Two-Dimensional Magnetic Nanoelectromechanical Resonators

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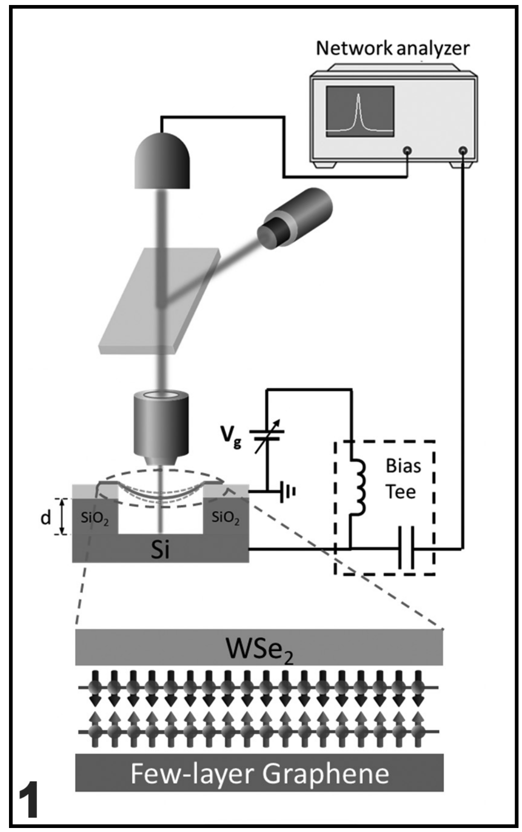
Abstract:

Two-dimensional (2D) layered materials possess out-standing mechanical, electronic and optical properties, making them ideal materials for nanoelectromechanical applications. The recent discovery of 2D magnetic materials has promised a new class of magnetically active nanoelectromechanical systems. In this project, we demonstrate resonators made of 2D magnet CrI_3, whose mechanical resonances depend on the magnetic state of the material.

Summary of Research:

Two-dimensional (2D) layered magnetic materials are attractive building blocks for nanoelectromechanical systems (NEMS): while they share high stiffness and strength and low mass with other 2D materials, they are magnetically active [1-3]. In this project, we develop magnetic NEMS resonators made of 2D chromium triiodide (CrI_3) and investigate the magnetostriction effects in the material.

Figure 1 shows the schematics of the drumhead device structure and the measurement system. The device is made of a bilayer CrI_3 membrane (an antiferromagnet) encapsulated by few-layer graphene and monolayer tungsten diselenide (WSe_2). The few-layer graphene acts as a conducting electrode, and monolayer WSe_2, as a strain gauge [4]. The heterostructure is suspended over a microtrench to form a mechanical resonator.



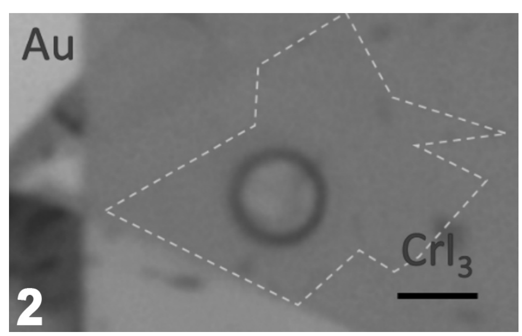


***Figure 1, top:** Schematic of the device structure and the measurement system. Filled spheres and arrows denote Cr atoms and spins in the top and bottom CrI_3 layer.*
***Figure 2, bottom:** Optical microscope image of a bilayer CrI_3 device suspended over a circular trench. Dashed line shows the boundary of the CrI_3 flake. Scale bar is 4 µm.*

Figure 2 is an optical image of a typical device. The circular microtrenches of 2-3 µm in radius and 600 nm in depth are patterned on Si/SiO_2 substrates by the combined UV photolithography and plasma etching of the SiO_2 layer. The Ti/Au electrodes are patterned on the Si/SiO_2 substrates by photolithography and metal evaporation. Atomically thin samples of CrI_3, WSe_2, and graphene are first exfoliated from their bulk crystals onto silicon substrates covered with a 300 nm thermal oxide layer. Selected thin flakes of appropriate thickness and geometry are then picked up one-by-one by a stamp consisting of a thin layer of polycarbonate on polydimethylsiloxane (PDMS). The complete heterostructure is first released onto a new PDMS substrate so that the residual PC film on the sample can be removed. The sample is then deposited onto the substrates with pre-patterned microtrench and Au electrodes.

The resonator is actuated by an R.F. voltage from a vector network analyzer (VNA) through a bias tee (Figure 1). A DC voltage V_g can be superimposed to apply static tension to the membrane. The motion is detected interferometrically by a HeNe laser, which is focused onto the center of the resonator. Figure 3 shows the fundamental resonance mode of a bilayer CrI_3 membrane at V_g = 0. It has a Lorentzian lineshape (solid line) with a peak frequency f around 25.5 MHz and a width around 10 kHz, corresponding to a quality factor of about 2500. The resonance frequency is well described by the continuum model (assuming zero bending stiffness) with fully clamped boundary [5]. It is inversely proportional to the drumhead radius, and is determined by the initial stress on the membrane and the 2D mass density of the membrane.

We investigate the effect of magnetic field on CrI_3 resonators. The nanomechanical resonance of the bilayer CrI_3 device is measured while the out-of-plane field is swept from 1 T to -1 T back to 1 T. The resonance frequency *f* is independent of field except an abrupt redshift of ~ 0.06% when the field magnitude exceeds ~ 0.5 T. We correlate the field dependence of *f* with the sample's magnetic circular dichroism. The latter shows that bilayer CrI_3 is antiferromagnetic (AF) under small fields and undergoes a first-order spin-flip transition around ± 0.5 T to become ferromagnetic (FM) [6]. The mechanical resonance frequency is thus correlated with the sample's magnetic state with the resonance frequency in the AF state larger than in the FM state. This phenomenon can be understood as exchange magnetostriction. We extract the intrinsic saturation magnetostriction in bilayer CrI_3 (10^{-5}), which is comparable to that of elemental ferromagnetic metals.

In conclusion, we have demonstrated a new type of magnetostrictive NEMS based on 2D CrI_3. Our results also establish the basis for mechanical detection of the magnetic states and magnetic phase transitions in 2D layered magnetic materials.

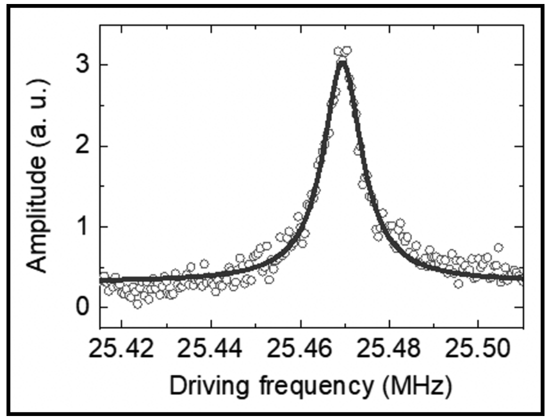


Figure 3: Fundamental mechanical resonance (symbols) of a bilayer CrI_3 resonator (radius 2 μm) and a Lorentzian fit of the resonance spectrum (solid line).

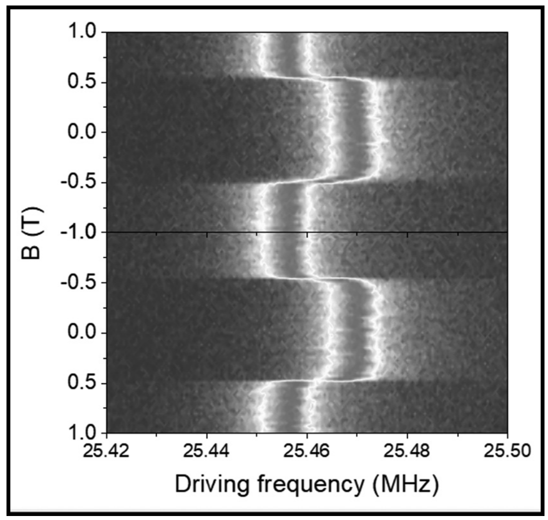


Figure 4: Normalized vibration amplitude of a bilayer CrI_3 resonator vs. driving frequency under an out of-plane magnetic field that sweeps from 1 T to -1 T to 1 T.

References:

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