Nanomechanics with correlated systems

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Abstract:
Nanomechanical resonators refer to suspended structures resembling a 'clamped beam' realized from nanomaterials (e.g. nanowires, nanotubes, ultrathin films). The natural frequency of resonance of these systems provides information regarding the elastic modulus and uniaxial strain of the resonator. This is particularly interesting when the nanomaterial involved has a phase transition accompanied by a structural change, allowing the transition characteristics to be probed by observation of the mechanical resonance of the device. We discuss two experiments - with nanowires of $NbSe_3$ (having a charge-density wave transition) and VO_2 (having a metal-insulator transition). In $NbSe_3$, we observe a large peak (12.8% change) in the elastic modulus as a function of temperature in the CDW phase resulting from the interaction between the lattice and the CDW. In VO_2, we track the evolution of the strained nanowire across the metal-insulator transition and observe signatures of the coexistence of metal and insulator domains over a finite range of temperatures.

Details of experiment:

$NbSe_3$ has a quasi-one-dimensional crystal structure and develops a charge density wave (CDW) phase below a critical temperature T_c = 60 K, when the electron density varies sinusoidally along the length of the crystal and the lattice develops a periodic distortion. We intended to probe the interaction between the CDW and the lattice by observing the elastic response of the system. The potential imposed by the CDW on the lattice would alter the phonon frequencies and this is expected to manifest itself as a change in the elastic modulus when observed as a function of temperature across the phase transition. The length of the nanowires in our experiment was comparable to the CDW phase coherence length (and the two lateral dimensions much shorter than the coherence length).

The devices were fabricated in the geometry of suspended nanomechanical resonators. The nanowire is clamped at two ends by metallic contacts and resembles a 'vibrating string' with a characteristic resonant frequency f_0. Mechanical vibrations are actuated capacitively by an a.c. gate voltage and the mechanical oscillation is detected by the principle of heterodyne mixing. The amplitude of oscillation is monitored by measuring a low frequency current component (called the 'mixing current'). By sweeping the frequency of the driving gate voltage, we determine the resonant frequency f_0 as that corresponding to the maximum amplitude of oscillation, and it yields information about the elastic modulus E by the relation $f_0 \propto E^{1/2}$.

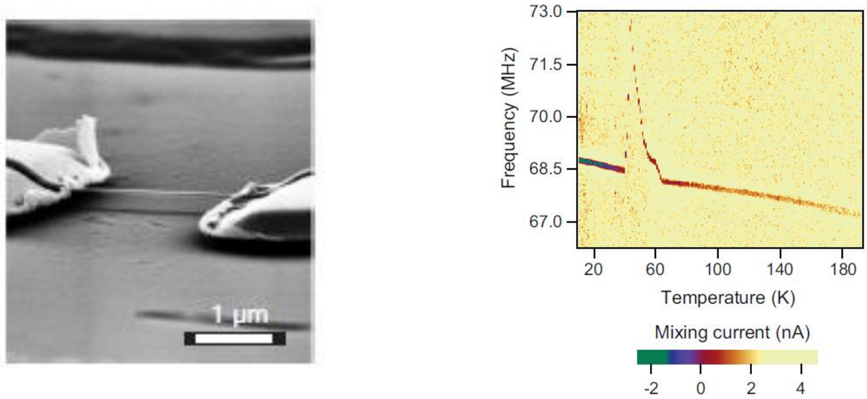

Fig. 1. (Left) Scanning electron microscope images of suspended $NbSe_3$ nanowires. (Right) Mixing current as a function of driving frequency and temperature. The CDW develops at 60 K and the sharp peak in resonant frequency at 42 K corresponds to a 12.8% change of the elastic modulus.

The key result of our experiments is that we observed a large increase in the elastic modulus (by 12.8%) at 42 K in the CDW phase. The microscopic dimensions of the nanowire allow the excited phonon frequency to be in close proximity of the plasmon mode of the CDW condensate, resulting in a dramatic influence on the elasticity of the crystal.

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We have also studied, with nanomechanical resonators, the metal-insulator transition in VO_2. A strain-free VO_2 crystal undergoes a transition from a low-temperature Mott insulating phase (monoclinic structure) to a high-temperature metallic phase (rutile structure) at 341 K. Across the phase transition from insulator to metal, the length of the crystal shrinks by 1% along the c-axis of the high-temperature phase. The phase transition temperature is largely altered in a strained crystal, when domains of both phases co-exist over a finite range of temperatures. In suspended nanobeams of VO_2, within the insulating phase at finite positive strain, we observed the coexistence of domains of M1 and M2 subphases. Above 341 K, we observe the growth of the metallic domain and the transition proceeds along the insulator-metal coexistence curve of the phase diagram manifested as a 7 MHz change in the resonant frequency. Our work demonstrates that nanomechanical resonance measurements can be effectively used to probe a wide variety of systems where the physics of correlations is important.

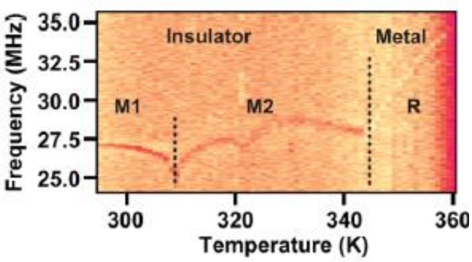

Fig. 2. The change in resonant frequency of a VO_2 resonator with temperature during the heating cycle from the insulator to the metallic phase.

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