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NanoElectroMechanical Systems - The Future

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Abstract:

NanoElectroMechanical Systems (NEMS) are class of devices or Microelectromechanical Systems (MEMS) scaled to submicron dimensions. In such nanoscales, it is possible to attain extremely high fundamental frequencies while simultaneously preserving very high mechanical susceptibility. NEMS have critical structural constituent at or below 100nm. NEMS combine smaller mass with higher surface area to volume ratio and are therefore very helpful in applications like high-frequency resonators and ultrasensitive sensors.

Keywords — NEMS.

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I. INTRODUCTION

One can proclaim that our abreast, collective conceptualization has been subjugated by things electronic: by default, we equate "device" to a transistor (in case of basic electronic devices), and "system" to the digital computer. It is only from the mid of the twentieth century that such a mindset has become embedded; the intuition of previous generations was firmly entrenched in the domain of mechanical bodies.

Using the fundamentals and components of microelectronics, scientists have been fashioning microscopic machines. These mechanical components and microelectronic circuits that control these microscopic machines are called microelectromechanical systems(MEMS). There are multiple fields in science and technology where the application of MEMS is seen. As there is so much in micro levels of devices, it is also required to go beyond and see other possibilities at very high fundamental frequencies which exist at a nano level. So now is the time to embark upon a concerted exploration of MEMS at submicron levels. MEMS, when scaled to submicron levels, give rise to nanoelectromechanical systems(NEMS).

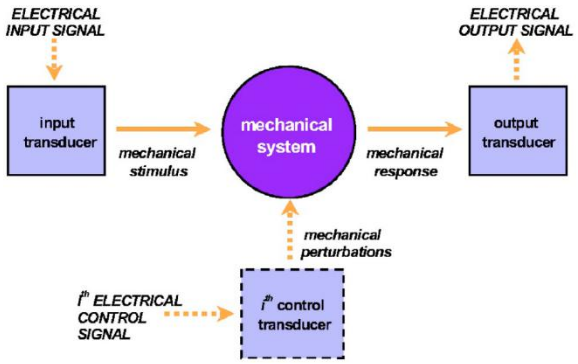

Fig.1. Schematic Diagram of Electromechanical device.[5]

II. MATERIALS

A. Approaches to Miniaturization

There are two interrelated approaches to fabrication of NEMS.

First, the Top-Down approach which uses the conventional microfabrication methods, i.e. optical, electron beam lithography and thermal treatments, to manufacture nanoscale devices. While the resolution of these methods is limited, it allows a large degree of control over the resulting structures. Thus, devices like nanowires, nanorods, and patterned nanostructures are manufactured from metallic thin films or etched semiconductor layers.

Second, the Bottom-Up approach uses the chemical properties of a single molecule to cause single-molecule components to self-organize or self-assemble into some useful arrangement, or rely on positional assembly. Such approaches utilize the theory of molecular self-assembly, molecular recognition. This allows manufacturing of much smaller structures, often at the cost of limited control of the fabrication process.

B. Carbon Allotropes

The materials used in NEMS technology are generally carbon-based due to its mechanical, electrical, metallic, semiconductor conductivity and chemical properties. Carbon allotropes such as Diamond, Carbon nanotubes and Graphene are commonly used.

Physical and mechanical properties like high Young's modulus, low friction, low density, exceedingly low mechanical dissipation, and large surface area are exhibited by Graphene and Diamond. The low friction of Carbon nanotubes allows practically frictionless bearings and has paved way for practical applications of Carbon nanotubes as integral elements in NEMS, such as nanomotors, switches, and high-frequency oscillators. The physical strength of carbon nanotubes and graphene allows carbon-based compounds to meet higher stress demands, where common materials would fail and thus support major use of carbon-based materials in NEMS technological development.

Despite all of the useful properties of carbon nanotubes and graphene for NEMS technology, both of these compounds face several restrictions on their implementation. One of the main problems is carbon's response to gases present in the atmosphere. Carbon nanotubes when exposed to oxygen present in the atmosphere, exhibit a large change in electronic properties. Similarly, other changes to the electronic and mechanical properties of carbon-based materials must be thoroughly experimented before its implementation, as they have a high surface area which can easily react with the surrounding environment. Graphene has complicated electrical conductivity properties compared to common semiconductors as it lacks an energy bandgap.

C. Biohybrid NEMS

The emerging field of use of NEMS in the biological field also called as bio-hybrid systems integrate biological and synthetic structural compounds for biomedical or robotic applications. The constituent compounds of bio-nanoelectromechanical systems (BioNEMS) are of nanoscale size, for example, DNA, proteins or nanostructured mechanical parts. The facile top-down nanostructuring of thiol-ene polymers to create cross-linked and mechanically robust nanostructures that are subsequently functionalized with proteins is an example of BioNEMS.

III. NEMS ATTRIBUTES

A. Frequency

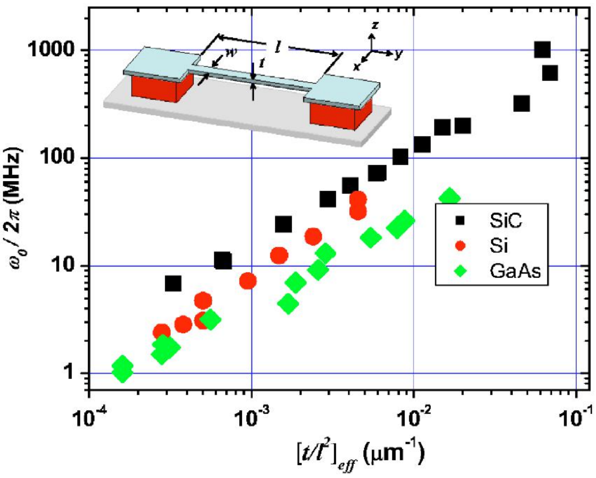

Fig. 2. Frequency versus effective geometry plot for single-crystal SiC, Si, and GaAs synthesized doubly clamped NEMS beams.[5]

The plot shows the experimentally attained frequencies for fundamental flexural modes of thin beams, for dimensions in the domain of MEMS to nano level domains in NEMS. The expression

$$\omega 0 / 2\pi = (1.05)\sqrt{E / \rho(t / l{*}l)}$$

determines the flexural resonance frequencies of NEMS beams which are thin doubly clamped in nature. Here, w x t x l are the dimensions, E is Young's modulus, and ρ is the mass density of the beam.
In the plot, t/l^2 values have been normalized to remove the effect of additional stiffness and mass loading due to electrode metallization. It is observed that structures of the same dimensions, Si yields frequencies of a factor of 2, and SiC a factor of 3, higher than those obtained with GaAs devices. This increase reflects the increased phase velocity $\sqrt{E / \rho}$ in the stiffer materials.

B. Quality (Q) Factor

The Q factors observed in semiconductor NEMS are in the range of 103-105. This exceeds the Q factors available from electrical oscillators. This small degree of internal dissipation imparts low operating power levels and high attainable sensitivities to NEMS. For signal processing devices high Q directly translates into low insertion loss.

As the Q value increases the bandwidth reduces. This can be eliminated by One, feedback control, which can be applied without the introduction of significant additional noise which may be useful to increase bandwidth as desired. Two, for resonators operating at ~1GHz, even in case of extremely high Q of $\sim 10^5$, bandwidths of ~10 kHz can be obtained, which is sufficient for various narrowband applications.

C. Characteristic Operating Power Level

Understanding the minimum operating power level P_{min} for a resonant NEMS device can be attained by realizing that the resonator is simply a lossy energy storage device. The ring-up or ring-down time of the resonator is the time interval $\tau \sim Q/\varpi_0$ in which the energy pumped into the device is dissipated. The energy of a system, which will drive the system at amplitudes comparable to those of the thermal fluctuations is called the minimum operation energy. With the energy $k_B T$ of thermal fluctuations given in the system, the minimum input power can be calculated as:

$$P_{min} \sim k_B T \varpi 0/Q$$

NEMS device dimensions accessible via electron beam lithography, have characteristic minimum power level in the order of 10 aW (10^{-17} W). Even if we multiply this by a factor of 1 000 000, to achieve robust signal-to-noise ratios, and to realize futuristic NEMS-based mechanical signal processing or computation systems, the system power levels are in the order of 1 mW. This is six orders of magnitude smaller than the power dissipation in current systems of comparable complexity based upon digital devices that work only in the electronic domain.

D. Responsivity

It is possible to attain high frequencies using MEMS Technology but this technology has serious disadvantages, which pave the way for the full scope of potentialities offered by NEMS technology.

To explain this we shall take the example of doubly clamped beams, with aspect ratios l /w or l / t. High frequencies can be achieved with micron-scale structures only if the aspect ratios are of order unity. Such geometries generate extremely high force constants k_{eff}. Large k_{eff} could adversely affect: (i) the dynamic range which is to be attained, (ii) the ability to tune the devices using "control" signals (applied mechanical forces), (iii) the attainment of maximum Q (minimizing acoustic radiation to the support systems i.e., clamping losses), and (iv) the excitation levels required to induce nonlinear response.

E. Active Mass

A small ratio of the resonator's total mass is involved in its motion. Multiplying the total mass of beams or cantilevers by the integral of a normalized function describing the modal shape gives the measure of the active mass M_{eff}. For a
doubly clamped beam operating in fundamental mode,
$M_{eff} \approx 0.73\ M_{tot}$, where M_{tot} is the total mass of the beam.

F. Non Linearity

The outset of non-linearity - which is crucial for many classes of switching applications and for parametric processes occurs for smaller applied force (low input power) in large aspect ratio systems. For doubly-clamped structures (which have very large aspect ratio) we have shown that the linear dynamic range, bounded by the thermomechanical noise floor and the outset of non-linearity, can vanish i.e. nanotube resonators are intrinsically nonlinear components.

IV. FUTURE PROJECTIONS

A. Vision 20/20

For NEMS development, we are still in the craftsman era. Scientists and Innovators routinely demonstrate the promise and potential of a new technology in the domain of nanotechnology, electronics and mechanics. So, the prospect of assembling architecture of mechanical logic is sufficiently complex, to be competitive, would seem distant. But building complex, atomically-assembled mechanical computers might happen in the next few years. In the past years, for example, we have seen high-frequency nanowire-based and nanotube-based mechanical resonators been realized.

B. Blocks or Modular Systems

Modularity is the key to building complex systems. But how shall we interconnect the modules in the case of nanomechanical elements? Information exchange between subsystems (e.g. mechanical logic gates) should be mediated purely in the mechanical domain. But any realistic form of purely mechanical computation requires to be formulated upon ultra-low dissipation (i.e. almost frictionless) mechanical interconnections capable of transmitting the output of one gate to others. For displacement-based mechanical logic, it is possible using external energy reservoirs i.e.the weight of levitated parts or elastic energy of springs which are continuously. recharged by external sources. For dynamical mechanical/acoustic logic, it is possible using non-linearities in mechanical response to create a parametric mechanical gain.

C. Maximum limits and Cross-Domain Fusion

The maximum limits of NEMS are at the molecular or atomic scale where the frequencies and time scales are set by vibrational properties of molecules. The hint of the future era of molecular mechanical systems is the buckyball resonators realized by Park, McEuen, and collaborators in 2001.
Molecular electronics and NEMS are moving towards the same end goal, in terms of future electronics and information processing systems. Both particularly depend upon mechanical conformations/configurations to derive their functionality.

D. Evolution or Revolution?

It is probably not possible to visualize a workable fusion between existing electronics (i.e. CMOS) and Nano-mechanical systems. Looking at the variations between the location of the operating dynamic range of NEMS (attowatts to picowatts) and CMOS, it seems true. The evolution required to merge these two technologies may not be profitable. To achieve the goal of merging the two technologies, full benefits of molecular electronics and nanotechnology may require shifting away from the existing, wellunderstood prototype of silicon electronics technology in which we have heavily invested over the past five decades.

V. CONCLUSION

Future applications of NEMS are difficult to predict. The prototypes of NEMS would be economically most interesting but are most hard to be commercialized. Combined applications of biology and nanotechnology seem to be the most promising ones. Nano resonators would have direct consequences for wireless communication technologies in the upcoming future. Nanofluidic pumps might use nanomotors for biochips or sensors.

Recent work by the department of Transducers Science and Technology of the University of Twente, Holland, is on the construction of truly 3-D nanostructures. This research might lead to further innovation in both MEMS and NEMS.

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