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Charge ordering in amorphous WO_x films

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Abstract

We observed highly anisotropic viscous electronic conducting phase in amorphous $WO_{1.55}$ films that occurs below a current (I)- and frequency (f)-dependent temperature $T^*(I,f)$. At $T<T^*(I,f)$ the rotational symmetry of randomly disordered electronic background is broken leading to the appearance of mutually perpendicular metallic- and insulating-like states. A rich dynamic behavior of the electronic matter occurring at $T<T^*(I,f)$ provides evidence for an interplay between pinning effects and electron–electron interactions. The results suggest a dynamic crystallization of the disordered electronic matter, viz. formation of sliding Wigner crystal, as well as the occurrence of quantum liquid-like crystal or stripe phase at low drives.

Keywords: Broken rotation symmetry; Electronic stripes; Wigner crystallization

Behavior of quasi-1D electronic stripes is one of the central issues of the physics of transition-metal oxides (TMO), e.g. cuprates [1]. The theory of quantum electronic liquid crystals predicts the occurrence of either superconducting or non-Fermi-liquid ground states associated with dynamics of charge-ordered phases. Experiments revealed the charge ordering in various TMO, indeed [1]. However, so far all the studies were performed on crystalline TMO compounds, where the atomic long-range order inevitably affects or governs the stripe formation.

Here we report on the observation of anisotropic electronic phase in amorphous WO_x ($x\sim1.55$) films, characterized by broken rotation symmetry below a current-(I) and frequency-(f) dependent temperature $T^*(I,f)$.

The studied $WO_{1.55}$ films were grown on glass substrates from WO_3 target under vacuum $P\approx(5–8)\times10^{-4}$ Pa at room temperature by pulsed laser deposition [2]. The film thickness $d=400$ nm was measured by a DEKTAK profilometer. The Rutherford Backscattering Spectroscopy analysis revealed a homogeneous oxygen distribution in the films. Obtained featureless X-ray diffraction patterns provide evidence for the film amorphization.

Van der Pauw-type resistance measurements with Pt contacts were performed on several amorphous $WO_{1.55}$ films for $2\,\mathrm{K}\leqslant T\leqslant 300\,\mathrm{K}$, $1\,\mathrm{Hz}\leqslant f\leqslant 1\,\mathrm{kHz}$, $10\,\mu\mathrm{A}\leqslant I\leqslant 1\,\mathrm{mA}$, and $0\leqslant B\leqslant 9\,\mathrm{T}$ by means of PPMS (Quantum Design) and Janis 9T-magnet He-cryostats. The resistances $R_h=V_{23}/I_{14}$ and $R_e=V_{34}/I_{12}$ were measured as shown in insets of Fig. 1(b) and (a), respectively.

Fig. 1(a,b) presents low-temperature portions of $R_e(T)$ and $R_h(T)$ measured for one of the studied films at various frequencies and current $I=10\,\mu$A. As can be seen from Fig. 1, for $T<10$ K, $R_e(T)$ and $R_h(T)$ demonstrate a pronounced frequency dependence. At low frequencies ($f=10$ Hz), and down to $T=2$ K, $dR_h/dT<0$ and $dR_e/dT>0$, such that the ratio R_h/R_e diverges (not shown) with temperature lowering; $R_h/R_e=A+B\exp(C/T^{1/2})$, where $A=1.5$, $B=0.003$, and $C=12[K^{1/2}]$. The R_h/R_e vs. T behavior suggests the formation of an ideal metal in the "easy" (more conductive) direction or/and an insulator-in the "hard" (less conductive) direction ground states ($A>1$ originates from the sample geometrical factor). At the same time, for $f=1$ kHz the resistance at $T<10$ K drops by two

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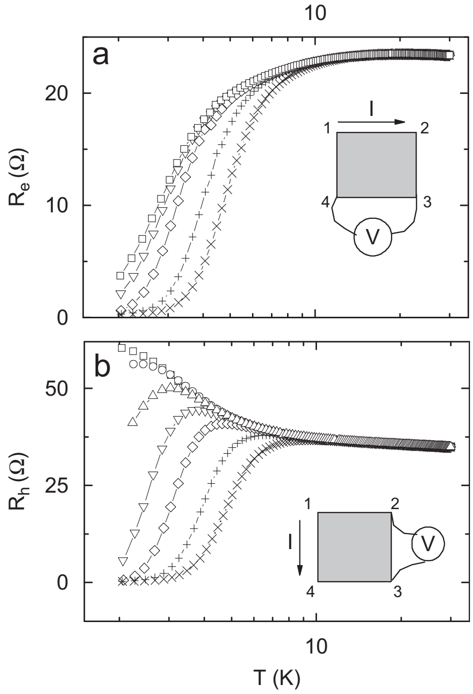

Fig. 1. Temperature dependencies of resistances measured in "easy" $R_e = V_{34}/I_{12}$, (a), and "hard" $R_h = V_{23}/I_{14}$, (b), directions for $I_{12} = I_{14} = 10\,\mu$A and frequencies: (a) $f = 10$, 100, 200, 500, 1000 Hz; (b) $f = 10$, 25, 50, 100, 200, 500, 1000 Hz, from top to bottom.

orders of magnitude, irrespectively of the current direction. No magnetoresistance has been observed that testifies against superconducting correlations as the origin of the resistance drop.

To shed light on the resistance behavior at low temperatures, we note that for $T > 10$ K, $R(\mathrm{T}) = 1/(A_1 + B_1 T)$, A_1, B_1 being constants, expected for systems in the vicinity of a metal–insulator transition (MIT) characterized by the incoherent electronic transport [3]. Then, the resistance drop would indicate the opening of an additional coherent channel. Taking $k_F l \sim 1$ at MIT and $\sigma(T_{max}) = (e^2/3\pi^2\hbar)k_F^2 l \sim 100\,\Omega^{-1}\,\mathrm{cm}^{-1}$, one gets $k_F \sim 10^7\,\mathrm{cm}^{-1}$ that translates to the carrier density $n = (k_F)^3/3\pi^2 \sim 10^{18}\,\mathrm{cm}^{-3}$. For such n, Wigner crystallization (WC) is expected to occur at $T_{WC} \leqslant 10$ K [4]. Noting, the Hall voltage could not be detected in our films, being in agreement with expectedly low Hall mobility in the vicinity of MIT.

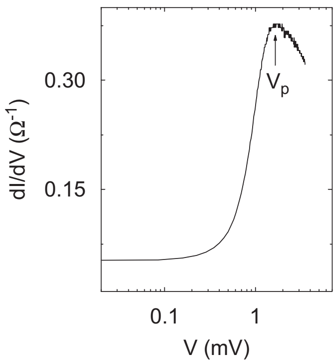

Fig. 2. Differential conductance $G \equiv dI/dV$ vs. V dependence measured at $T = 5$ K and $f = 60$ Hz in "hard" direction; V_p marks the maximum in $G(V)$.

Fig. 2 presents differential conductance $G \equiv dI/dV$ vs. V measured at $T = 5$ K and $f = 60$ Hz in the "hard" direction. The results can be understood as follows. At low drives, the electron motion is dominated by the quenched disorder (pinning) effects, leading to the plastic (channel-like) motion. With increasing the driving force, (re)ordering or dynamic Wigner crystallization takes place at $V = V_p$ [5] (see Fig. 2). Also, considering a combined effect of quenched disorder and electron–electron interactions, R vs. f behavior shown in Fig. 1 can be accounted for by the frequency-induced de-pinning of the elastic electronic media.

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