Position Paper: Nanotechnology in Microsystems: Prospects and Challenges of Nanomechanical Devices

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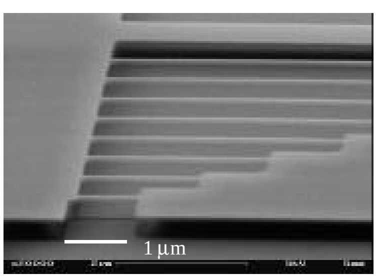
Microelectromechanical systems (MEMS) have revolutionized the microelectronics industry by providing a new range of functionalities previously unavailable from traditional devices. Such new functionalities are of high interest in fields such as biotechnology, communications, physicochemical sensing, and safety devices. Further device reduction towards *nanomechanical* systems (nems) will bestow fascinating new functionalities to integrated microsystems (Fig. 1).

The high resonant frequencies of NEMS open fascinating possibilites for the development of highly efficient RF electromechanical filters and oscillators. [1] Carr, Evoy *et al* have indeed reported the fabrication and electrostatic actuation of 50 nm-wide single crystal silicon beams with record resonant frequencies reaching 380 MHz. [2] The much smaller masses of NEMS also open the door to ultrasenstive force detecting devices. Roukes *et al* have recently reported a NEMS-based electrometer that should ultimately reach sensitivities of the order of 10^{-6}e $Hz^{-0.5}$, comparable to charge-detection capabilities of cryogenic single-electron transistors. [3] Moving towards molecular-scale dimensions, De Heer *et al* have reported electrostatically-induced mechanical resonances in multiwalled carbon nanotubes. The quality factors of the nanotube resonances were on the order of 500. Their experimental framework has successfully been deployed as a nanobalance for the weighing of nanoscopic particles, and also to a nanotube-based Kelvin probe [4].

a) 

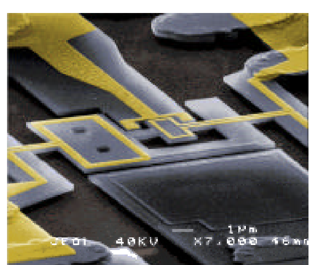
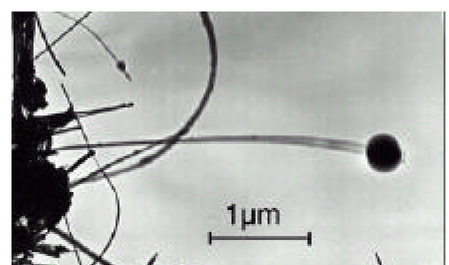
b) 
c) 

Fig. 1. State of the art NEMS. a) 50 nm-wide Si beams resonating at 10-400 MHz (Carr, Evoy, *et al*, Cornell Univ. [1]. b) Nanofabricated paddle as ultrasensitive electrometer (Roukes et al, Cal Tech [3]) c) Carbon nanotube (1-5 MHz range resonances) as a ultrasensitive nanobalance (De Heer et al., Ga Tech [4])

Issues ranging from materials science to industrial amenability hinder the deployment of NEMS. For instance, internal dissipation is known to increase steadily with reduced dimensions, severely limiting the quality factors and potential bandwidth of such devices. Such high internal losses are the combination of both extrinsic and intrinsic issues that must be well understood for the optimization of resonator quality, and for the experimental access to fundamental mesoscopic mechanical phenomena. For instance, the Cornell studies strongly suggested that some interface between some damaged/oxidized layer and the crystalline core was responsible for most of the internal friction in MHz-range silicon NEMS. Clearly departing from bulk materials paradigms, this observation demonstrates the relevance of renewing our understanding of mechanical phenomena at such MHz frequencies and nanometer scale dimensions.

However, even armed with a solid background in the dynamics and mesoscopic materials science, such *nano*systems demand a drastic revision of design paradigms. First and foremost, they require a skilled integration of nano- and microfabrication processes. The lack of a sensitive transduction mechanism also seriously hinders their practical deployment. Finally, integration with logical circuitry represents technological challenges that must carefully be addressed. For instance, a RF electrical signal has yet to be directly extracted from an integrated NEMS. This functionality can only be provided through the skillful integration of amplifying RF circuitry.

"Traditional" microelectronic and optoelectronic systems have been the subject of continuous device dimension reduction. Dimension reduction indeed universally provides previously unavailable functionalities: quantum phenomena, reduction of threshold current, and tunability in optoelectronic devices; enhanced speeds, and reduction of power consumption in microelectronic systems. Such progression is *de facto* applicable to mechanical systems, as dimension reduction again bestows new functionalities that are unavailable from larger systems: higher operating frequencies, potentially greater durability, ultrasensitive force detection, and deployment of novel experimental toolbox for nanostructural studies of materials. Furthermore, the revolution of fabrication and design paradigms that NEMS represents for integrative systems is, in my humble debatable opinion, not as drastic as what molecular electronics calls for in the microelectronics area, for instance.

Nanotechnology has been recognized as one of the top research priorities of this nation by a recent inter-agency panel. [5] The Clinton administration has recently announced the inception of a 475 M$ nanotechnology initiative aimed at enhancing research in such areas. [6] Solely referring to a length scale, *nanotechnology* is indeed an extremely potent and far-reaching term that encompasses a wide range of range of equally important areas. I humbly suggest to this MEMS panel to reflect on, and delineate the relevance, impact and serious prospect of "nanotechnology" to their field. As far as the current topic is concerned, I humbly encourage to NSF to better define and further support applications of *nanomechanical* systems in specific device-oriented programs of the Division of Electrical and Communication Systems and the Division of Civil and Mechanical Systems, as well as the Division of Materials Research.

[1] C.T.-C. Nguyen, “Micromechanical components for miniaturized low-power communications (invited plenary),” 1999 IEEE MTT-S International Microwave Symposium RF MEMS Workshop, Anaheim, California, June 18, 1999, pp. 48-77.

[2] D.W. Carr, S. Evoy, L. Sekaric, J.M. Parpia, and H.G. Craighead, "Measurement of mechanical resonances and losses in nanometer-scale silicon wires", Appl. Phys. Lett 75, 920 (1999).

[3] A. N. Cleland and M.L Roukes, "A nanometre-scale mechanical electrometer", Nature **392**, 160 (1998).

[4] P. Poncharal, Z.L Wang, D. Ugarte, and W.A De Heer, "Electrostatic deflections and electromechanical resonances of carbon nanotubes", Science **283**, 1513 (1999).

[5] WTEC Panel Report on Nanostructure Science and Technology: R&D Status and Trends in Nanoparticles, Nanostructured Materials, and Nanodevices, edited by R.W. Siegel, E. Hu, M.C. Roco, August 1999. Available at http://www.itri.loyola.edu/nano/final/

[6] Executive Office of the President of the United States, Office of Management and Budget "Budget of the United States Government-Fiscal Year 2001", p. 100