# Mechanical Mode Imaging of a High-Q Hybrid hBN/Si<sub>3</sub>N<sub>4</sub> Resonator

David Jaeger, Francesco Fogliano, Thibaud Ruelle, Aris Lafranca, Floris Braakman, and Martino Poggio\*

**Cite This:** *Nano Lett.* 2023, 23, 2016–2022



ACCESS	III Metrics & More	Article Recommendations	51	Supporting Information

**ABSTRACT:** We image and characterize the mechanical modes of a 2D drum resonator made of hBN suspended over a high-stress  $Si_3N_4$  membrane. Our measurements demonstrate hybridization between various modes of the hBN resonator and those of the  $Si_3N_4$  membrane. The measured resonance frequencies and spatial profiles of the modes are consistent with finite-element simulations based on idealized geometry. Spectra of the thermal motion reveal that, depending on the degree of hybridization with modes of the heavier and higher-quality-factor  $Si_3N_4$  membrane, the quality factors and the motional mass of the hBN drum modes can be shifted by orders of magnitude. This effect could be exploited to engineer hybrid drum/membrane modes that combine the low motional



mass of 2D materials with the high quality factor of  $Si_3N_4$  membranes for optomechanical or sensing applications.

**KEYWORDS:** hexagonal boron nitride, mode imaging, 2D materials, nanomechanical resonators

wo-dimensional materials enable the fabrication of nanomechanical resonators with high aspect ratios, very low mass, and high resonance frequencies.<sup>1-5</sup> They have remarkable mechanical properties, such as extremely high fracture strength and Young's modulus.<sup>6</sup> A wide variety of 2D materials are now the subject of large research efforts due to their unique electronic,<sup>7,8</sup> magnetic,<sup>9,10</sup> and optical<sup>11,12</sup> features as well as the potential to combine these materials in layered heterostructures.<sup>13</sup> Hexagonal boron nitride (hBN) is known to have comparable mechanical properties to graphene,<sup>14</sup> but in contrast to graphene and other 2D materials, it has a large band gap of almost 6 eV,<sup>15</sup> making it a transparent insulator with low absorption in the visible and near-infrared ranges.<sup>16</sup> hBN has also been shown to host bright and stable quantum emitters,<sup>17</sup> which are strain-coupled to the motion of the crystal lattice.<sup>18,19</sup> These properties make hBN a prime candidate for optomechanical devices and integration into high-finesse optical cavities.<sup>20</sup>

Most devices based on suspended flakes of 2D materials are fabricated by direct exfoliation<sup>1,21</sup> or dry stamping onto a prepatterned substrate.<sup>22</sup> Due to the thickness of the substrate and the fact that there is usually no optical access from both sides, these samples are not suitable for integration with microscale optical cavities in the membrane-in-the-middle (MIM) configuration.<sup>23–25</sup> In addition, mechanical mode imaging on such devices has revealed that these transfer techniques have a deleterious effect on the mode shapes and potentially on the mechanical properties of the resonators due to the inhomogeneous stress they impart to the flake.<sup>2,26,27</sup> Aside from degrading the overall performance of the devices and their reproducibility, this is also problematic for sensing implementations that require calibrated mode shapes.<sup>26</sup> Suspended devices made from 2D materials grown by chemical vapor deposition are fabricated with wet transfer techniques,<sup>28</sup> but they usually exhibit many folds, cracks, or other imperfections that affect the resulting mechanical resonators to a similar degree.<sup>29,30</sup>

In this work, we employ a wet transfer technique to fabricate devices from exfoliated flakes of hBN (Figure 1 (a)), which are placed on top of holes in  $Si_3N_4$  membranes, resulting in thin devices with optical access from both sides (Figure 1 (b)). We characterize such an hBN/Si<sub>3</sub>N<sub>4</sub> mechanical resonator by recording thermal mode spectra as well as detailed spatial mode shapes. We find that the mode shapes match well with COMSOL Multiphysics simulations based on idealized geometries. Finally, we explore how hybridization between the mechanical modes of the  $Si_3N_4$  membrane and of the hBN drum affects the mechanical properties of the latter.

While hybridization between 2D material resonators and underlying  $Si_3N_4$  membranes has been observed before,<sup>31,32</sup> here we focus on changes in the quality factor (Q) and effective mass ( $m^*$ ). In our case, the underlying  $Si_3N_4$ membrane has a much higher Q than that of the hBN drum. This results in hybridization where the  $Si_3N_4$  membrane lends its mechanical properties to the modes of the hBN drum, which could be useful for sensing applications<sup>31,33,34</sup> and the engineering of functionalized mechanical systems.

Our device fabrication starts with exfoliated hBN flakes (hqgraphene) on a Si/SiO<sub>2</sub> substrate with a 300 nm oxide layer. hBN offers a poor optical contrast when on PDMS, which is typically used in stamping techniques.<sup>35</sup> However, when on a

Received:January 18, 2023Revised:February 14, 2023Published:February 27, 2023







**Figure 1.** (a) Sample fabrication procedure. hBN flakes are exfoliated onto  $Si/SiO_2$  substrates and then spin-coated with PMMA in step 1. In step 2, the oxide layer is removed, releasing the PMMA layer with embedded hBN flakes. In step 3, this PMMA layer is brought into contact with the  $Si_3N_4$  membrane, producing an hBN drum resonator. Finally, in step 4, the PMMA is removed in a solvent clean. (b) Photograph of a finished sample. (c) AFM measurement of the area indicated by the small white rectangle in (b), giving a flake thickness of 48 nm.



Figure 2. Mode images and spectrum obtained for the sample shown in Figure 1 (b). The top row shows the measured mode images, and the second row shows mode images simulated with COMSOL. Since often more than one mode could be found with matching mode images, the modes are represented with a shaded area rather than with a specific peak in the thermal spectrum shown below. The last two mode images are beyond the frequency range of the thermal spectrum shown; therefore, no shaded area is indicated. Arrows highlight modes of the Si<sub>3</sub>N<sub>4</sub> membrane that did not hybridize with any hBN drum modes, starting with the fundamental Si<sub>3</sub>N<sub>4</sub> mode. The last row shows an example of a series of apparently identical modes in one of the shaded areas.  $m^*$ , Q, and the resonance frequency are displayed on each of the six graphs. Scale bars correspond to 10  $\mu$ m.

 $Si/SiO_2$  substrate, the flakes can be carefully evaluated and selected, making it possible to find flakes without defects, steps, or folds. The  $Si/SiO_2$  chip is then spin-coated with a layer of poly(methyl methacrylate) (PMMA), after which the oxide layer is removed in a 2 M NaOH solution. This results in a floating PMMA membrane with hBN flakes attached to its bottom surface (Figure 1 (a) steps 1 and 2). We have found that slow etching of the  $SiO_2$  at room temperature yields a smoother and cleaner PMMA membrane compared to a faster process at elevated temperatures, as is often employed. After replacing the NaOH solution with DI water in several rinsing steps, the PMMA/hBN membrane is transferred to another vessel where it floats above the target substrate. This substrate is a stoichiometric (900 MPa stress)  $Si_3N_4$  membrane (Norcada). It is 200 nm thick, has lateral dimensions of 300  $\mu$ m × 300  $\mu$ m, and features 30- $\mu$ m-diameter holes in a grid pattern. The  $Si_3N_4$  membrane is glued with Crystalbond to a metal holder so as not to float away or move during the transfer. To position the PMMA membrane on top of the  $Si_3N_4$  chip, we used a micromanipulator setup under an optical microscope. While positioning the hBN flake above the target hole in the  $Si_3N_4$  membrane, the water is slowly removed until the hBN flake settles on top of the hole (Figure 1 (a) step 3). The device is left to dry overnight, after which the PMMA is



**Figure 3.** (a) Thermal spectrum of the fundamental mode with the fit in red. *Q* and  $m^*$  extracted from this fit are shown to the right of the peak, while the inset to the left shows the expected deflection as simulated with COMSOL. The motion is confined to the hBN that covers the central hole. (b, c) *Q* and  $m^*$  as a function of the resonance frequency for all observed modes at different temperatures. The six modes shown at the bottom of Figure 2 are represented with star-shaped markers. (d) *Q* vs  $m^*$ . The dashed lines in (c) and (d) indicate  $m_{th}^*$  of hBN and Si<sub>3</sub>N<sub>4</sub>. (e) and (f) show the extracted force sensitivity vs *Q* and  $m^*$ ; the diamond-shaped markers represent the fundamental hBN mode at room temperature.

removed in acetone followed by IPA at  $50^{\circ}$  for 30 min each (Figure 1 (a) step 4). Finally, the sample is put into a UV/ ozone cleaner for 10 min to remove organic residue.

The characterization of the sample is carried out in a roomtemperature vacuum chamber (pressure  $<10^{-4}$  mbar) with optical access for a modified Michelson interferometer (ref 36.). A single-frequency diode laser (630 nm) is used to detect the motion of the hBN drum in a balanced detection scheme. We use a long-working-distance 50× objective with an NA of 0.5 (Mitutoyo G-Plan Apo 50x), giving us a spot size of around 800 nm. The length of the reference arm of the interferometer is stabilized via a feedback loop to keep the interferometer stable and at maximum sensitivity throughout the measurements. We also use this length control of the reference arm, which can cover more than the laser wavelength, as calibration to convert from units of  $(V^2/Hz)$  to  $(m^2/Hz)$ . The mechanical response is measured by exciting the sample resonantly with a piezoelectric shaker to an amplitude of a few nanometers while recording the demodulated signal with a lock-in amplifier (Zurich HF2LI). A stack of piezo scanners (Attocube ANSxy50) makes it possible to map the reflected intensity of the sample as well as to image the mechanical modes as in Figure 2.

Mode imaging is not only a tool that can give insight into the imperfections (folds, wrinkles, inhomogeneous strain, etc.) of the membrane and their effect on the mode shapes but also allows us to identify to which mode each resonance peak found in the spectrum belongs. This turns out to be particularly useful when the resonance spectrum is not well predicted by theory or, as in our case, is complicated by hybridization of the modes.

We characterized and imaged a wide array of mechanical modes visible in the thermal spectrum (Figure 2) of the sample shown in Figure 1 (b). These data give insight into the resonance spectrum and confirm that the mode shapes (first row of images in Figure 2) match the ones simulated with COMSOL (second row of images in Figure 2). We can also use the thermal spectra to characterize the mechanical properties of the modes in question, in particular, their  $m^*$ and Q. For example, the thermal spectrum recorded for the fundamental mode of the hBN drum at around 2 MHz is shown in Figure 3 (a). The theoretical effective mass  $m_{\text{th}}^*=1.89$  $\times 10^{-14}$  kg agrees with the measured  $m^* = 1.71 \times 10^{-14}$  kg. For the theoretical value, we assumed a density of hBN of  $\rho_{\rm hBN}$  = 2100 kg m<sup>-3</sup> and a ratio between  $m^*$  and geometrical mass m of  $m^*/m = 0.265$ .<sup>37</sup> The drum has a diameter of  $d = 30 \,\mu\text{m}$  and a thickness of t = 48 nm (Figure 1 (c)). To fit the thermal spectra, we use the power spectral density

$$S_{xx}(\omega) = \frac{2\Gamma k_{\rm B}T}{m^* ((\omega_0^2 - \omega^2)^2 + \Gamma^2 \omega^2)}$$
(1)

where  $\omega/2\pi$  is the frequency ( $\omega_0$  at resonance),  $\Gamma = \omega_0/Q$  is the line width, *T* is the temperature, and  $k_{\rm B}$  is the Boltzmann constant. We assume that the sample is in thermal equilibrium with the surrounding bath. The optical power ( $\sim 100 \ \mu W$ ) was chosen so as to cause a negligible shift in the resonance frequencies of the hBN drum; this was done by increasing the power until a heating effect could be observed and then reducing the power well below that point.

We measure a quality factor of Q = 6250 for the fundamental mode of the hBN drum. We are not aware of a device with higher Q at room temperature based on a 2D

Letter

material. Typically, Q factors of such devices are in the range of  $10^{1}-10^{2}$ .<sup>1,3,21,30,38,39</sup>

We often find several copies of a specific mode shape in a frequency interval, indicated by the shaded regions in Figure 2. An example of a series of such modes with observable thermal motion can be seen at the bottom of Figure 2. We attribute the presence of such copies to hybridization between an hBN drum mode and several modes of the Si<sub>3</sub>N<sub>4</sub> membrane that are close in frequency (Figure S3 (c)). We again employ COMSOL simulations to gain more insight into the combined system (Figure S1). The simulations predict a variety of hybridized modes, where the Ince-Gaussian-type modes expected for the hBN drum are combined with modes of the Si<sub>3</sub>N<sub>4</sub> membrane.<sup>40</sup> This results in a much larger number of modes compared to that of a bare hBN drum and also affects the rotational orientation of the hBN drum modes. When taking a closer look at the bottom row in Figure 2, it becomes apparent that some of the mode images show motion (bright color) surrounding the typical double maxima of the drum mode, hinting at hybridization with the surrounding Si<sub>3</sub>N<sub>4</sub> membrane. As expected, the mode with the lowest Q factor (second image) shows no motion in the surrounding  $Si_3N_4$ membrane, while the one with the highest Q factor (last image) shows strong motion that even merges with the mode shape of the hBN drum. The fundamental mode of the hBN drum is not expected to show any hybridization (inset Figure 3 (a)), since it sits in a frequency gap in the mode spectrum just after the fundamental mode of the Si<sub>3</sub>N<sub>4</sub> membrane (arrows in Figure 2; Figure S3). Instead, for higher-order modes of the hBN drum, we expect hybridization with modes of the Si<sub>3</sub>N<sub>4</sub> membrane based on the simulations.

To further investigate this hybridization, we extract  $m^*$  and Q for all of the modes observed in the thermal spectrum. We also performed measurements both at liquid nitrogen (77 K) and liquid helium (4 K) temperatures. The sample was cooled in a liquid helium bath cryostat (Cryomagnetics), and measurements were performed using a fiber-based microscope as described in ref 41.

In Figure 3 (b), we show Q as a function of the resonance frequency. For a small frequency interval, there are often many modes at different Q values that almost appear in a vertical line, representing groups of modes such as the one shown at the bottom of Figure 2. The room-temperature quality factor  $Q = 1.8 \times 10^5$  for the Si<sub>3</sub>N<sub>4</sub> membrane (Figure S3 (a)) is much higher than the one for the fundamental mode of the hBN drum (Figure 3 (a)). Among the observed thermal spectra whose mode images match modes expected for the hBN drum (e.g., Figure 2 bottom row), we have found Q factors in excess of  $1 \times 10^5$ , almost reaching the value of the Si<sub>3</sub>N<sub>4</sub> membrane.

If the motion that we detect on the hBN drum were coupled to motion in the Si<sub>3</sub>N<sub>4</sub>, then we would expect an increase in  $m^*$  of this hybridized mode since the Si<sub>3</sub>N<sub>4</sub> membrane is a much heavier oscillator. As can be seen in Figure 3 (c), where we look at  $m^*$  instead, we indeed find an increase in these values. The observed values for room temperature (red markers) fall between a lower limit (red dashed line) corresponding to  $m_{th}^*$  of the fundamental mode of the hBN drum and an upper limit (green dashed line) corresponding to  $m_{th}^*$  of the Si<sub>3</sub>N<sub>4</sub> membrane. While these limits are only estimates, especially for the circular hBN drum where the effective mass depends on the mode in question,<sup>37</sup> the behavior matches our expectations for different degrees of hybridization. If we plot the observed Q vs  $m^*$  (Figure 3 (d)), we find that the modes with higher Q tend to have a higher  $m^*$ , and the two values appear to be correlated. From this observation, we can conclude that, via hybridization, the Si<sub>3</sub>N<sub>4</sub> membrane can lend its high Q factor to the hBN at the cost of a higher effective mass. In Figure 3 (e,f), we show the extracted force sensitivity (Supporting Information). At room temperature, the best value is achieved for the fundamental mode, showing that hybridization does not have a positive effect for this sample. The improvement observed at low temperature is partially due to a drop in effective mass of the observed modes. To explain the shift toward lower  $m^*$ , we need to take changes in the resonator geometry during cool down into account.

Bulk hBN is known to have a negative thermal expansion coefficient;<sup>42</sup> therefore, as in graphene, it is reasonable to expect that this property is preserved or even enhanced in the 2D limit.<sup>43</sup> Therefore, we expect a bulging of the membranes when going to low temperatures. While no such effect was observed for monolayer hBN,<sup>30</sup> the sample presented here is not thin enough to be clearly in the membrane regime, where the drum would be expected to stay under tension by adhering to the side walls of the underlying substrate.<sup>2</sup> Indeed, we observe buckling for our sample, as can be seen in the reflected intensity maps in Figure 4 (a,b). While we observe an increase



**Figure 4.** (a, b) Maps of the height differences extracted from the reflected intensity, showing the bulging effect at lower temperatures. (c) Fundamental hBN mode at room temperature (left) and modes of the bulged drum at 4 K (middle, right). The image in the middle shows a complex mode that spans a large area, for which thermal motion could not be observed. The image on the right is a more typical mode representing the ones that we were able to characterize (Figure 3). Dashed circles show the drum edge, and the white squares in the last two images indicate the limited scan window at 4 K.

in Q (Figure 3), especially when comparing similar effective masses, the effect is not as large as in other published work.<sup>7,29,30,44</sup> It is difficult to draw clear comparisons since the nature of the mechanical modes significantly changes after the bulging takes place (Figure 4 (c)). For example, we cannot observe the evolution of the Q factor of the fundamental mode as a function of temperature, since no corresponding mode exists after buckling.

Looking at Figure 3,  $m^*$  tends toward lower values for lower temperatures, even falling well below the expected value for the

fundamental mode of hBN. This is not surprising, as the mode images reveal that a much smaller area of the membrane takes part in the motion for some of the observed modes in the bulged membranes (Figure 4 (c)). Unlike at room temperature, we do not observe  $m^*$  reaching the upper limit given by the motional mass of the Si<sub>3</sub>N<sub>4</sub> membrane. We believe that this is due to our inability to observe thermal motion in such modes. The thermal motion scales with *T* and inversely with  $m^*$  and  $\omega$  (eq 1), limiting the range of observable spectra at low temperatures.

To summarize, the device presented here shows excellent mechanical properties and exhibits mode shapes that are consistent with theory up to high mode orders. We believe that the most likely explanation for this good performance is the fabrication procedure. The Si/SiO<sub>2</sub> substrate enables good visibility of any imperfections in the flake, and the wet transfer allows the flakes to gently settle onto the Si<sub>3</sub>N<sub>4</sub> membrane, avoiding inhomogeneous stress in the drum. While the thickness does not appear to have an effect on the *Q* of similar devices,<sup>1-3,20,21</sup> there may be a positive effect due to the large drum diameter of our devices.<sup>45</sup> Another factor that is known to influence *Q* is the tension,<sup>29</sup> which we estimate in our samples to not be any higher than in similar published work (Supporting Information).<sup>2,7,30</sup>

The hybridization between the  $Si_3N_4$  membrane and the hBN drum not only boosts the Q of the hBN modes but also allows the selection of different values of Q or  $m^*$  because the hybridization splits the expected hBN modes into several copies with different degrees of hybridization. With the addition of temperature control, it should be possible to tune this hybridization in a similar way as in refs 31 and 32.

While the gain in Q does not outweigh the increase in  $m^*$ when estimating the sensitivity of our devices (Figures 3 and S2), Si<sub>3</sub>N<sub>4</sub> membranes with higher Q or lower  $m^*$  have been demonstrated and could make this trade-off more favorable.<sup>46,47</sup> In particular, since the placement of hBN on our membranes resulted in only a modest drop in Q of the fundamental mode (Supporting Information), we are optimistic that hybrid modes with much higher Q values are feasible. Schwarz et al. demonstrated theoretically and experimentally that hybridization can increase the thermally limited sensitivity in a similar system.<sup>31</sup> Crucially, this increase in sensitivity requires the fine-tuning of the two modes to be hybridized, implying the need for a specifically designed Si<sub>3</sub>N<sub>4</sub> membrane for the task. Hybridization of a Si<sub>3</sub>N<sub>4</sub> resonator with a 2D membrane can also boost its motional amplitude, allowing for larger optomechanical coupling in a cavity or giving access to nonlinear mechanical effects such as signal amplification and noise squeezing.<sup>4,32,34</sup> The ability to study high-Q mechanical modes in 2D materials also opens possibilities for studying their mechanical properties, for mechanical coupling to embedded quantum emitters, or even for measuring magnetic properties of 2D materials via the magnetic torques and forces acting on drum resonators made from 2D magnets or on 2D magnets encapsulated in suspended hBN drum resonators.

# ASSOCIATED CONTENT

#### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.3c00233.

COMSOL simulations; force- and mass-sensitivity estimates; and mechanical properties of the  $Si_3N_4$  membrane (PDF)

### AUTHOR INFORMATION

#### **Corresponding Author**

Martino Poggio – Department of Physics and Swiss Nanoscience Institute, University of Basel, 4056 Basel, Switzerland; orcid.org/0000-0002-5327-051X; Email: martino.poggio@unibas.ch

#### Authors

- David Jaeger Department of Physics and Swiss Nanoscience Institute, University of Basel, 4056 Basel, Switzerland; orcid.org/0000-0002-2974-0155
- **Francesco Fogliano** Department of Physics, University of Basel, 4056 Basel, Switzerland
- **Thibaud Ruelle** Department of Physics, University of Basel, 4056 Basel, Switzerland
- Aris Lafranca Swiss Nanoscience Institute, University of Basel, 4056 Basel, Switzerland
- Floris Braakman Department of Physics, University of Basel, 4056 Basel, Switzerland

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.nanolett.3c00233

#### Notes

The authors declare no competing financial interest.

## ACKNOWLEDGMENTS

We thank Sascha Martin and his team in the machine shop of the Physics Department at the University of Basel for help in building the apparatus. We acknowledge the support of the Canton Aargau and the Swiss National Science Foundation (SNSF) under Ambizione grant no. PZ00P2-161284/1 and Project grant no. 200020-178863 and via the NCCR Quantum Science and Technology (QSIT).

#### REFERENCES

(1) Bunch, J. S.; van der Zande, A. M.; Verbridge, S. S.; Frank, I. W.; Tanenbaum, D. M.; Parpia, J. M.; Craighead, H. G.; McEuen, P. L. Electromechanical Resonators from Graphene Sheets. *Science* **2007**, *315*, 490–493.

(2) Zheng, X.-Q.; Lee, J.; Feng, P. X.-L. Hexagonal Boron Nitride Nanomechanical Resonators with Spatially Visualized Motion. *Microsystems & Nanoengineering* **2017**, *3*, 17038.

(3) Castellanos-Gomez, A.; van Leeuwen, R.; Buscema, M.; van der Zant, H. S. J.; Steele, G. A.; Venstra, W. J. Single-Layer MoS2Mechanical Resonators. *Adv. Mater.* **2013**, *25*, 6719–6723.

(4) Steeneken, P. G.; Dolleman, R. J.; Davidovikj, D.; Alijani, F.; van der Zant, H. S. J. Dynamics of 2D Material Membranes. 2D Materials **2021**, *8*, 042001.

(5) Xu, B.; et al. Nanomechanical Resonators: Toward Atomic Scale. *ACS Nano* **2022**, *16*, 15545–15585.

(6) Lee, C.; Wei, X.; Kysar, J. W.; Hone, J. Measurement of the Elastic Properties and Intrinsic Strength of Monolayer Graphene. *Science* **2008**, *321*, 385–388.

(7) Chen, C.; Rosenblatt, S.; Bolotin, K. I.; Kalb, W.; Kim, P.; Kymissis, I.; Stormer, H. L.; Heinz, T. F.; Hone, J. Performance of Monolayer Graphene Nanomechanical Resonators with Electrical Readout. *Nat. Nanotechnol.* **2009**, *4*, 861–867.

(8) Chen, C.; Lee, S.; Deshpande, V. V.; Lee, G.-H.; Lekas, M.; Shepard, K.; Hone, J. Graphene Mechanical Oscillators with Tunable Frequency. *Nat. Nanotechnol.* **2013**, *8*, 923–927.

(9) Gong, C.; Li, L.; Li, Z.; Ji, H.; Stern, A.; Xia, Y.; Cao, T.; Bao, W.; Wang, C.; Wang, Y.; Qiu, Z. Q.; Cava, R. J.; Louie, S. G.; Xia, J.; Zhang, X. Discovery of Intrinsic Ferromagnetism in Two-Dimensional van Der Waals Crystals. *Nature* **2017**, *546*, 265–269.

(10) Huang, B.; Clark, G.; Navarro-Moratalla, E.; Klein, D. R.; Cheng, R.; Seyler, K. L.; Zhong, D.; Schmidgall, E.; McGuire, M. A.; Cobden, D. H.; Yao, W.; Xiao, D.; Jarillo-Herrero, P.; Xu, X. Layer-Dependent Ferromagnetism in a van Der Waals Crystal down to the Monolayer Limit. *Nature* **2017**, *546*, 270–273.

(11) Splendiani, A.; Sun, L.; Zhang, Y.; Li, T.; Kim, J.; Chim, C.-Y.; Galli, G.; Wang, F. Emerging Photoluminescence in Monolayer MoS2. *Nano Lett.* **2010**, *10*, 1271–1275.

(12) Srivastava, A.; Sidler, M.; Allain, A. V.; Lembke, D. S.; Kis, A.; Imamoğlu, A. Optically Active Quantum Dots in Monolayer WSe2. *Nat. Nanotechnol.* **2015**, *10*, 491–496.

(13) Novoselov, K. S.; Mishchenko, A.; Carvalho, A.; Castro Neto, A. H. 2D Materials and van Der Waals Heterostructures. *Science* **2016**, 353, aac9439.

(14) Falin, A.; Cai, Q.; Santos, E. J. G.; Scullion, D.; Qian, D.; Zhang, R.; Yang, Z.; Huang, S.; Watanabe, K.; Taniguchi, T.; Barnett, M. R.; Chen, Y.; Ruoff, R. S.; Li, L. H. Mechanical Properties of Atomically Thin Boron Nitride and the Role of Interlayer Interactions. *Nat. Commun.* **2017**, *8*, 15815.

(15) Watanabe, K.; Taniguchi, T.; Kanda, H. Direct-Bandgap Properties and Evidence for Ultraviolet Lasing of Hexagonal Boron Nitride Single Crystal. *Nat. Mater.* **2004**, *3*, 404–409.

(16) Lee, S.-Y.; Jeong, T.-Y.; Jung, S.; Yee, K.-J. Refractive Index Dispersion of Hexagonal Boron Nitride in the Visible and Near-Infrared. *physica status solidi* (b) **2019**, 256, 1800417.

(17) Tran, T. T.; Bray, K.; Ford, M. J.; Toth, M.; Aharonovich, I. Quantum Emission from Hexagonal Boron Nitride Monolayers. *Nat. Nanotechnol.* **2016**, *11*, 37–41.

(18) Mendelson, N.; Doherty, M.; Toth, M.; Aharonovich, I.; Tran, T. T. Strain-Induced Modification of the Optical Characteristics of Quantum Emitters in Hexagonal Boron Nitride. *Adv. Mater.* **2020**, *32*, 1908316.

(19) Lazić, S.; Espinha, A.; Yanguas, S. P.; Gibaja, C.; Zamora, F.; Ares, P.; Chhowalla, M.; Paz, W. S.; Burgos, J. J. P.; Hernández-Mínguez, A.; Santos, P. V.; van der Meulen, H. P. Dynamically Tuned Non-Classical Light Emission from Atomic Defects in Hexagonal Boron Nitride. *Communications Physics* **2019**, *2*, 113.

(20) Shandilya, P. K.; Fröch, J. E.; Mitchell, M.; Lake, D. P.; Kim, S.; Toth, M.; Behera, B.; Healey, C.; Aharonovich, I.; Barclay, P. E. Hexagonal Boron Nitride Cavity Optomechanics. *Nano Lett.* **2019**, *19*, 1343–1350.

(21) Lee, J.; Wang, Z.; He, K.; Shan, J.; Feng, P. X.-L. High Frequency MoS2 Nanomechanical Resonators. *ACS Nano* **2013**, *7*, 6086–6091.

(22) Castellanos-Gomez, A.; Buscema, M.; Molenaar, R.; Singh, V.; Janssen, L.; van der Zant, H. S. J.; Steele, G. A. Deterministic Transfer of Two-Dimensional Materials by All-Dry Viscoelastic Stamping. 2D *Materials* **2014**, *1*, 011002.

(23) Ruelle, T.; Jaeger, D.; Fogliano, F.; Braakman, F.; Poggio, M. A Tunable Fiber Fabry–Perot Cavity for Hybrid Optomechanics Stabilized at 4 K. *Rev. Sci. Instrum.* **2022**, *93*, 095003.

(24) Flowers-Jacobs, N. E.; Hoch, S. W.; Sankey, J. C.; Kashkanova, A.; Jayich, A. M.; Deutsch, C.; Reichel, J.; Harris, J. G. E. Fiber-Cavity-Based Optomechanical Device. *Appl. Phys. Lett.* **2012**, *101*, 221109.

(25) Rochau, F.; Sánchez Arribas, I.; Brieussel, A.; Stapfner, S.; Hunger, D.; Weig, E. M. Dynamical Backaction in an Ultrahigh-Finesse Fiber-Based Microcavity. *Physical Review Applied* **2021**, *16*, 014013.

(26) Davidovikj, D.; Slim, J. J.; Bueno, S. J. C.; van der Zant, H. S. J.; Steeneken, P. G.; Venstra, W. J. Visualizing the Motion of Graphene Nanodrums. *Nano Lett.* **2016**, *16*, 2768–2773.

(27) Garcia-Sanchez, D.; van der Zande, A. M.; Paulo, A. S.; Lassagne, B.; McEuen, P. L.; Bachtold, A. Imaging Mechanical Vibrations in Suspended Graphene Sheets. *Nano Lett.* **2008**, *8*, 1399–1403.

(28) Reina, A.; Jia, X.; Ho, J.; Nezich, D.; Son, H.; Bulovic, V.; Dresselhaus, M. S.; Kong, J. Large Area, Few-Layer Graphene Films on Arbitrary Substrates by Chemical Vapor Deposition. *Nano Lett.* **2009**, *9*, 30–35.

(29) van der Zande, A. M.; Barton, R. A.; Alden, J. S.; Ruiz-Vargas, C. S.; Whitney, W. S.; Pham, P. H. Q.; Park, J.; Parpia, J. M.; Craighead, H. G.; McEuen, P. L. Large-Scale Arrays of Single-Layer Graphene Resonators. *Nano Lett.* **2010**, *10*, 4869–4873.

(30) Cartamil-Bueno, S. J.; Cavalieri, M.; Wang, R.; Houri, S.; Hofmann, S.; van der Zant, H. S. J. Mechanical Characterization and Cleaning of CVD Single-Layer h-BN Resonators. *npj 2D Materials and Applications* **2017**, *1*, 16.

(31) Schwarz, C.; Pigeau, B.; Mercier de Lépinay, L.; Kuhn, A. G.; Kalita, D.; Bendiab, N.; Marty, L.; Bouchiat, V.; Arcizet, O. Deviation from the Normal Mode Expansion in a Coupled Graphene-Nanomechanical System. *Physical Review Applied* **2016**, *6*, 064021.

(32) Singh, R.; Sarkar, A.; Guria, C.; Nicholl, R. J.; Chakraborty, S.; Bolotin, K. I.; Ghosh, S. Giant Tunable Mechanical Nonlinearity in Graphene–Silicon Nitride Hybrid Resonator. *Nano Lett.* **2020**, *20*, 4659–4666.

(33) Reiche, C. F.; Körner, J.; Büchner, B.; Mühl, T. Introduction of a Co-Resonant Detection Concept for Mechanical Oscillation-Based Sensors. *Nanotechnology* **2015**, *26*, 335501.

(34) Singh, R.; Nicholl, R. J.; Bolotin, K. I.; Ghosh, S. Motion Transduction with Thermo-mechanically Squeezed Graphene Resonator Modes. *Nano Lett.* **2018**, *18*, 6719–6724.

(35) Zheng, X.-Q.; Lee, J.; Feng, P. X.-L. Hexagonal Boron Nitride (h-BN) Nanomechanical Resonators with Temperature-Dependent Multimode Operations. 2015 Transducers - 2015 18th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANS-DUCERS); 2015; pp 1393–1396.

(36) Barg, A.; Tsaturyan, Y.; Belhage, E.; Nielsen, W. H. P.; Møller, C. B.; Schliesser, A. Measuring and Imaging Nanomechanical Motion with Laser Light. *Appl. Phys. B: Laser Opt.* **2017**, *123*, 8.

(37) Hauer, B. D.; Doolin, C.; Beach, K. S. D.; Davis, J. P. A General Procedure for Thermomechanical Calibration of Nano/Micro-Mechanical Resonators. *Annals of Physics* **2013**, 339, 181–207.

(38) van Leeuwen, R.; Castellanos-Gomez, A.; Steele, G. A.; van der Zant, H. S. J.; Venstra, W. J. Time-Domain Response of Atomically Thin MoS2 Nanomechanical Resonators. *Appl. Phys. Lett.* **2014**, *105*, 041911.

(39) Kramer, E.; van Dorp, J.; van Leeuwen, R.; Venstra, W. J. Strain-Dependent Damping in Nanomechanical Resonators from Thin MoS2 Crystals. *Appl. Phys. Lett.* **2015**, *107*, 091903.

(40) Bandres, M. A.; Gutiérrez-Vega, J. C. Ince–Gaussian Modes of the Paraxial Wave Equation and Stable Resonators. *Journal of the Optical Society of America A* **2004**, *21*, 873.

(41) Högele, A.; Seidl, S.; Kroner, M.; Karrai, K.; Schulhauser, C.; Sqalli, O.; Scrimgeour, J.; Warburton, R. J. Fiber-Based Confocal Microscope for Cryogenic Spectroscopy. *Rev. Sci. Instrum.* **2008**, *79*, 023709.

(42) Paszkowicz, W.; Pelka, J.; Knapp, M.; Szyszko, T.; Podsiadlo, S. Lattice Parameters and Anisotropic Thermal Expansion of Hexagonal Boron Nitride in the 10–297.5 K Temperature Range. *Appl. Phys. A: Mater. Sci. Process.* **2002**, *75*, 431–435.

(43) Yoon, D.; Son, Y.-W.; Cheong, H. Negative Thermal Expansion Coefficient of Graphene Measured by Raman Spectroscopy. *Nano Lett.* **2011**, *11*, 3227–3231.

(44) Morell, N.; Reserbat-Plantey, A.; Tsioutsios, I.; Schädler, K. G.; Dubin, F.; Koppens, F. H. L.; Bachtold, A. High Quality Factor Mechanical Resonators Based on WSe2Monolayers. *Nano Lett.* **2016**, *16*, 5102–5108.

(45) Barton, R. A.; Ilic, B.; van der Zande, A. M.; Whitney, W. S.; McEuen, P. L.; Parpia, J. M.; Craighead, H. G. High, Size-Dependent Quality Factor in an Array of Graphene Mechanical Resonators. *Nano Lett.* **2011**, *11*, 1232–1236. (46) Tsaturyan, Y.; Barg, A.; Polzik, E. S.; Schliesser, A. Ultracoherent Nanomechanical Resonators via Soft Clamping and Dissipation Dilution. *Nat. Nanotechnol.* **2017**, *12*, 776–783.

(47) Reetz, C.; Fischer, R.; Assump ç ao, G.; McNally, D.; Burns, P.; Sankey, J.; Regal, C. Analysis of Membrane Phononic Crystals with Wide Band Gaps and Low-Mass Defects. *Phys. Rev. Appl.* **2019**, *12*, 044027.

# **Recommended by ACS**

## All-Optical Noise Spectroscopy of a Solid-State Spin

Demitry Farfurnik, Edo Waks, et al. FEBRUARY 27, 2023 NANO LETTERS

READ 🗹

## Generation of Perfect Electron Vortex Beam with a Customized Beam Size Independent of Orbital Angular Momentum

Ruixuan Yu, Ting Xu, et al. FEBRUARY 01, 2023 NANO LETTERS

READ 🗹

## Room-Temperature Polaron-Mediated Polariton Nonlinearity in MAPbBr, Perovskites

Mikhail A. Masharin, Ivan A. Shelykh, et al. FEBRUARY 14, 2023 ACS PHOTONICS

READ 🗹

## Level Attraction due to Dissipative Phonon–Phonon Coupling in an Opto-Mechano-Fluidic Resonator

Qijing Lu, Shusen Xie, et al. FEBRUARY 16, 2023 ACS PHOTONICS

READ 🗹

#### Get More Suggestions >