Nanoelectromechanical Systems

Michael L. Roukes
Condensed Matter Physics, 114-36
California Institute of Technology
Pasadena, CA 91125 USA

SUMMARY

Nanoelectromechanical systems, or NEMS, are MEMS scaled to submicron dimensions [1,2,3]. In this size regime, it is possible to attain extremely high fundamental frequencies while simultaneously preserving very high mechanical responsivity (small force constants). This powerful combination of attributes translates directly into high force sensitivity, operability at ultralow power, and the ability to induce usable nonlinearity with quite modest control forces. In my presentation I shall provide an introduction to NEMS and will outline several of their exciting initial applications.

Keywords: Nanomechanical Systems, NEMS.

INTRODUCTION

The promise of NEMS is immense, however a stiff entry fee exists at the threshold to this new domain: new engineering is crucial to realizing their full potential. Certain mainstays in the methodology of MEMS will, simply, not scale usefully into the regime of NEMS. The most problematic of issues stem from the minute size of the devices compared to their embedding circuitry, their extreme surface-to-volume ratios, and their unconventional "characteristic range of operation". These give rise to some of the principal current challenges in developing NEMS. Most prominent among these are the need for: ultrasensitive, very high bandwidth displacement transducers; an unprecedented control of surface quality and adsorbates; novel methods of efficient actuation at the nanoscale, and precise, robust, and routinely reproducible new approaches to surface and bulk nanomachining. I shall attempt to survey each of these aspects in turn, and will conclude by describing some exciting prospects in this new field.

NEMS have a host of intriguing attributes. They offer access to fundamental frequencies in the microwave range; Q's, i.e. mechanical quality factors, in the tens of thousands (and quite possibly much higher); active masses below the femtogram range; force sensitivities at the attonewton level [4]; mass sensitivity at the level of individual molecules, heat capacities far below a "yoctocalorie" [5] — this list goes on. These attributes spark the imagination, and a flood of ideas for new experiments and applications ensues. Of course, in time this initial enthusiasm gives way to deeper reflection, and a multitude of new questions and concerns emerge. Prominent among these is what will be our ultimate ability for optimally controlling and engineering these miniature systems. Clearly, the characteristic parameters of NEMS are extreme by all current measures.

Some of the most important questions in NEMS relate to their engineering: How shall transducers and actuators be realized at the nanoscale? How shall surface properties be controlled? How can reproducible fabrication be attained?

As we move forward in the development of NEMS it will become increasingly apparent what aspects will be susceptible to improvement through systematic engineering, and what immutable limits are imposed by their fundamental physics. However, certain issues are already clear at the outset. I will try to summarize those that seem most apparent at this juncture.

Multiterminal Mechanical Devices

The attributes of NEMS described in the next section make clear that we should be envisioning applications for electromechanical devices with response times and operating frequencies that are as fast as most of today's electron devices. Furthermore, multiterminal electromechanical devices are possible -i.e. two-, three-, four-ports, etc. - in which electromechanical transducers provide input stimuli (i.e. signal forces), and read out a mechanical response (i.e. output displacement). At additional control terminals, electrical signals – either quasi-static or time-varying – can be applied, and subsequently converted by the control transducers into quasi-static or time-varying forces to perturb the

Table I: Fundamental Frequency vs. Geometry for SiC, [Si], and (GaAs) Mechanical Resonators.

Boundary Conditions	Resonator Dimensions ($L \times w \times t$, *in* μm)			
	$100 \times 3 \times 0.1$	$10 \times 0.2 \times 0.1$	$1 \times 0.05 \times 0.05$	$0.1 \times 0.01 \times 0.01$
Both Ends Clamped or Free	*120 KHz* [77] (42)	*12 MHz* [7.7] (4.2)	*590 MHz* [380] (205)	*12 GHz* [7.7] (4.2)
Both Ends Pinned	*53 KHz* [34] (18)	*5.3 MHz* [3.4] (1.8)	*260 MHz* [170] (92)	*5.3 GHz* [3.4] (1.8)
Cantilever	*19 KHz* [12] (6.5)	*1.9 MHz* [1.2] (0.65)	*93 MHz* [60] (32)	*1.9 GHz* [1.2] (0.65)

properties of the mechanical element in a controlled, useful manner.

There is an important point to be made regarding the "orthogonality" attainable between the input, output and (the possibly multiple) control port(s). Different physical processes of electromechanical transduction available make it conceivable to achieve highly independent interaction between these ports, i.e. to have each of these strongly interacting with the mechanical time-varying stimuli when frequency conversion is the goal, this orthogonality can be provided by tuned (narrowband) transducer response to select input and output signals from control (e.g. pump) signals.

Important Attributes of NEMS

Frequency. Table I displays attainable frequencies for the fundamental flexural modes of thin beams, for dimensions spanning the domain from MEMS (leftmost entries) to deep within NEMS. The mode shapes, and hence the force constants and resulting frequencies, depend upon the way the beams are clamped; Table I lists the results for the simplest, representative boundary conditions along three separate rows. The last column represents dimensions currently attainable with advanced electron beam lithography. Of course, even smaller sizes than this will ultimately become feasible; clearly the ultimate limits are reached only at the molecular scale. Nanodevices in this ultimate limit will have resonant frequencies in the THz range, i.e. that characteristic of molecular vibrations.

Each entry is in three parts, corresponding to structures made from silicon carbide, silicon, and gallium arsenide. These materials are of particular interest to my group, and are among the "standards" within MEMS. They are materials available with extremely high purity, as monocrystalline layers in epitaxially grown heterostructures. This latter aspect yields dimensional control in the "vertical" (out of plane) dimension at the monolayer level. This is nicely compatible with the lateral dimensional precision of electron beam lithography that approaches the atomic scale. The numbers should be considered loosely as "typical"; they represent rough averages for the various commonly used crystallographic orientations.

It is particularly notable that for structures of the same dimensions, Si yields frequencies a factor of two, and SiC a factor of three, higher than that obtained with GaAs devices [6]. This increase reflects the increased phase velocity, $\sqrt{(E/\rho)}$, in the stiffer materials. Here E is Young's modulus, and ρ is the mass density.

One might ask at what size scale does continuum mechanics break down and corrections from atomistic behavior emerge. Molecular dynamics simulations for ideal structures appear to indicate that this becomes manifested only at the truly molecular scale, of order tens of lattice constants in cross section [7]. Hence, for most initial work in NEMS, it appears that continuum approximation will be adequate. However a very important caveat must be kept in mind. The frequencies in Table 1 are for structures with zero internal strain. In bi- or multi- layered structures (common for devices that include transducers) this may actually be the exception rather than the rule [8]. Even for homogenous mechanical devices, e.g. those patterned from doped semiconductor materials, surface nonidealities in nanoscale devices may impart significant corrections to this simple picture.

Quality Factor. The Q's attained to date for NEMS in moderate vacuum, are in the range from 10^3 to 10^5. This greatly exceeds those typically available from electrical resonators. This small degree of internal dissipation (D=1/Q) impart to NEMS their low operating power levels and high attainable force sensitivity. For signal processing devices, high Q directly translates into low insertion loss [9].

One might expect nanomechanical resonators fabricated from ultrapure, single crystal semiconductor materials to have extremely high quality factors. But in our group similar Q's have been obtained for NEMS with resonant frequencies in the 20 MHz range from polycrystalline silicon. This trend holds at lower frequencies for very thin quasi-amorphous, low-strain silicon nitride devices. There is a rough trend that seems to be manifested in mechanical resonators in general – Q seems to decrease

with increasing surface-to-volume ratio. This appears to hold from resonators that are truly macroscopic in size, to those well within the domain of NEMS.

It is important to note that large Q does imply a reduction of bandwidth, yet this need not be deleterious to performance for two reasons. First, feedback damping, which can be applied without introduction of significant additional noise, may be useful to increase bandwidth as desired. Second, for resonators operating at 1GHz, even with extremely high Q's of order 100,000, bandwidths of order 10KHz are obtained, already sufficient for various narrow band applications.

Characteristic Operating Power Level. Applications of NEMS resonators will typically involve the use of a specific mode. A rough understanding of the minimum operating power levels using this mode can be obtained by dividing the thermal energy, k_BT, by the characteristic time scale for energy exchange between the mode, at frequency ω_0, and its surroundings (i.e. "the environment"). The time scale is set, roughly, by the "ring-up" or "ring-down" time of the resonator, $\tau = Q/\omega_0$. This simple estimate for the minimum power is then given by the ratio, $P_{min} \sim k_BT\omega_0/Q$. It represents the signal power that must be fed to the system to drive it to an amplitude equal to the thermal fluctuations.

This minimum power is remarkably small for NEMS. For device dimensions accessible today via electron beam lithography, the characteristic level is of order ten attowatts (10^{-17} W). Even if we multiply this by a factor of a million, to achieve robust signal-to-noise ratios, and then further envision a million such devices acting in concert to realize some sort of future NEMS-based mechanical signal processing or computation system — the total system power levels still are only of order 1 μW. This is six orders of magnitude smaller than power dissipation in current systems of similar complexity based upon digital devices that work solely in the electrical domain.

Active Mass. Only a fraction of the total resonator's mass is involved in its motion. For beams or cantilevers, multiplying the total mass by the integral of a normalized function describing the mode shape yields a measure of the active mass. For a doubly-clamped beam operating in fundamental mode, this turns out to be about half (actually, ~ 0.523) of the total mass of the beam.

Mass Sensitivity. For NEMS resonators, their minuscule active masses compounded with their high Q yields an extreme sensitivity to added mass. We can make a simple estimate of the added mass required to shift the resonant frequency by its halfwidth, i.e. $\omega_0 \rightarrow (\omega_0 + \partial\omega_0)$ where $\partial\omega_0 \sim \omega_0/(2Q)$. This is simply given by multiplying $\partial\omega_0$ by the inverse of what one can call the frequency "responsivity" to added mass, $\partial M|_{\min} \sim (\partial\omega_0/\partial m)^{-1}\,\partial\omega_0$.

Approximating the resonator mode as a simple harmonic oscillator one finds

$$\partial M|_{\min} \sim (2m/\omega_0)(\omega_0/2Q) \sim m/Q .$$

Here m is the "active mass" of the resonator. This leads to remarkably high mass sensitivities. For the smallest beams envisioned in the near term, mass resolution at the level of a few hundred Daltons ($1\text{D} = 1.7\text{x}10^{-24}$ g) is obtained. Clearly it is possible to resolve shifts of the centroid of the line shape far smaller than the resonance linewidth. Hence, with these smallest NEMS, it appears to be completely feasible to resolve frequency shifts for added masses as small as 1D [10].

This mass sensitivity, however, can be double-edged sword; on the one hand it offers unprecedented sensitivity for mass sensing, but this sensitivity can also make device reproducibility challenging, even elusive. We have found that it places quite stringent requirements on the cleanliness of fabrication techniques with regard to processing residues, etc.

It is also clear that adsorbates on NEMS will play an important role in their properties. We are embarking upon a program to investigate NEMS placed in UHV at room temperature, to allow studies that commence with careful surface preparation cycles. Recent work at Stanford has shown improvement of resonator properties after a high temperature, annealing step in-vacuo [11].

CONCLUSIONS

NEMS offer access to a parameter space for sensing and fundamental measurements that is unprecedented and intriguing. Taking full advantage of it will stretch our collective imagination, as well as our current methods and "mindsets" in micro- and nanodevice science and technology. It seems certain that many new applications will emerge from this new field. Ultimately, the nanomechanical systems outlined here will yield to true nanotechnology. By the latter I envisage reproducible techniques allowing mass-production of devices of arbitrary complexity, that comprise, say, a few million atoms - each of which is placed with atomic precision [12]. Clearly, realizing the "Feynmanesque" dream will

take much sustained effort in a host of laboratories. Meanwhile, NEMS, as outlined here, can today provide the crucial scientific and engineering foundation that will underlie this future nanotechnology.

REFERENCES

[1] M.L. Roukes, "Nanoelectromechanical Systems Face the Future", Physics World, **14**, 25, 2001.
See: **http://www.physicsweb.org/bestof/cond-mat**

[2] M.L. Roukes, "Nanoelectromechanical Systems" Technical Digest of the 2000 Solid-State Sensor and Actuator Workshop, Hilton Head Isl., SC, 6/4-8/2000, Transducer Research Foundation, Cleveland (2000) ISBN 0-9640024-3-4.
See: **http://arxiv.org/pdf/cond-mat/0008187**

[3] A.N. Cleland and M.L. Roukes, "Fabrication of high frequency nanometer scale mechanical resonators from bulk Si substrates", Appl. Phys. Lett., **69**, 2653 (1996).

[4] T.D. Stowe, K. Yasumura, T.W. Kenny, K. Wago and D. Rugar, "Attonewton force detection using ultrathin silicon cantilevers", Appl. Phys. Lett. **71**, 288 (1997).

[5] M.L. Roukes, "Yoctocalorimetry: Phonon Counting in Nanostructures", Physica B: Condensed Matter **263-264**, 1 (1999).

[6] Y.T. Yang, K.L. Ekinci, X.M.H. Huang, L.M. Schiavone, C. Zorman, M. Mehregany, and M.L. Roukes, "Monocrystalline Silicon Carbide Nanoelectromechanical Systems", Appl. Phys. Lett. **78**, 162 (2001).

[7] R.E. Rudd and J.Q. Broughton, "Coarse-grained molecular dynamics and the atomistic limit of finite elements", Phys. Rev. B **58**, R5893 (1998).

[8] K.L. Ekinci, X.-M. Huang, and M.L. Roukes, "Frequency tuning and internal strain in NEMS and MEMS devices", to be published.

[9] C.T.-C. Nguyen, L.P.B Katehi, G.M. Rebeiz, "Micromachined devices for wireless communications", Proc. IEEE **86**, 1756 (1998).

[10] K.L. Ekinci, X.M.H. Huang, and M.L. Roukes, "Ultrasensitive Nanoelectromechanical Mass Sensing", to be published.

[11] K.Y. Yasumura, T.D. Stowe, E.M. Chow, T. Pfafman, T.W. Kenny, B.C. Stipe, and D. Rugar, "Quality factors in micron- and submicron-thick cantilevers", Journ. Micromech. Syst. **9**, 117 (2000).

[12] R.P. Feynman, "There's plenty of room at the bottom", American Physical Society Meeting, Pasadena, CA, 29 Dec. 1959; originally published in Caltech's Engineering and Science magazine, Feb. 1960; reprinted as R.P. Feynman, "Infinitesimal Machinery," Journal of Microelectromechanical Systems, **2**, 1 (1993).