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

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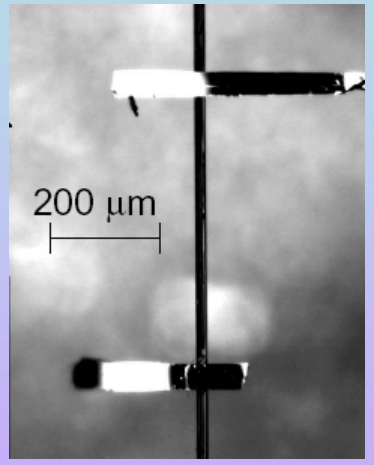
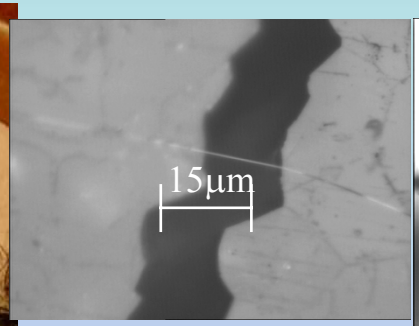


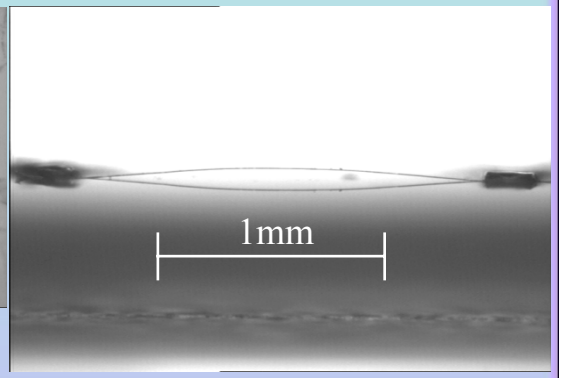
1. Introduction (long)
   a) CDW deformation. Interaction with the lattice
   b) Torsional strain – the main features
   c) Why self-detection?
2. The inverse effect: TS-induced current modulation
3. Self-detection of torsional oscillations
   a) 3-contact way
   b) Heterodyne mixing technique with frequency modulation
   c) Application to the CDW compounds
   d) Towards high frequencies
4. The progress in physical understanding (negative)

CDW crystals

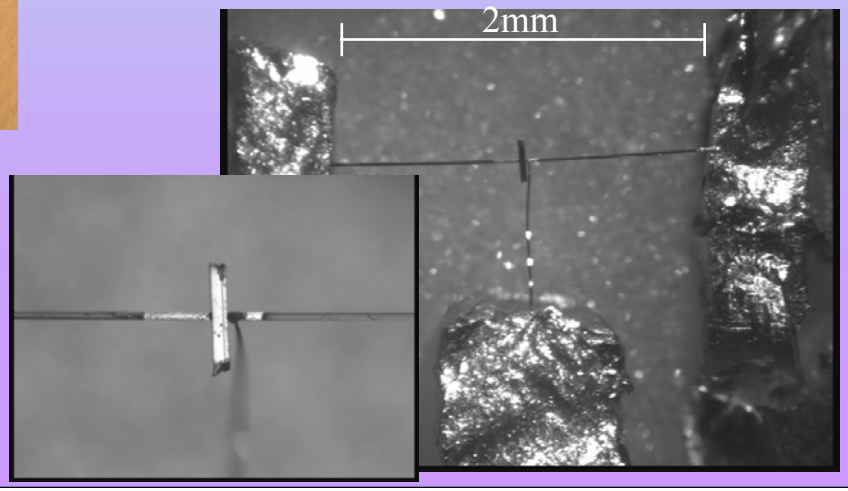
Experimental arrangements

For AFM

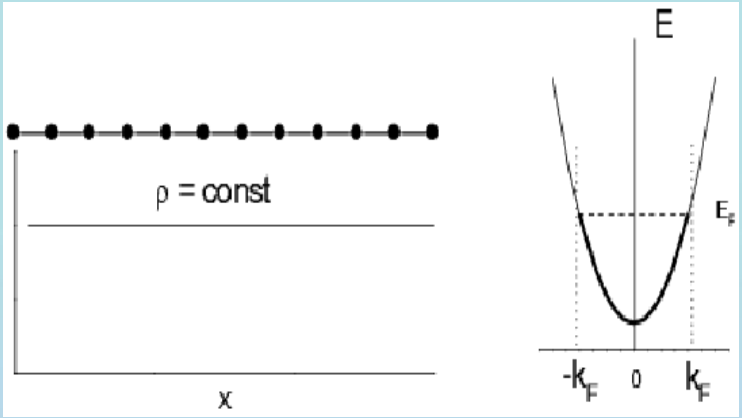


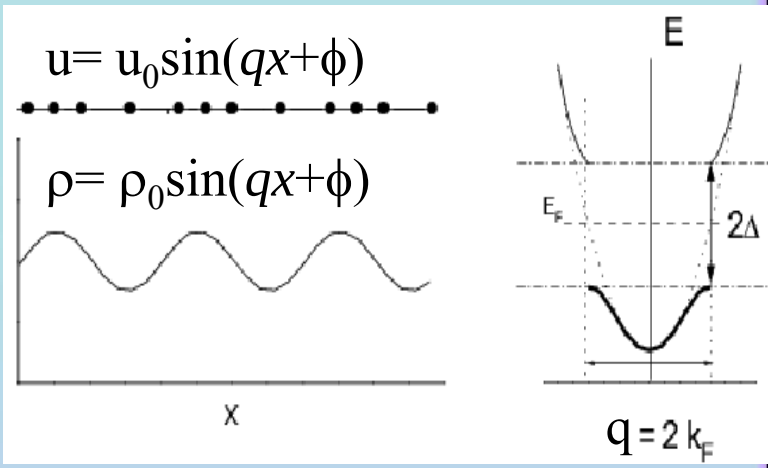


For torsional measurements



The CDW basics. CDW-lattice interaction.





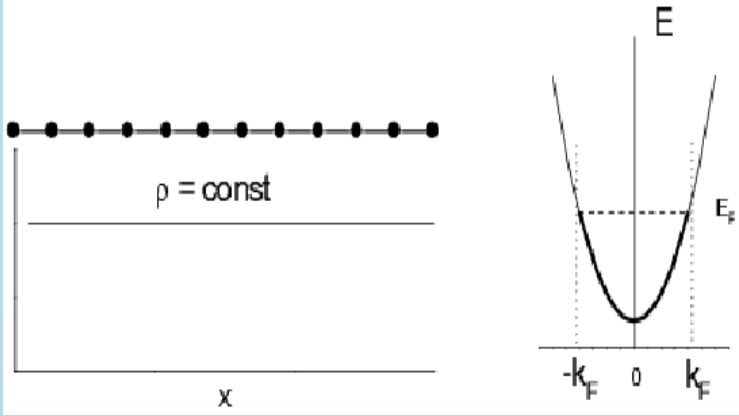
CDW – is deformable electronic crystal, – a spring inside the crystal.

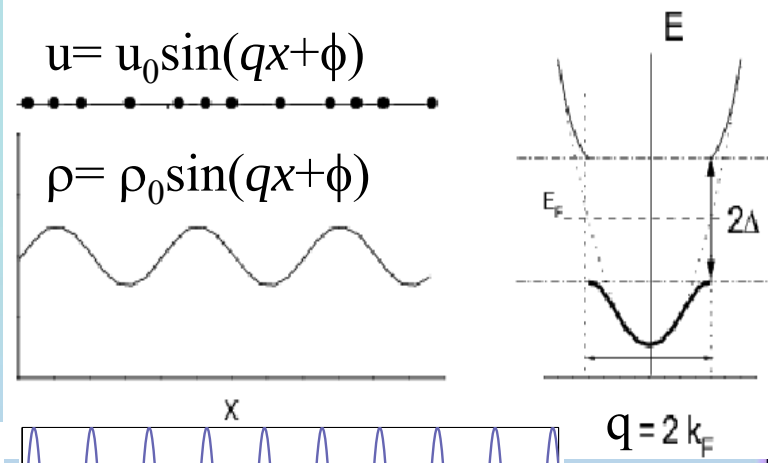
CDW

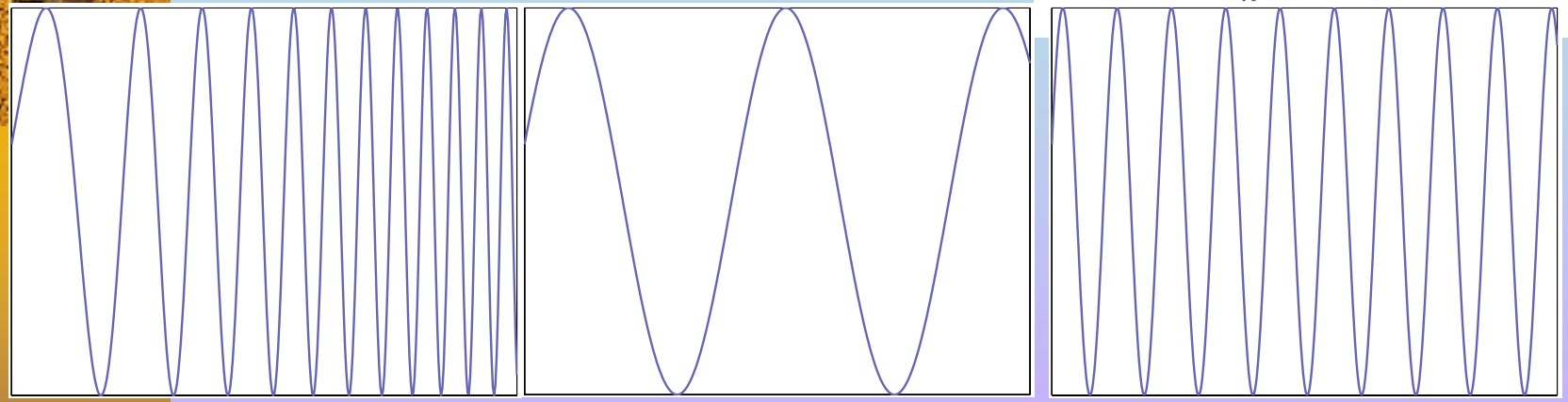
Lattice

In the simple 1D model the equilibrium CDW wavelength follows the lattice deformation:
$\Delta\lambda(c)/\lambda = \Delta L/L \equiv \Delta c/c$, L – sample length, c – lattice period.
HOWEVER, λ/c strongly depends on c. Thus, the two springs interact somehow giving rise to an "analogue" of the piezoelectric effect.

The CDW basics. CDW-lattice interaction.







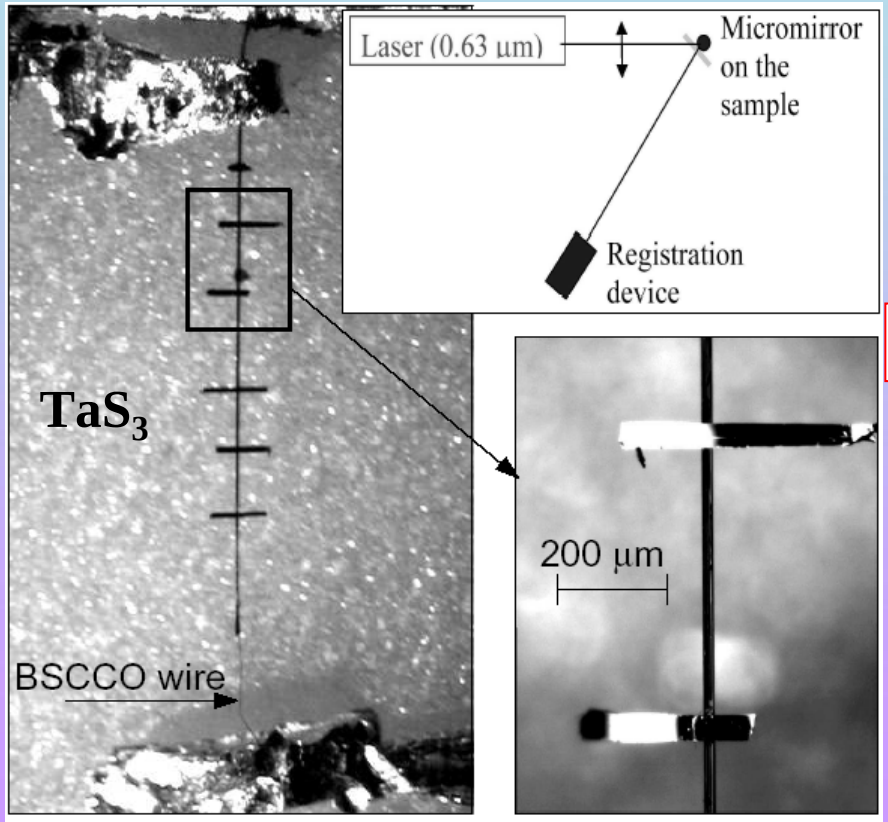
$$W = \frac{1}{2}\left[Y_l\left(\frac{c - c_{eq}}{c_{eq}}\right)^2 + Y_c\left(\frac{\lambda - \lambda_{eq}(c)}{\lambda_{eq}}\right)^2 \right]$$

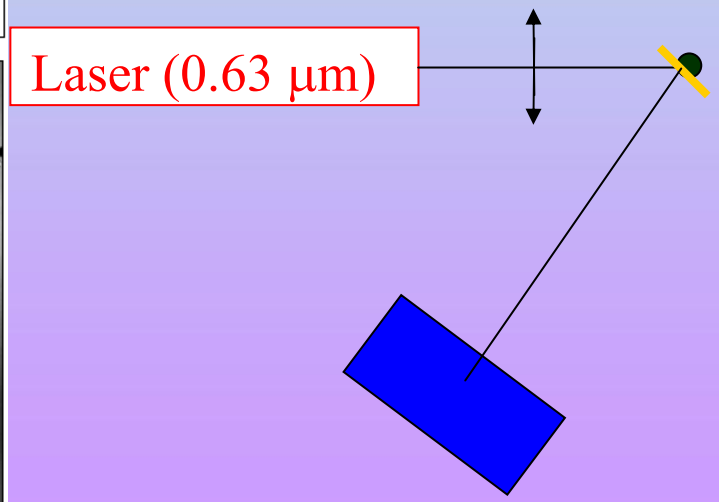
Lattice

Different methods – AFM, TEM, interferometry for different kinds of non-uniform deformation: longitudinal, flexural, BUT unexpectedly:

Torsional strain (TS) of TaS_3 under electric field.

1) Whiskers arrangement allows free torsion.
2) Optical (mirror) methods for the strain registration are developed.





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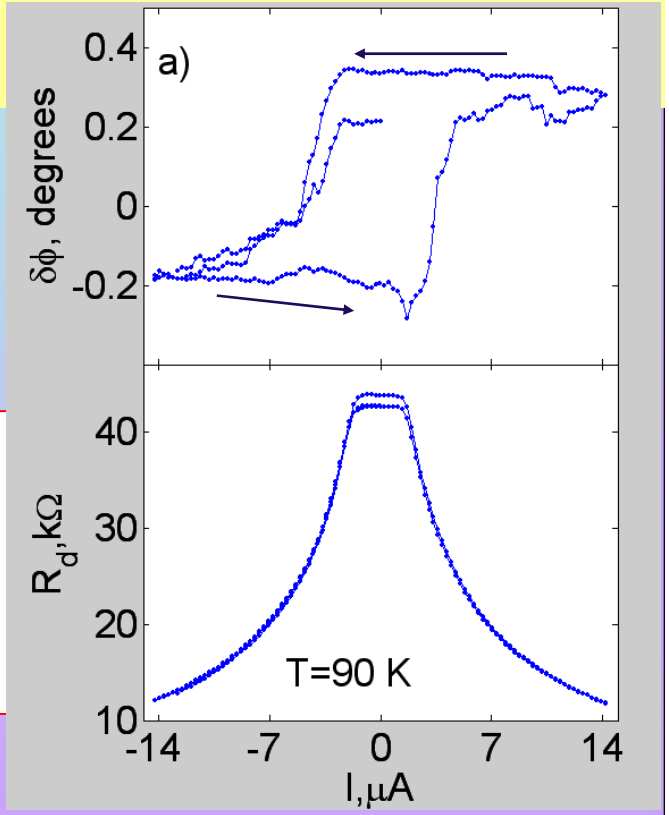
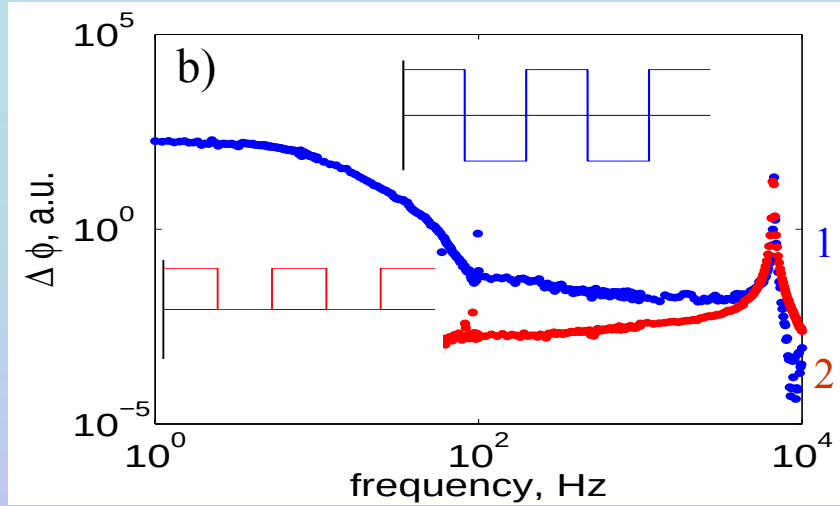
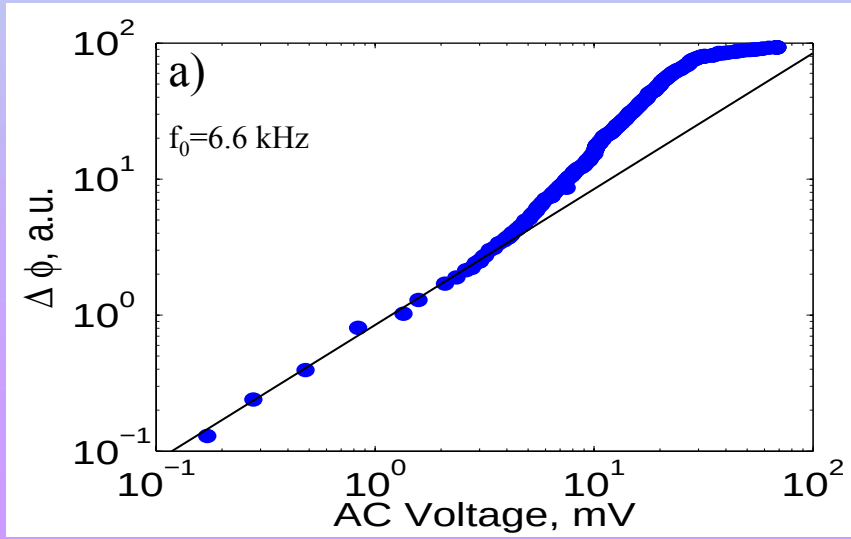


Torsional strain up to 10° (shear ~10^{-4} at *E*~300mV/cm, "piezomodulus" >10^{-4} cm/V) is observed –
a powerful intrinsic actuator.

Related to the CDW depinning and deformation:
Hysteretic, threshold.

The fast linear (thresholdless) contribution



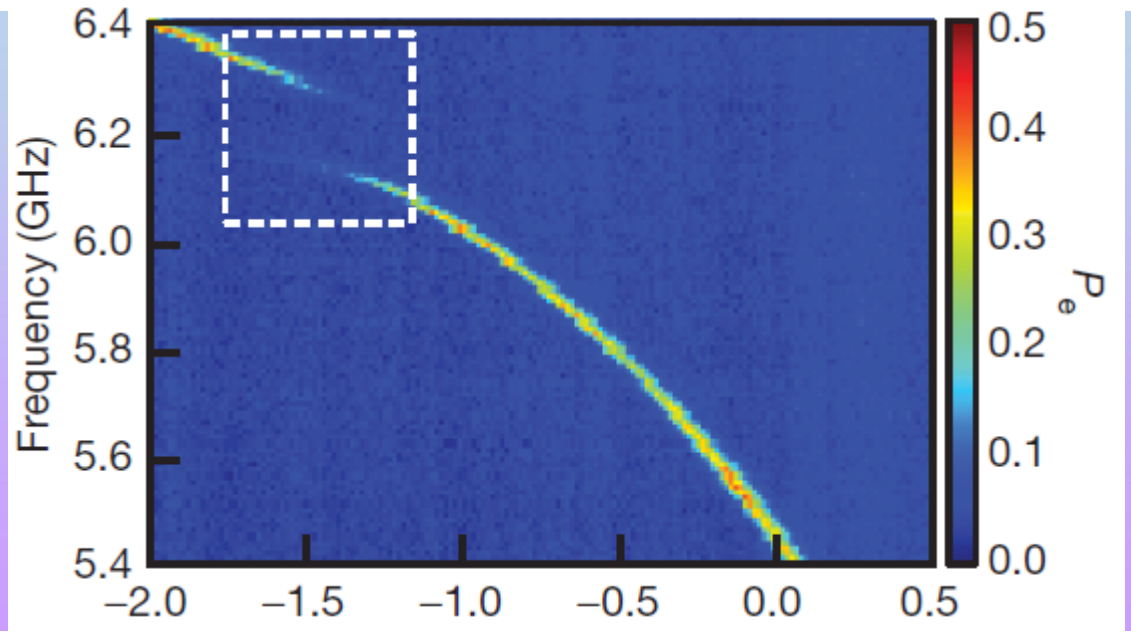


High-frequency mechanical oscillations?

$\omega_0=(\pi/L)\sqrt{(G/\rho)}$, [flexural $\sqrt{(E/\rho)}(2\pi/L)(R/L)$]

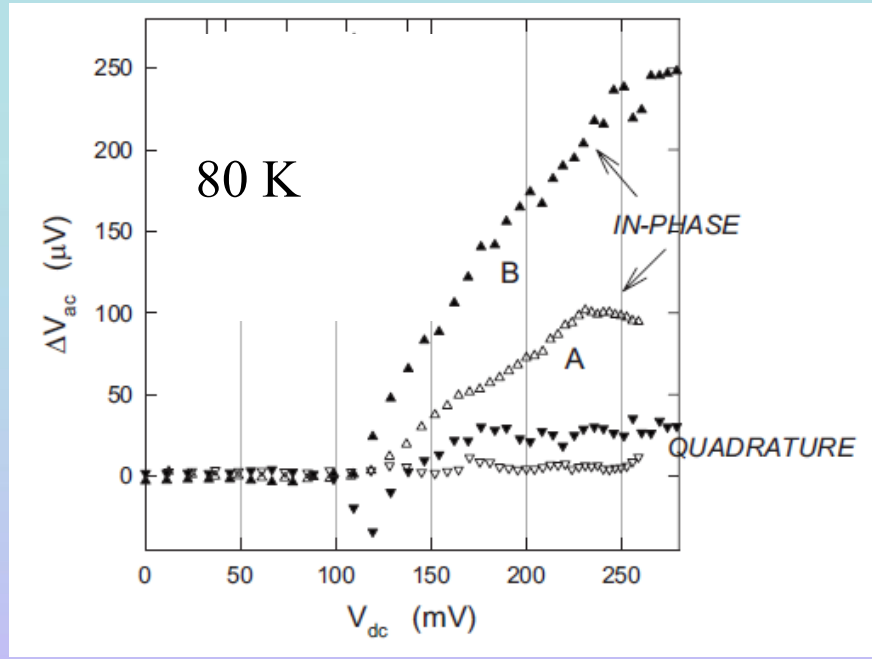
L – sample length, G - shear modulus, ρ – density.

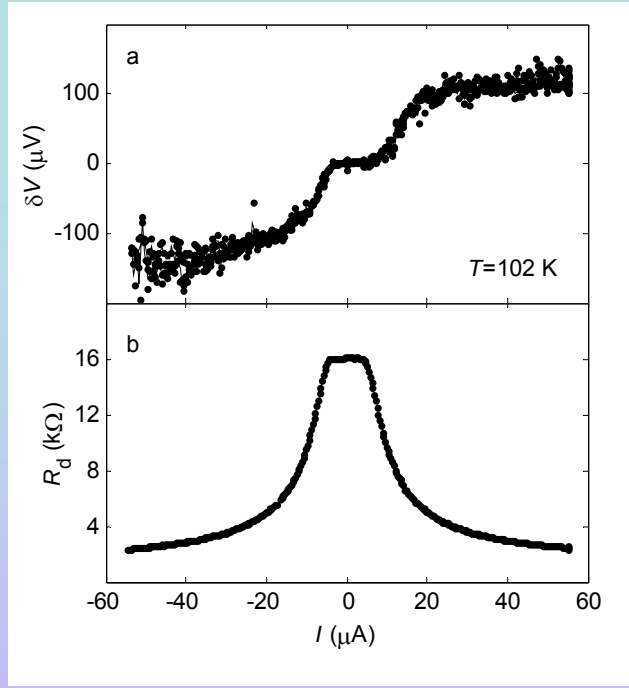
TaS_3: G=5 GPa, $\rho=6.4\cdot10^3$ kg/m^3, L=1 μm $\Rightarrow$ $\omega_0=2.8$ s^{-1}.



Из [A. D. O'Connell et al., "Quantum ground state and single-phonon control of a mechanical resonator", Nat. **464**, 697 (2010)]

Tortional modulation of the CDW conductivity



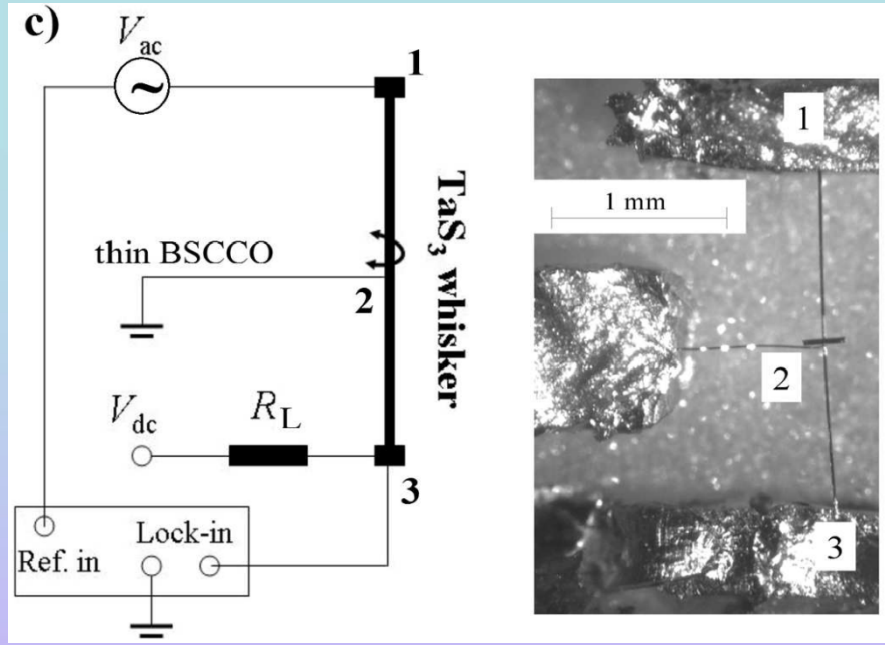


Ac voltage across a TaS_3 sample induced by modulation of torsional angle. f=10 Гц.
[J. Nickols et al., PRB 79, 241110R (2009)]

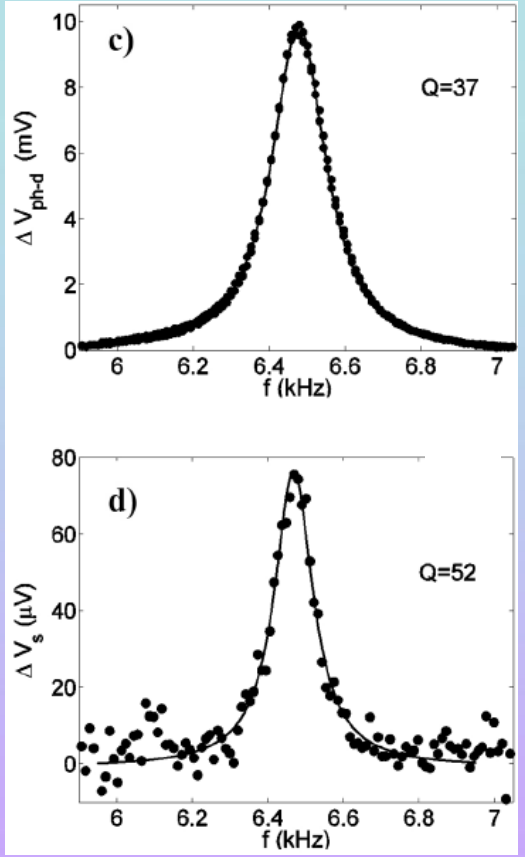
a) Ac voltage across a TaS_3 sample induced by modulation of torsional angle. f=3 Гц, amplitude 4°, L= 3 mm. b) R_d vs I at the same conditiond [V.Ya. Pokrovskii et al., Physics Uspekhi].

$(\delta V/V)/G$~1-10 ⇒
a good sensor=> self-detection

Tortional modulation of the CDW conductivity



An arrangement for observation of torsional oscillations. The electric scheme providing the feedback is shown. AC voltage is applied across 1-2, dc current is set betwee 3-2. In the resonance modes the lock-in detects torsional modulation of V_{32}.
V.Ya. Pokrovskii and S.G. Zybtsev, Cond-mat/07082694 (2007)



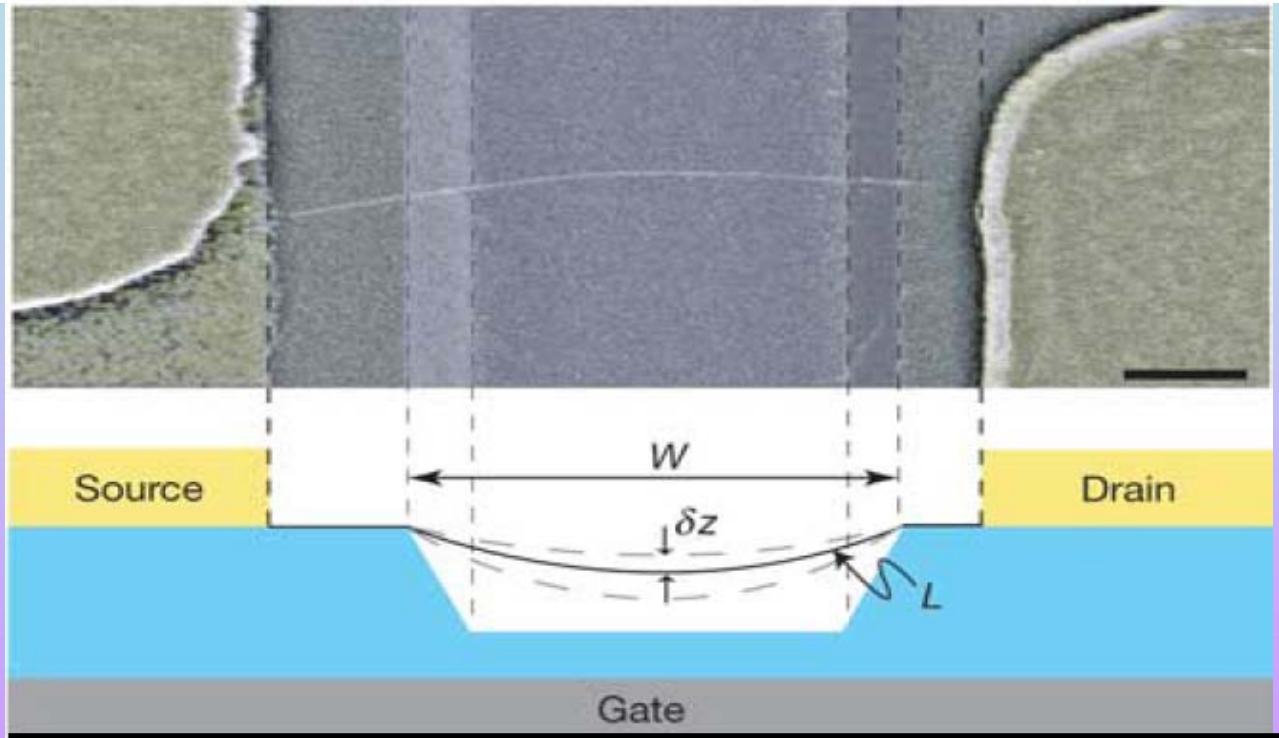
Resonance peaks detected with the lock-in technique. (c,d) – signal from the photodiode and V_{32} under identical conditions

Detection of mechanical resonance with heterodine mixing–allows 2-probe detection!

No f limitations

$$I = V \times \sigma =$$

$$V_0\cos(\omega t)\sigma_0(1+\delta\varphi_0\Pi\cos(\omega t+\Phi)) = V_0\sigma_0(\cos(\omega t)+\delta\varphi_0\Pi\cos(2\omega t+\Phi)/2+\boxed{\delta\varphi_0\Pi\cos(\Phi)/2})$$



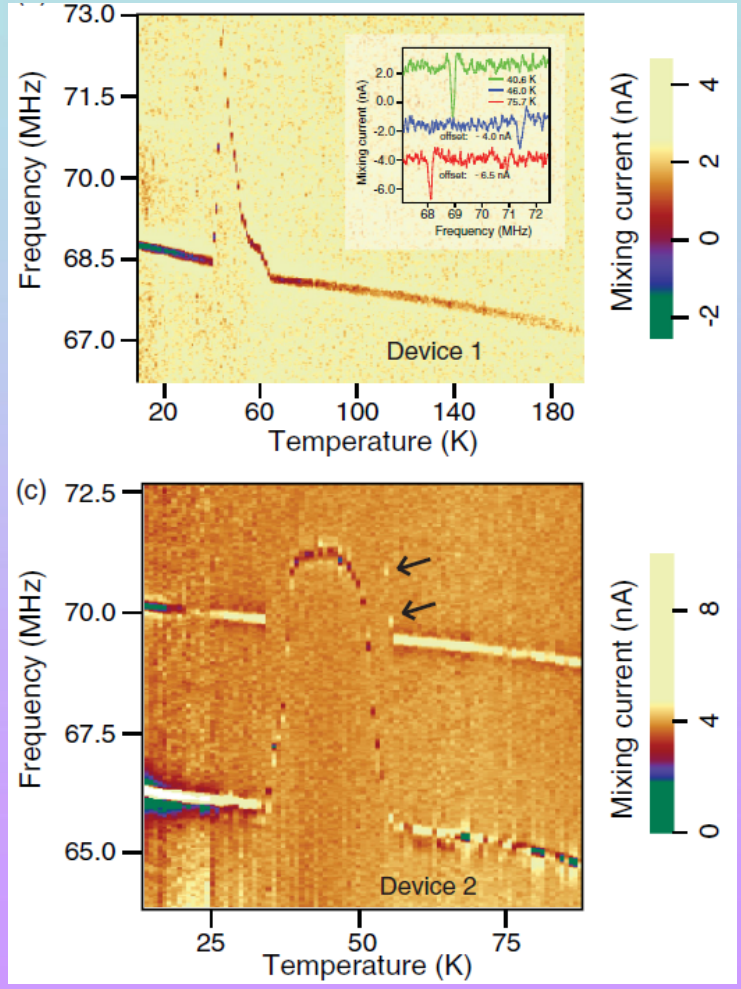
$(\Pi \equiv (\delta\sigma/\sigma)/\delta z$
or
$\Pi \equiv (\delta\sigma/\sigma)/\delta\varphi)$

Sazonova V., Yaish Y., Ustunel H. et al. // Nature 2004. V. 431. P. 284-287.

J. Chaste et al., APL 99, 213502 (2011); 4.2 GHz & 11 GHz

Detection of mechanical resonance with heterodine mixing

- elastic anomaly in $NbSe_3$

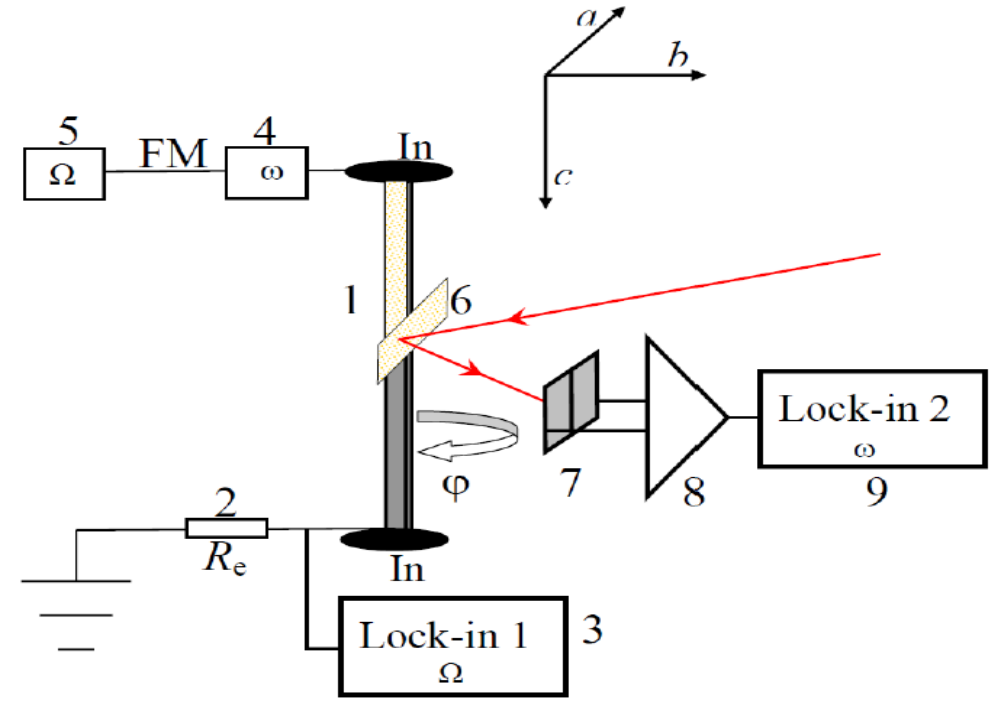


Shamashis Sengupta et al., PRL **110**, 166403 (2013)

Growth of Young modulus by 13%!!
CDW plasmon mode?

Detection of torsional resonances in TaS_3 with heterodine mixing

1) Torsional modes are excited.
2) The oscillations are excited not with a gate, but with intrinsic for CDW forces
3) Current is modulated not due to field effect, but due to intrinsic CDW current modulation



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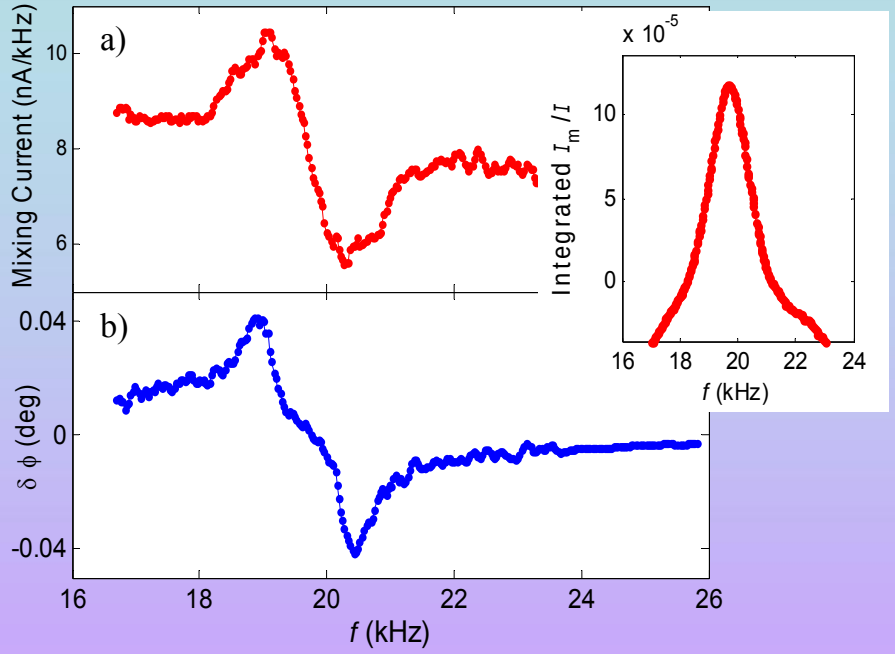
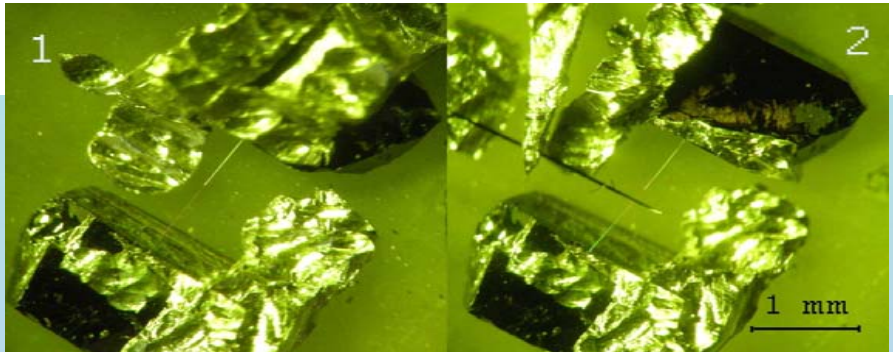
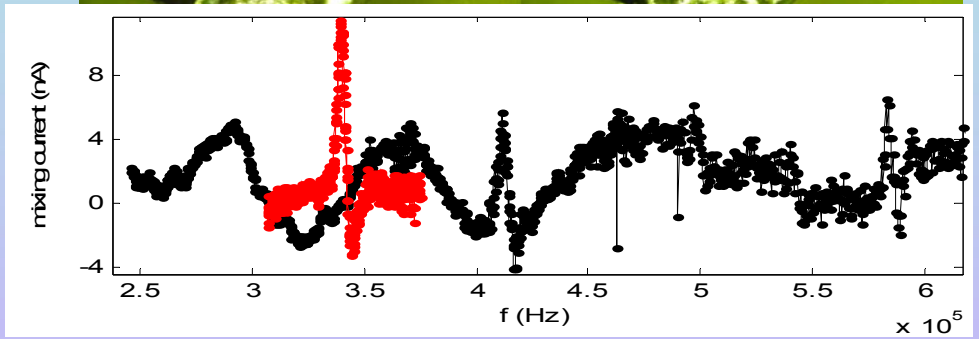
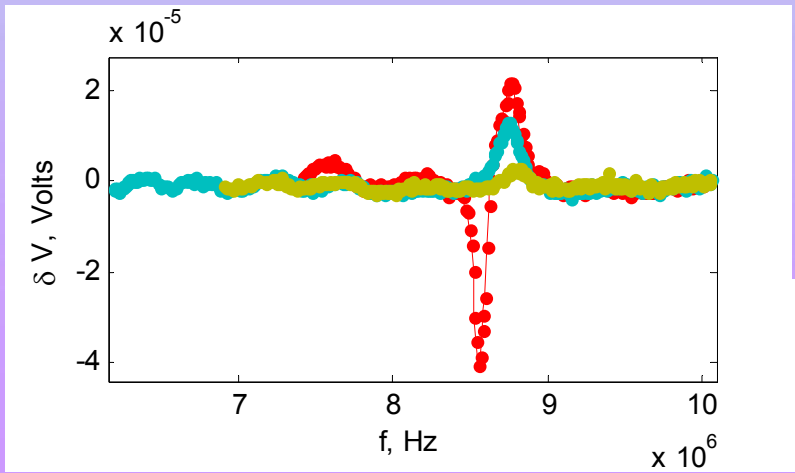


Signals from Lock-in 1 (translated in nA/kHz) (a) and lock-in 2 (in degrees), (b) as a function of *f*, detected simultaneously. The **inset:** integrated and normalized signal from Lock-in 1. The sample: *L*=1.1 mm, w=6.4 μm. *T*=96 K

Detection of torsional resonances in TaS_3 with heterodine mixing – *f* increase?

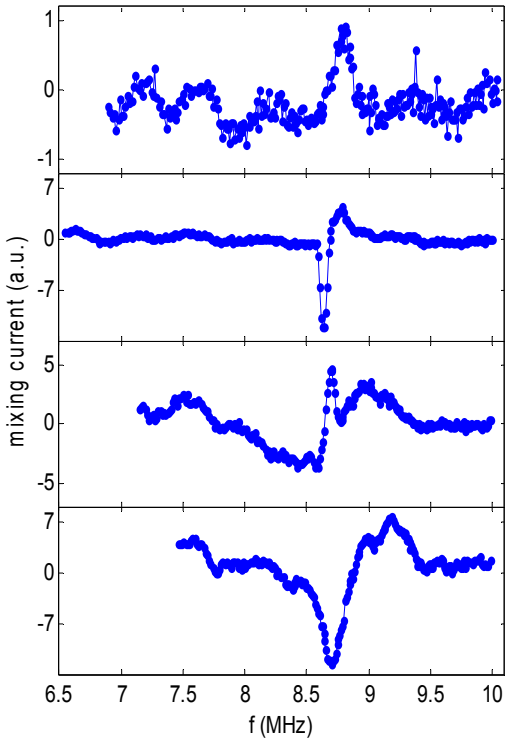




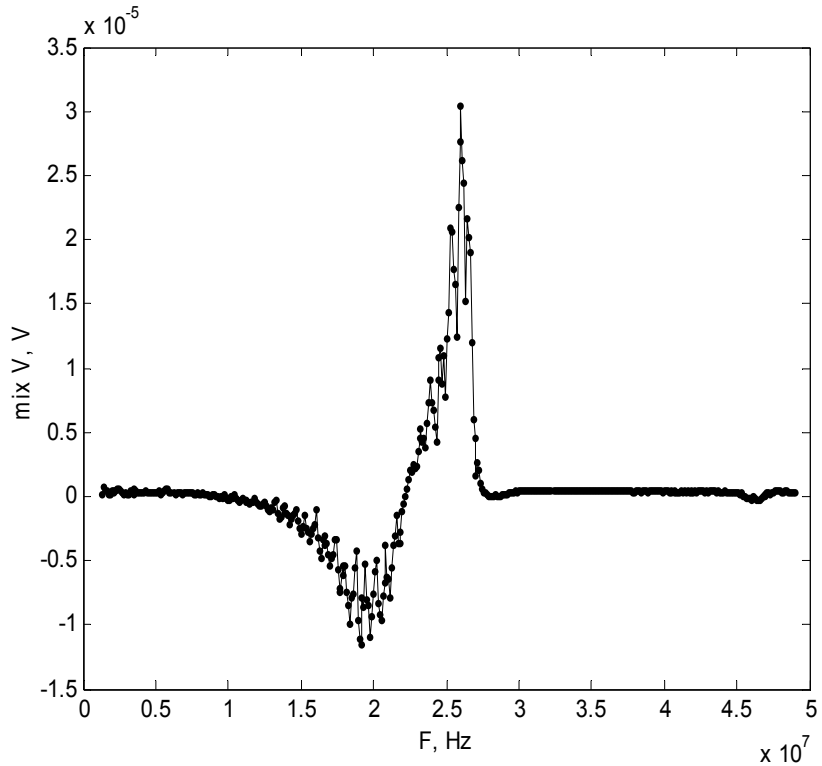


Signal at V=±150,180,260 mV.
L=161 μm, *w*=4 μm. *T*=105 K.
Without mirrors

Detection of torsional resonances in TaS_3 with heterodine mixing – *f* increase?



Frequency dependencies of the mixing current at several amplitudes of ac. voltage across the sample: V=±150, 230, 300 and 490 mV (the bottom panel). *L*=161 μm, *w*=4 μm. *T*=105 K.



The physical ground: the electron transitions in sulphides

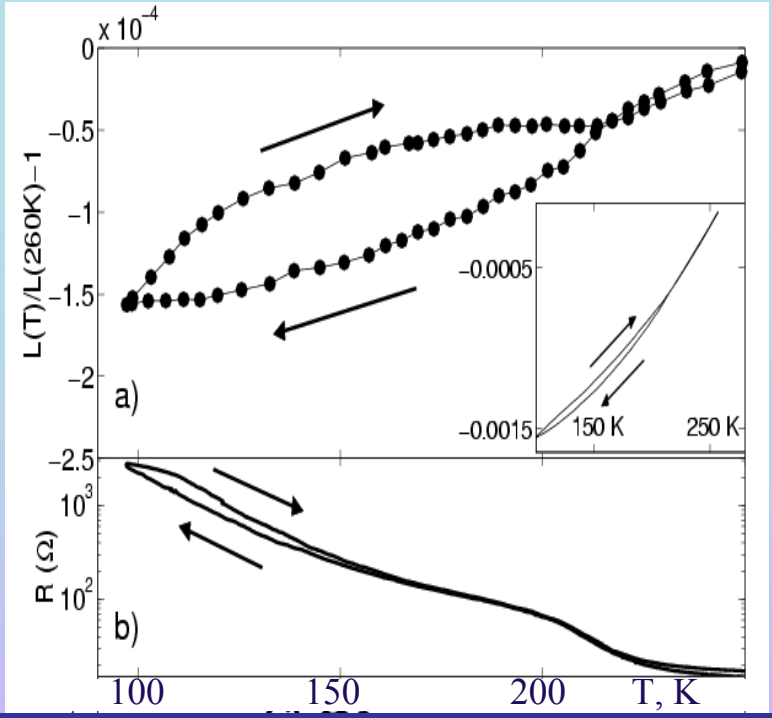
$\Delta\lambda(c)/\lambda \neq \Delta L/L \ (\equiv \Delta c/c)$

The most probable reason: dependence of k_F on deformation. A slight change in S-S distance can result in a notable change of free carriers concentration. In [Meerschaut & Rouxel, in Crystal Chemistry and Properties of Materials with Quasi-One-Dimensional Structures, 205-279. J. Rouxel (ed.) © 1986 by D. Reidel Publishing Company] it is emphasized that in MX_3 "**a lengthening of the X-X pair corresponds to a weakening of the X-X bond. The X-X pair behaves as an electron reservoir, which governs indirectly the electronic density available along the metallic chains.**" The X-X pairs may be bonded with each other or only with the M atom. The general formula of MX_3: $M_x^{4+}M_{(2-x)}^{5+}(X_2)^{2-}_{x/2+1}X^{2-}_{4-x}$, with the x value very uncertain. But x governs the electron concentration. Its variation changes k_F and, thus $q=2k_F$.

Charge disproportionation?

The simplest case:

uniaxial expansion under uniform CDW strain.

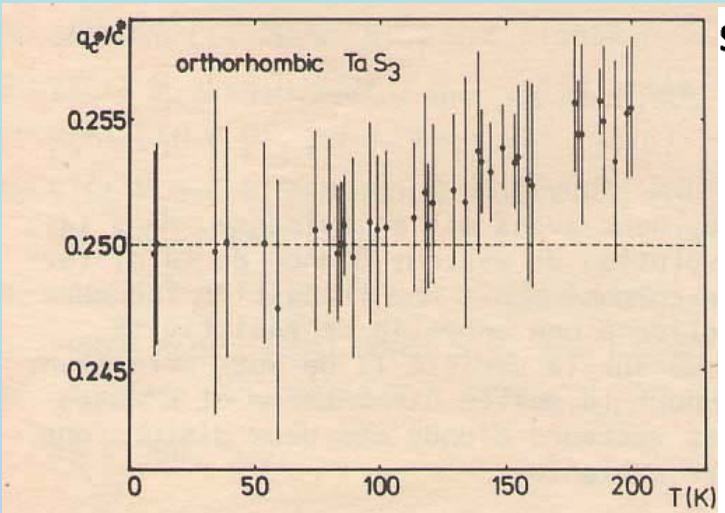


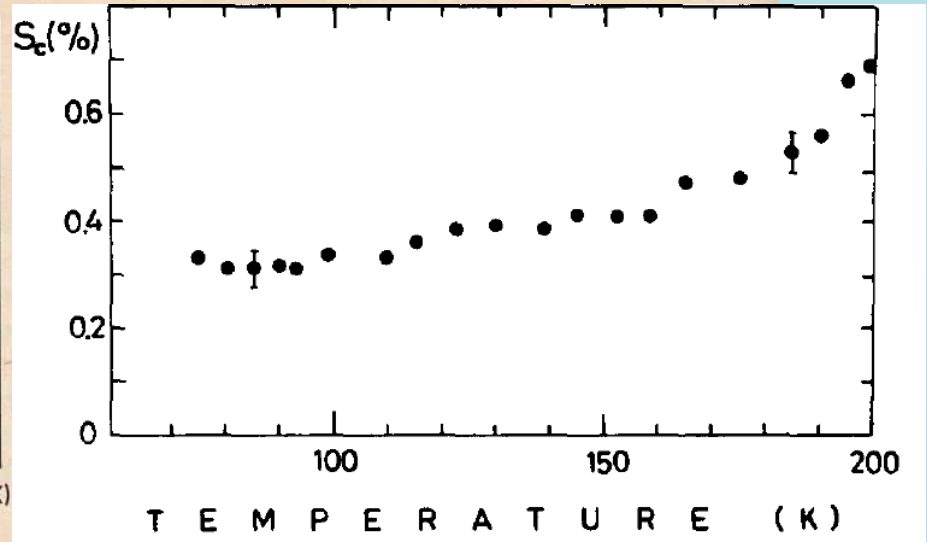
Thermally-induced deformation:

A.V. Golovnya, V.Ya. Pokrovskii,
P.M. Shadrin,
Phys. Rev. Lett. **88**, 246401 (2002).

$\Delta L/L \sim 6 \cdot 10^{-5}$

Experimental ideas: how to estimate $(\Delta\lambda(c)/\lambda)/(\Delta c/c)$?





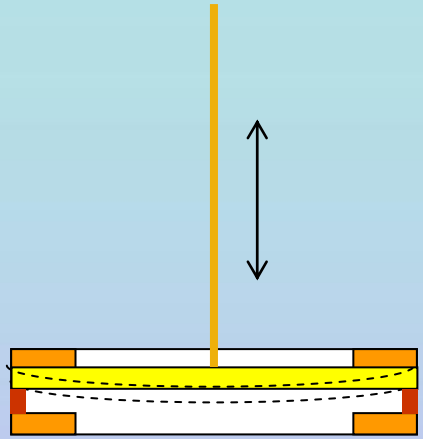
FIGURES 1 – Variation of the component of the distortion wave vector $\vec{q}$ along the directions b and c* as a function of the temperature measured on the sample holder. The star is the result obtained in ref. 1.*

Z. Z. Wang, H. Salva, P. Monceau, M. Renard, C. Roucau, R. Ayroles, F. Levy, L. Guemas, and A. Meerschaut, J. Phys. (Paris), Lett. **44**, L315 (1983).

V. B. Preobrazhensky, A. N. Taldenkov, and I. Yu. Kal'nova, JETP Lett. **40**, 944 (1984).
Kanta Das, M. Chung, M. J. Skove, and G. X. Tessema, Phys. Rev. B 52, 7915 (1995).

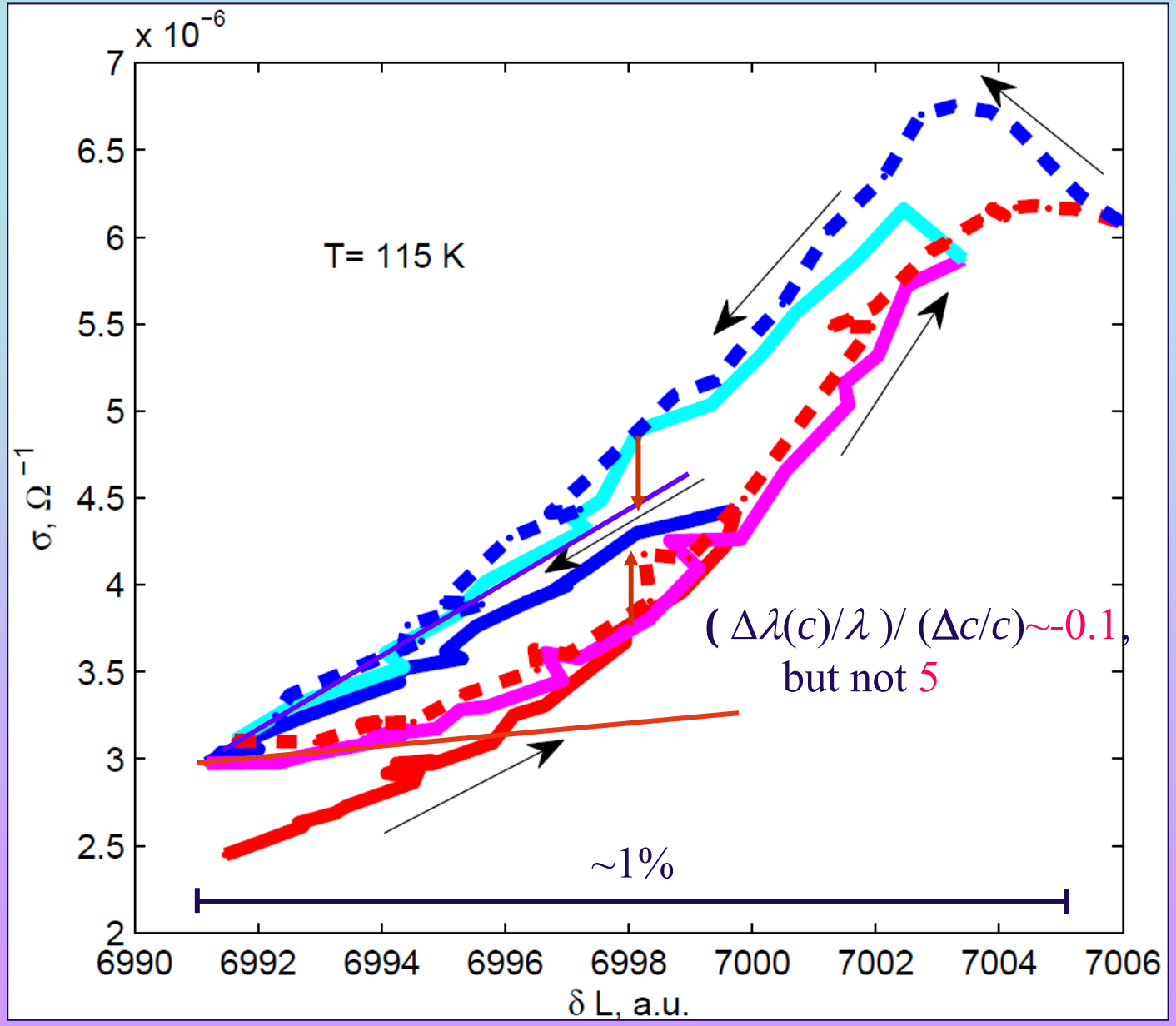
Connecting $L(q)$ with $q(\varepsilon)$ through the Le Chatelier principle

How to estimate ($\Delta\lambda(c)/\lambda$)/ ($\Delta c/c$)? – **σ(ε) dependence**.



$$\varepsilon \approx \delta y \cdot t/L^2$$

How to estimate ($\Delta\lambda(c)/\lambda$)/ ($\Delta c/c$)? – σ(ε) dependence.



The conclusions

1) A number of CDW conductors in the Peierls state show unique electromechanical properties.
2) CDW strains result in the sample deformations. TS is the most studied.
3) Large "torsioresistance" observed for $E \gg E_t$ allows self-detection of torsional oscillations of TaS_3.
4) The mixing technique with FM allows 2-probe detection of torsional resonances.
5) The frequencies achieved (25 MHz) are already comparable with plasma ones and promising for search of elastic anomalies.
6) Shortening samples results in frequency growth $\propto 1/L$. GHz range?
7) The anomalous electromechanical properties of the CDW conductors can be treated in terms of elastic lattice-CDW interaction, which can be strong due to electron transitions between bounded and conducting states governed by strain-induced S atoms rearrangements. However, the picture could be more complex.
8) Direct structural studies (at LT, under strain) are required to reveal the structural and charge changes.