Electrically tunable single- and few-layer MoS$_2$ nanoelectromechanical systems with broad dynamic range

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Atomically thin semiconducting crystals such as molybdenum disulfide (MoS$_2$) have outstanding electrical, optical, and mechanical properties, thus making them excellent constitutive materials for innovating new two-dimensional (2D) nanoelectromechanical systems (NEMS). Although prototype structures have recently been demonstrated toward functional devices such as ultralow-power, high-frequency tunable oscillators and ultrasensitive resonant transducers, both electrical tunability and large dynamic range (DR) are critical and desirable. We report the first experimental demonstration of clearly defined single-, bi-, and trilayer MoS$_2$ 2D resonant NEMS operating in the very high frequency band (up to ~120 MHz) with outstanding electrical tunability and DR. Through deterministic measurement and calibration, we discover that these 2D atomic layer devices have remarkably broad DR (up to ~70 to 110 dB), in contrast to their 1D NEMS counterparts that are expected to have limited DR. These 2D devices, therefore, open avenues for efficiently tuning and strongly coupling the electronic, mechanical, and optical properties in atomic layer semiconducting devices and systems.

INTRODUCTION

In the ubiquitous devices and systems that detect, transduce, and communicate signals, dynamic range (DR), a ratio (often in decibel) between the highest nondistorted magnitude (linear “signal ceiling”) of a physical quantity (for example, intensity, energy/power, amplitude of current, voltage, displacement, and pressure) and its lowest detectable (“noise floor”), is a critically important measure (as illustrated in Fig. 1). In everyday life, the importance of DR is widely recognized by sensory systems of humans and other animals. In hearing, human eardrums normally have DRs of ~100 to 120 dB, from sensing minimum sound pressure fluctuations (at ~10$^{-5}$ N/m$^2$, threshold of audibility) to reaching pain thresholds (at ~10 N/m$^2$), in the range of ~0.5 to 10 kHz, whereas the DRs quickly decrease outside this frequency range (1, 2). Other animals (for example, cats and dolphins in aquatic environments) can have comparable or even wider DRs in higher frequency bands. In regards to olfaction (sense of smell), canines can have a very low threshold, thus broad DR for many kinds of odors, enabling such animals to smell and discern information beyond human olfactory capabilities (3). In engineering, broad DRs are indispensable in a wide spectrum of applications and have been actively pursued in devices and systems in every signal domain, including the electrical (for example, amplifiers) (4, 5), optical (photo detectors and cameras) (6), thermal (temperature sensors and calorimeters) (7), mechanical (pressure sensors) (8), and other transduction domains.

The critical importance of DR in signal transduction has presented important challenges to promising new sensing technologies. For example, nanoelectromechanical systems (NEMS) offer a variety of functionalities, and their performance metrics have been enhanced by reducing devices’ size (9), innovating and tailoring structures (10), and using newly emerging materials with unique properties (11–15). However, DR in such NEMS can often be reduced when the device sizes become smaller—it is predicted that DR of carbon nanotube resonators could be below 0 dB, thus completely eliminating linear operation regime (16). Consequently, it is imperative and attractive to explore effective approaches to attaining both small device size and broad DR.

Besides large DR, in resonant NEMS, achieving continuous, wide-range frequency tuning is often essential for developing functions such as ultralow-power signal transduction, generation, communication, and sensing, especially for systems requiring tunability and reconfigurability. Frequency tuning can be attained by applying external forces to vary and control the stiffness of the devices, such as via the electrostatic force induced by gate voltage ($V_g$), as illustrated in Fig. 1D based on modeling (also see discussions in section S3). In state-of-the-art resonant NEMS enabled by mainstream materials such as silicon (Si), silicon nitride (SiN), and silicon carbide (SiC), nonetheless, electrostatic tuning range is often very limited (usually only up to ~1 to 5%) because of the small fractional variations in stiffness that are achievable by external forces (17–23).

Here, we demonstrate atomic layer semiconductor NEMS resonators with excellent electrical tunability under different driving mechanisms (including photothermal and electrostatic excitation) and characterize their dynamic behavior, from the completely undriven, Brownian motion thermomechanical noise floor all the way to the nonlinear responses with increasing drive. Greatly benefiting from the materials’ outstanding mechanical properties (ultra-elastic, low areal mass density, high elastic modulus, and high intrinsic strength) (24–28), atomic layers such as semimetallic graphene and semiconducting transition metal dichalcogenides (TMDCs) have been used to innovate new two-dimensional (2D) NEMS devices. Among existing TMDC building materials, molybdenum disulfide (MoS$_2$) is a semiconducting 2D crystal with unconventional and excellent properties (25, 27–35). Its band structure depends on the number of atomic layers (29, 30) and can be continuously tuned by strain (33–35), promising distinct advantages for coupling nanomechanical
manipulations to its electrical, optical, and plasmonic (36) properties. Although initial experiments have demonstrated the potential of using MoS$_2$ as NEMS resonators (37–40), major challenges remain toward creating devices with unconventional attributes, advanced functionalities, and high performance. Here, we specifically address two challenges: (i) electrical tunability (41–43), which often dictates the degree of control over the device resonance, critical to applications such as tunable radio frequency signal transduction, generation, and communication (44), and (ii) the operating DR that affects how the device responds to stimuli, because a large DR is required for any transducer relying on performance in its linear regime (45, 46), such as many NEMS mass (47) and force sensors (48, 49). Unlike previous studies on DRs in the voltage domain (where the noise floors are obscured by extrinsic noise of measurement systems, thus yielding only compromised DRs), here, we achieve measurement down to the device intrinsic noise floors, thus capable of resolving the intrinsic DRs in the actual displacement domain of device motion. The approach of exploiting atomic layer crystals for 2D NEMS significantly facilitates the attainment of surprisingly broad DRs in these ultimately thin devices and systems.

RESULTS

We first demonstrate nanomechanical resonators made of circular membranes (Figs. 1 and 2) of atomic layer MoS$_2$ crystals in the thickness limit of only 1 to 4 layers (1L to 4L). Atomic layer MoS$_2$ flakes are mechanically exfoliated onto prefabricated circular microtrenches with diameters of $D \approx 0.5$ to $1.5 \mu$m ($D = 2a$ (a is radius)) to yield suspended drumhead structures (section S1). 1L to 4L devices are first identified by optical microscopy (Fig. 2, insets) and then confirmed by photoluminescence (PL) measurements of their corresponding distinct PL signatures (Fig. 2, right panels). The measured spectra with pronounced and intense PL peaks verify the high quality of our samples. We measure the nanomechanical resonances of these MoS$_2$ membranes by using sensitive laser interferometry for motion readout (Fig. 1A and B; see section S2 for details and analysis) at room temperature and in vacuum ($p \sim 5$ mTorr) (37). A 633-nm red laser is used to detect motions (both undriven and driven). For excitation, we use either a modulated 405-nm blue laser (Fig. 1A) or patterned electrodes with applied ac gate voltage (Fig. 3B).

We first measure the device resonance response without external drive and then with optical excitation via photothermal effect.
Fig. 2. Resonance characteristics of 1L, 2L, 3L, and 4L MoS2 membranes vibrating at very high frequencies. (A to D) Measured nanomechanical resonance (left panel) and PL (right panel) for 1L to 4L MoS2 resonators with diameter \(D = 1.5 \mu m\). The vertical dashed lines in right panels of (A) to (D) indicate the indirect interband transition in 2L to 4L MoS2 crystals, which are at lower energies than the direct interband transition (which is the only visible peak in the PL data from 1L MoS2). Inset: Optical images. Scale bars, 2 \(\mu m\). Both undriven thermomechanical resonances [as in (A) and (C)] and optically driven resonances [as in (B) and (D)] are shown. Red dashed lines in resonance plots are fittings to a finite Q harmonic resonator, a.u., arbitrary units.

(FIG. 1A). Figure 2 shows the measured undriven thermomechanical resonances (Fig. 2, A and C) and photothermally driven responses (Fig. 2, B and D) from four 1L to 4L devices. Typical 1L to 4L devices with a diameter \(D = 1.5 \mu m\) exhibit resonance frequencies of \(f_{res} \sim 30\) to 120 MHz and quality (Q) factors of Q ~ 40 to 1000 (fig. S3 shows an example of device resonance with Q exceeding 1000).

The sensitive motion detection enables us to reveal the discreteness in integer numbers of MoS2 layers that are manifested in the devices’ Brownian motion, with on-resonance displacement-domain thermomechanical noise spectral density, \(S_{\Delta x}^\alpha (f_0) = 4k_\beta TQ / (\omega_0^2 M_{eff})\) (where \(k_\beta\) is the Boltzmann constant, \(\omega_0 = 2\pi f_{res}\), \(M_{eff}\) is the effective mass that scales with the integer number of layers for a given diameter, and Q is the quality factor), which sets the lower boundary of the devices’ linear response (section S2). For 1L to 3L devices, the thermomechanical motion amplitudes are discretized: Their \(S_{\Delta x}^{1/2}\) values fall on separate surfaces (fig. S4), with thinner devices exhibiting greater thermal motions due to smaller masses. This discreteness is a signature of devices based on 2D materials, whose thicknesses can only vary in discrete steps (thus discretized masses for a given device geometry, for example, circular, rectangular, or other shapes of drumheads).

We now investigate electrical tuning of the optically driven resonances. We fabricate electrodes onto the already suspended MoS2 membranes by evaporating metal through a stencil mask, avoiding conventional chemical processes that usually contaminate the atomic layer flakes. The devices (Fig. 3) exhibit tunable resonances upon varying the gate voltage \(V\). For a 2L membrane (\(D \approx 1.5 \mu m\)) with an initial tension \(\gamma_0 = 0.2\) N/m (corresponding to an initial strain \(\varepsilon_0 = 0.071\%\); see section S3), varying \(V\) from 0 to \(\pm 20\) V symmetrically tunes down the resonance from 87 to 78 MHz (Fig. 3C).

Direct electrostatic excitation (Fig. 3B) is also enabled when an ac voltage \(\delta v_{ac} = \delta V_g \cos(\omega t)\) is superposed to the dc voltage \(V\). Figure 3D shows the electrically driven resonance from a 2L device (\(D \approx 1.5 \mu m\)) with the initial tension \(\gamma_0 = 0.15\) N/m and initial strain \(\varepsilon_0 = 0.054\%\). Sweeping the dc gate voltage again (in the range of \(V_g = 0\) to \(\pm 20 V\)) demonstrates strong tuning of the resonance (Fig. 3E), with \(f_{res}(V_g)\) taking a “W”-shaped curve (see Fig. 1D)—\(f_{res}\) first tunes down when \(|V_g|\) is from 0 to \(\sim 15\) V because of capacitive softening, then tunes up at higher \(|V_g|\) when tensioning induced by gating becomes dominant, leading to stiffening. Here, the stiffening from gating is easily visible because of a relatively lower initial strain built in this device than that in the device of Fig. 3C, where even higher \(|V_g|\) values would be needed to access the stiffening regime and to attain the full W-shaped curve (section S3 and eq. SI4). Furthermore, we have observed a “U”-shaped frequency tuning curve in a 4L device (\(D \approx 1.5 \mu m\)) with \(\gamma_0 = 0.11\) N/m and \(\varepsilon_0 = 0.020\%\), an even lower initial strain (fig. S5). Peak amplitudes of electrically driven resonances exhibit linear dependence on \(|V_g|\) (Fig. 3E) because the driving force at the frequency \(\omega = \omega_{res}\) is proportional to \(\delta V_{ac} V_g\), whereas those of optically driven resonances appear to depend on \(|V_g|\) quadratically (Fig. 3C). Furthermore, in both driving schemes, Q values decrease with \(|V_g|\) (Fig. 3F), suggesting extra damping and a loaded Q effect associated with \(|V_g|\) (section S3).

Toward efficient resonant tuning, there is a key trade-off between the tuning range and the initial tension (or strain). 2D NEMS are especially attractive for simultaneously achieving higher frequency and tunability due to greater stretchability (compared to conventional NEMS). Accordingly, we define a figure of merit (FOM)\(_{tuning} = f_{max}\varepsilon_0/\omega_0^2\varepsilon_0^2\gamma_0\) (\(\varepsilon_0\), initial strain range; \(\omega_0\), applied electrical field) to evaluate the tuning efficiency. Although the observed tuning characteristics are qualitatively consistent with other NEMS resonators (12, 17, 50, 51), these MoS2 devices show highly efficient frequency tuning [84 parts per million (ppm)/electron charge; see section S3] at much higher frequencies (and tension levels). Their FOM\(_{tuning}\) values greatly surpass conventional NEMS, matching the best of graphene NEMS (section S3, fig. S6, and table S1). We note that FOM\(_{tuning}\) has the unit of hertz per (voltage per micrometer), very intuitively quantifying the actual “efficiency” of frequency tuning by applying electrical field.

We now investigate the high amplitude–driven operations. Figure 4A shows that the resonance from a 1L device (\(D \approx 1.5 \mu m, f_{res} \approx 28.5\) MHz)
exhibits bifurcation and hysteresis (as frequency is swept up and down) under increased driving, with a clear Duffing nonlinearity (52). We model this by solving displacement \( x \) for a driven Duffing resonator, \( M_{\text{eff}}\ddot{x} + (M_{\text{eff}}\alpha_0/Q)x + k_1x + k_3x^3 = F_{\text{ext}} \), where \( k_1 \) and \( k_3 \) are the linear and Duffing stiffness, with \( k_1 = M_{\text{eff}}\alpha_0^2 \), and \( k_3/k_1 \) representing the degree of (cubic) nonlinearity. The solutions (dashed lines in Fig. 4A) recover the measured bifurcation and backbone curve, from which we determine the critical amplitude, \( a_c \approx 4.9 \text{ nm} \) (onset of the bifurcation; red solid circle in Fig. 4A). Likewise, analyzing the measured softening response in a 2L device (\( D \approx 1.5 \mu m, f_{\text{res}} \approx 90 \text{ MHz} \)) leads to accurately determining \( a_c \approx 17 \text{ nm} \) (Fig. 4B and section S6).

Directly detecting both the thermomechanical noise floor and the nonlinear driven responses enables us, for the first time, to precisely measure the DRs of 2D NEMS resonators. The achieved DR of linear operations is defined as (16) \( \text{DR}_{\text{linear, achieved}} \equiv 20 \log(0.745a_c/\sqrt{2S_x\Delta f}) \). Here, \( S_x^{1/2} \) is the measured noise level (Fig. 4, C and D, bottom blue curves), and \( \Delta f \) is the measurement bandwidth (we choose \( \Delta f = 1 \text{ Hz} \), which is widely used). Figure 4 (C and D) demonstrates \( \text{DR}_{\text{linear, achieved}} \approx 70 \text{ dB} \) for 1L and 3L devices. The \( \text{DR}_{\text{linear, achieved}} \) values are limited by excess electronic noise in the measurement, which increases the noise floor. The best available (intrinsic) value, \( \text{DR}_{\text{linear, int}} \), is set by only the thermomechanical noise and onset of Duffing: \( \text{DR}_{\text{linear, int}} \equiv 20\log(0.745a_c/\sqrt{2S_{x,\text{th}}\Delta f}) \approx 76 \text{ dB} \) for both devices (section S6).

The linear DRs of the MoS\(_2\) devices measured here are surprisingly and exceptionally broad, surpassing the values reported in other 2D systems (11, 12, 53, 54), and are even higher than those in nanobeams and nanowires (17, 23, 55–58). These great DR values can potentially translate into high device performance, such as ultrahigh mass and force sensitivities at room temperature and low phase noise in self-sustained oscillators (section S4).

Beyond the onset of Duffing nonlinearity, operations deep in the nonlinear regime are especially intriguing because MoS\(_2\) atomic layers are greatly stretchable with ultrahigh strain limits (25, 28, 59). Accordingly, we define a new DR of nonlinear operations, from the onset of Duffing to the maximum achievable deflection \( d_{\text{fracture}} \) (red dotted lines in Fig. 4, C and D) at the fracture limit, \( \text{DR}_{\text{nonlinear}} \equiv 20\log(d_{\text{fracture}}/0.745a_c) \) (red regions). Data show \( \text{DR}_{\text{nonlinear}} \sim 30 \text{ to } 50 \text{ dB} \) in these devices (section S5). This can potentially provide a new approach toward directly probing mesoscopic dynamical processes such as resonant bandgap modulation, elasticity-plasticity transition, and prefraction defects evolution, all in the 2D crystal platform.

Figure 5A summarizes the DRs of 1L, 2L, 3L, and 4L devices. We note that, given \( a_c, Q, f_{\text{res}}, \) and \( D \), DR increases with the number of layers, because thinner devices have lower masses and therefore exhibit larger thermomechanical motions, which reduce DR (section S8). Figure 5B illustrates the frequency scaling of drumhead MoS\(_2\) resonators. In contrast to thicker devices that behave like plates or disks,
Fig. 4. Discovering nanomechanical nonlinearity and very large DR in 1L, 2L, and 3L MoS2 resonators. (A) Duffing response measured from a 1L MoS2 resonator ($D = 1.5 \, \mu m$). Solid curve: Experimental data showing hysteresis. Dashed curves: Theoretical frequency response curve of a Duffing resonator. The backbone curve, response curve under critical driving, and the critical amplitude $a_c$ are highlighted. (B) Nonlinear response of a 2L MoS2 resonator ($D = 1.5 \, \mu m$) with increasing driving amplitude. The backbone curve and the level of $a_c$ are illustrated. (C) Measured DR of a 1L MoS2 resonator ($D = 1.5 \, \mu m$). The DR for linear operation (green zone) is limited by the measurement noise floor and the onset of nonlinearity ($0.745 \, a_c$, the 1-dB compression point below $a_c$). The DR for nonlinear operation (red zone) is limited by the fracture strength of the material. (D) Measured DR for a MoS2 resonator (3L, $D = 1.5 \, \mu m$), with the same conventions in (C).

Fig. 5. Scaling of DR and resonance frequency in atomically thin MoS2 resonators. (A) Intrinsic DR of 1L (green), 2L (magenta), 3L (blue), and 4L (black) devices ($D = 1.5 \, \mu m$) as a function of measured critical amplitude $a_c$ and $f_{res}^{-1}/Q$. (B) Resonance frequency scaling with device diameter $D$ and MoS2 thickness $t$. Theory is shown as lines, and measured data points are sphere symbols. Dark yellow lines: $f_{res}$ versus $D$ for 1L (0.7 nm) MoS2 membrane with surface tension $\gamma = 0.5$ and 0.1 N/m. Gray line: $f_{res}$ versus $D$ for $t = 100 \, nm$ MoS2 plate. Curves: $f_{res}$ versus $t$ for tensioned MoS2 plate resonators. For $D = 0.5 \, \mu m$ (magenta curves) and $6 \, \mu m$ (red curves), calculations are shown for $\gamma = 0.5$, 0.2, and 0.1 N/m. For devices with 1.5-$\mu m$ diameter (blue curves), additional tension values of $\gamma = 0.05, 0.02$, and 0.01 N/m are also shown. Spherical symbols show the measured $f_{res}$ values for 1L (green), 2L (magenta), 3L (blue), and 4L (black) devices ($D = 1.5 \, \mu m$). Data for thicker devices with $D = 6 \, \mu m$ (red) are taken from the study of Lee et al. (37).

DISCUSSION

It is worth noting that, although large frequency tunability is desirable, it could potentially translate the voltage noise in the gate voltage to frequency instability of the device. We find that, for a typical device, single- to few-layer devices operate in the membrane limit and exhibit great $f_{res}$ responsiveness to tension.

to tune the resonance frequency by applying a dc gate voltage (for example, 20 V) while maintaining the frequency stability achieved at 0-V gate, it requires a dc power supply with output voltage stability of about 5 ppm, which is available in some commercial models (see section S7 for detailed calculation).

The >70-dB linear DR values achieved and directly calibrated in this work are the highest among all NEMS resonators based on low-dimensional (1D and 2D) nanomaterials reported to date and are
comparable to those in top-down nanomachined structures (from conventional 3D crystals) that have much larger device volumes and much narrower frequency tunability. Table S3 compares the achieved DRs in NEMS resonators (and provides references to earlier work), and fig. S8 summarizes such comparison and shows that the 2D NEMS in this work achieve high DRs while having small volumes (note the logarithmic scale on both axes). Such unique combination of ultrasmall device volume, very wide frequency tunability, and broad DR has important implications for enabling novel sensing and signal processing functions in these atomically thin nanostructures.

The broad DRs achieved in these 2D NEMS resonators show strong contrast to the DRs predicted for 1D NEMS resonators. This can be understood by considering the upper and lower limits of the DR and that 2D nanostructures have lower thermomechanical fluctuations than their 1D counterparts, with details provided in section S8. A detailed theoretical analysis of DR in 2D NEMS is available in the literature (46).

In conclusion, we have demonstrated atomic layer MoS2 crystalline NEMS resonators with excellent electrical tunability of resonances and remarkably broad DRs, all achieved at the limit of single- to few-layer (1L to 4L) semiconductor devices. With careful measurements and displacement-domain calibration from Brownian motion thermomechanical noise to well beyond the onset of Duffing nonlinearity, we are able to observe and deterministically quantify the intrinsic DRs of these 2D NEMS resonators. The surprisingly broad linear DRs (~70 to 110 dB) are important attributes for making 2D NEMS an interesting new platform for exploring multiphysics coupling effects in 2D crystals and for pursuing resonant sensing (60–62) and ultralow-power information processing applications (63) in ultimately thin solid-state systems. In addition, our demonstration of broad DRs in 2D NEMS platforms opens up new possibilities for engineering large DRs in nanoscale devices that conventionally only have compromised DRs because of their highly miniaturized dimensions (16). Furthermore, extremely large nonlinear DRs (~40 to 50 dB) up to device fracture offer rich nanomechanical dynamics in 2D resonators and may facilitate exploring many exotic physical effects [for example, chaos (64), mode coupling (65–67), and internal resonance (39)] that stemmed from strong nonlinear interactions in such uniquely wide nonlinear regimes built in these 2D resonant systems.

### MATERIALS AND METHODS

#### Device fabrication

The single- to few-layer (1L to 4L) MoS2 resonators were fabricated by mechanically exfoliating MoS2 crystal onto 290-nm SiO2 on Si substrates with prepatterned microtrenches and cavities of various shapes. The diameters of the circular microtrench cavities on the substrates are \( D \approx 0.5, 0.75, 1, 1.25, \) and \( 1.5 \) \( \mu \)m, and depths are 250 and 290 nm. We cleaned the substrate thoroughly by using Piranha, a mixture of sulfuric acid and hydrogen peroxide, before exfoliation of MoS2.

#### PL measurement

PL responses from the fabricated MoS2 resonators were measured to confirm the number of device layers. A 532-nm laser was focused on the center of the suspended MoS2 diaphragm by using a microscope objective [100×, numerical aperture (NA) = 0.9], and laser power is limited below ~50 \( \mu \)W, to avoid excessive laser heating. PL responses from the devices were resolved using a spectrometer (Princeton Instruments SpectraPro) with grating (600 g/mm) and recorded using a liquid nitrogen–cooled charge-coupled device.

#### Laser interferometry setup and resonance measurement

Figure 1B shows the configuration and components used in the measurement set-up. The resonance was optically heated and interferometrically detected using an amplitude-modulated 405-nm diode laser and a 633-nm He-Ne laser, respectively. Both lasers were focused using microscope objective (50×, NA = 0.5). The 405-nm laser was focused onto the substrate next to the device (~5 \( \mu \)m away), with an estimated spot size of ~5 \( \mu \)m. Laser power of the 405-nm laser is limited to below 250 \( \mu \)W. The 633-nm laser was focused on the center of the suspended MoS2 drumhead. The calibrated on-device spot size of the 633-nm laser is ~1 \( \mu \)m, and the laser power was adjusted to below 350 \( \mu \)W. A long-pass filter was installed in front of the photodetector to remove the signal from the 405-nm laser. Reflected intensity of 633-nm light from the device was detected by a photodetector and recorded with a spectrum analyzer and/or a network analyzer.

#### Electrical excitation of device resonance motion

In addition to the photothermal excitation, device motions were actuated using electrostatic force. Electrodes are made by evaporating nickel onto the suspended MoS2 devices through a stencil mask. This method does not require any chemical processing, and the MoS2 membrane remains in its pristine condition. The electrical actuation was performed by applying through a bias-T an ac + dc signal generated by a network analyzer and a dc power supply.

### SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/5/eaao6653/DC1

section S1. Device fabrication

section S2. Optical interferometry measurement system

section S3. Electrical tuning of device resonance

section S4. Power handling, mass sensitivity, and frequency stability

section S5. Nanomechanical tuning and sensing of device strain and bandgap

section S6. Measuring nonlinearity and estimating critical amplitude

section S7. Translation of voltage fluctuations into frequency instability

section S8. Comparison of DR in 1D and 2D NEMS resonators

fig. S1. Calculated displacement versus reflectance values for 1L to 3L MoS2 resonators.

fig. S2. Calculated displacement-to-reflectance responsivity \( \left( \text{Ref} \right) \) and measured displacement-to-voltage responsivity \( \left( \text{V}_{\text{in}} \right) \) values for 1L to 3L MoS2 resonators.

fig. S3. Thermomechanical resonance with qualify \( (Q) \) and measured displacement-to-voltage responsivity \( \left( \text{V}_{\text{in}} \right) \) for 1L to 3L MoS2 resonators.

fig. S4. Thermomechanical response with qualify \( (Q) \) factor exceeding 1000.

fig. S5. Thermomechanical vibrations with distinct signatures of digitized thicknesses (number of layers) as a function of \( f_{\text{in}} \) and \( Q \).

fig. S6. FOM for frequency tuning: Comparison across reported 2D NEMS devices.

fig. S7. Schematic for calculating the total surface area on a deformed membrane.

fig. S8. Measured DR in 1D and 2D NEMS operated at room temperature.

fig. S9. Resonance frequency scaling with device diameter \( D \) and MoS2 thickness \( t \).

table S1. FOM for frequency tuning.

table S2. List of devices with measured nonlinear characteristics.

table S3. DRs measured in 1D and 2D resonators.

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