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# Nano electromechanical systems: Its features, Challenges and Carbon Nanotubes

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***Abstract:*** *With the study of nanoscale effects, Nano electromechanical systems (NEMS) present interesting and unique characteristics, which diverges greatly from their predecessor micro-electromechanical systems (MEMS). When MEMS are scaled to submicron dimension[5], NEMS are formed. NEMS are able to preserve very high mechanical responsivity (small force constants); the quality (Q) factors of resonance are remarkly higher than those of electrical resonant cavity (i.e. in range $Q = 10^3 – 10^5$) and acquire tremendously high fundamental frequencies concurrently. These features are responsible for technological applications like signal processing components, actuators and ultrafast sensors. However, some technological fundamental challenges still exist due to NEMS optimization. This paper aims at to review NEMS by introducing the challenges quickly in the growing field. Along with this a brief discussion on Carbon nanotubes is also discussed.*
***Keywords:*** *Nano electromechanical system, attribute, transducers, carbon nanotubes.*

## I. Introduction:

Those electromechanical devices that have dimensions of a few nanometers are called Nano electromechanical systems (NEMS). They have unique features, which are different from micro electromechanical (MEMS). NEMS have a host intriguing attributes. Let us consider an example, devices based on NEMS can have basic frequencies in microwave range ( ~ 100 GHz) [29]; force sensitivity at the attonewton level; mass sensitivity up to attogram [6] and following sub attogram [36] levels; low–energy dissipation; active mass in the femtogram range; heat capacities large below a “Yactocalorie” [20]; utmost high integration level of about $10^{12}$ elements centimeter per square [29].
All these different features of these devices give rise to application like biological sensors, ultrahigh-frequency resonators, chemical and force sensors.

The behaviour of energetic parts is the main reason for the fascinating properties of NEMS. The materials used for the active components lists carbon nanotubes, Gold, platinum, silicon and silicon carbide. For last few decades, silicon is widely used for integrated circuit (IC) technology as well as for NEMS. However, because of the dominance of the surface oxidation and reformation, ultrasmall silicon based NEMS fail to have desired high-quality factors. Since carbon nanotubes have one–dimensional structures with outstanding mechanical and electrical properties, perfect terminated surfaces, high-aspect ratio, carbon nanotubes can well implement the ideas of NEMS. Due to the growth in properties, they have become the most favourable building blocks of the coming generation Fig.1. It is the scanning electron microscopy (SEM) image of a double-clamped resonator fabricated from a heavy and single crystal substrate.

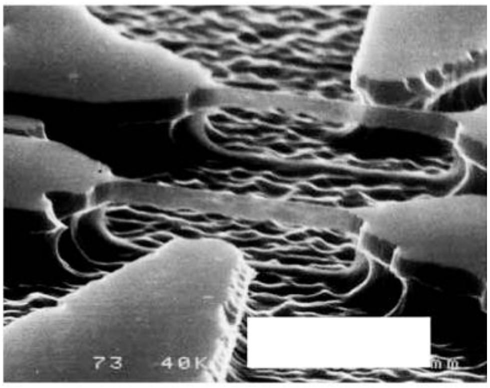


**Figure1.** SEM Image of an undercut Si beam, with length of 7.7 _m, width of 0.33 _m and height of 0.8 _m.Reprinted with permission from [3], A. N. Cleland and M. L. Roukes, *Appl. Phys. Lett.* 69, 2653 (1996). c 1996,American Institute of Physics.

This paper first discusses carbon nanotubes then attributes of NEMS.

**Carbon Nanotubes:**

They were discovered by Sumino Iijima in 1991 and are a part of family of fullerene structure [27]. A sheet of graphite rolled into a cylinder is analogous to carbon nanotubes; they exist as a macromolecule of carbon. The atomic arrangement (how sheets of graphite are rolled to form a cylinder), their length and their diameter are important factors on which properties of nanotubes depends. They are thermally stable, chemically insert, light, flexible and stiff. Due to helicity of the tube, these nanotubes can be either metabolic or semi-conducting. They may exist single- walled or multiwalled structures. Multiple concentric single–walled carbon nanotubes (SWNTS) fig.2(A) are the composition of multi walled carbon nanotubes (NWNTS) fig.2(B). These grahite layers interact with each other via Vander Waals forces since the distance between neighbouring graphite layers is $\sim 0.34$ nm.

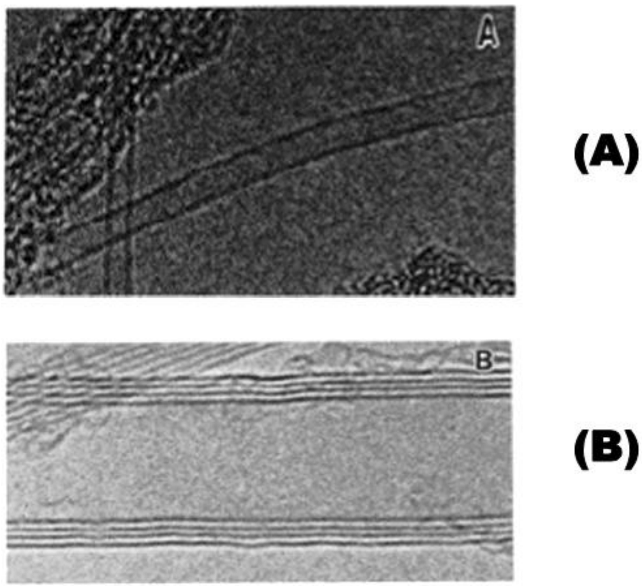


**Figure2.** High-resolution transmission electron microscopy image of typical single-walled carbon nanotubes (SWNT) (A) and multi-walled carbon nanotubes (MWNT) (B). Reprinted with permission from [24], P. Ajayan, *Chem. Rev.* 99, 1787 (1999). c 1999, American Chemical Society.

Electric arc–discharge [8,30], Catalytic chemical vapour deposition (CVD) and laser ablation are the methods to synthesize these nanotubes. These nanotubes are generally mixed with residues (carbon particles) during synthesis.

During last decade, the electrical and mechanical properties of carbon nanotubes have been under intensive investigation. Qian et al. [9] contributed a complete review article "Mechanics of Carbon Nanotubes" from the perspective of both experimental and modeling. Some fascinating results came into picture regarding the fact that the electrical properties of carbon nanotubes are sensitive to variation of structures and can be changed dramatically due to the change of atomic bonds induced by mechanical deformation. It is known that when carbon nanotubes are subjected to mechanical deformation, they can even change from mechanical to semiconducting [7,28,31]. McEven et al. [25] extensively reviewed the electronics of carbon nanotubes.

**NEMS as multiterminal electromechanical devices :**

NEMS as multiterminal electromechanical devices are possible i.e. having 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). Additional electrical signals- either time-varying or quasi-static and control terminals can also be applied and eventually the quasi –static or time varying forces are transformed by the control transducers to disturb the properties of mechanical element in a useful and controlled manner. This common picture of this scheme is shown in Fig 2.

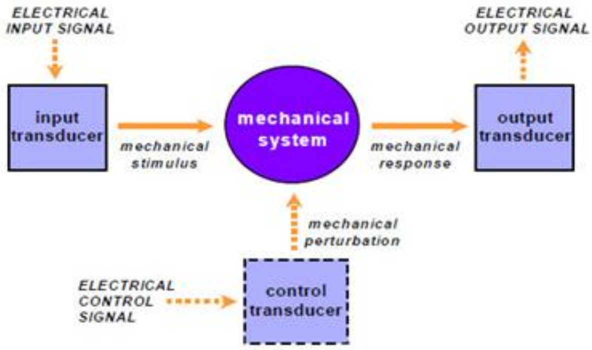


**FIG. 2.** (Color online). Schematic representation of a multiterminal electromechanical device.

"Orthogonality" between input, output & (the possibly multiple) control parts (s) is an important point which needs to be understand. With this, it is conceivable to achieve highly independent interaction between these parts i.e. strong interactions with mechanical element occurs but only with weak direct coupling to each other. This orthogonality can be provided by narrowband transducer response to select input and output signals from control (i.e. pump) signals when frequency conversion has to be achieved for time varying stimuli.

**NEMS Attributes:**
**A) Quality (Q) Factor:** The range upto which Q factors in semiconductor NEMS varies between $10^3$-$10^5$ which is much more than those commonly available from electrical oscillators. In case of signal processing devices, high Q directly translates into low insertion loss. Large Q signifies a reduction of bandwidth.
**B) Characteristic operating Power level:**
The minimum operating power level $P_{min}$ for a resonant NEMS device can be achieved by understanding that resonator is lossy energy storage device. The time interval ($\tau$) can which energy pumps into this device is lost is know as ring-up and ring-down time of the resonator and,

$$\tau = \frac{Q}{w_0}.$$

The energy which will drive the amplitudes comparable to those of chemical fluctuations is called minimum operation energy. Hence, the minimum input power can be calculated as:

$$P_{\min} = \frac{K_B T w_o}{Q}$$

Provided the thermal fluctuations energy $K_B T$ in the mode is given. The characteristic minimum power level is of the order $10^{-17}$W for NEMS device dimensions accessible nowadays, via electron beam lithography. To have robust signal- to- noise- ratio, if we multiply $10^{-17}$ by a factor of 1,ooo,ooo the total system power levels are still of the order of 1 μw only. Table (1) shows the notably small value of NEMS.

**Table 1:** Representative operating power levels for NEMS.

| $f_0$ | Q | $P_{min}$ | $10^6 \cdot P_{min}$ |
|---|---|---|---|
| 100 MHz | 10,000 | 40 aW | 40 pW |
| " | 100,000 | 4 aW | 4 pW |
| 1 GHz | 10,000 | 0.4 f W | 0.4 nW |
| " | 100,000 | 40 aW | 40 pW |

**C) Responsitivity and aspect ratio:** The mechanical components must be scaled down from the present size domain of NEMS to reach VHF, UHF and then ultimately microwave bands. To acquire high frequencies, it is possible to use existing micron-scale MEMS technology. However, it has disadvantages which include realization of the complete scope of potentialities offered by NEMS technology. To examine this, discussion again focuses on doubly clamped beams, with aspect ratio *l*/t or *l*/w. With foreshortened aspect ratios of order unity, attainment of high frequencies with micro-scale structures can take place. Such geometries give extremely high force constants $K_{eff}$. This large $K_{eff}$ could seriously affects (a) the attainment of maximum Q. (through minimization of acoustic radiation to support structures i.e. clamping losses) (b) the excitation levels required to induce nonlinear response (c) the attainable dynamic range and (d) the ability to tune the devices using "control" signals (applied mechanical forces). To induce nonlinear response, all these excitation levels are required. These all features are optimized in larges aspect ratio structures i.e. structures with geometries currently used in MEMS, but with all dimensions reduced to nanoscale dimensions. The effective force constant,

$K_{eff}=\frac{32Et^3w}{l^3}$, is defined for point loading in beam's center.

**D) Frequency :** The mode shapes and hence the force constants and resulting frequencies, depend upon the way the beam are clamped; Table (2) shows attainable frequencies for the basic flexural modes of thin beam, for dimensions spanning the domain from MEMS (left most entries) to deep within NEMS.

**Table 2:** Fundamental frequency vs Geometry of (Si) GaAs, SiC Mechanical Resonator.

| **Boundary Coniditions** | **Resonator Dimensions (*Lxwxt, in $\mu m$*)** | | | |
|---|---|---|---|---|
| | **100x3x0.1** | **10x0.2x0.1** | **1x0.05x0.05** | **0.1x0.01x0.01** |
| **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** | 53KHz [34] (18) | 5.3MHz [3.4] (1.8) | 260 MHz [170] (92) | 5.3 GHz [3.4] (1.8) |
| **Cantilever** | 19 KHz [12] (6.5) | 1.9MHz [1.2] (0.65) | 93MHz [60] (32) | 1.9 GHz [1.2] (0.65) |

The dimensions currently attainable with advanced electron beam lithography are represented by last column. Nano devices in this limit will have resonant frequencies in THz range i.e. the characteristic of molecular vibrations. It is specially notable that for structures of the similar dimensions, Si gives frequencies a factor of two and SiC a factor of three higher than that obtained with GaAs devices [35]. This increase reflects the increased phase velocity. $\sqrt{\left(\frac{E}{\rho}\right)}$, in the rigid materials, where, ρ is mass Density and E is young's modulus. A main point which must be kept in mind is that the frequencies in the table are structures for zero internal strain. In bi-, tri-or multi layered structures (common for devices that include transducers) this may actually be the exception rather than the rule [14].

## II. Challenges:

NEMS offer intriguing properties in the area of electronic computing and sensing. Although a notable advancement has been achieved, there are many challenges that need to overcome before NEMS can replace and transform present technologies. Some of the issues that need used further development and research are:

1) **Better understanding the quality factor:** To achieve ultra-high quality factors is one of the keys to realize the potential application of NEMS. However, with constant observation it has been found that the quality factor of resonators decreases remarkably with size scaling [21]. The factors that can dampen the movement of resonators are fabrication-induced surface damages, thermoelastic dampling, adsorbates on the surface and interfaces. Unfortunately still the dominant energy dissipation mechanism in nanoscale is unclear.
2) **Quantum limit for mechanical devices:** The final limit for NEMS is its operation at or even beyond the quantum limit [21]. In the context of quantum, the single mechanical quanta are of the equal order of magnitude or greater than the thermal energy. To understand and optimize displacement and force measurements, quantum theory should be used. Now, for a single electron transistor with high-quality factor at multi-kelvin temperature [17], position resolution with a factor of 4.3 above the quantum limit has been achieved. It will potentially open new fields in science at molecular level because of the pursuit of NEMS devices operating at the quantum limit.
3) **Reproducible Nanofabrication:** The fabrication reproducibility is the key for NEMS. Device trimming is ubiquitous in quartz frequency control technology. Such technologies will also be required for NEMS. However, technique like optical fabrication will reign in the device-to-device spreads which arises from mass variation.
4) **Transducers:** Electrostatic transduction doesn't scale well into the region of NEMS although being the staple of MEMS. At the nanoscale, electrode capacitances of order $10^{-18}$ F and smaller are to be expected for the electrodes, so the dynamical capacitance of interest will be dominated by parasitic capacitance. In effect, as size shrinks and frequency of operation increases the static parasitic and embedding impedances continue to grow while the motional modulation of the impedance becomes progressively smaller.

## III. Conclusion:

NEMS presents ways to basic measurements and to a parametric space for sensing that is unmatched and fascinating. It seems certain that many applications will emerge from this new area. Taking whole advantage of NEMS will stretch our overall imagination, as well as our recent methods and "mind sets" in nano and micro-device science and technology. Ultimately, the nano-mechanical systems mentioned here will result to true technology. They can also provide the important scientific and engineering foundation that will underlie this future technology.

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