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Self-detection of mechanical oscillations of charge-density wave conductors

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ABSTRACT

Heterodyne mixing technique with frequency modulation is applied for detection of torsional resonances of whiskers of orthorhombic TaS_3—a typical quasi one-dimensional conductor with charge-density wave (CDW). In contrast to the previous applications of this technique, both actuation (the torque) and detection (torsional modulation of current) are based on the intrinsic properties of the CDW systems and do not require positioning of the sample in vicinity of a gating electrode. The technique allows studies of electromechanical and elastic properties of the CDW systems at the MHz range at least.

1. Introduction

A developing area of nanomechanics is excitation and detection of high-frequency oscillations in nanosized objects. A system based on such a nanoresonator can work as an atomic balance [1]. Another intriguing goal of the studies, an aspect of which was recently achieved [2], is direct observation of quantum manifestations of a hand-made system.

A typical oscillating object is a nanowire. Usually it is positioned in a double-clamped configuration above a gate, which is used as a source of electrostatic force inducing flexural oscillations [3]. Excitation of the oscillations is only half the work. A complex goal is detection of such oscillations. Optical techniques fail at high frequencies. In some cases flexural resonances have been detected by means of a transmission [4] or scanning [5] electron microscope: smearing out of the images of the wires could be seen. Apart from complexity, a disadvantage of these techniques is the damaging effect of the electron beam. For carbon nanotubes a technique was suggested based on coupling between the field emission current and the nanotube's mechanical vibrations [1,6], but, unfortunately, this technique is not applicable to other type nanowires.

A way out of these difficulties is gathering an electric signal generated by the wire itself. In the case of a gated wire the signal can root in the conductivity modulation due to the charging–discharging of the wire in the field of the gate (the field effect). An important step in this direction was the technique of heterodyne mixing with frequency modulation (HMFM), originally proposed in [3]. In this case an ac voltage at frequency ω is applied to one of the wire ends, while the other contact is grounded. The voltage induces both mechanical oscillations in the field of the gate and ac current through the wire. The current equals the product of the ac voltage and conductivity of the wire, which also contains the ac component, proportional to the amplitude of flexural oscillations. Multiplication of the two ac signals results in a dc component. To extract it from other dc contributions, frequency modulation at low frequency Ω is typically used. A lock-in amplifier tuned at frequency Ω gives the frequency derivative of the dc component, which shows a feature at the frequency of the resonance (the main flexural mode). This technique allows extraction of a very weak modulation of conductivity of the wire on top of the large ac current flowing through it.

Not long ago the HMFM technique has been applied to $NbSe_3$ nanowhiskers [7]. Evidently, this is the first report of the technique applied to a quasi one-dimensional conductor with charge-density wave (CDW), and it appeared fruitful. A large anomaly in the temperature dependence of the resonance frequency (60–70 MHz) was found in the region of the lower-CDW transition temperature, 59 K: the 13% growth of the Young modulus at these frequencies was attributed to the excitation of the plasmon mode of the CDW. This example demonstrates that high-frequency studies of the CDW crystals can reveal new interesting effects, apart from those found at low frequencies [8–10].

In this paper we suggest and implement a new approach to generation–detection of the mechanical oscillations of the CDW conductors. Like in the above examples HMFM technique is applied, but both actuation and gathering the feed-back signal are

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based on the properties intrinsic to the CDW. The possibility of propagation into the high-frequency region is discussed. In the next sections (Sections 2 and 3) we are resuming the relevant features of the CDW: voltage-induced torsional strain (TS) and torsional modulation of the CDW current. In Section 4 we describe the experimental technique, in Section 5, the experimental results are presented.

2. Voltage-induced torsional strain

The anomalously strong voltage-induced deformations of the samples below the Peierls transition temperature, T_P, are one of the most unusual effects specific for charge-density wave (CDW) systems [10]. Generally speaking, this phenomenon can be treated as a transfer of the deformation of the CDW, an electronic crystal within the host crystal, to the host lattice.

The kind of deformation studied in most detail is the TS. The voltage induced TS was found for a number of CDW conductors in the Peierls state [10,11]. More detailed studies have been performed for orthorhombic TaS_3 (o-TaS_3), a typical quasi one-dimensional conductor. Below we are concerning this particular compound.

The TS in TaS_3 appears extremely large. Typical torsional angles achieve several degrees under electric fields 0.1–1 V/cm, which corresponds to the surface share $\sim 10^{-4}$. Normalized to the electric field this strain gives the value exceeding 10^{-6} m/V, which is 3–4 orders of magnitude above the highest values of piezomoduli known for piezoelectric materials. Such samples can be considered as ready for use torsional actuators. In contrast to the nanowires considered above, the CDW whiskers do not need external drives, such as the gates, for excitation of oscillations. Apart from the TS, flexural strain can also be induced by voltage applied across the sample [11], though its value (in terms of the piezomoduli) appears much lower.

For considering the frequency range of the CDW-based actuators, we should note that two contributions to the TS can be distinguished [11]. The 1st one, hysteretic, is characterized with high time of response ($\tau \sim 10^{-3}$–10^{0} s, depending on temperature) and with pronounced threshold dependence on the voltage applied. The 2nd contribution is approximately linear in voltage and is roughly an order of magnitude below the 1st contribution. The characteristic time of the fast response has been not established yet because of the limitations in the resonance frequencies and of the measurement techniques applied. The highest frequency of torsional oscillations detected was about 200 kHz.

The particular kind of voltage-induced CDW deformations resulting in TS is not clear yet. Nevertheless, there is no doubt that both the slow and the fast contributions to TS originate from the CDW strain. For the slow contribution it is obvious from the hysteretic and threshold dependence on voltage [17], as well as from the slowing down with temperature decrease: $\tau \propto \exp(\Delta/T)$, where 2Δ is the Peierls gap value [11]. The relevance of the fast contribution to the CDW strain is evident from the temperature dependence of the TS amplitude: it decreases abruptly with heating at T around T_P [11]. The slow TS can be attributed to large long-range metastable CDW strains, while the fast contribution– to the local reversible deformations of the CDW around the pinning centers [11]. Therefore, the upper frequency limit of the actuation signal can lie in the range of the pinning frequency, i.e., in the Gigahertz region [9,12,13].

3. Torsional modulation of CDW conductivity

In most of the previous experiments optical [10,11] or capacitive [14,15] technique has been applied for the registration of TS. Correspondingly, a mirror or a steel wire was attached to the whisker studied, and this limited the frequency of the 1st torsional resonance down to at most several tens kHz.

As we noted above, a solution of the problem could be generation of electrical signal by the wire itself. Note, that, in contrast to flexural strain, TS of a sample suspended in the field of a gate would not result in modulation of its charge. However, the sample conductivity, or, more exactly, the conductivity of the CDW appeared rather sensitive to the TS.

The 1st attempt to use “torsioresistance” for self-detection of resonant torsional oscillations did not involve the HMFM technique [16]. Detection of the ac signal generated by the twisting sample on top of the ac signal actuating it was achieved by spatial separation of the actuator and detector: 3-contacts were used, the central one being suspended. The current to it was supplied through a thin flexible wire. AC current was passed through one segment of the sample (actuator), while dc current through the other one (sensor).

In [16] it was noticed that the TS-induced modulation of resistance could be observed only at high dc currents, well above the threshold value, I_t. Systematically the torsional modulation of voltage as a function of dc current across TaS_3 samples was studied in [14]. The TS oscillations were provided with an external drive. The non-zero signal was detected only above the threshold current and was found to grow approximately linear in dc voltage. In [14] the torsional angle was not calibrated. The result from [14] was repeated in [10] with known amplitude of torsional oscillations. Normalized to the surface shear, γ, the relative modulation of the sample conductivity. $\delta\sigma/\sigma$ was found to achieve $(\delta\sigma/\sigma)/\gamma \sim 10$. This value (tensosensitivity) characterizes TaS_3 as a good tensoresistor, keeping in mind that TS (in contrast with longitudinal strain) does not change the sample volume in the linear approximation.

This threshold dependence of the “torsioresisitive” response can be qualitatively explained. TS does not result in notable changes of carriers' concentration or mobility. However, the CDW dissipation should be sensitive to changes in the spatial arrangement of the defects. Probably, the modulation of CDW conductivity couples with possible chirality of TaS_3 (intrinsic for the 222 point group, [9]). Anyhow, it is evident that modulated is the CDW current, and the observed “torsioresistance” is a specific feature of CDW.

4. Experimental details

The results described above forward the CDW conductor TaS_3 as self-sensitive torsional resonator, which can be studied with HMFM technique. The main advantage of this technique is the possibility of detection of high-frequency resonances at the low frequency Ω. The only scheme requirement is application of the high-frequency voltage to one of the sample contacts. Another advantage is the possibility of studies of a sample in a 2-probe configuration. Originally, for TS studies a suspended contact was mounted [17] allowing nearly free TS of the whisker. However, later a configuration with two fixed probes was proposed. In this case about half of the sample is covered with conducting gold film shunting the current through the sample [15,18]. This half of the sample works as a passive bracing, while the gold-free part of the sample works as an actuator. Clearly, arrangement of such a sample is much easier.

The eigenmode frequencies, ω_0, can be very high for nanowires. For a sample cylindrical in cross-section

$$\omega_0 = (\pi/L)\sqrt{(G/\rho)}, \qquad (1)$$

where L is the sample length, G is the shear modulus, and ρ is the density. It is independent of the diameter $2r$. For a rectangular