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NANOLECTROMECHANICAL SYSTEMS: ATTRIBUTES & CHALLENGES

Physics

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Sarita Aggarwal Goel — Department of Physics, MVN University, Palwal

Anuradha Sharma — Department of Humanities & Applied Sciences, YMCA University of Science & Technology, Faridabad

ABSTRACT

Nanoelectromechanical Systems (NEMS) [1, 2] has been important from both the scientific and technical perspective since a few decades. Above and beyond the long-established microfabricated sensors and actuators the NEMS domain envelops micromechanical equivalents and the systems that are integrated or micro-assembled with electronics on the same substrate or package with the sole aim of achieving high performance. NEMS along with their counterparts MEMS in their short history have taken part in many consumer and scientific applications such as communication, transportation, defense, automated manufacturing, ink-jet printing, monitoring of the environment, health care, probe microscopy and a large variety of other consumer products. The intrinsically small size of NEMS offers fascinating avenues such as diminutive size, weight and power dissipation in addition to the superior speed and precision in comparison to their macroscopic counterparts. The fabrication of nano-machines is the most insightful concern. The fabrication techniques must ensure the definition of small geometries, precise dimension control and design flexibility in addition to repeatability, reliability, high yield, interfacing with the microelectronics and low cost.

INTRODUCTION

Microscopic machines such as beams, cantilevers, gears, and membranes that utilize the materials as well as the processes of microelectronics had long been the focus of the research. These mechanical elements that are controlled by the microelectronic circuits are generally referred to as microelectromechanical systems (MEMS). In the present day technology MEMS have been set up to perform everyday tasks such as regulating electric current or light flow, opening and closing valves, turning mirrors and so on. With time microelectronics technology is pushing deep into the submicron scale and placed us in the nanoscale range giving rise to Nano-electromechanical systems [1, 2]. Nano-electromechanical systems (NEMS) are the electromechanical devices that are sized in the critical range from hundreds of nanometers to a few nanometers. To design NEMS methodical studies of the mechanics of the components of device within themselves and their interactions with the applied forces or fields is required. As the dimensions of the electromechanical devices shrink from the micron to nanometer scale, the new concepts of Physics come into sight. The theories that are applicable to MEMS could not be as such transformed to NEMS. At nanometer scale the materials behave atomistically i.e. the quantum effects rather than continuum effects become evident. This leads to the uncharacteristic and nonlinear effects. At nanometer scale surface effects and crystal defects become governing. The NEMS devices are more submissive as compared to the predictions of the continuum models i.e. MEMS devices.

NEMS are off course better than MEMS. However, a stiff entry fee is required to enter the province of NEMS. It crucially demands a new engineering to completely realize the prospective of NEMS. The chief recorded problematic issues include: the extremely small size of the devices comparable to their embedding circuitry, extremely high surface-to-volume ratios and unusual characteristic range of operation. They lead to a number of current engineering challenges in the expansion of NEMS. It would encourage the need for ultrasensitive and very high bandwidth displacement transducers that in turn require an unparalleled control of surface quality and adsorbates.

ATTRIBUTES OF NEMS

Nanoscale effects provide NEMS some interesting and unique characteristics which distinguished them greatly from their predecessor microelectromechanical systems (MEMS). They could achieve very high fundamental frequencies [1] at the same time upholding high mechanical responsivity. The two simultaneously give rise to high force sensitivity at the atto-Newton (10-18 Newton) level utilizing very small power inputs of the order of 10 atto-Watts (10-18 Watts) [3]. The mechanical quality factors of these devices are approximately tens of thousands and therefore they have low-energy dissipation. They could also persuade functional nonlinearity with the help of controlled forces. Their active mass is in the femtogram (10-15 gram) range and mass sensitivity is up to attogram (10-18 gram) [2] and subattogram (<10-18 gram) [4] levels. The heat capacity of NEMS devices is too small (less than "yoctocalorie" i.e. 10-24 calories) [5]. They have extremely high integration level that comes up to 1012 elements per square centimeter [1].

These attributes sparkles the mind's eye and ensues the flood of ideas for new experiments and applications. Undoubtedly, by all the current measures it had been realized that the distinctive parameters of NEMS are extreme.

Frequency: The frequencies of fundamental modes of thin beams depend upon their force constants which in turn depend upon the way the beams are clamped. Table 1 shows the frequencies that could be attained by the resonators of the dimensions ranging from MEMS to NEMS for the three simplest boundary conditions. As evident from the table Nano-devices of about 10 nm size that have been attained till date, could have resonant frequencies in GHz range. However, much smaller dimensions than it (in the molecular scale) would be eventually feasible in the near future leading to resonant frequencies in the THz range. These frequencies are off course characteristic of molecular vibrations. As soon as the structures reach the truly molecular scale i.e. in order of tens of lattice constants in cross section, the continuum mechanics becomes irrelevant and quantum corrections emerging from atomistic behavior are considered [1,6]

TABLE-1
FUNDAMENTAL FREQUENCY V/S. GEOMETRY FOR SiC MECHANICAL RESONATORS

Boundary Conditions	Resonator Dimensions (L × w × t , in μm)			
	100x3x0.1	10x0.2x0.1	1x0.05x0.05	0.1x0.01x0.01
Both Ends Clamped or Free	120 kHz	12 MHz	519 MHz	12 GHz
Both Ends Pinned	53 kHz	5.3 MHz	260 MHz	5.3 GHz
Cantilever	19 kHz	1.9 MHz	93 MHz	1.9 GHz

The table corresponds to the structures made of SiC. For stiffer materials the frequencies decreases reflecting an increase in the phase velocity $\sqrt{(E/\rho)}$ where E is Young's modulus and ρ is the mass density. However it should also be kept in mind that the frequencies in Table 1 are for the structures with zero internal strain only. For others the surface irregularities at nano-scale may impart further corrections.

Quality Factor: The quality factors that have been achieved for nano-devices nowadays range from 103 to 105 in moderate vacuum. These values are much higher than the Q values for typically available electrical resonators. The larger Q values lead to smaller dissipation of internal power (D=1/Q) and thus lower operating powers are required. It produces remarkable force sensitivity. The quality factors of the nano-resonators made from ultrapure semiconductors are extremely high.

It should be taken into account that larger Q values indicate a smaller bandwidth but it would not deteriorate the performance of the resonator for two reasons. First reason being the feedback damping which could increase the bandwidth to desired level without introducing considerable extra noise. Secondly for the nano-devices with frequencies of the order of 1GHz and Q values of the order of 100,000 the bandwidths are of the order 10 kHz. This range is adequate for different narrow band applications.

Characteristic Operating Power Level: An estimate of minimum operating power levels can be obtained by dividing the thermal energy, kBT , by the distinctive time interval ($\tau = Q/\omega 0$) required for the energy exchange between the mode and its surroundings at fundamental frequency $\omega 0$.

TABLE 2
REPRESENTATIVE OPERATING POWER LEVELS FOR NEMS

fo	Q	Pmin
100 MHz	10,000	40 aW
100 MHz	100,000	4 aW
1 GHz	10.000	0.4 fW
1 GHz	100.000	40 aW

This value represents the required operating power of the resonator to match its amplitude with the thermal vibrations. It can be evidently seen from the Table 2 that the NEMS require considerably small operating power of the order of ten attowatts (10-17 W) for the dimensions that are reachable till date. These power levels would still not exceed 1 μW even if we consider million times robust signal-to-noise ratios and then further envisage a million of such devices working altogether as a system. The power dissipation in the existing systems of same level based on digital devices is about a million times greater [3].

Responsivity and Aspect Ratios: The VHF (30 MHz – 300 MHz), UHF (300 MHz – 3 GHz) and even microwave bands (up to 300 GHz) can be attained if the size of the resonators is reduced from micron scale to nano scale. These high frequencies could be achieved by exceptionally small aspect ratios of the order of unity. The aspect ratio corresponds to L/w or L/t in the current situation. At such geometries the force constants becomes very high and hence to achieve substantial mechanical deflection large excitation signals are required. This deficiency of responsivity is harmful for the processing of electro-acoustic signals of ultralow power.

Outsized force constants badly affect the required operational power level, possible dynamic range, applied mechanical forces, clamping losses and excitation levels required to induce nonlinear response. Larger aspect ratios structures i.e. the structures having the same geometry as that used in MEMS but with all their dimensions minimized to nano-scale are able to optimize all these affected features.

Estimation of Available Dynamic Range: It is evident that NEMS are very prospective as they offer new types of ultralow power electromechanical signal processing and computation and it would be significant to realize them. However to exploit the full potential of nano-devices they must be employed within their characteristic operating range. The lower limit of a mechanical resonator's accessible dynamic range would be surrendered unless best possible noise matched transducers are utilized to interpret its motion. In particular, the noise output of the transducer must have magnitude comparable or smaller than the thermo-mechanical fluctuations. The major challenge is that as the size of the beam scales down the r.m.s. amplitude of vibration also scales downward in direct proportion to its size.

It leads to take care of two fundamental areas for NEMS engineering. First is development of highly sensitive transducers that have high displacement resolution and larger frequencies for small device sizes and second is development of techniques and system architectures tailored to operate within the distinctive dynamic range (femto- to picoWatt regime) NEMS.

PRINCIPAL NEMS ENGINEERING CHALLENGES

The technology now exists to fabricate the nanostructures below 10 nm. But still there are three principle challenges that must be concentrated on before utilizing the dream prospects of the nano-devices. It include communication of signals or information from the nano world to macroscopic world; knowledge and control of the mesoscopic (pertaining to a size regime, intermediate between the microscopic and the macroscopic dimensions) dynamics; development of methods that could replicate the nano-devices recurrently.

Transducers: It is obvious that the displacements of NEMS devices would be only a few percent of its dimensions. Thus, for a beam about 10 nm in diameter the displacement would correspond to only a fraction of nano-meter. It demands highly sensitive transducers that could accurately read the positions of the beam with precision and thereby allow transfer of information from the micro to macro world. The transducer must be capable to resolve these displacements in the 10-15 to 10-12 m range at frequencies of GHz that is the natural frequency of nano-resonators. The problem is further hoisted since some of the transducers that are strongholds of the micromechanical dominion could not be applied to nano-mechanical sphere. Electrostatic transduction that is the staple of MEMS, does not fit well into the realm of NEMS.

Quest of ultra-high Q: It has been comprehended that to realize the full potential of NEMS ultra high Q factors are tremendously desirable. However in existent devices both external and internal factors are responsible for the limiting values of Q. The internal factors include the defects in the bulk and crossing points of the resonator, surface damaged that are induced due to inconsistent fabrication techniques and effect of adsorbates on the surface. But many of these factors could be restrained by choosing the materials, device geometry and fabrication techniques carefully. External factors such as air resistance, clamping losses at the supports of the resonators, thermo-elastic damping originating from inharmonic coupling between mechanical modes of the resonator and the phonon reservoir [7] and coupling losses that are introduced by the transducers are also effective. These losses are fundamental thus could not be dealt with absolutely however they could be reduced considerably through vigilant engineering.

Surface Effects: In particular, another aspect that comes out rigorously says that as the device size shrinks to the domain of NEMS, the device characteristics are governed by the surface effects. In this size regime, high surface to volume ratio amalgamated with the non-optimized surface properties play a key role. It has been estimated that in Silicon beam of nano-size (100 nm x 10 nm x 10 nm) about 10%

atoms reside at the surface or near the surface.

Approach to quantum limit and beyond: Ultimately, as MEMS reduces to NEMS the continuum macroscopic mechanics break down and atomistic Physics i.e. quantum mechanics emerges. Most of the current nano-electromechanical devices are already on the verge of quantum limit. The quantum limit could be determined by comparing the thermal energy kBT with the resonator's energy in the fundamental mode h*f*o. At low temperature and high frequency the intrinsic quantum noise greatly exceeds the thermal fluctuations and mean square amplitude of the vibration is quantized.

It appeared that these quantized amplitude jumps are observable in the resonator if two important criteria can be met. The first requirement says that the resonator must have some definite quantum number. The second requirement is more challenging. It demands the ultrahigh sensitivity of the transducers to displacements.

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. 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.

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