

## Quality-Factor Enhancement of Nanoelectromechanical Systems by Capacitive Driving Beyond Resonance

T. Barois, S. Perisanu, P. Poncharal, P. Vincent, S. T. Purcell, and A. Ayari\*

*Univ Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière,  
F-69622 Lyon, France*

(Received 18 April 2016; published 21 July 2016)

Nanoelectromechanical systems are considered as ultrasensitive devices for mass and force detection. Capacitive actuation is widely used in these devices but is known to degrade the quality factor of the resonator due to dc electrostatic damping. We report the enhancement of the quality factor of SiC vibrating nanowires detected nano-optomechanically and electrically by applying an ac capacitive driving at a frequency above both the resonance frequency and the electrical cutoff frequency. Self-oscillations are demonstrated for optimal conditions. We develop an analytical model of the phenomenon and show that it can lead to an improvement of the force sensitivity.

DOI: 10.1103/PhysRevApplied.6.014012

### I. INTRODUCTION

Nanoelectromechanical systems (NEMSs) [1], where electrons are coupled to mechanical motion, have generated tremendous interest over the past years, as they are promising candidates for testing macroscopic quantum physics [2–4], nonlinear dynamics at the nanoscale [5,6], and for their capability in sensor applications. These systems have shown record limits of detection reaching yoctogram mass resolution [7] and a sensitivity of  $12 \text{ zN}/\sqrt{\text{Hz}}$  [8]. In these electromechanical devices, the continuous improvement of the electrostatic transduction and the elimination of different sources of damping will ultimately be limited by the electrostatic damping [9], as is already the case for some single-electron devices [10,11] or semiconducting nanowire cantilevers [12]. It is possible to reduce this damping by lowering the device resistance [12] or by applying a dc offset to compensate for residual voltages originating from work function differences and contact potentials [13], but such solutions are not always convenient. Recently, it has been theoretically proposed [14] that electrostatic coupling can also lead to a decrease of damping and to self-oscillations by simply applying an ac signal to a suspended electromechanical graphene resonator and taking into account nonlinear effects. The driving frequency is not related to the resonance frequency but just needs to be higher than the inverse of the charge relaxation time.

This method is appealing as (i) the operating frequency range is much less stringent than for systems coupled to a cavity [15] or a resonator [16–18], (ii) it needs no additional elements than the already present coupling capacitor and NEMS resistance, (iii) it works for single- and double-clamped geometries, and (iv) it gives a simple means to

tune the damping and to improve the signal-to-noise ratio for force sensing [19] as already demonstrated, for instance, for magnetometers [20,21]. In this article, an experimental proof of this capacitively induced decrease of a NEMS mechanical damping is presented. We demonstrate that this effect can be large enough to induce self-oscillations in a mechanical resonator. The model of Eriksson *et al.* [14] is then extended, as this effect raises interesting questions about the influence of the electrostatic actuation itself to perform an accurate measurement of the damping in NEMS and about the noise it induces for cooling and sensing applications.

### II. RESULTS

We study two different SiC nanowires (samples NW1, length  $L = 34 \mu\text{m}$ , radius  $r = 75 \text{ nm}$ ; NW2,  $L = 86 \mu\text{m}$ ,  $r = 90 \text{ nm}$ ) fixed at one end to  $W$  rigid tips and submitted to ac and dc capacitive forces [see Fig. 1(a)]. The measurements are performed in two different ultrahigh vacuum chambers, one equipped with a scanning-electron-microscope (SEM) column and the other equipped with a nano-optomechanical setup. Piezoinertial nanomanipulators are used to position the sample close to a counterelectrode and in the focal point of the electron or light beam.

In the electron chamber, the mechanical motion of the nanowire can be imaged as in standard electron microscopy or measured by recording the secondary electron signal in spot mode [12]. Figure 1(b) is a SEM image of NW2 close to the counterelectrode. The resonance frequencies of NW2 are measured with a lock-in amplifier for an applied ac voltage of 50 mV. The first transverse-mechanical eigenmode shows two polarizations at 39.83 and 40.01 kHz where the degeneracy is lifted by either the clamping condition or the nanowire asymmetry. The second and third eigenmodes are at 230 and 620 kHz. The width of the

\*anthony.ayari@univ-lyon1.fr

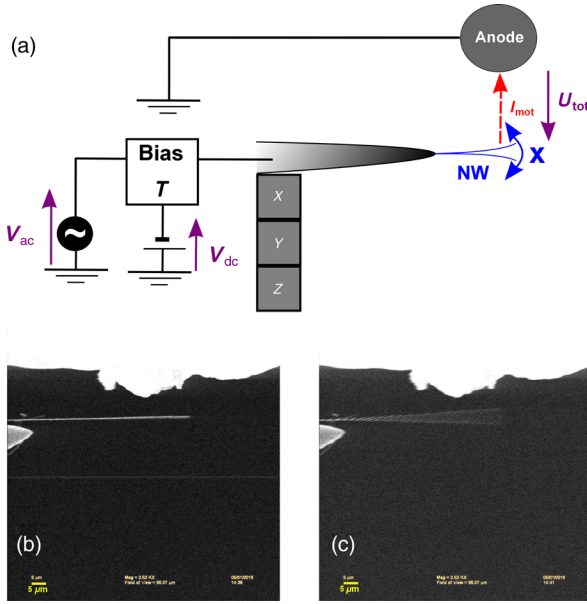


FIG. 1. (a) Schematic of a vibrating SiC nanowire on a tungsten tip submitted to an ac voltage  $V_{ac}$  or a dc voltage  $V_{dc}$ . (b) SEM image of the silicon carbide nanowire NW2 close to a gold counter electrode for  $V_{ac} = V_{dc} = 0$  V. (c) SEM image of NW2 in self-oscillation for  $V_{ac} = 19$  V,  $V_{dc} = 0$  V, and a driving frequency  $\Omega/2\pi = 810$  kHz well above the resonance frequency of 40 kHz.

resonance peaks is about 5 Hz, and outside these peaks no mechanical signal can be measured or observed with the SEM imaging. However, when a higher ac signal above 18 V is applied, spontaneous mechanical vibrations are observed for driving frequencies ranging from 750 to 850 kHz. The excitation of higher eigenmodes can be ruled out because the imaging of the mode does not show any nodes, as observed in Fig. 1(c). Nonlinear high-order parametric excitation of the first mode and parametric coupling between the first mode and high-order mechanical mode [18] seem dubious because of the discrepancy between the theoretical expected frequency and the observed frequency range for spontaneous oscillations. For this type of sample, the resistance is of the order of 1 G $\Omega$  and the capacitance in the femtofarad range [12,22]. This corresponds to an inverse of the charge relaxation time

of the order of hundreds of kilohertz, so our observations are in agreement with the model of Eriksson *et al.* [14] predicting self-oscillations for a driving frequency higher than the charge relaxation time.

We perform additional measurements with NW1 in our UHV optical setup in order to get a more quantitative agreement with theory. In the optical chamber, a 35- $\mu$ W and 633-nm laser beam is strongly focused on the free end of the nanowire, and the transmitted light is collected using a differential measurement based on a dual quadrant photodiode [23,24] giving access to the thermomechanical motion of the resonator with high signal-to-noise ratio. So, in this experimental setup, no ac probe signal is required to measure the mechanical motion, and electron-beam-induced self-sustained oscillations [25] will not interfere with our measurements. The first transverse-mechanical eigenmode shows two polarizations at 113.434 and 114.071 kHz. In the rest of the text, we focus only on the low-frequency polarization, as the high-frequency polarization shows the same behavior. An ac signal of 10 V is applied to the nanowire and swept back and forth between 150 kHz and 2 MHz in 25-kHz increments while recording the power-spectrum density of the thermomechanical motion as plotted in Fig. 2(a). A shift in frequency and an increase in vibration amplitude is observed when the frequency increases. The resonance peaks are fitted with a Lorentzian (see Fig. 1 in Ref. [26]). Figure 2(b) shows the variation of the quality factor defined as  $\omega_0/\Gamma_{ac}$  where  $\omega_0/2\pi$  is the resonance frequency and  $\Gamma_{ac}$  the resonance width. The dashed line indicates the initial quality factor  $Q_0 = 30\,600$  in the absence of ac or dc voltages. At low driving frequencies, the quality factor is strongly reduced but increases with the frequency until it reaches a maximum above 40 000 around 650 kHz. This maximum is significantly higher than the initial quality factor. At higher frequencies,  $Q$  tends to  $Q_0$ .

At first sight, this effect seems rather counterintuitive as the electrostatic interaction usually induces an increase in damping when a dc voltage is applied, and ac actuation is very often used as a reliable means to drive NEMS. Furthermore, the possibility to increase or decrease the damping is reminiscent of coupling with a blue-detuned or red-detuned cavity, whereas no cavity is involved in this system. The mechanical

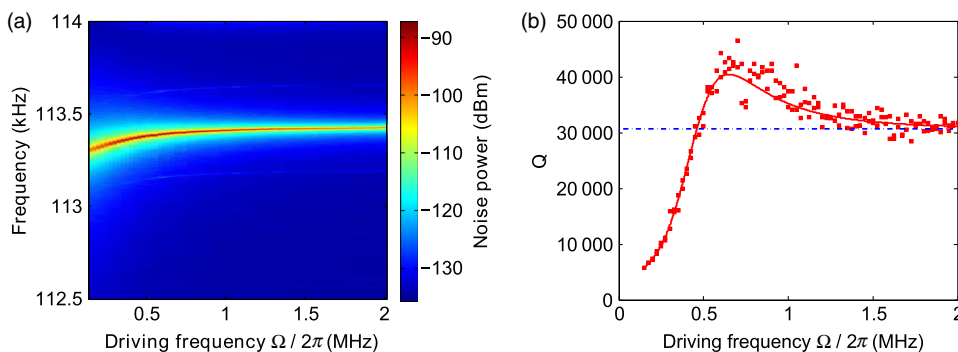


FIG. 2. (a) Evolution of the displacement noise spectrum of NW1 as a function of the driving frequency  $\Omega/2\pi$  for  $V_{ac} = 10$  V and  $V_{dc} = 0$  V. (b) Evolution of the quality factor  $Q$  as a function of the driving frequency. The solid line is a fit of the quality factor with Eq. (4). The dashed line is the quality factor without an ac voltage.

system can be modeled as a mechanical resonator capacitively connected to its environment

$$m\ddot{x} + m\Gamma_0\dot{x} + m\omega_0^2x = \frac{C'}{2}(U_{\text{tot}})^2 + F_T(t), \quad (1)$$

where  $x$  is the position in the transverse direction of the free end of the nanowire,  $m$  is the effective mass of the mechanical resonator, the dot refers to the derivative versus time  $t$ ,  $\Gamma_0$  is the intrinsic mechanical damping,  $F_T(t)$  is the Langevin force coming from the thermal bath,  $C'$  is the space derivative of the capacitance  $C$  formed between the resonator and the electrostatic environment, and  $U_{\text{tot}}$  is the total voltage difference between the point  $x$  and the ground [see Fig. 1(a)]. This voltage is provided by a transmission line that can be roughly described by the following equation:

$$RC\dot{U}_{\text{tot}} + U_{\text{tot}} = -RC'U_{\text{tot}}\dot{x} - RC'\dot{U}_{\text{tot}}x + V_{\text{ac}} \cos \Omega t, \quad (2)$$

where  $R$  is the resistance of the resonator including the contact resistance, and  $V_{\text{ac}}$  is the applied ac voltage at frequency  $\Omega/2\pi$ . The important terms are those related to the change in capacitance when the nanowire moves and changes its distance from the counterelectrode. This motion induces a motional current  $C'U_{\text{tot}}\dot{x} + C'\dot{U}_{\text{tot}}x$ . These nonlinear terms mix the driving voltage at angular frequency  $\Omega$  with the nanowire motion at angular frequency  $\omega$ . A redshifted (Stokes) electromagnetic wave at  $\omega_- = \Omega - \omega$  and a blue-shifted (anti-Stokes) electromagnetic wave at  $\omega_+ = \Omega + \omega$  are then produced and down-mixed by the squared term of the

electrostatic actuation in Eq. (1) (see Fig. 3 and Ref. [26]). This induces a feedback mechanism that modifies the damping and resonance frequency of the nanowire. At low driving frequencies, the electrical circuit should behave as if a dc voltage is applied, and so an increase in damping is expected. The electrical actuation is a low-pass filter, so for frequencies beyond the inverse of the charge relaxation time  $\tau = RC$  (i.e., the cutoff frequency), the effect of the applied voltage on the apex of the nanowire should vanish and the initial damping should be recovered. However, in the intermediate regime of frequency, the actuation is dephased compared to the dc actuation, and the amplitude of the electromagnetic actuation although smaller can still influence the resonator. This dephasing allows a decrease of damping for a wide frequency range. The effective mechanical equation is then

$$\ddot{x} + \Gamma_{\text{ac}}\dot{x} + \omega_{\text{ac}}^2x = 0 \quad (3)$$

with

$$\begin{aligned} \Gamma_{\text{ac}} &= \Gamma_0 + g_1^2 V_{\text{ac}}^2 \Re \Omega \frac{\Im^{\omega_+} - \Im^{\omega_-}}{2\omega}, \\ \Re \Omega &= \frac{1}{1 + (\Omega\tau)^2}, \\ \Im \Omega &= \frac{\Omega\tau}{1 + (\Omega\tau)^2}, \\ g_1 &= \frac{C'}{\sqrt{2mC}}, \end{aligned} \quad (4)$$

where  $g_1$  is the electrostatic coupling strength for an applied voltage of 1 V. It characterizes the strength of the electrostatic

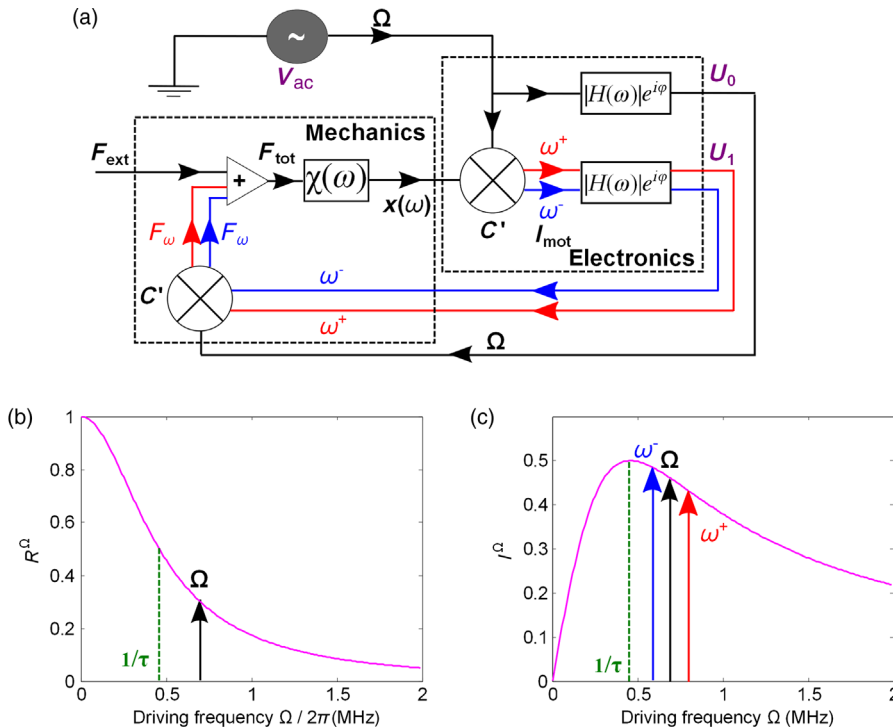


FIG. 3. (a) Schematic of the mechanism involved in the quality-factor enhancement induced by an ac voltage.  $F_{\text{ext}}$  is an external force like the thermal-noise force.  $F_{\text{tot}}$  is the sum of the external force and the two feedback forces.  $\chi(\omega)$  is the mechanical susceptibility of the nanowire.  $H(\omega)e^{i\varphi}$  is the transfer function of the transmission line.  $U_0$  and  $U_1$  are calculated in Ref. [26]. The two crossed circles represent signal mixers responsible for the nonlinear effects and originating from the  $C'$  terms. (b) Evolution of the term  $\Re \Omega$  as a function of the driving frequency with the experimental parameters of NW1. The smaller the black arrow, the smaller the effect on the damping. (c) Evolution of the term  $\Im \Omega$  as a function of the driving frequency with the experimental parameters of NW1. The damping is reduced as long as the blue arrow is longer than the red arrow.

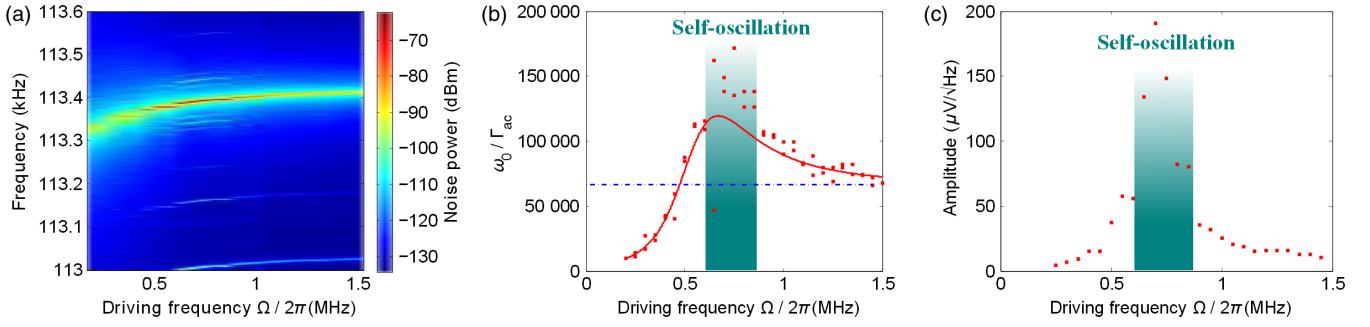


FIG. 4. (a) Evolution of the displacement noise spectrum of NW1 after annealing as a function of the driving frequency  $\Omega/2\pi$  for  $V_{ac} = 10$  V and  $V_{dc} = 0$  V. Satellite peaks related to self-oscillation appear between 650 and 850 kHz. (b) Evolution of  $\omega_0/\Gamma_{ac}$  (which corresponds to the quality factor  $Q$  outside the self-oscillation region) as a function of the driving frequency after annealing. The solid line is a fit of the quality factor with Eq. (4). The dashed line is the quality factor without an ac voltage. (c) Evolution of the vibration amplitude at resonance as a function of the driving frequency.

coupling. The blueshifted term  $\mathfrak{S}^{\omega+}$  always leads to an increase in damping, whereas the redshifted term  $\mathfrak{S}^{\omega-}$  reduces the damping as long as  $\omega < \Omega$ . So this mechanism cannot lead to a reduction in damping for a driving lower than the resonance frequency. For  $\omega \ll \Omega$ , the damping can be approximated by

$$\Gamma_{ac} \approx \Gamma_0 + g_1^2 V_{ac}^2 \tau \frac{1 - (\tau\Omega)^2}{(1 + (\tau\Omega)^2)^3}. \quad (5)$$

For  $\Omega\tau > 1$ , the ac driving starts to decrease the damping. The quality-factor enhancement is maximum for  $\Omega = \sqrt{2}/\tau$  where the damping decreases by  $g_1^2 V_{ac}^2 \tau / 27$ . The data in Fig. 2(b) are fitted with Eq. (5). A very good agreement is observed between theory and experiment. It gives a charge relaxation time of 347 ns corresponding to a cutoff frequency of 460 kHz, a maximum quality-factor enhancement at 650.5 kHz, and a coupling strength of 2098.5 rad/s/V corresponding to 333.98 Hz/V. Thus, our system is in the weak coupling regime  $g_1 V_{ac} \tau \approx 0.007 \ll 1$ , and this explains why a rather important voltage of 10 V is necessary to observe this effect. A much more spectacular effect should be expected in the strong coupling regime. As a comparison, we perform a measurement of the resonance width as a function of the dc voltage without an ac voltage. As expected [12], a square dependence in voltage is observed [26] and fitted. From this fit and using a value of  $\tau = 347$  ns as determined previously, the coupling strength is estimated at 1622.5 rad/s/V in agreement with the  $g_1$  value obtained from the ac experiment.

An annealing of the nanowire is performed in order to remove surface adsorbates and increase the initial quality factor up to 66 700. An ac signal of 10 V is applied to the nanowire and swept back and forth between 200 kHz and 1.5 MHz in 50-kHz increments while recording the power-spectrum density of the thermomechanical motion as plotted in Fig. 4(a). Figure 4(b) shows a quality factor above 150 000 between 650 and 850 kHz. The peak width cannot be measured accurately in this frequency range due

to the 1-Hz limitation of the spectrum analyzer bandwidth. If these points are excluded, a fit is still possible and gives similar values for  $g_1$  and  $\tau$  as before the annealing. The clear departure of the quality factor from the fit between 650 and 850 kHz indicates that the nanowire self-oscillates and the quality factor is no longer defined. It can be pointed out here that this is a true self-oscillation where the phase is free, contrary to the instability of the parametric oscillator where the phase is fixed by the ac generator. Indeed, we observe that the enhancement of the quality factor is improved when the system is driven by two independent frequency generators. Furthermore, in our model, adding a phase in the driving does not modify the final dynamical equation for  $x$  and the expression of the effective damping. This phase independence comes from the fact that the driving frequency does not need to be commensurate with the resonance frequency, contrary to a parametric oscillator.

### III. DISCUSSION

An interesting point concerning our derivation of Eq. (4) is that it gives a simple expression of the damping valid for any  $\Omega$  (except for  $\Omega = 0$  where a slight correction is needed). In particular, it appears from Eq. (4) that when  $\Omega$  is close to the resonance frequency, the damping obtained with a capacitive ac driving is overestimated by  $g_1^2 V_{ac}^2 \tau / [1 + (\tau\omega_{ac})^2]^3$ . This overestimation can be even higher when mixing techniques are used. So, in the strong coupling regime and in the study of nonlinear effects like the Duffing regime, the change in damping might have to be taken into account. Then, it can be expected that a change in quality factor with temperature can be simply related to, for instance, a change in the contact resistance. This can have implications also for the study of NEMS frequency noise by applying a capacitive driving close to the resonance and measuring the vibration noise spectrum as proposed by Zhang *et al.* [27].

In our particular experiment at room temperature, although the transduction is improved, this does not lead

to an improvement in the force sensitivity as the signal and thermal vibrations are amplified by an equal amount (see, for instance, Ref. [19] p. 701). Nevertheless, at a lower temperature or in systems where thermal vibrations are not the dominant source of noise, a gain in sensitivity can be expected as long as the Johnson noise from the resistance is not too high. In Ref. [26], this additional force noise is estimated to be of the same order as the thermal force noise for NW1, and an example of an improvement of the sensitivity is given. The effective temperature is also calculated, and we show that, contrary to the dc electrostatic damping, the ac mechanism leads to heating of the mechanical mode. This heating can be, in our case, as high as 4 times the room temperature.

#### IV. CONCLUSION

In conclusion, we show experimentally that applying a capacitive ac signal can improve the quality factor of a nanowire mechanical resonator and lead to self-oscillations. The enhancement of the quality factor is maximum for a driving angular frequency at  $\sqrt{2}$  the inverse of the charge relaxation time. We derive an analytical expression for this effect valid on a wide frequency range and calculate the influence of the ac driving on the force sensitivity of the device. This enhancement is not limited to single-clamped geometry or nanowires but is more suitable for a resistive sample such as a semiconducting 2D sample like MoS<sub>2</sub> or samples contacted by a tunneling resistance. The simplicity of this mechanism opens up a new path for the simultaneous driving and ultimately synchronization of NEMS array as a single ac driving can lead to self-oscillations of all the devices even when they are not perfectly identical. The coupling mechanism can be of capacitive origin or through the substrate. A demonstration of a synchronization state can be provided by simply applying a capacitive ac signal close to the resonance frequency as in Ref. [28]. This technique can be seen also as a means to measure the charge relaxation time of a NEMS in the case where cross talk makes direct electrical detection difficult.

#### ACKNOWLEDGMENTS

The authors thank the Plateforme Nanofils et Nanotubes Lyonnaise of the University Lyon1 and are especially grateful to the NOF team for their support. This work is supported by the French National Research Agency (ANR) through its Blanc Programme (FOCUS, Grant No. ANR-13-BDS10-0012-01).

- 
- [1] H. G. Craighead, Nanoelectromechanical systems, *Science* **290**, 1532 (2000).  
 [2] J. D. Teufel, Tobias Donner, Dale Li, J. W. Harlow, M. S. Allman, Katarina Cicak, A. J. Sirois, Jed D. Whittaker,

- K. W. Lehnert, and Raymond W Simmonds, Sideband cooling of micromechanical motion to the quantum ground state, *Nature (London)* **475**, 359 (2011).  
 [3] Aaron D. O'Connell, Max Hofheinz, Markus Ansmann, Radoslaw C. Bialczak, Mike Lenander, Erik Lucero, Matthew Neeley, Daniel Sank, H. Wang, M. Weides, J. Wenner, John M. Martinis, and A. N. Cleland, Quantum ground state and single-phonon control of a mechanical resonator, *Nature (London)* **464**, 697 (2010).  
 [4] Jasper Chan, T. P. Mayer Alegre, Amir H. Safavi-Naeini, Jeff T. Hill, Alex Krause, Simon Gröblacher, Markus Aspelmeyer, and Oskar Painter, Laser cooling of a nano-mechanical oscillator into its quantum ground state, *Nature (London)* **478**, 89 (2011).  
 [5] S. Perisanu, T. Barois, A. Ayari, P. Poncharal, M. Choueib, S. T. Purcell, and P. Vincent, Beyond the linear and duffing regimes in nanomechanics: Circularly polarized mechanical resonances of nanocantilevers, *Phys. Rev. B* **81**, 165440 (2010).  
 [6] A. Eichler, J. Moser, J. Chaste, M. Zdrojek, I. Wilson-Rae, and A. Bachtold, Nonlinear damping in mechanical resonators made from carbon nanotubes and graphene, *Nat. Nanotechnol.* **6**, 339 (2011).  
 [7] J. Chaste, A. Eichler, J. Moser, G. Ceballos, R. Rurali, and A. Bachtold, A mechanical mass sensor with yoctogram resolution, *Nat. Nanotechnol.* **7**, 301 (2012).  
 [8] Joel Moser, J. Güttinger, A. Eichler, María J. Esplandiu, D. E. Liu, M. I. Dykman, and Adrian Bachtold, Ultra-sensitive force detection with a nanotube mechanical resonator, *Nat. Nanotechnol.* **8**, 493 (2013).  
 [9] Guillaume Jourdan, Gauthier Torricelli, Joël Chevrier, and Fabio Comin, Tuning the effective coupling of an AFM lever to a thermal bath, *Nanotechnology* **18**, 475502 (2007).  
 [10] Benjamin Lassagne, Yury Tarakanov, Jari Kinaret, Daniel Garcia-Sanchez, and Adrian Bachtold, Coupling mechanics to charge transport in carbon nanotube mechanical resonators, *Science* **325**, 1107 (2009).  
 [11] Marc Ganzhorn and Wolfgang Wernsdorfer, Dynamics and Dissipation Induced by Single-Electron Tunneling in Carbon Nanotube Nanoelectromechanical Systems, *Phys. Rev. Lett.* **108**, 175502 (2012).  
 [12] T. Barois, A. Ayari, A. Siria, S. Perisanu, P. Vincent, P. Poncharal, and S. T. Purcell, Ohmic electromechanical dissipation in nanomechanical cantilevers, *Phys. Rev. B* **85**, 075407 (2012).  
 [13] A. Siria, T. Barois, K. Vilella, S. Perisanu, A. Ayari, D. Guillot, S. T. Purcell, and P. Poncharal, Electron fluctuation induced resonance broadening in nano electromechanical systems: The origin of shear force in vacuum, *Nano Lett.* **12**, 3551 (2012).  
 [14] Axel M. Eriksson, Marina V. Voinova, and Leonid Y. Gorelik, Nonresonant high frequency excitation of mechanical vibrations in a graphene based nanoresonator, *New J. Phys.* **17**, 033016 (2015).  
 [15] Constanze Höhberger Metzger and Khaled Karrai, Cavity cooling of a microlever, *Nature (London)* **432**, 1002 (2004).  
 [16] Yves Rocard, *Dynamique générale des vibrations* (Masson et Cie, Editeurs, Paris, 1971).

- [17] K. R. Brown, J. Britton, R. J. Epstein, J. Chiaverini, D. Leibfried, and D. J. Wineland, Passive Cooling of a Micro-mechanical Oscillator with a Resonant Electric Circuit, *Phys. Rev. Lett.* **99**, 137205 (2007).
- [18] I. Mahboob, K. Nishiguchi, H. Okamoto, and H. Yamaguchi, Phonon-cavity electromechanics, *Nat. Phys.* **8**, 387 (2012).
- [19] D. Rugar and P. Grütter, Mechanical Parametric Amplification and Thermomechanical Noise Squeezing, *Phys. Rev. Lett.* **67**, 699 (1991).
- [20] Matthew J. Thompson and David Horsley, “Parametrically amplified MEMS magnetometer,” in Proceedings of International Solid-State Sensors, Actuators and Microsystems Conference, 2009, TRANSDUCERS 2009 (2009), pp. 1194–1197.
- [21] Varun Kumar, Mohammad Mahdavi, Xiaobo Guo, Emad Mehdizadeh, and Siavash Pourkamali, “Ultra sensitive Lorentz force MEMS magnetometer with pico-tesla limit of detection,” in Proceedings of the 2015 28th IEEE International Conference on Micro Electro Mechanical Systems (MEMS) (2015), pp. 204–207.
- [22] Thomas Barois, S. Perisanu, P. Vincent, Stephen T. Purcell, and A. Ayari, Role of fluctuations and nonlinearities on field emission nanomechanical self-oscillators, *Phys. Rev. B* **88**, 195428 (2013).
- [23] Babak Sanii and Paul D. Ashby, High Sensitivity Deflection Detection of Nanowires, *Phys. Rev. Lett.* **104**, 147203 (2010).
- [24] Arnaud Gloppe, Pierre Verlot, Eva Dupont-Ferrier, Alessandro Siria, Philippe Poncharal, Guillaume Bachelier, Pascal Vincent, and Olivier Arcizet, Bidimensional nano-optomechanics and topological backaction in a non-conservative radiation force field, *Nat. Nanotechnol.* **9**, 920 (2014).
- [25] P. Vincent, S. Perisanu, A. Ayari, M. Choueib, V. Gouttenoire, M. Bechelany, A. Brioude, D. Cornu, and S. T. Purcell, Driving self-sustained vibrations of nanowires with a constant electron beam, *Phys. Rev. B* **76**, 085435 (2007).
- [26] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevApplied.6.014012> for experimental resonance peaks, dc damping, and calculation for dc-ac electrostatic damping and force sensitivity.
- [27] Yaxing Zhang, J. Moser, J. Güttinger, A. Bachtold, and M. I. Dykman, Interplay of Driving and Frequency Noise in the Spectra of Vibrational Systems, *Phys. Rev. Lett.* **113**, 255502 (2014).
- [28] Thomas Barois, S. Perisanu, Pascal Vincent, Stephen T. Purcell, and Anthony Ayari, Frequency modulated self-oscillation and phase inertia in a synchronized nanowire mechanical resonator, *New J. Phys.* **16**, 083009 (2014).