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Nanoelectro-Mechanical System

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ABSTRACT

A host of novel applications and new physics could be unleashed as Micro-Electro-Mechanical Systems (MEMS) shrink towards the nano scale. The time is ripe for a concerted exploration of Nano-ElectroMechanical-Systems (NEMS) - i.e. machines, sensors, computers and electronics that are on the nano-scale. Many years of research by university, government, and industrial groups have been devoted to developing cutting-edge NEMS technologies for enabling revolutionary NEMS devices. NEMS has revolutionized nearly every product category by bringing together silicon-based nano-electronics with nanolithography and nanomachining technology, making possible the realization of complete systems-on-a-chip (SOC). Historically, sensors and actuators are the most costly and unreliable part of a micro scale sensor-actuator-electronics system. The NEMS-devices can be used as extremely sensitive sensors for force and mass detection down to the single molecule level, as high-frequency resonators up to the THz range, or as ultra-fast, low-power switches. NEMS technology allows these complex electromechanical systems to be manufactured using batch fabrication techniques, increasing the reliability of the sensors and actuators to greater than that of integrated circuits. Thus, it provides a way to integrate mechanical, fluidic, optical, and electronic functionality on very small devices, ranging from 1 nano meter to 100 nano meters. NEMS devices can be so small that hundreds of them can fit in the same space as one single micro-device that performs the same function and are lighter, more reliable and are produced at a fraction of the cost of the conventional methods. Many device designs have been proposed, some have been developed, and fewer have reached commercialization.

***Keywords* – Revolutionary, Nanolithography, Commercialization**

1. INTRODUCTION

Nano-Electro-Mechanical Systems (NEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through nano fabrication technology.While the electronics are fabricated using integrated circuit (IC) process sequences (e.g., CMOS, Bipolar, or BICMOS processes), the nanomechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices. Nano-electronic integrated circuits can be thought of as the "brains" of a system and NEMS augments this decision-making capability with "eyes" and "arms", to allow nano systems to sense and control the environment. Sensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena. The electronics then process the information derived from the sensors and through some decision making capability direct the actuators to respond by moving, positioning, regulating, pumping, and filtering, thereby controlling the environment for some desired outcome or purpose.

NEMS promises to revolutionize nearly every product category by bringing together silicon-based nanoelectronics with micromachining technology, making possible the realization of complete systems-on-a-chip. NEMS is an enabling technology allowing the development of smart products, augmenting the computational ability of nano-electronics with the perception and control capabilities of nano sensors and nano actuators and expanding the space of possible designs and applications. Despite such optimistic statistics, investment in NEMS design and production is insufficient. Most NEMS devices are modeled using analytical tools that result in a relatively inaccurate prediction of performance behavior. As a result, NEMS design is usually trial and error, requiring several iterations before a device satisfies its performance requirements.

2. OVERVIEW

2.1 The benefits of Nano-machines

Nano-mechanical devices promise to revolutionize measurements of extremely small displacements and extremely weak forces, particularly at the molecular scale. Indeed, with surface and bulk nano-machining techniques, NEMS can now be built with masses approaching a few attograms (10-18 g) and with cross-sections of about 10 nm. The small mass and size of NEMS gives them a number of unique attributes that offer immense potential for new applications and fundamental measurements. EMS devices are extremely small - for example, NEMS has made possible electrically-driven motors smaller than the diameter of a human hair (right), but NEMS technology is not primarily about size. NEMS is also not about making things out of silicon, even though silicon possesses excellent materials properties, which make it an attractive choice for many high-performance mechanical applications; for example, the strength-to-weight ratio for silicon is higher than many other engineering materials which allows very high-bandwidth mechanical devices to be realized. Instead, the deep insight of NEMS is as a new manufacturing technology, a way of making complex electromechanical systems using batch fabrication techniques similar to those used for integrated circuits, and uniting these electromechanical elements together with electronics.

3. FABRICATION OF NEMS DEVICES

There are three basic building blocks in NEMS technology, which are the ability to deposit thin films of material on a substrate, to apply a patterned mask on top of the films by photolithographic imaging, and to etch the films selectively to the mask. A NEMS process is usually a structured sequence of these operations to form actual devices and includes:

- Deposition processes
- Lithography
- Etching processes

3.1 Deposition processes

One of the basic building blocks in NEMS processing is the ability to deposit thin films of material. The thin film can have a thickness anywhere between a few nanometers to about 100 nanometer. Chemical methods are often used in NEMS deposition technology and major among them are:

- Chemical Vapour Deposition (CVD)
- Epitaxy

3.1.1 Chemical vapour deposition (cvd)

In this process, the substrate is placed inside a reactor to which a number of gases are supplied. The fundamental principle of the process is that a chemical reaction takes place between the source gases. The product of that reaction is a solid material with condenses on all surfaces inside the reactor. The two most important CVD technologies in NEMS are the Low Pressure CVD (LPCVD) and Plasma Enhanced CVD (PECVD). The LPCVD process produces layers with excellent uniformity of thickness and material characteristics

3.1.2 Epitaxy

This technology is quite similar to what happens in CVD processes, however, if the substrate is an ordered semiconductor crystal (i.e. silicon, gallium arsenide), it is possible with this process to continue building on the substrate with the same crystallographic orientation with the substrate acting as a seed for the deposition. If an amorphous/polycrystalline substrate surface is used, the film will also be amorphous or polycrystalline.

3.2 Lithography

Lithography in the NEMS context is typically the transfer of a pattern to a photosensitive material by selective exposure to a radiation source such as light. A photosensitive material is a material that experiences a change in its physical properties when exposed to a radiation source. If we selectively expose a photosensitive material to radiation (e.g. by masking some of the radiation) the pattern of the radiation on the material is transferred to the material exposed, as the properties of the exposed and unexposed regions differ.

3.3 Etching processes

In order to form a functional NEMS structure on a substrate, it is necessary to etch the thin films previously deposited and/or the substrate itself. In general, there are two classes of etching processes-Wet etching where the material is dissolved when immersed in a chemical solution and dry etching where the material is sputtered or dissolved using reactive ions or a vapour phase etchant.

4. NEED OF NEMS DEVICE

4.1 Advantages

4.1.1 Cost effectiveness: Like integrated circuits, they can be fabricated in large numbers, so that cost of production can be reduced substantially. They can be directly incorporated into integrated circuits; so that far more complicated systems can be made than with other technologies. NEMS is an extremely diverse technology that potentially could significantly impact every category of products.

4.1.2 System Integration: NEMS blurs the distinction between complex mechanical systems and integrated circuit electronics. Historically, sensors and actuators are the most costly and unreliable part of a macro scale sensory-actuator-electronics system. In comparison, NEMS technology allows these complex electromechanical systems to be manufactured using batch fabrication techniques allowing the cost and reliability of the sensors and actuators to be put into parity with that of integrated circuits.

4.1.3 High Precision: NEMS-based switches must be extremely reliable to meet the standards and requirements of optical telecommunications networks – they must remain in precise position over millions of operations, and they must be designed to meet stringent environmental specifications involving temperature and vibration.

4.1.4 Small size: NEMS based devices are extremely small in size because of the large scale integration of the nano electronics and the mechanical systems which include sensors and actuators. NEMS devices can be so small that hundreds of them can fit in the same space as one single macro-device that performs the same function.

4.2 Disadvantages

NEMS technology is currently used in low- or medium volume applications. Some of the obstacles preventing its wider adoption are:

- Limited Options
- Packaging
- Fabrication Knowledge Required

5. Applications of NEMS

Ultimately, NEMS could be used across a broad range of applications. At Caltech we have used NEMS for metrology and fundamental science, detecting charges by mechanical methods and in thermal transport studies on the nano-scale. In addition, a number of NEMS applications are being pursued that might hold immense technological promise.

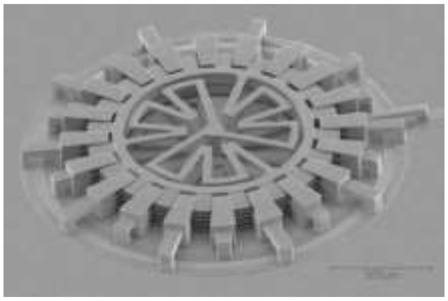

Fig. Thermal Actuator

Thermal actuator is one of the most important NEMS devices, which is able to deliver a large force with large displacement, thus they have found various applications in electro-optical-communication, micro-assembly and micro-tools. Currently Si-based materials have been predominantly used to fabricate thermal actuators due to its mature process and stress-free materials.

5.1 Biotechnology: NEMS technology is enabling new discoveries in science and engineering such as the Polymerase Chain Reaction (PCR) nano systems for DNA amplification and identification, nano machined Scanning Tunneling Nanoscopes (STMs), biochips for detection of hazardous chemical and biological agents, and nano systems for highthroughput drug screening and selection.

5.2 Accelerometers: NEMS accelerometers are quickly replacing conventional accelerometers for crash air-bag deployment systems in automobiles. The conventional approach uses several bulky accelerometers made of discrete components mounted in the front of the car with separate electronics near the air-bag; this approach costs over $50 per automobile.

5.3 Nano nozzles : Another wide deployment of NEMS is their use as nano nozzles that direct the ink in inkjet printers. They are also used to create miniature robots (nano-robots) as well as nano-tweezers, and are used in video projection chips with a million moveable mirrors. NEMS have been rigorously tested in harsh environments for defense and aerospace where they are used as navigational gyroscopes, sensors for border control and environmental monitoring, and munitions guidance. In medicine they are commonly used in disposable blood pressure transducers and weighing scales.

5.4 NEMS in Wireless Wireless system manufacturers compete to add more functionality to equipment. A 3G “smart” phone, PDA, or base station, for example, will require the functionality of as many as five radios – for TDMA, CDMA, 3G, Bluetooth and GSM operation. A huge increase in component count is required to accomplish this demand.

5.5 NEMS in Optical Networks: An important new application for NEMS devices is in fiber optic networks. At the nanons level, NEMSbased switches route light from one fiber to another. Such an approach enables a truly photonic (completely lightbased) network of voice and data traffic, since switching no longer requires conversion of light signals into digital electronic signals and then back tooptical.This is important because switching using optical-electrical-optical (OEO) conversion can often cause substantial bottlenecks, preventing the realization of truly broadband networks. But NEMS and nano machined devices can be used as more than switches in the optical network. Additional applications include active sources, tunable filters, variable optical attenuators, and gain equalization and dispersion compensation devices.

6. FUTURE OUTLOOK

- NEMS offer unprecedented and intriguing opportunities for sensing and fundamental measurements. Both novel applications and fascinating physics will undoubtedly emerge from this new field, including single-spin magnetic resonance and phonon counting using mechanical devices.
- But there remains a gap between today's NEMS devices that are sculpted from bulk materials and those that will ultimately be built atom by atom. In the future, complex molecular-scale mechanical devices will be mass-produced by placing millions of atoms with exquisite precision or by some form of controlled self-assembly. This will be true nanotechnology. Nature has already mastered such remarkable feats of atomic assembly, forming molecular motors and machinery that can transport biochemical within cells or move entire cells.
- Clearly, to attain such levels of control and replication will take sustained effort, involving a host of laboratories. Meanwhile, in the shorter term, NEMS are clearly destined to provide much of the crucial scientific and engineering foundation that will underlie future nanotechnology.
- We focus on the exploration of NEM-physics and the development of NEM-devices that can be used as extremely sensitive sensors for force and mass detection down to the single molecule level, as highfrequency

resonators up to the GHz range, or as ultra-fast, low-power switches. Both a top-down and bottom-up approach is followed. The top-down approach consists of scaling down the existing micron-size MEMS technology far into the sub-100 nm range. In the bottom-up approach suspended structures of single-walled carbon nano-tubes and of (semi conducting) nano-wires are fabricated. In particular, (new) mechanisms for detection of displacements and eigen frequencies are studied with the goal to reveal the physical processes (e.g. damping, thermal effects, and momentum noise) that limit the sensitivity of the devices. Novel optical and magnetic detection schemes need to be investigated.

- The search for the limits of mechanical motion is a central theme. At low temperature, quantum friction starts to limit the Q-factor and vibrating NEM-devices are limited by zero-point motion. This quantum limitation poses an ultimate limit to sensitivity of NEM-devices. In addition, other quantum phenomena are expected to be present. Quantum optics-like experiments with phonons, phonon lasers or quantum-tunneling experiments with massive objects (strained suspended nano-tubes placed between two gate electrodes) are just a few examples. As the size of NEM-devices shrinks down, electron-phonon coupling translates into an increasingly strong interplay between electrical and mechanical degrees of freedom. Device operation results in charge distributions that are inhomogeneous on the nanometer scale, giving rise to Coulomb forces that are strong enough to change device geometry. The classical theory of elasticity breaks down and the regime of quantum elasticity has been entered.
- Current projects involve Coulomb blockade and noise properties (quantum transport) of single-wall nano-tubes, mixing experiments to detect the guitar-like modes of SWNTs and the fabrication of a SET in the vicinity of a suspended SWNT to detect its motion. Singly-clamped semi conducting nano-wires are used as switches with the goal to fabricate nano-mechanical shuttles.

7. CONCLUSION

The MEMS revolution that began at Defense Advanced Research Projects Agency in the early 1958s will continue to bring new and more powerful microsystems to the commercial world and defense community.

Nano-systems have the enabling capability and potential similar to those of nano-processors in the 1970s and software in the 1980s.Since NEMS is a nascent and synergistic technology, many new applications will emerge, expanding the markets beyond that which is currently identified or known. As breakthrough technology allowing unparalleled synergy between hitherto unrelated fields of endeavor such as biology and nano-electronics, NEMS is forecasted to have growth similar to its parent IC technology. For a great many applications, NEMS is sure to be the technology of the future

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