Hexagonal boron nitride cavity optomechanics

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Hexagonal boron nitride (hBN) is an emerging layered material that plays a key role in a variety of two-dimensional devices, and has potential applications in nanophotonics and nanomechanics. Here, we demonstrate the first cavity optomechanical system incorporating hBN. Nanomechanical resonators consisting of hBN beams with dimensions of 13.5 µm × 1.1 µm × 31 nm were fabricated using electron beam induced etching and positioned in the optical nearfield of silicon microdisk cavities. The resulting cavity optomechanical system has sub-picometer/√Hz sensitivity to hBN nanobeam motion, allowing observation of thermally driven mechanical resonances with frequencies of 4.6 and 23 MHz, and quality factors of ∼ 260 and ∼ 1100, respectively, at room temperature in high vacuum. In addition, the role of air damping is studied via pressure dependent measurements. Our results constitute an important step towards realizing integrated optomechanical circuits employing hBN.

Integration of nanoscale photonic and mechanical resonators into cavity optomechanical devices1–3 has enabled fundamental discoveries and applications spanning quantum information science4–9, sensing10–16, and optical signal processing17–21. Key to these breakthroughs is the ability of nanoscale cavity optomechanical devices to enhance the interaction between light and motion of mechanical resonators, and to provide sensitive transduction of this interaction via its effect on the response of narrow cavity optical resonances.

A natural application of cavity optomechanics is the study and manipulation of the mechanical properties of 2D materials22,23, whose intrinsically nanoscale dimensions can make observing and controlling their mechanical motion challenging. It is these same properties that make 2D materials attractive for many applications of nanomechanics whose performance can be enhanced with a decrease in resonator mass2, for example molecule detection24–26. Recently, hexagonal boron nitride (hBN) has attracted considerable attention as a promising platform to study nanophotonic effects in 2D materials27,28. hBN is a hyperbolic material that supports propagation of phonon polaritons, assisting in confining light to the deep sub-wavelength regime29,30. Moreover, hBN is the only 2D material that has been observed to host ultra-bright single photon sources that operate at room temperature27,31,32. It is therefore very attractive to develop optomechanical devices from hBN, for future interfacing of mechanical motion and individual quantum system within the context of applications in quantum sensing, quantum optomechanics and quantum information processing13,33.

In this work, we demonstrate the first application of cavity optomechanics employing hBN nanomechanical resonators. hBN has optical properties that are beneficial for cavity optomechanics, including a large refractive index (n ∼ 1.8) and an electronic bandgap of ∼ 6 eV that corresponds to a transparency window spanning the entire visible and infrared range34. hBN can be exfoliated into flakes with thickness as low as a single monolayer, and their mechanical properties can be studied when these flakes are partially suspended35–37.

Recently, a top-down hBN patterning technique combining reactive ion etching (RIE) and focused electron beam induced etching (EBIE) was demonstrated38. Initial applications of this direct nanoscale patterning technique created photonic crystal cavities made entirely from monolithic hBN39. Here, we expand on this technique to create nanomechanical resonators from hBN that are integrated with silicon (Si) nanophotonic devices to realize a cavity optomechanical system. Thermally driven motion of the hBN mechanical resonator is read-out via its interaction with a high optical quality factor (Qo ∼ 104 – 105) Si microdisk, allowing observation of mechanical resonances with quality factor Qm > 103 – among the highest reported for 2D materials at room temperature40, and exceeding previously reported values for hBN resonators35–37,41.

Figures 1(a – c) show a schematic illustration, as well as optical microscope and SEM images of the hybrid hBN-Si microdisk cavity optomechanical system studied here. The system consists of an hBN nanobeam with length l = 13.4 µm, width w = 1.1 µm suspended adjacent to a Si microdisk optical cavity of diameter 11.6 µm and thickness 220 nm. Note that the reported hBN thickness, although not directly measured here, was estimated during the fabrication process to be less than 50 nm, and is predicted from nanomechanics measurements presented below to be ∼ 31 nm. The hBN nanobeam is positioned within 160 nm of the microdisk edge, as measured using the SEM during fabrication, which is close enough for its fluctuations in position to perturb the microdisk optical response. The microdisk fabrication follows the

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chemical reactions with hBN, which leads to localized volatilization (Fig. 1(e)). The electron beam lithography pattern used to define the microdisk creates a ring shaped trench surrounding the device over which an hBN nanobeam can be suspended. The first step in creating the nanobeam is to transfer an hBN flake with homogeneous thickness and reactive ion etching, followed by HF undercutting to remove the underlying 3 μm of SiO₂ until the microdisk is supported by a thin SiO₂ pedestal.

The process for integrating an hBN mechanical resonator with the microdisk is summarized in Figs. 1(d-f). The electron beam lithography pattern used to define the microdisk is patterned in the Si layer of a silicon-on-insulator chip using electron beam lithography and reactive ion etching, followed by HF undercutting to remove the underlying 3 μm of SiO₂ until the microdisk is supported by a thin SiO₂ pedestal. 

Measurement of the optomechanical properties of the hBN-microdisk system was achieved using a dimpled optical fiber taper to couple light into and out of the microdisk. In order to reduce damping of the hBN nanobeam’s motion, measurements were performed in a vacuum chamber (base pressure, P ~ 2 × 10⁻⁵ Torr), inside of which nanopositioners (Attocube) were used to position the device and the optical fiber taper. Figure 2(a) shows a typical transmission spectrum of the fiber taper when it is coupled evanescently to the microdisk and input with a tunable laser. This measurement the taper typically is in contact with the microdisk to ensure long-term stability of the coupling. Sharp dips in the transmission correspond to coupling to whispering gallery mode resonances of the microdisk, while broad low amplitude dips in transmission are related to wavelength dependent variations in the fiber taper transmission and laser output. A high-Q₀ resonance near 1531.7 nm was used in the following measurements to probe the optomechanical properties of the device, which is highlighted in Fig. 2(a), and found to have Q₀ ~ 88,000 (see below). The dominant electric field polarization of this mode is along the radial direction (TE-like), as determined from the fiber taper input polarization that maximizes the resonance contrast.

Mechanical motion of the nanobeam was probed by fixing the input laser wavelength λ within the high-Q₀ resonance, and measuring the electronic power spectral density S_eν(f) of the photoreceiver output (New Focus 1811) as in Ref.41. A typical spectrum is shown in Fig. 2(b). For frequencies f below a few MHz this spectrum is dominated by 1/f noise. However, near resonance frequencies f_m⁽¹⁾ = 4.6 MHz and f_m⁽³⁾ = 23 MHz, peaks in the spectrum associated with thermally driven motion.
of normal mechanical modes of the hBN nanobeam are identifiable. Based on Lorentzian fits, these peaks are observed to have linewidths corresponding to $Q_m = 260$ and 1100, respectively.

Finite element simulations (COMSOL) were used to calculate the normal mode spectrum of the nanobeam, whose frequencies were then compared with the observed resonances. Assuming a Young’s modulus of 865 GPa$^{36}$ and a nanobeam thickness of 31 nm, we find good agreement between the observed resonances and predicted $f_{m}$ of 4.59 MHz and 23.24 MHz for the 1st and 3rd order vertical modes of the nanobeam, respectively. The simulated displacement profiles of these modes are shown in Fig. 2(b). Note that other studies have reported lower Young’s modulus, e.g. 392 GPa$^{37}$, which could be related to differences in material quality or the presence of internal compressive stress. Using this lower Young’s modulus in our simulations results in a predicted hBN thickness of 47 nm. The 2nd order vertical mode is not observed due to the odd symmetry of its displacement profile with respect to the $x$-axis (defined in Fig. 1(a)) and the even symmetry of the microdisk mode intensity about this axis. As a result, the optomechanical coupling coefficient, $G$, which predicts the shift in $\lambda_m$ for a given mechanical displacement $z$, vanishes, resulting in nominally no cavity optomechanical transduction of the motion of this mode$^{15}$. The lowest order horizontal mechanical mode is predicted to have $f_{m} = 131.87$ MHz, and was not observed. This could be explained by its lower thermally driven amplitude ($\propto 1/f_{m}^2$) owing to its high frequency. Note that this effect is also responsible for the low observed amplitude of the $f_{m}^{(3)}$ peak.

To confirm that the peaks are related to the hBN motion, their amplitudes were measured as a function of input laser detuning $\Delta \lambda = \lambda - \lambda_o$ from the microdisk resonance wavelength $\lambda_o$. This is shown in Fig. 2(c) for the 4.6 MHz mode, from which we see that the peak amplitude follows the slope of the cavity optical response: $S_{m}^{\infty}(f_{m}^{(1)}; \lambda) \propto |dT(\lambda)/d\lambda|^2$, and that it is maximum when the laser is near the point of maximum slope. This behaviour is consistent with the sideband unresolved system studied here exhibiting predominantly dispersive optomechanical coupling between the hBN and the microdisk. Dominantly dispersive coupling is possible due to the low optical absorption of hBN at the operating wavelength, and in contrast to the dissipative optomechanical coupling observed in highly absorbing graphene cavity optomechanics systems$^{22}$. Note that the asymmetry in $S_{m}^{\infty}(\Delta \lambda)$ is well predicted from the asymmetry in the lineshape of the microdisk resonance, which is shown in Fig. 2(c), and arises from interference effects related to higher order modes of the fiber taper waveguide$^{44}$ as well as slight thermal instability in the microdisk$^{45}$.

The measurement resolution of the cavity optomechanical system can be extracted from measured signal to noise ratio $\alpha$ of each thermomechanically driven peak using the expression $s_{xx}^{\min} = \sqrt{4k_B T Q_{m}/(m_{eff}^{(1)} \Omega_{m}^{2})}$, where
The properties of the hBN nanomechanical resonator were further probed by studying its dynamics as a function of vacuum pressure. Figures 3(a) and 3(b) show the observed dependence of $Q_m$ for the 4.59 MHz and 23.24 MHz mode, respectively. In each case, $Q_m(P)$ is unaffected by pressure for $P < 10^{-1}$ Torr, taking a constant value $Q_{vac}$ in this pressure range. This indicates that air damping is not limiting $Q_m$ for the measurements reported above. At higher pressure, as shown by the fits in Figs. 3(a-b), the pressure dependence of $Q$ was well modeled by $1/Q_m = 1/Q_{vac} + 1/Q_{mf}(P)$, where $1/Q_{mf} \propto P$ describes the influence of free molecular flow damping.\cite{54,55} Note that the relatively similar pressures at which $Q_m$ of the first and third order modes begin to degrade is in agreement with the analytically predicted dependence of $Q_{mf}$ on mode frequency.\cite{54,55}

The mechanical frequencies of the hBN nanomechanical resonators were also observed to change with $P$, as shown in Figs. 3(c) and 3(d). This pressure dependent shift can be caused by several mechanisms. For $P \gtrsim 1$ Torr, the shift follows $\Delta f_m(P) \propto P$. This behaviour is consistent with a squeeze film spring effect observed in nanomechanical resonators when the oscillation period is smaller than the response time of the gas molecules trapped between the resonator and the substrate.\cite{56} This effect requires that the air mean free path is sufficiently small for molecules to fill the gap between the resonator and the substrate. However, at $P \sim 1$ Torr the mean free path of air is $\sim 40 \mu m$, which is larger than the maximum dimension ($\sim 16 \mu m$) of the aperture defined by the gap between the nanobeam and the microdisk, as $G$ depends exponentially on this parameter.\cite{15}

From the data in Fig. 2(b), which was obtained with $\lambda$ tuned to maximize the signal, we find $\alpha = 2.59$ and 0.21, for the first and third order modes respectively. From these we find $s_{xx}^{min} = 0.47$ and 0.29 pm/Hz$^{1/2}$. An input optical power, $P_{in} \sim 90 \mu W$ was used for these measurements, limited by the presence of optical bistability from two photon absorption in the Si microdisk.\cite{45} As $\alpha$ typically increases with $P_{in}$,\cite{44} improved measurement resolution could be achieved using a microdisk fabricated from a material with better high power handling such as diamond.\cite{52}

The optomechanical coupling affects the measurement resolution through $S_{nm} \propto G^2$, and can be optimized through the positioning of the nanobeam relative to the microdisk.\cite{15} To assess $G$ in our system, we implemented the calibration technique from Refs.\cite{58,49} which adds a known phase modulation to the input laser that is then transduced by the cavity into an optical intensity modulation. From the measured tone height relative to the area under nanomechanical resonance peak, we extracted $G/2\pi = 0.4$ MHz/\mu m. This is smaller than, but in reasonable agreement with, $G/2\pi = 0.6$ MHz/\mu m predicted from a perturbation theory calculation of the dependence of \lambda on the nanobeam height.\cite{15} This calculation was performed by evaluating the overlap of the microdisk mode intensity with the nanobeam dielectric, where finite difference time domain simulations (MEEP)\cite{50} were used to determine the azimuthally symmetric field (fundamental TE-like mode, azimuthal number $m = 55$, travelling wave field distribution) of the unperturbed microdisk. This calculation does not take into account the local field correction to the microdisk field by the nanobeam,\cite{51} which may account for the discrepancy. Significant uncertainty can also arise from variation in the gap between the hBN nanobeam and the microdisk, as $G$ depends exponentially on this parameter.\cite{15}

\begin{figure}
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\includegraphics[width=\textwidth]{figure3.png}
\caption{(a,b) Dependence of $Q_m$ on pressure for the $f_m^{(1)}$ and $f_m^{(3)}$ modes, respectively. The red lines show fits following the free molecular flow damping model described in the text. (c,d) Power spectral density of the photodetected fiber taper output intensity at different pressures for the $f_m^{(1)}$ and $f_m^{(3)}$ modes, respectively. The dashed line in (d) is a guide for the eye. (e,f) Dependence of mechanical frequency on vacuum pressure for the $f_m^{(1)}$ and $f_m^{(3)}$ modes, respectively. The red lines are fits based on the squeeze film spring effect.}
\end{figure}
and substrate. This suggests that the vacuum chamber pressure in the vicinity of the device may be larger than measured by the pressure gauge, which is located near the turbo pump used to evacuate the chamber. Note that the chamber used here is a Montana Instruments Nanoscope Workstation nominally designed for low temperature operation.

Below $P \sim 0.1$ Torr the frequencies of both modes also increase with pressure, although with a different pressure dependence. Similar behaviour was observed by Dollman et al. where it was ascribed to stress induced by the local pressure differential experienced by the nanobeam caused due to restriction of air molecules from entering the volume between the nanobeam and the underlying silicon chip\(^6\). Finally, note that optical power dependent measurements of $f_n$ confirmed that local photothermal heating was not influencing the results reported here.

To conclude, we have experimentally demonstrated an hBN cavity optomechanical system, and have shown that hBN nanobeams support mechanical resonances with $Q$\(_m\) exceeding 1000 at 23 MHz frequency in room temperature vacuum conditions. Our results are the first step towards integration of hBN as vital component of an integrated quantum optomechanical systems. Future experiments will be focused on optimizing the design of the hBN nanomechanical resonator and its integration with the optical cavity, implementation of fully integrated hBN cavity optomechanical devices, and measurement of hBN nanomechanical properties at cryogenic temperatures. Finally, integration of quantum light sources hosted by hBN crystals promises to enable new approaches for using optomechanics to interface with single photons.

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References

1. T. Kippenberg and K. Vahala, “Cavity opto-mechanics,” Opt. Express 13, 17172–17205 (2007).
2. M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, “Cavity optomechanics,” Rev. Mod. Phys. 86, 1391–1452 (2014).
3. J. Chan, T. P. M. Alegre, A. H. Safavi-Naeini, J. T. Hill, A. Krause, S. Groblacher, M. Aspelmeyer, and O. Painter, “Laser cooling of a nanomechanical oscillator into its quantum ground state,” Nature 478, 89–92 (2011).
4. J. Teufel, T. Donner, D. Li, J. Harlow, M. Allman, K. Cicak, A. Sirois, J. D. Whittaker, K. Lernert, and R. W. Simmonds, “Sideband cooling of micromechanical motion to the quantum ground state,” Nature 475, 359–363 (2011).
5. A. Schliesser, O. Arcizet, R. Rivière, G. Anetsberger, and T. Kippenberg, “Resolved-sideband cooling and position measurement of a micromechanical oscillator close to the heisenberg uncertainty limit,” Nature Phys. 5, 509–514 (2009).
6. J. Cohen, S. M. Meehan, G. S. MacCabe, S. Groblacher, A. H. Safavi-Naeini, F. Marsili, M. D. Shaw, and O. Painter, “Phonon counting and intensity interferometry of a nanomechanical resonator,” Nature 520, 522 (2015).
7. T. P. Purdy, K. E. Grutter, K. Srivinasa, and J. M. Taylor, “Quantum correlations from a room-temperature optomechanical cavity,” Science 356, 1265–1268 (2017).
8. V. Sudhir, R. Schilling, S. A. Fedorov, H. Schütz, D. J. Wilson, and T. J. Kippenberg, “Quantum correlations of light from a room-temperature mechanical oscillator,” Phys. Rev. X 7, 031055 (2017).
9. S. Hong, R. Riedinger, I. Marinković, A. Wallucks, S. G. Hofer, R. A. Norte, M. Aspelmeyer, and S. Groblacher, “Hanbury brown and twiss interferometry of single phonons from an optomechanical resonator,” Science 358, 203–206 (2017).
10. G. Anetsberger, O. Arcizet, Q. Unterreithmeier, R. Riviere, A. Schliesser, E. Weig, J. Kotthaus, and T. Kippenberg, “Near-field cavity optomechanics with nanomechanical oscillators,” Nature Phys. 5, 909–914 (2009).
11. K. Srivinasa, H. Miao, M. Rakher, M. Davanço, and V. Aksyuk, “Optomechanical transduction of an integrated silicon cantilever probe using a microdisk resonator,” Nano Lett. 11, 791 (2011).
12. P. Kim, C. Doolin, B. Hauer, A. MacDonald, M. Freeman, P. Barclay, and J. Davis, “Nanoscale torsional optomechanics,” Appl. Phys. Lett. 102, 053102 (2013).
13. S. Forstner, S. Franss, J. Knittel, E. van Ooijen, J. Swain, G. Harris, A. Szorkovskyy, W. Bowen, and H. Rubinsztein-Dunlop, “Cavity optomechanical magnetometer,” Phys. Rev. Lett. 108, 120801 (2012).
14. W. Yu, W. C. Jiang, Q. Lin, and T. Lu, “Cavity optomechanical spring sensing of single molecules,” Nature Communications 7, 12311 EP – (2016).
15. R. Schilling, H. Schütz, A. H. Ghadimi, V. Sudhir, D. J. Wilson, and T. J. Kippenberg, “Near-field integration of a SiN nanobeam and a SiO\(_2\) microcavity for heisenberg-limited displacement sensing,” Phys. Rev. Applied 5, 054019 (2016).
16. M. Wu, N. L.-Y. Wu, T. Firdous, F. F. Sani, J. E. Losby, M. R. Freeman, and P. E. Barclay, “Nanocavity optomechanical torque magnetometry and radiofrequency susceptibility,” Nat. Nano. 12, 127–131 (2017).
17. V. Fiore, Y. Yang, M. C. Kuzyk, R. Barbour, L. Tian, and H. Wang, “Storing optical information as a mechanical excitation in a silica optomechanical resonator,” Phys. Rev. Lett. 107, 133601 (2011).
18. J. T. Hill, A. H. Safavi-Naeini, J. Chan, and O. Painter, “Coherent optical wavelength conversion via cavity optomechanics,” Nature Communications 3, 1196 (2012).
19. Y. Liu, M. Davanço, V. Aksyuk, and K. Srivinasa, “Electromagnetically induced transparency and broadband wavelength conversion in silicon nitride microdisk optomechanical resonators,” Phys. Rev. Lett. 110, 223603 (2013).
20. P. Fang, J. Luo, A. Metelmann, M. H. Matheny, F. Marquardt, A. A. Clerk, and O. Painter, “Generalized non-reciprocity in an engineering circuit via synthetic magnetism and reservoir engineering,” Nature Physics 13, 465 (2017).
21. F. Ruesink, J. P. Mathew, M.-A. Miri, A. Aliu, and E. Verhagen, “Optical circulation in a multimode optomechanical resonator,” Nature Communications 9, 1708 (2018).
22. R. M. Cole, G. A. Brawley, V. P. Adiga, R. De Alba, J. M. Parpia, E. Lic, H. G. Craighead, and W. P. Bowen, “Evanescent-field optical readout of graphene mechanical motion at room temperature,” Physical Review Applied 3, 024004 (2015).
23. X. Song, M. Oksanen, J. Li, P. J. Hakenon, and M. A. Sillanpää, “Graphene optomechanics realized at microwave frequencies,” Phys. Rev. Lett. 113, 027404 (2014).
24. K. Ekinici, Y. Yang, and M. Roukes, “Ultimate limits to inertial mass sensing based upon nanoelectromechanical systems,” J. Appl. Phys. 95, 2682–2689 (2004).
25. P. Gil-Santos, C. Baker, D. Nguyen, W. Hease, C. Gomez, A. Lemaître, S. Ducii, G. Leo, and I. Favero, “High-frequency nano-optomechanical disk resonators in liquids,” Nat. Nano. 10, 810 (2015).
43Q. K. Roy, V. T. Sauer, J. N. Westwood-Bachman, A. Venkata- 
subramanian, and W. K. Hiebert, “Improving mechanical sen- 
sor performance through larger damping,” Science 360, eaar5220 
(2018).
44T. T. Tran, K. Bray, M. J. Ford, M. Toth, and I. Aharonovich, 
“Quantum emission from hexagonal boron nitride monolayers,” 
Nat. Nanon. 11, 37 (2016).
45F. Xia, H. Wang, D. Xiao, M. Dubey, and A. Ramasubrama- 
nian, “Two-dimensional material nanophotonics,” Nat. Photon. 
8, 899 (2014).
46J. D. Caldwell, A. V. Kretinin, Y. Chen, V. Giannini, M. M. 
Fogler, Y. Francescato, C. T. Ellis, J. G. Tischler, C. R. Woods, 
A. J. Giles, M. Hong, K. Watanabe, T. Taniguchi, S. A. Maier, 
and K. S. Novoselov, “Sub-diffractional volume-confined polarit- 
s in the natural hyperbolic material hexagonal boron nitride,” 
Nature Communications 5, 5221 (2014).
47S. Dai, Z. Fei, Q. Ma, A. Rodin, M. Wagner, A. McLeod, 
M. Liu, W. Gannett, W. Regan, K. Watanabe, T. Taniguchi, 
M. Thiemens, G. Dominguez, A. H. Castro Neto, A. Zettl, 
F. Keilmann, P. Jarillo-Herrero, M. M. Fogler, and D. N. Basov, 
“Tunable phonon polaritons in atomically thin van der waals 
crystals of boron nitride,” Science 343, 1125–1129 (2014).
48A. L. Exarhos, D. A. Hopper, R. R. Grote, A. Alkauskas, and 
L. C. Bassett, “Optical signatures of quantum emitters in sus- 
pended hexagonal boron nitride,” ACS Nano 11, 3328–3336 
(2017).
49N. R. Jungwirth, B. Calderon, Y. Ji, M. G. Spencer, M. E. Flatté, 
and G. D. Fuchs, “Temperature dependence of wavelength se- 
lectable zero-phonon emission from single defects in hexagonal 
boron nitride,” Nano Lett. 16, 6052–6057 (2016).
50M. Abdi, M.-J. Hwang, M. Aghtár, and M. B. Plenio, “Spin-
mechanical scheme with color centers in hexagonal boron nitride 
membranes,” Phys. Rev. Lett. 119, 233602 (2017).
51G. Cassabois, P. Valvin, and B. Gil, “Hexagonal boron nitride 
is an indirect bandgap semiconductor,” Nat. Photon. 10 (2016).
52T. H. Li and Y. Chen, “Atomically thin boron nitride: unique 
properties and applications,” Advanced Functional Materials 26, 
2594–2608 (2016).
53A. Fulin, Q. Cai, E. J. Santos, D. Scullion, D. Qian, R. Zhang, 
Z. Yang, S. Huang, K. Watanabe, T. Taniguchi, M. R. Barnett, 
Y. Chen, R. S. Ruoff, and L. H. Li, “Mechanical properties of 
atomically thin boron nitride and the role of interlayer interac- 
tions,” Nature Communications 8, 15815 (2017).
54X.-Q. Zheng, J. Lee, and P. X.-L. Feng, “Hexagonal boron nitride 
nanomechanical resonators with spatially visualized motion,” 
Microsystems & Nanoengineering 3, 17038 (2017).
55C. Elbadawi, T. T. Tran, M. Koliá, T. Šikola, J. Scott, Q. Cai, 
L. H. Li, T. Taniguchi, K. Watanabe, M. Toth, I. Aharonovich, 
and C. Lobo, “Electron beam directed etching of hexagonal boron 
nitride,” Nanoscale 8, 16182 (2016).
56S. Kim, J. E. Fröch, J. Christian, M. Straw, J. Bishop, D. Toton-
jian, K. Watanabe, T. Taniguchi, M. Toth, and I. Aharonovich, 
“Photonic crystal cavities from hexagonal boron nitride,” Nature 
Communications 9, 2623 (2018).
57A. Castellanos-Gomez, V. Singh, H. S. van der Zant, and G. A. 
Steele, “Mechanics of freely-suspended ultrathin layered materi-
als,” Annalen der Physik 527, 27–44 (2015).
58S. J. Cartamil-Bueno, M. Cavaliere, R. Wang, S. Houri, S. Hof-
mann, and H. S. van der Zant, “Mechanical characterization and 
cleaning of CVD single-layer h-BN resonators,” npj 2D Materials 
and Applications 1, 16 (2017).
59M. Borselli, T. J. Johnson, and O. Painter, “Beyond the rayleigh 
scattering limit in high-Q silicon microdisks: theory and experi-
ment,” Opt. Express 13, 1515–1530 (2005).
60C. P. Michael, M. Borselli, T. J. Johnson, C. Chrystala, and 
O. Painter, “An optical fiber-taper probe for wafer-scale micro-
photonics,” Opt. Express 15, 4745–4752 (2007).
61M. Wu, A. C. Hryciw, C. Healey, D. P. Lake, M. R. Freeman, J. P. 
Davis, and P. E. Barclay, “Dissipative and dispersive optome-