# [PS2.1004] Mapping nanosecond time scale nanoelectromechanical phenomena in 2D Materials on nanometre length scale via ultrasonic and heterodyne force microscopies

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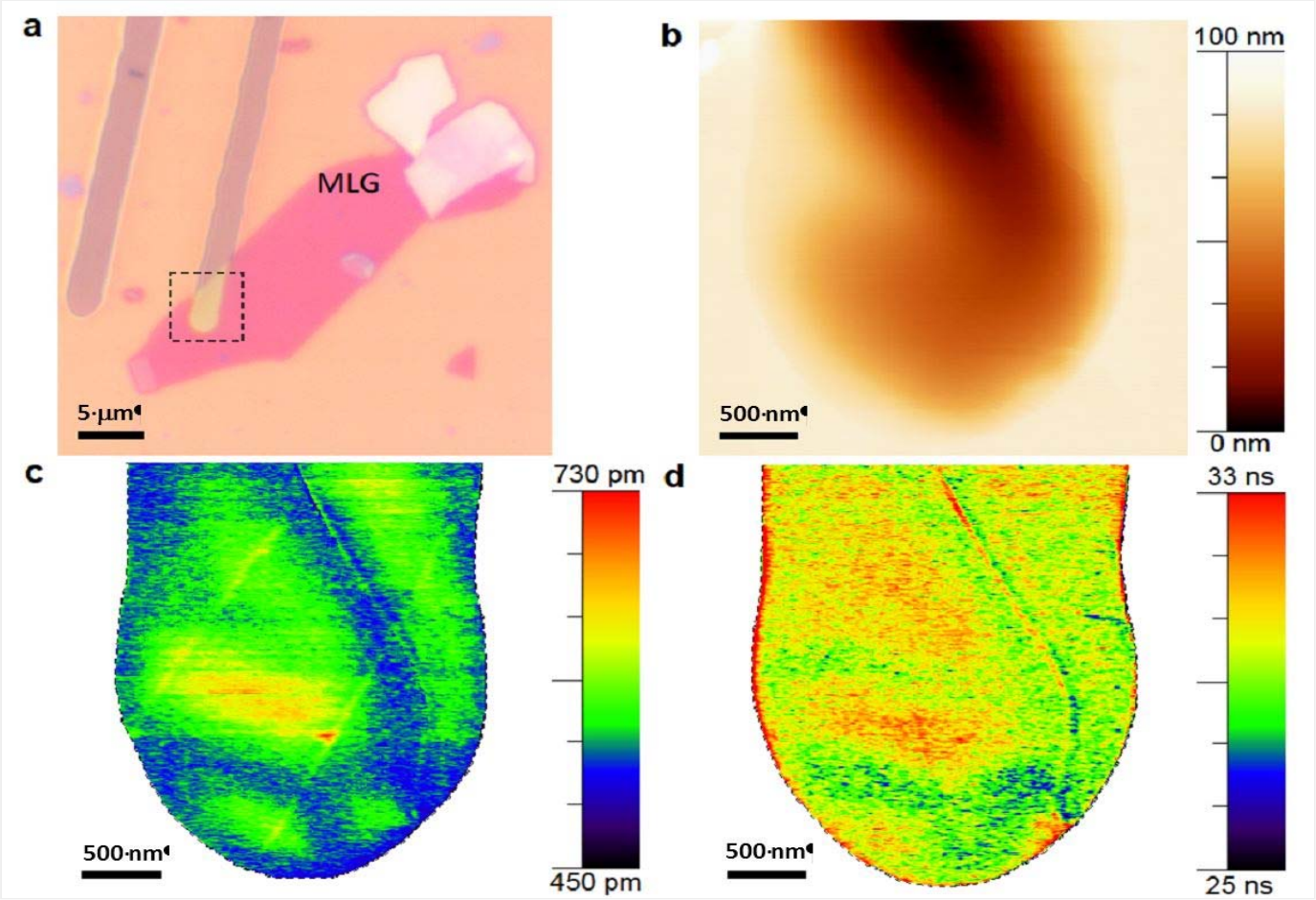
Atomically thin layers of graphene (GR) and other two-dimensional materials (2DM) such as hexagonal Boron Nitride (hBN) possess unique mechanical, electronic and thermal properties making them ideal materials for variety of nanoelectromechanical sensors (NEMS) [1].

Exploration of such 2DM NEMS requires both ultimate resolution approaching atomic scale as well as ability to explore short time scale phenomena in such devices. Here we explore 2DM nanostructures using combination of scanning probe microscopy (SPM), ultrasonic vibrations and electrostatic interactions that reveal key nanomechanical and nanoelectromechanical properties of 2DM essential for the systems where the atomically thin layers are subjected to the flexural and normal stresses and electrical fields [2].

We use quantitative analysis of the stress field generated by the SPM probe vibrated at the ultrasonic frequencies in the 2DM's and show that in these elastically transversely isotropic materials, a stress propagation of the 2DM and it heterostructures is directly governed by the ratio of the out-of-plane Young modulus and the in-plane shear modulus. This shows direct proof of "ultrasonic transparency" of few layer graphene and MoS2 observed in ultrasonic force microscope (UFM) and allows to observe defects and structures under immediate surface of such materials [3].

We demonstrate that anisotropic properties of 2DMs allow exploration of local electrostatic interactions between the material and the substrate via nanomechanical actuation, revealing and mapping with nanoscale resolution the charges hidden under the layers of such materials. We then use nonlinear detection of nanoelectromechanical actuation via heterodyne force microscopy (HFM) [4] allowing to port the phase and amplitude of the high frequency vibration to kHz frequencies easily detected by atomic force microscopy. This allowed us to detect vibrations in 2DM NEMS with pm vertical resolution, and ps time-scale sensitivity. Significantly, the charges hidden between the 2D materials and substrate interface can be revealed due to resulting electromechanical actuation of such material.




(https://www5.shocklogic.com/Client_Data/RMS/al/MMC2017/upload/IRMS-MMC2017-37078931-Fig1.JPG)

Figure 1. **E-HFM mapping of the amplitude and time-domain response of a multi-layer graphene (MLG) flake. a** Optical microscopy image of the 7 nm thick MLG sample studied with the area of interest (dashed box), scale bar 5 µm. **b** AFM topography of the suspended region taken simultaneously to images **c** and **d** with a set force of 0 nN. **c** Amplitude and **d** response time maps of the E-HFM electromechanical response of the flake, scale bar in b-d) is 500 nm, only the suspended region is considered in **c** and **d** and an artificial white background is applied.

In summary, using mechanically or electromechanically actuated ultrasonic vibrations of the sample and nonlinear and frequency down-converting methodology for detection of these vibrations the scanning probe microscopy allows and efficient and non-invasive nanoscale exploration of 2D materials, their heterostructures and devices based on such materials. We show that morphology of the interfaces, internal defects of 2DMs and charges hidden under the 2DM heterostructures can be efficiently detected. Furtehrmore, the dynamic behaviour of the electromechanical responce of such materials can be detected with the time resolution of several tens of picoseconds.

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