# Quantum Optomechanical Coupling in Hexagonal Boron Nitride Membranes

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## Abstract:

**We report on the fabrication, electrostatic actuation, and optical detection of micro-mechanical resonator devices composed of a hexagonal boron nitride (hBN)/graphene membrane covering a 285 nm-deep circular hole. The mechanical resonant frequency of the fundamental mode is 11 MHz, with a *Q* factor of 2000. We also used a focused ion beam (FIB) to create defects in suspended hBN membranes and then used confocal laser-scanning microscopy to study single-photon photoluminescence from the exposed regions. By resonantly driving a membrane in which quantum emitters are embedded, we hope to take advantage of strong defect-strain coupling to explore the physics of a hybrid quantum system.**



## Summary of Research:

Solid-state single-photon sources are an essential component of emerging quantum technologies. Point defects in hBN are a bright source of single-photons at room temperature with interesting coupling to strain in the crystal. This strong coupling has been used to statically tune defect emission [1,2] and it gives hBN the potential to be used in a hybrid quantum system entangling single photons with single phonons [3].

To study the dynamic optomechanical coupling of an hBN defect to a driven membrane, we first design devices that achieve high strain through electrostatic actuation.

To fabricate these devices, we use DUV photolithography to etch a pattern of holes and trenches into $SiO_2$ and then align a second layer of patterned photoresist to evaporate Ti/Au electrodes at the top and bottom of the holes. Figure 1 shows a scanning electron micrograph of such a device before transferring the heterostructure membrane over the electrodes. After the photolithography, we use a polymer-assisted exfoliation method to transfer a multilayer hBN/graphene heterostructure over the hole such that the graphene is in contact with only the top electrodes and suspended above the bottom electrode (Figure 2). By applying voltage across the electrodes, the electrostatic force deflects the suspended membrane and the induced strain shifts the optical transition energy of defects within the hBN flake.

We detect motion of the membrane using interferometric techniques by focusing a 637 nm laser onto the center of the membrane while the device is under high vacuum ($< 10^{-5}$ Torr). When the membrane is vibrating, the optical phase difference created by

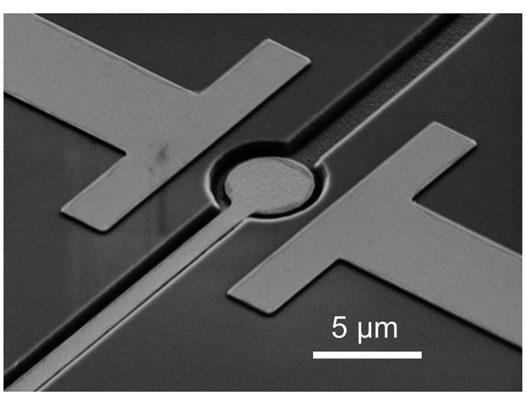


*Figure 1: SEM of the fabricated device substrate onto which the heterostructure membrane was transferred. The trenches are etched 285 nm into the $SiO_2$ substrate and a 30 nm film of Ti/Au is evaporated to define the electrodes.*

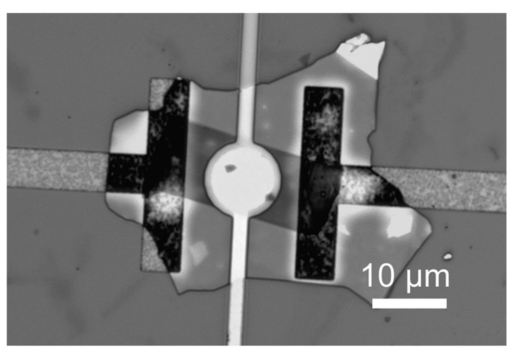


*Figure 2: Optical micrograph of a 25 nm thick hBN/graphene heterostructure membrane exfoliated onto the device substrate. (See pages vi-vii for full color version.)*

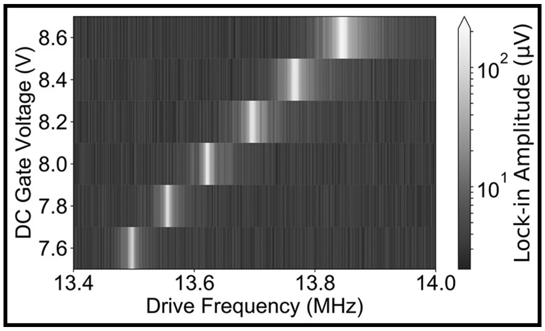


*Figure 3: Lock-in sweep data showing the mechanical resonance at varying DC offset voltages.*

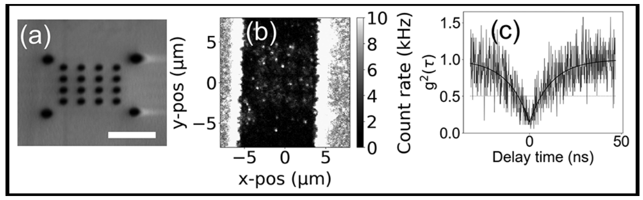


*Figure 4: a) SEM of a suspended multilayer hBN membrane, patterned with an array of circular pits milled using a gallium FIB. Scale bar is 5 μm. b) Photoluminescence map of FIB-exposed region. c) Second-order autocorrelation function of the emission from an isolated defect, fit to a two-level model. The measurement of* $g(2)(\tau = 0) < 0.5$ *indicates that the source is emitting single-photons.*

the gap between the membrane and bottom electrode fluctuates and thus so does the reflection intensity. We direct the reflected light onto a high-frequency photodiode, whose voltage is the input to a lock-in amplifier with the electrostatic drive as the reference. When we sweep the driving frequency while monitoring the lock-in signal, we detect the fundamental resonant mode at around 11 MHz. Additionally, by applying a DC offset, the static pre-tension can be used to tune the resonant frequency and improve the resonator $Q$ factor (Figure 3).

Although much progress has been made in creating optically stable defects in hBN, most methods produce emitters at random positions [4]. To integrate and couple the emitters with other structures, defects must be created with nanometer precision and reproducible properties. We have made significant progress on this front by producing arrays of quantum emitters at deterministic locations. Using a gallium FIB [5], we mill shallow circular pits 300 nm across and 5 nm deep on exfoliated hBN (Figure 4a), suspended over trenches to avoid background fluorescence induced by the substrate. We then anneal the devices for 30 minutes at 850°C in a $N_2$ environment.

Using a confocal laser-scanning microscope, we measure photoluminescence from the milled regions (Figure 4b). Upon close inspection, we observe high-purity single-photons from several defect-based emitters close to the perimeter of each milled circle. Autocorrelation statistics from one of these quantum emitters is shown in Figure 4c.

## Conclusions and Future Steps:

While driving on resonance, we will be able to scan the interferometry laser position over the entire membrane and achieve high spatial resolution of the mechanical mode. We can then infer the strain profile using a finite element model of the device. We will then create isolated point defects in the hBN using the FIB method discussed and will be able to quantify the shift in the optical transition, elucidating the potential for hBN to be used in quantum optomechanical devices.

## References:


[1] N. Mendelson, M. Doherty, M. Toth, I. Aharanovich, T. T. Tran, “Strain-Induced Modification of the Optical Characteristics of Quantum Emitters in Hexagonal Boron Nitride” Adv. Mater. 2020, 1908316 (2020).

[2] G. Grosso, H. Moon, B. Lienhard, S. Ali, D. K. Efetov, M. M. Furchi, P. Jarillo-Herrero, M. J. Ford, I. Aharonovich, and D. Englund, “Tunable and high purity room-temperature single photon emission from atomic defects in hexagonal boron nitride” Nat. Commun. 8, 705 (2016).

[3] X. Guo, Z.-Q. Yen, T. Li, “High-speed quantum transducer with a single-photon emitter in an atomically thin resonator” arXiv:1712.09245 (2017).

[4] I. H. Abidi, N. Mendelson, T. T. Tran, A. Tyagi, M. Zhuang, L. T. Weng, B. Özyilmaz, I. Aharonovich, M. Toth, Z. Luo, “Selective Defect Formation in Hexagonal Boron Nitride” Adv. Opt. Mater. 7, 1900397 (2019).

[5] J. Ziegler, R. Klaiss, A. Blaikie, D. Miller, V. R. Horowitz, B. J. Alemán, “Deterministic Quantum Emitter Formation in Hexagonal Boron Nitride via Controlled Edge Creation” Nano Lett. 19, 3, 2121-2127 (2019).