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# Strain-induced formation of ultra-coherent CDW in quasi one-dimensional conductors

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ABSTRACT

We have developed techniques for stretching whiskers up to 1.5–3%, including those of nanometer cross-section. An exceptionally high coherence of the CDW transport for $TaS_3$ and $NbS_3$ has been observed under the uniaxial strain, $\varepsilon$. For $TaS_3$ samples with transverse dimensions ~0.1–1 μm for $\varepsilon$ approaching $\varepsilon_c$ the CDW coherence falls down and a new, ultra-coherent, CDW phase begins to form. At $\varepsilon \sim \varepsilon_c$ the two phases coexist within a very narrow range $\delta\varepsilon \sim 2 \times 10^{-4}$. Further stretching results in a complete vanishing of the transport of the incoherent CDW. The threshold fields, $E_t$, of the ultra-coherent CDW, as well as the dissipation, appear by an order of magnitude lower; giant negative differential resistance is observed. The narrow-band noise shows up to 10 harmonics of the fundamental frequency. RF irradiation results in complete synchronization of the CDW sliding. The CDW transformation shows features of the 1st order transition. We also report hysteresis of resistance vs. $\varepsilon$, from which we conclude that the transition cannot be associated with the lock-in of the CDW: the strain draws the CDW away from 4-fold commensurability with the lattice.



## 1. Introduction

Collective transport is one of the most representative features of the quasi one-dimensional conductors with charge-density waves (CDW). Though nearly no hope is left to achieve the "Fröhlich superconductivity", the limiting characteristics of the CDW transport (the threshold fields, dissipation) are not understood yet.

Recently submicron whiskers of $NbS_3$ (phase II) were shown to demonstrate highly coherent CDW transport at room temperature. The synchronization of the CDW under a source of RF voltage achieves 100% in some cases [1]. Another recent result is the drastic improvement of the CDW coherence (both of depinning and sliding) under asynchronous RF irradiation. It has been demonstrated for $NbS_3$ (phase II), $TaS_3$ and $(TaSe_4)_2I$ [1].

Here we report exceptionally high coherence of CDW transport for $NbS_3$ and $TaS_3$ under uniaxial strain. For $TaS_3$ it has been noticed earlier that under the strain above a critical value, $\varepsilon_c$~0.4–1%, coherence of CDW grows strongly. This effect was tentatively interpreted in terms of soliton transport [2], strain-induced lock-in transition [3] or a 1st-order phase transition of the CDW [4]. In [4] the possible phase transition between CDW1 (unstretched, low stress) and CDW2 (under strain, high stress) was inferred from the feature observed on stress-strain dependences. The transition was rather smeared out, over about 0.2% in strain. The difference between the two CDW phases remained unclear. Both in [2] and in [4] two threshold voltages, $V_t$, on the $I$–$V$ curves were reported for strained $TaS_3$ samples interpreted as thresholds for solitons and CDW depinning [2] respectively.

In this paper, basing on transport studies, including Shapiro steps, we show that the two-threshold $I$–$V$ curves are observed only in a very narrow region of strains around $\varepsilon_c$. Thus, $\varepsilon_c$ signifies transition between two CDW phases: low-coherent and highly coherent.

## 2. Methods of stretching of micro- and nano-samples

In the family of quasi one-dimensional compounds $TaS_3$ whiskers are among most defect-reach crystals. Apparently, they are usually multi-block crystals with numerous growth steps on the surfaces. For our studies we visually selected single crystals with plain surfaces. The selected crystals appeared rather thin, of micron widths or below. For stretching such crystals we designed special techniques. In the 1st one the sample was attached to a surface of a polymer substrate made from an organic epoxy. The uniaxial strain was achieved by means of bending the substrate, which was resting on two bearings near its ends. The bending was provided by a long bar driven from outside the cryostat. The resulting strain is:

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$$\varepsilon = 4\delta y d / L_{sub}^{2}, \quad (1)$$

where $\delta y$ is the displacement of the bar, $d$ – thickness and $L_{sub}$ – length of the substrate. The technique appeared applicable to samples with cross section areas down to at least $10^{-3}$ μm$^2$ and allowed stretching them up to 1.5–3%.

One of the ways of $\varepsilon$ control is measuring $\delta y$. The set-up allows a closely continuous ($\delta\varepsilon$ below $10^{-4}$) change of the sample length at constant temperature. The strain can be increased until the substrate looses elastic properties or the sample acquires defects. To be sure that these limitations are not violated, we always control, if the sample resistance and the shape of the $I$–$V$ curve are the same after returning back to $\delta y = 0$.

We must note, that the values of $\varepsilon$ were estimated with a certain error. First, $L_{sub}$ could slightly change in the process of bending. Second, the sample could be initially strained, or, vice versa, loose. Thus, the reference point for $\varepsilon$ was somewhat arbitrary. To avoid this uncertainty, we counted ε from the beginning of $R$ change, like in [2,4]. Third, the advancement of the bar could be non-uniform because of the friction. However, in this work exact determination of $\varepsilon$ was not our goal.

For direct monitoring the strain of the substrate surface we deposited a thin gold stripe (100–300 Å) on the substrate near the sample. It played the role of a strain gauge. Thin metallic films are known to show pronounced piezoresistive properties [5]. The tensoresistive coefficient of the film was calibrated with the help of the relation (1). We managed to monitor the strain with resolution well below $10^{-4}$. The disadvantage of the technique is thermal expansion of the mechanical drive, which complicates measurements of temperature dependences at fixed strain. For such studies we developed another technique. Before starting the experiment we stretched the sample between two oblong silicon plates, forming a lever (Fig. 1). The plates are fixed on a substrate with the help of indium. The strain of the sample is provided through displacement of one end of one of the plates by means of pressing In. The strain is easily defined from the relation $\varepsilon = L1/L2\Delta y/l$, where $L1,2$ are lengths of shoulders, $\Delta y$ – the shift of the plate end, $l$ – the length of the whisker. The plastic properties of In allow smooth displacement of the plate with the accuracy of approximately 1 μm (with the help of a microscope). With the ratio of the lever shoulders about 10, it corresponds to sample expansion by 0.1 μm, which for a 200–300 μm sample makes 0.05% or less. It means that it is possible to control the sample elongation with rather high precision in the range from zero to several percents. This compact microstructure (a 3–10 mm sized chip) was placed in a cryostat and could be cooled down to cryogenic temperatures with a relatively small change of the deformation (thermal expansivity of $TaS_3$ is about $10^{-5}$ K$^{-1}$ [6], for silicon it is

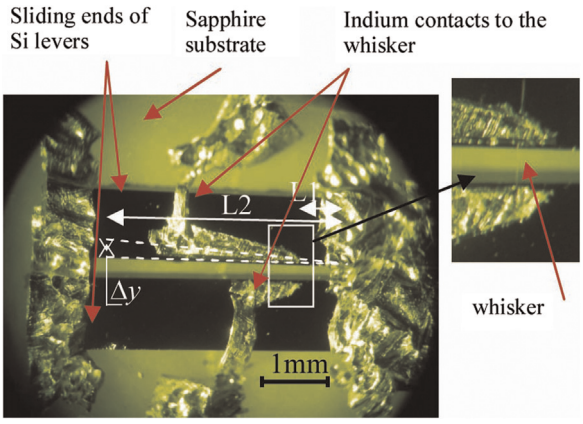


**Fig. 1.** Photo of a chip for straining whiskers with the lever method.

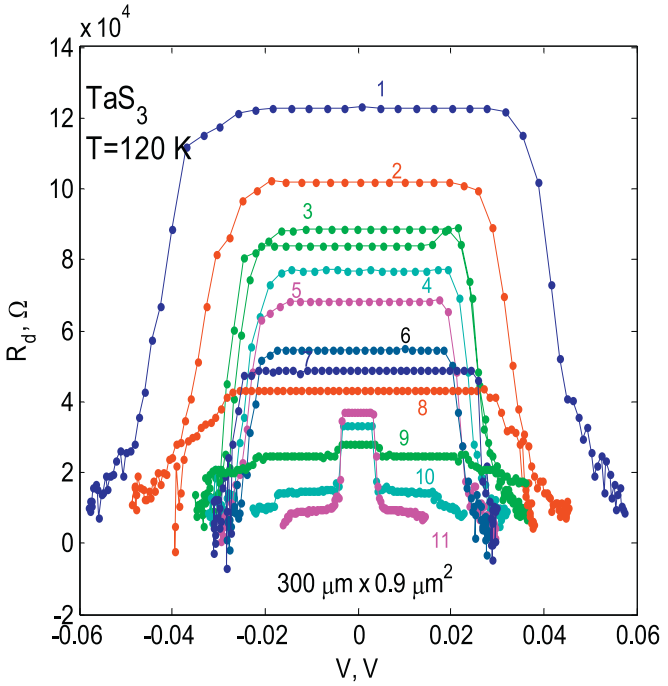


**Fig. 2.** Evolution of $R_d(V)$ curves with $\varepsilon$ increase for sample no. 1. The curves are numbered in the order of the strain increase. $\varepsilon$ was increased in 10 approximately equal steps; the strain for curve 11 is about 1%. Two thresholds can be seen on the curves 9 and 10.

significantly less). Such structures are convenient, e.g., for measurement of temperature dependences of resistance, $R(T)$, at nearly constant strain. The strain for the results presented in Figs. 2–4, 6 was applied with the 1st technique, for the results in Fig. 5 – with the 2nd one.

## 3. Experiment

Fig. 2 shows evolution of differential $I$–$V$ curves for a $TaS_3$ sample (no. 1) with growth of $\varepsilon$. One can see that with growth of strain $V_t$ at first slightly decreases, and the drop of $R_d$ becomes sharper. Then $V_t$ begins to grow, and the CDW depinning becomes more gradual. Simultaneously, at a strain about 0.8%, another threshold appears, an order of magnitude lower. The $R_d$ drop at this threshold is very sharp, looking like a nearly vertical step. The result indicates formation of an ultra-coherent CDW (UCCDW) state. In a narrow range of ε two thresholds can be seen on the $R_d(V)$ curves. With strain growth the step at the lower threshold increases, while the nonlinearity above the higher ("old") threshold gradually vanishes. Qualitatively, the evolution of the $I$–$V$ curves resembles that reported in [2,4] with reserve that the thresholds in our case are much sharper: the CDW is much more coherent. Thus, the overall picture is as follows: with strain growth the CDW coherence at first grows, then falls abruptly. Simultaneously, the new, UCCDW appears. Its fraction grows until it spreads over the whole sample volume. The strain-induced formation of the UCCDW was observed for more than 10 $TaS_3$ samples.

Fig. 3 shows $R_d(V)$ curves for the sample no. 2 together with the corresponding $R(\varepsilon)$ dependence at $V \ll V_t$. One can see that the CDW turns into the ultra-coherent state within a narrow range of $\varepsilon$, below 0.02%. In this strain region the drop of zero-voltage resistance, $R(\varepsilon)$, gives place to a nearly vertical increase of $R$ (Fig. 2b). The previously observed growth of resistance was more gradual [2,4,7,8].

Below the transition the $R(\varepsilon)$ curve shows pronounced