Mechanical nano-resonators at ultra-high frequency and their potential applications

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Ultrafast nanomechanical resonators have attracted significant attention in research, and have promised a wide range of future applications. Choosing appropriate materials, optimizing fabrication processes, applying ultra-sensitive ultra-high-frequency readout techniques and adapting such devices to a variety of applications are all important subjects to address. This article reviews the current status of this field, and discusses future development directions.

Introduction

Nearly half a century has elapsed since the first envisaging of the concept of nanotechnology by Richard Feynman, at his lecture at a meeting of the American Physical Society in 1959.[1,2] Generations of scientists and engineers have subsequently been inspired by the study of tiny machines at the nanometre scale.[3] Extensive research results have accumulated from long-lasting commitments, so as to take us closer to the ability to mass-produce machines on an atomic scale.

The promise of novel functionalities has been a critical aspect of nanoscience and nanoengineering.[3] This is especially true with small mechanical systems. When we look at inventions from ancient times, from the abacus to clocks, it makes sense that the first computing machines ever built were indeed mechanical,[4] in contrast to current electronic dominance in the modern computing world. With the emergence of ultrafast micro- and nano-electromechanical systems (MEMS/ NEMS), one speculates whether mechanical computing might return in a brand new perspective, drawing deeper understanding of physical principles and creating novel technology.[5] A very significant direction of development is the fabrication and testing of ultrafast nanomechanical resonator devices, the topic of this article.

Materials and fabrication

For the doubly clamped beam geometry of resonator construction, the fundamental mode resonance frequency of the beam can be estimated by

$$f_0 = 1.03\sqrt{\frac{E}{\rho}}\frac{t}{l^2}, \qquad (1)$$

where E is Young's modulus of the material, ρ is the mass density, t is the thickness of the beam along the direction of motion, and l is the length of the beam. Materials with a higher Young's modulus and lower mass density are more desirable for fabrication of ultra-high-frequency nanomechanical resonator devices. Table 1 lists these important properties for a few commonly used NEMS materials, including silicon,[6,7] the traditional material for the semiconductor industry, and a few other examples of relatively newer materials under current investigation.[8–11]

Table 1. Properties of NEMS materials.

Material	Young's modulus (GPa)	Mass density (10^3 kg/m^3)	Ref.
Si	110	2.4	6
SiC	440	3.2	8
AlN	345	3.3	9
Diamond	1000	3.5	10

Another important parameter characterizing resonator performance is its spring constant, which can be calculated by

$$k = 4\pi^2 m f_0^2, \qquad (2)$$

where m is the effective mass of the resonator.

From Equation (1), we can see that ultra-high-frequency devices can be achieved by either making them short and wide, or by reducing the size of the mechanical device by the same linear ratios in all three dimensions. The latter approach is considered more desirable for many purposes, since the spring constant of the resonator device, calculated by Equation (2), will be lower for beams with a larger aspect ratio. A lower spring constant provides better responsivity, namely, a larger induced displacement for a specific applied force.

While the detailed theoretical studies and modelling of nano-resonators is beyond the scope of this brief review, these are absolutely critical for the development of nanodevices, and for the advancement of nanotechnology, in general.

NEMS devices can be made by both top-down methods through electron-beam lithography, or bottom-up strategies starting from self-assembled nanostructures, and then linking them with the outside world. Typical process flows for both schemes are illustrated in Fig. 1.

Top-down methods start from a thin-film device-layer on top of a substrate, with a sacrificial layer between. Device patterns are defined by nanolithography techniques, usually a combination of photolithography and electron beam lithography. The pattern is then transferred to a metallic etch mask. The device-layer surface that is not covered by the mask will be etched away anisotropically, followed by a controlled isotropic etch of the sacrificial layer, to suspend the beam over the substrate. The beam is clamped at both ends by larger support structures.

Alternatively, bottom-up nanolithography starts from a nanowire, nanotube, or a single molecule, located on top of a sacrificial layer above the substrate. Electrodes, which also act as support pads for a suspended mechanical beam, are created by electron beam lithography. A timed isotropic etch of the sacrificial layer then suspends the nanowire beam.

Both methods are schematically illustrated in Fig. 1. For specific experiments, there could be variations of process details. These are only general outlines.

Ultra-high-frequency readout

In order to have an ultra-high-frequency nanomechanical resonator, we not only have to construct the device, but we also have to devise sensitive measurement strategies to communicate with these tiny entities. To date, two transduction methods have been demonstrated to be quite successful for the purpose of communicating with ultra-high-frequency NEMS devices. Both methods require the mechanical beam to be electrically conductive. A thin metal layer is deposited on top of the mechanical structure, to provide electrical conductivity in cases where the material is an insulator, or is highly resistive.

Magnetomotive transduction can be used to excite the nanostructure into resonance for testing.[6,8,12–15] The sample is loaded into a vacuum, and mounted so that the surface normal is aligned with the direction of the magnetic field. An RF

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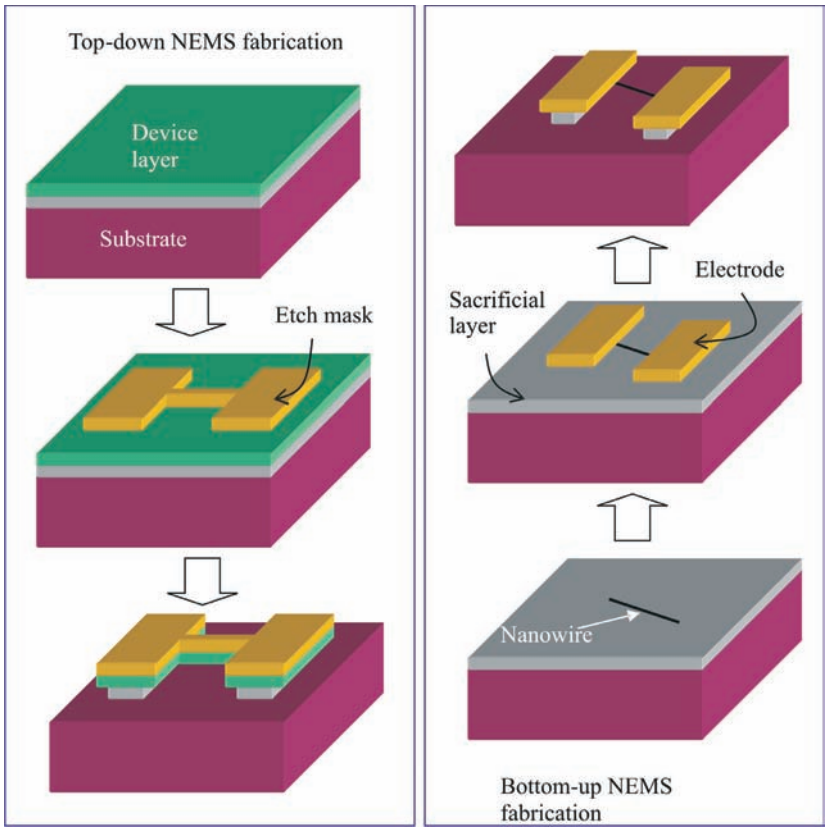

Fig. 1. Schematic process flow diagrams for top-down and bottom-up NEMS fabrication processes.

current through the conducting layer of the beam generates an RF force to flex the beam. The frequency of the RF drive is swept. Resonant motion is induced when the driving frequency matches the in-plane fundamental resonance mode frequency of the beam. Such motion cuts the magnetic field lines, and generates an EMF voltage peak at the mechanical resonance frequency. This EMF is amplified and measured by a network analyser.

Another successful method for ultra-high-frequency nanomechanical detection is optical,[7] through detection of variations in scattered light arising from the motion of the nanomechanical structure. In this case, the motion is excited capacitively.

Both methods are currently under laboratory development. Important achievements so far are depicted in Fig. 2. Integrated versions of these concepts, combining mechanical, electronic, magnetic and optical devices onto the same chip, are under consideration. This is an important step towards practical applications.

Applications of UHF NEMS

NEMS offer promise for a variety of novel applications. We list a few of the important areas where their potential lies, without giving details.

Sensitive mechanical charge detectors have recently been demonstrated by Cleland and Roukes.[13] Mechanical devices for high-frequency signal processing are providing new, simplified configurations for communications systems.[16] Ultra-sensitive nanomechanical mass detection has been demonstrated by several prominent research groups.[17–19] The prospects of biological imaging, based upon single-spin magnetic resonance spectroscopy, now appears feasible via mechanical detectors.[20] Entirely new approaches to quantum measurement should be achievable with high-frequency nanomechanical systems, cooled to low temperatures. [21–24]

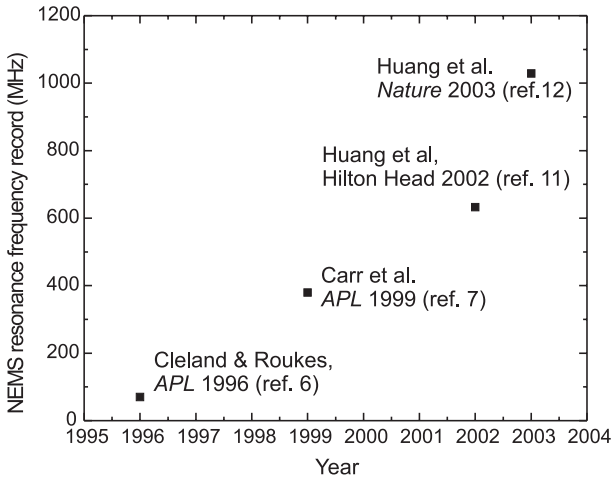

Fig. 2. A roadmap towards microwave-frequency nanomechanical resonators. Important milestones for achieving higher frequency of operation by NEMS devices are shown.

Future directions

It is still an open project to make and test mechanical resonators in the deep-nano regime with a typical size of a few nanometres. These can be fabricated by either top-down electron-beam lithography with state-of-the-art facilities, or bottom-up schemes, such as nano-imprinting[25] and self-assembling synthesis.[26–28] At such dimensional scale, it should be possible to make microwave mechanical resonators with lower spring constants, thus achieving greater responsivity. Such characteristics would make a broad range of applications more plausible. Important examples of related application fields include (but are not limited to) ultrasensitive mass detection, bioNEMS sensing, magnetic resonance force microscopy (MRFM) and spintronics.[5]

At even higher frequency, and on an even smaller scale, mechanical resonators may cross the boundary between classical mechanics and quantum mechanics.[5] Development will require both scientific advancement and strong engineering support.

For an emerging field with a short history of less than fifty years, it has been a process of seeing predictions becoming reality. It has also been a process of evolving from fundamental science into the realm of practical implementation. The prospects of such potential applications have been the driving force for nanotechnology to move out of the research labs within just a few elite research institutions, and into a worldwide endeavour.

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1. Feynman R.P. (1959). Plenty of room at the bottom. Online: www.its.caltech.edu/~feynman/plenty.html
2. Feynman R.P. (1984). Tiny machines. In *Feynman*

Lecture on Nanotechnology, videotape, Caltech, Pasadena, CA.
3. Roukes M.L. (2001). Plenty of room indeed. *Sci. Am.* **285**(3), 48–57.
4. Swade D. (2001). *The Difference Engine: Charles Babbage and the Quest to Build the first Computer.* Viking-Penguin, New York.
5. Roukes M. L. (2001). Nanoelectromechanical systems face the future. *Physics World* **14**, 25–31.
6. Cleland A.N. and Roukes M.L. (1996). Fabrication of high frequency nanometer scale mechanical resonators from bulk Si crystals. *Appl. Phys. Lett.* **69**, 2653–2655.
7. Carr D.W., Evoy S., Sekaric L., Craighead H.G. and Parpia J.M. (1999). Measurement of mechanical resonance and losses in nanometer scale silicon wires. *Appl. Phys. Lett.* **75**, 920–922.
8. Yang Y.T. *et al.* (2001). Monocrystalline silicon carbide nanoelectromechanical systems. *Appl. Phys. Lett.* **78**, 162–164.
9. Cleland A.N., Pophristic M. and Ferguson I. (2001). Single-crystal aluminum nitride nanomechanical resonators. *Appl. Phys. Lett.* **79**, 2070–2072.
10. Sekaric L. *et al.* (2002). Nanomechanical resonant structures in nanocrystalline diamond. *Appl. Phys. Lett.* **81**, 4455–4457.
11. Huang X.M.H. *et al.* (2002). In *Solid-State Sensor, Actuator and Microsystems Workshop 2002*, pp. 368–369. Hilton Head, SC.
12. Huang X.M.H., Zorman C.A., Mehregany M. and Roukes M.L. (2003). Nanodevice motion at microwave frequencies. *Nature* **421**, 496–498.
13. Cleland A.N. and Roukes M.L. (1998). A nanometre-scale mechanical electrometer. *Nature* **392**, 160–162.
14. Cleland A.N. and Roukes M.L. (1999). External control of dissipation in a nanometer-scale radio-frequency mechanical resonator. *Sens. Actuator A-Phys.* **72**, 256–261.
15. Ekinci K.L., Yang Y.T., Huang X. M.H. and Roukes M.L. (2002). Balanced electronic detection of displacement in nanoelectromechanical systems. *Appl. Phys. Lett.* **81**, 2253–2255.
16. Nguyen C.T.C., Katehi L.P.B. and Rebeiz G.M. (1998). Micromachined devices for wireless communications. *Proc. IEEE* **86**, 1756–1768.
17. Lavrik N.V. and Datskos P.G. (2003). Femtogram mass detection using photothermally actuated nanomechanical resonators. *Appl. Phys. Lett.* **82**, 2697–2699.
18. Ilic B. *et al.* (2004). Attogram detection using nanoelectromechanical oscillators. *J. Appl. Phys.* **95**, 3694–3703.
19. Ekinci K.L., Huang X.M.H. and Roukes M.L. (2004). Ultrasensitive nanoelectromechanical mass detection. *Appl. Phys. Lett.* **84**, 4469–4471.
20. Sidles J.A., Garbini J.L., Bruland K.J., Rugar D., Zuger O., Hoen S. and Yannoni C.S. (1995). Magnetic-resonance force microscopy. *Rev. Mod. Phys.* **67**, 249–265.
21. Caves C.M., Thorne K.S., Drever R.W.P., Sandberg V.D. and Zimmermann M. (1980). On the measurement of a weak classical force coupled to a quantum-mechanical oscillator. 1, Issues of principle. *Rev. Mod. Phys.* **52**, 341–392.
22. Bocko M.F. and Onofrio R. (1996). On the measurement of a weak classical force coupled to a harmonic oscillator: Experimental progress. *Rev. Mod. Phys.* **68**, 755–799.
23. Armour A.D., Blencowe M.P. and Schwab K.C. (2002). Entanglement and decoherence of a micromechanical resonator via coupling to a Cooper-pair box. *Phys. Rev. Lett.* **88**, 148301.
24. Cho A. (2003). Researchers race to put the quantum into mechanics. *Science* **299**, 36–37.
25. Melosh N.A. *et al.* (2003). Ultrahigh-density nanowire lattices and circuits. *Science* **300**, 112–115.
26. Iijima S., Ichihashi T. and Ando Y. (1992). Pentagons, heptagons and negative curvature in graphite microtubule growth. *Nature* **356**, 776–778.
27. Amelinckx S. *et al.* (1994). A formation mechanism for catalytically grown helix-shaped graphite nanotubes. *Science* **265**, 635–639.
28. Saito R., Dresselhaus G. and Dresselhaus M.S. (2001). *Physical Properties of Carbon Nanotubes.* Imperial College Press, Singapore.