of a 150-μm-long bar at $T = 120$ K and various B values. Similar dependences were also observed at other temperatures. Clearly, the magnetic field hardly affects the threshold field. We should

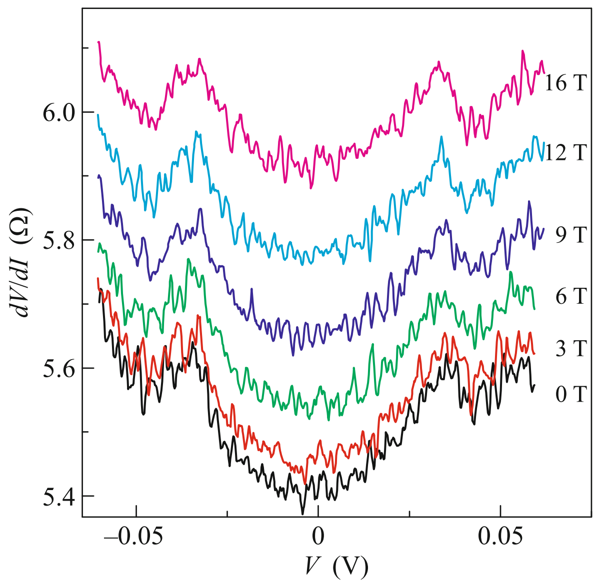

Fig. 3. (Color online) Differential current–voltage characteristics $dV/dI(V)$ of the 150-μm-long bar structure in various magnetic fields.

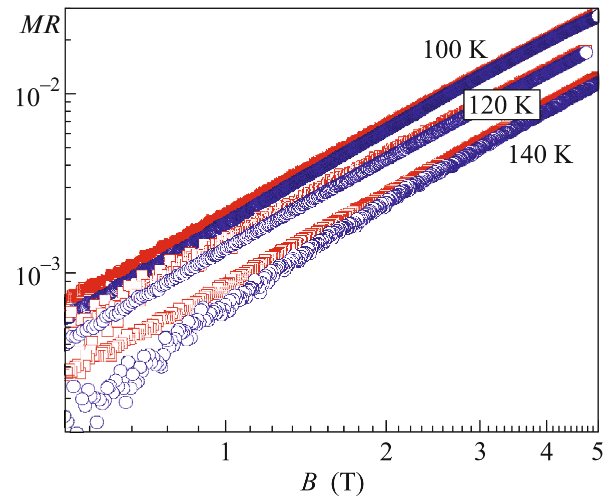

Fig. 4. (Color online) Magnetoresistance versus the magnetic field at $T = 100$, 120, and 140 K in the regimes of (red squares) static and (blue circles) sliding CDW.

mention only a slight tendency of a decrease in E_t with an increase in B and a noticeable increase in the amplitude of the jump of the differential resistance in the magnetic field at the transition of the CDW to the sliding state, which can indicate an increase in the contribution of the moving CDW to the electronic transport. The authors of [11, 12] theoretically predicted an increase in E_t with the magnetic field for quasi-one-dimensional CDW systems, which is opposite to the effect observed in this work. A weak increase in E_t with the magnetic field was actually observed in the quasi-one-dimensional compound $NbSe_3$ [13] at a relatively high temperature ($T/T_{CDW} \sim 0.7$). Dissimilar behaviors of the threshold fields in $TbTe_3$ and $NbSe_3$ in the magnetic field can indicate a qualitative difference between the mechanisms of sliding of the CDW in quasi-two-dimensional and quasi-one-dimensional compounds, as was already mentioned in [14].

Figure 4 shows the measured magnetoresistance $MR(B)$ on a log–log scale in the regimes of (red squares) static and (blue circles) sliding CDW at $T = 100$, 120, and 140 K. Clearly, the effect of sliding CDW is visible at these temperatures only in relatively weak magnetic fields $B < 5$ T and is manifested by a change in the exponent α of the power dependence $MR \propto B^{\alpha}$, more specifically, by a noticeable increase in this parameter at the transition of the CDW to the sliding state. The initial part of the quadratic dependence $MR(B)$ becomes more pronounced and appears in a wider range of magnetic fields when the CDW occurs in the sliding state, although one could initially expect an opposite behavior: a decrease in the exponent α owing to a more effective scattering of normal carriers by the "hot spots" of the Fermi surface.

We attribute the observed effect to an increase in the scattering of normal carriers directly by the sliding CDW as a kind of defect rather than by the hot spots of the Fermi surface. In this case, we deal already with ordinary scattering, which should lead to the standard quadratic dependence $MR(B)$. The fact that an increase in the exponent α appears only in weak fields indicates that the scattering by "hot spots" of the Fermi surface remains the dominant mechanism in strong fields, in agreement with the model [6]. As a result, the dependences $MR(B)$ for the sliding and static CDWs nearly coincide in this region. The above model is also supported by a significant expansion of the range of magnetic fields in which a change in α is seen with an increase in temperature, as should be the case for ordinary scattering [6].

An increase in the scattering of normal carriers by the sliding CDW was indicated earlier in [15, 16], where a significant decrease in the amplitude of Shubnikov–de Haas oscillations was observed in the quasi-one-dimensional compound $NbSe_3$ when the CDW passed to the sliding regime. The effect of strong interaction of normal carriers with a sliding CDW was also discovered in the measurement of the Hall effect [17–19]. An additional factor that can lead to such scattering could be an extraordinary low velocity of a sliding CDW in RTe_3 compounds [9]. In a sense, the motion at such a velocity is an analog of the CDW creep in quasi-one-dimensional systems, the regime in which a considerable increase in scattering of normal carriers was also observed [20].

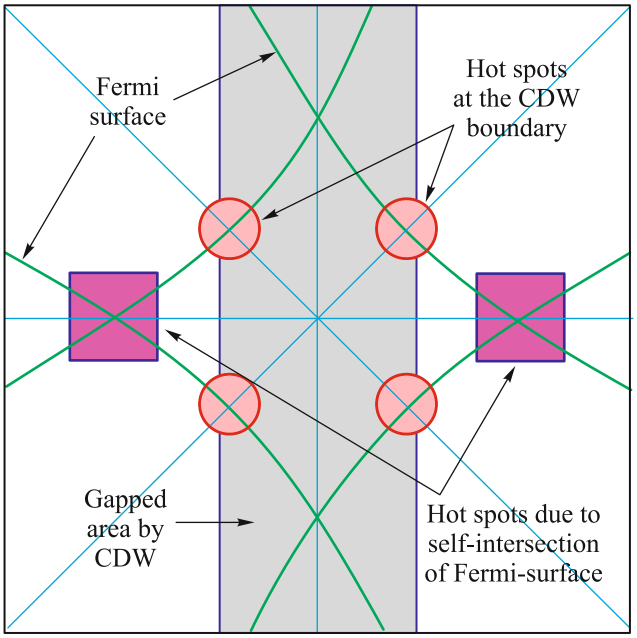

Fig. 5. (Color online) Schematic of the Fermi surface in $TbTe_3$ and its possible hot spots.

It is quite surprising that sliding of the CDW did not lead to a considerable strengthening of scattering by the hot spots and only introduced an additional mechanism of electron scattering similar to ordinary crystal defects. Actually, one would expect sliding of the CDW to smear out (or make spatially inhomogeneous) the momentum-space boundary between the gapped (owing to the CDW) and gapless states of electrons on the Fermi surface shown in Fig. 5. This would expand the region of hot spots at this boundary shown by small red circles in Fig. 5 and hence would strengthen the mechanism of electron scattering by the hot spots and lead to an increase in the linear contribution to the magnetoresistance. The absence of this effect in the present experiment can be explained by two factors. First, the above arguments on the nature of hot spots at the CDW boundary are simplified, especially in the sliding CDW state, and the question requires further investigation. For example, an opposite effect, although less probable, is also possible owing to a partial suppression of the CDW and an increase in the fraction of the metallic phase. The theoretical consideration requires a specific microscopic mechanism of scattering by hot spots and the role of the spatial inhomogeneity of the CDW order parameter, magnetic breakdown, and other factors in this process. Second, the absence of the influence of CDW sliding on the linear magnetoresistance in strong magnetic fields can indicate that the "hottest" spots, i.e., the points at which the electron scattering is strongest, do not belong to the momentum-space boundaries of the CDW. We can suggest as alternative hot spots the self-intersection regions of the Fermi surface marked by violet squares in Fig. 5. In these regions, two branches $\epsilon_1(\mathbf{k})$ and $\epsilon_2(\mathbf{k})$ of the electron spectrum corresponding to two nearly perpendicular sheets of the Fermi surface have close energies at the same momentum. This leads to the electronic instability and reconstruction of the electron spectrum and the Fermi surface, which is clearly seen in the ARPES data [21] as a discontinuity and rounding of the Fermi surface. In addition, the width of the gap formed in the electron spectrum at the point where $\epsilon_1(\mathbf{k}) = \epsilon_2(\mathbf{k})$ must be much greater than the gap caused by the CDW because the former and latter gaps are determined by the interactions $V(Q = 0)$ and $V(Q_{CDW}) < V(0)$ at zero and finite momentum, respectively. In confirmation, reconstruction of the Fermi surface near the self-intersection points is clearly seen in the ARPES data [21] already at a temperature of 300 K and higher, where the spectrum reconstruction caused by the CDW is hardly seen owing to a low resolution of the ARPES technique.

The influence of the self-intersection region of the Fermi surface, possibly accompanied by a change in its topology, on the observed electronic properties and phase transitions associated with various electronic instabilities is an important and interesting problem and requires further investigation. Rare-earth tritellurides seem to be very convenient for such studies.

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