Dynamics of an interfacial bubble controls adhesion mechanics in a van der Waals heterostructure

L.D. Varma Sangani[1], Supriya Mandal[1], Sanat Ghosh[1], Kenji Watanabe[2], Takashi Taniguchi[3], and Mandar M. Deshmukh[1,*]

[1]Department of Condensed Matter Physics and Materials Science, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India. [2]National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan. [3]International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan.

Email: sldvarma.999@gmail.com, deshmukh@tifr.res.in

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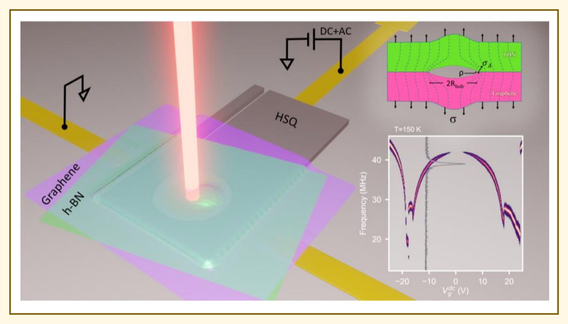
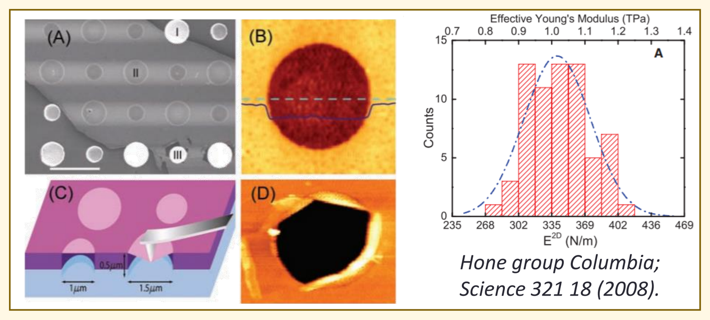
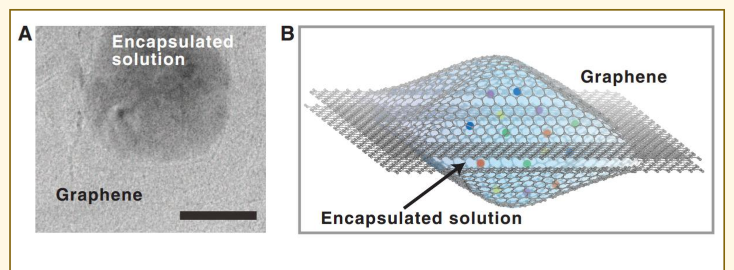
Introduction



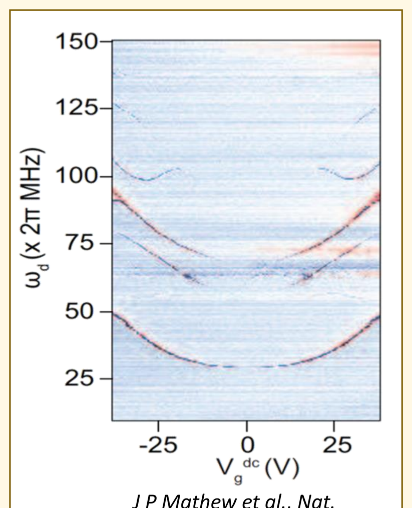


Hone group Columbia; Science 321 18 (2008).

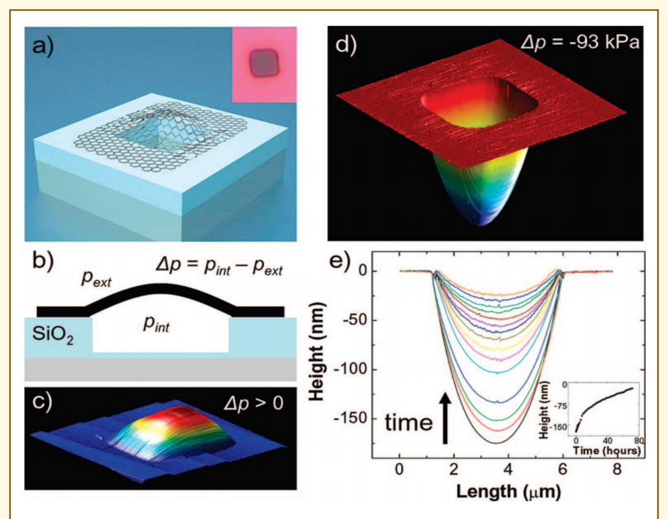


Alivisatos group Berkeley; Science, 336, 61, 2012.

- Two-dimensional (2D) material based Nano-electromechanical systems (NEMS) are remarkable due to their low mass, high strength, large tunability and impermeability to many gases.
- A wide range of NEMS with different classes of 2D materials, including graphene, hexagonal boron nitride (hBN), MoS_2, and CrI_3, have been successfully demonstrated.
- Their versatile properties are promising for gas and chemical sensors, pressure sensors, magnetic sensors, mass sensors, and switches.

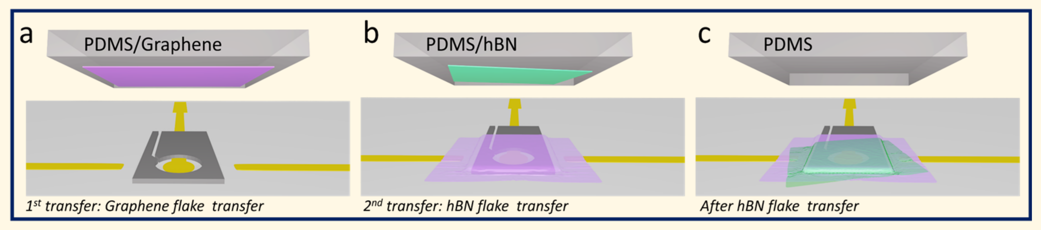


J P Mathew et al., Nat. Nanotech. **11**, 747 (2016)



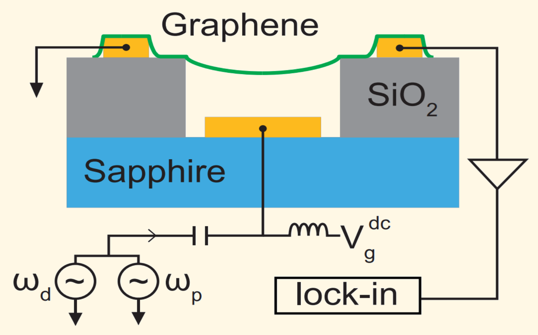
McEuen group Cornell; Nano Lett., 8 2458, 2008.

Fabrication steps of drums



- Graphene and hBN transfer using PDMS (a-c).
- Devices with no bubble (D1), few small bubbles (D2), single large bubble (D3) (d-f).

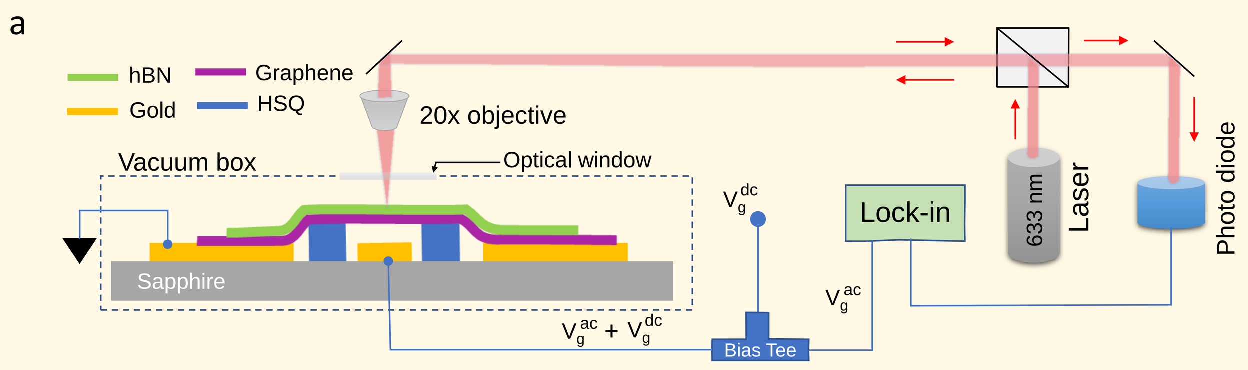
Measurement scheme



$$F_{total} = -\frac{1}{2}\frac{dC_g}{dz}(V_g^{dc} + \tilde{V}_g)^2$$
$$= -\frac{1}{2}\frac{dC_g}{dz}(V_g^{dc})^2 - \frac{dC_g}{dz}(V_g^{dc}\tilde{V}_g) - \frac{dC_g}{dz}(\tilde{V}_g)^2$$
$$\approx -\frac{1}{2}C_g'(V_g^{dc})^2 - C_g' V_g^{dc}\tilde{V}_g$$

$$I_{cap} = \frac{d}{dt}(C_g V_g) = C_g\frac{dV_g}{dt} + V_g\frac{dC_g}{dz}\frac{dz}{dt}$$

Optical detection and frequency dispersion



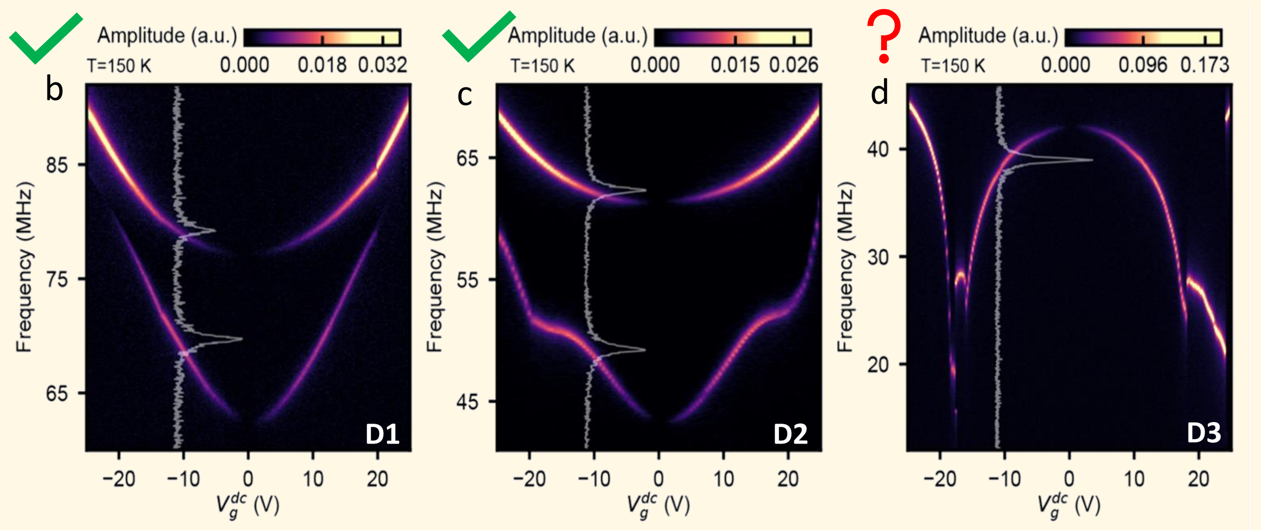
- Detection using laser interference technique.
- We choose 150 K : To avoid the phase transition of gases.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}}$$

k - Spring constant
m_{eff} - effective mass

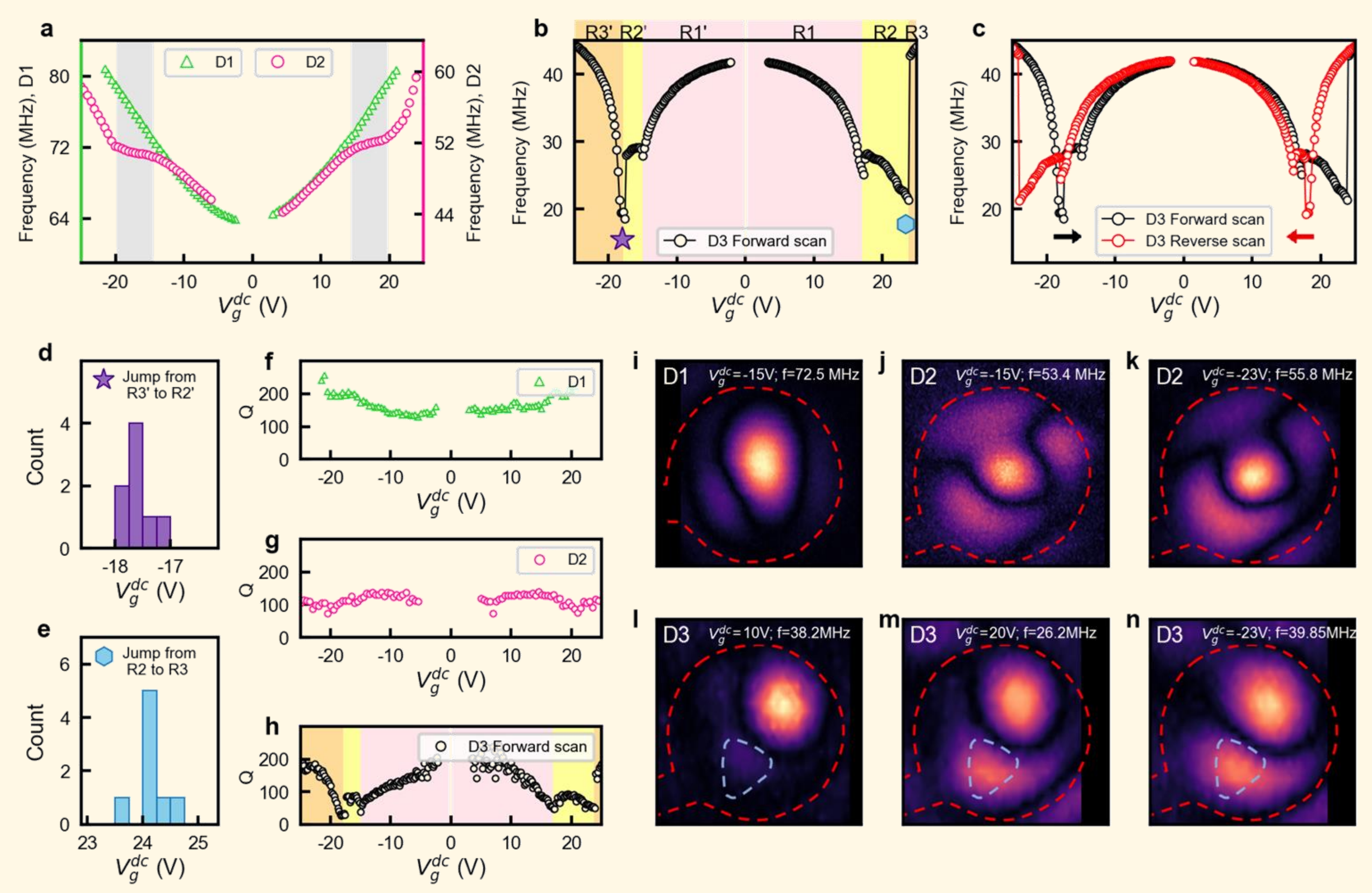
D1: Convectional drum response.
D2: Kinks in the lower mode caused by interlayer slip. *(S. Kim et. al, Nano Lett. 18, 6686 (2018))*

D3: Nontrivial negative dispersion, huge Jumps in frequency.



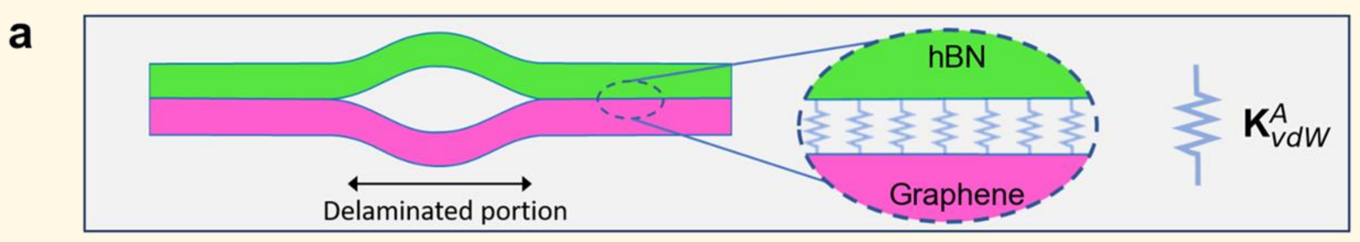
Drum without bubbles (D1) · Few small bubbles drum (D2) · Single large bubble drum (D3)

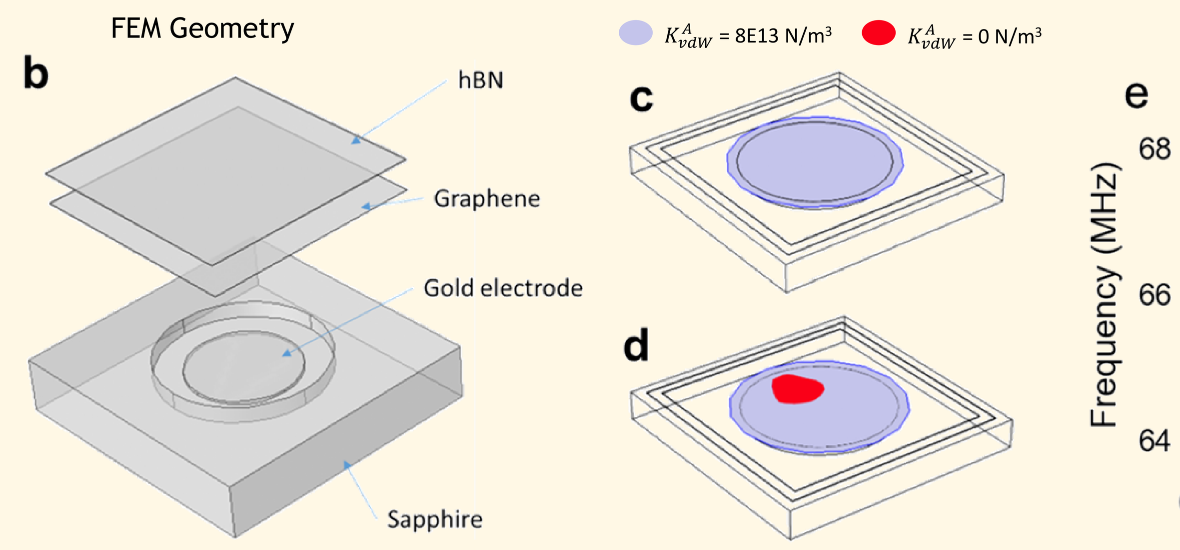
Comparison of drums with different interface conditions

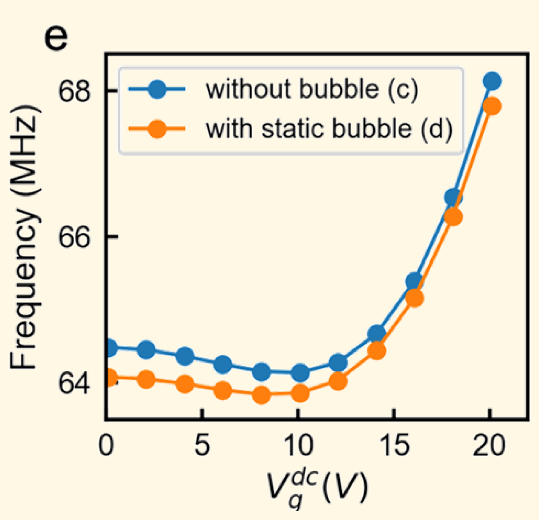


- The resonator with a single large bubble drum (D3) shows a hysteretic behaviour with nontrivially large negative dispersion (≈ 4 MHz/V) and huge frequency jumps (≈ 20 MHz) at higher gate voltages.
- Three regions (R1,R2 & R3) in the frequency response and variation of Q in corresponding areas suggests the additional dissipation pathway.
- The spatial mode map of D3 shows significant variation near the bubble region at a higher voltage.
- The above observations suggest membrane detachment and re-attachment physics at the interface of the heterostructure.

Finite element simulations (FEM) for drum with a bubble

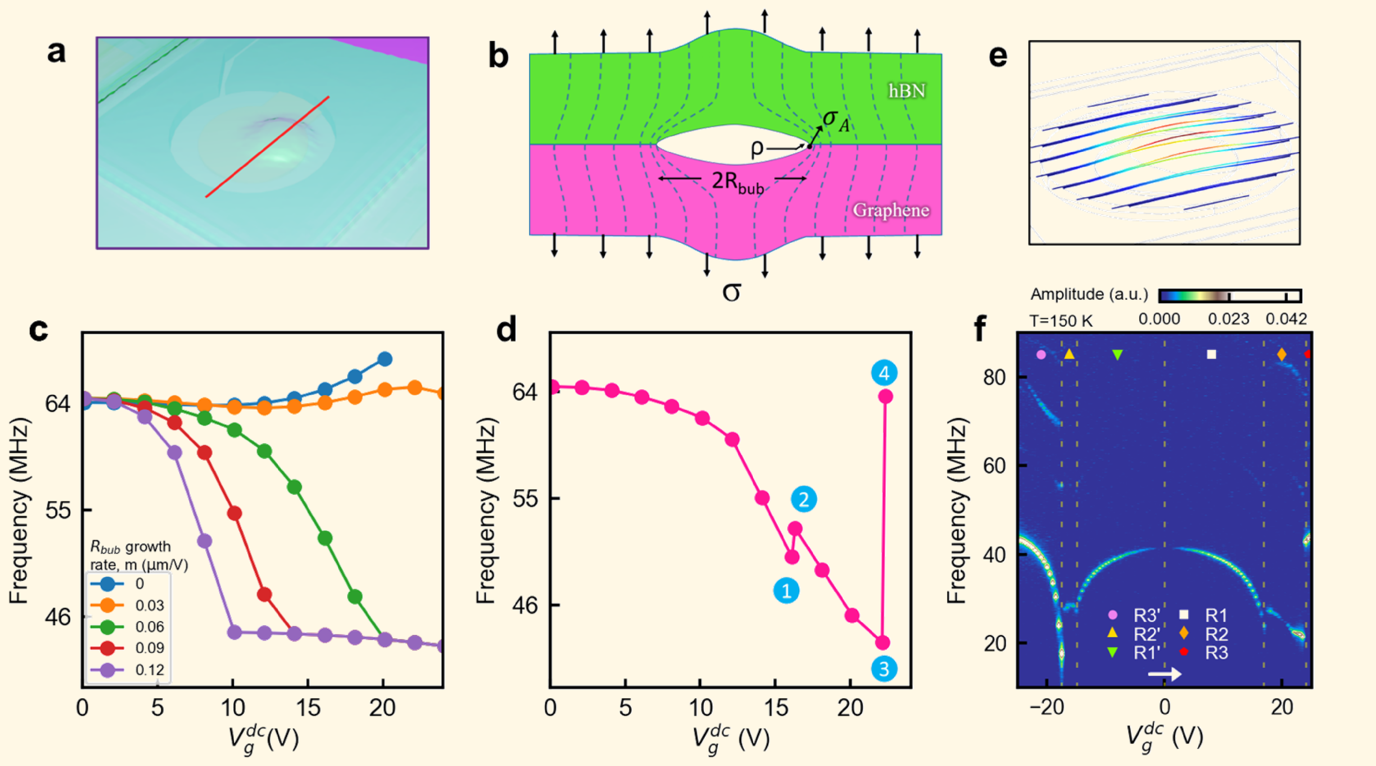






- COMSOL has been used for finite element modelling (FEM).
- Van der Waals interaction is considered as a thin elastic layer with spring constant per unit area K_{vdW}^{A}.
- FEM results suggest the mere presence of a bubble does not effect the device performance.

FEM simulations including fracture mechanics



- FEM suggests that the growth rate of the bubble, rather than its mere presence, affects the device's performance.
- Griffith's critical length → $\sigma_A = 2\sigma\sqrt{R_{bub}/\rho}$
- We see new mode emerging at higher frequencies after delamination.

Summary

- Dynamical interfacial properties including dissipation can be probed by embedding the interface in a nanomechanical device.
- Nanoscale bubbles, above a critical size, in a van der Waals heterostructure, can lead to delamination.
- Many smaller bubbles instead of a big bubble improve the fracture strength of a heterostructure.
- 2D NEMS are sensitive detectors on the internal state.
- The present work opens a way to resonant studies of nanoscale friction, fracture and delamination.
- For more details, Kindly refer to L. D. Varma Sangani et al., Nano Lett. 22, 3612 (2022)