NEMS—emerging products and applications of nano-electromechanical systems

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Summary

In this article we investigate points of contact between micro-electromechanical systems (MEMS) and nanotechnology. Several examples of companies harnessing nano-electromechanical systems (NEMS) are presented, highlighting the fields in which a downscaling of MEMS will become commercially important. Although major MEMS companies do not feel concerned with nanotechnology, NEMS are likely to have an impact on mass markets in the fields of storage, sensing, radio frequency (RF) MEMS, and systems based on carbon nanotubes (CNTs).

1. Introduction

Industrial and academic R&D activities as well as conference series and funding programmes seem to indicate that the micro- and nano-worlds are continuously merging. We ask whether this trend is also manifest in the field of MEMS. Specifically, this paper focuses on electromechanical systems and identifies points of contact between MEMS and nanotechnology. By means of examples of companies already commercializing NEMS, we will address the relevant questions occurring in this context. Are there real connexions between MEMS and nanotechnology? Is there a trend to the downscaling of MEMS? If yes, what are the benefits and how can potential synergies be exploited? Which NEMS applications already exist, which are in development, and what are the opportunities offered by nanotechnology?

In some cases, "nano"-products emanate as natural, inevitable extensions of their well-established "micro"-precursors simply by the downscaling of conventional technology. The global semiconductor industry, in the meantime adopting processes in the sub-100 nanometre (nm) range, is a prominent example. In addition, there are fields in which the idea of "nano" is accompanied by disruptive mechanisms and completely novel concepts, mostly dominated by

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the laws of quantum physics. Devices based on the electron's spin rather than on its charge ("spintronics") and new classes of nano-objects like quantum dots and carbon nanotubes are prominent instances here.

Within the framework of this paper, WTC uses the term "nanotechnology" referring to:

- structures of sub-100 nm scale
- new fabrication methods based on self-assembly (bottom up, see below)
- operation principles based on nano or quantum effects.

In general, there are two fundamental approaches for the realization of NEMS:

- In a top down approach, structures are miniaturized mainly by means of well established semiconductor fabrication techniques
- In a bottom up approach, functional systems are made up by assembling nanosized components like carbon nanotubes or DNA.

The figure below illustrates these concepts and gives an overview of the time scales relevant for the commercialization of promising NEMS devices, which will be discussed in the following sections.

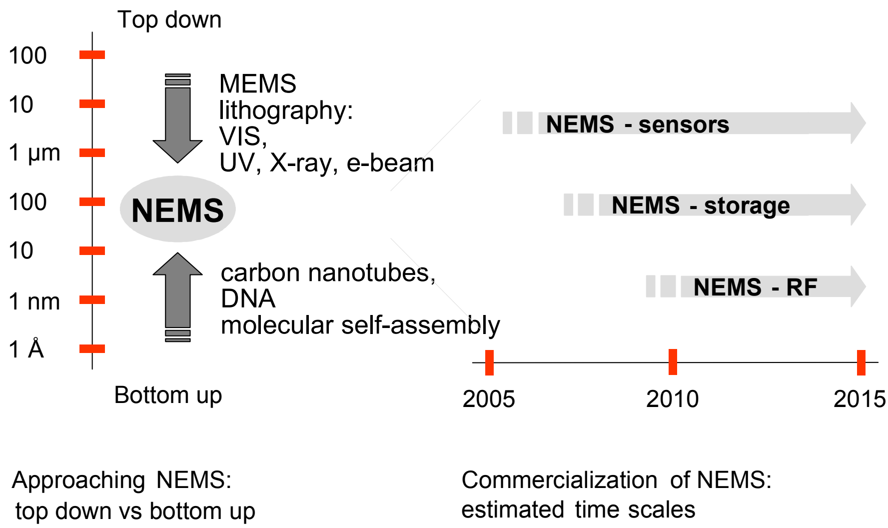

Figure. (Left) fundamental models for approaching NEMS and (right) estimated commercial timing for NEMS.

2. NEMS applications and products

Many of the established MEMS manufacturers believe that nanotechnology will not play a major role in their activities within the next three to five years, since in a variety of applications, e.g. in some sensor concepts, there is no need to further reduce the device dimensions.

For instance, MEMS applications in the automotive industry demand relatively large electrical signals in order to achieve adequate signal-to-noise ratios. As a result, devices like gyroscopes, typically working on a membrane-based capacitive measurement principle, must not fall below a certain capacity value and hence not below a certain critical size. Generally speaking, sensor concepts relying on the inertia of a mechanical probe, like the accelerometer deploying the airbag in a passenger car, require a minimum mass to function properly—a trivial consequence of the detection principle.

Therefore many MEMS companies are not planning to downsize their products and do not feel concerned with nanotechnology. In these cases, MEMS remains MEMS without any real overlap with the nano-world.

However, some promising approaches are opening up new possibilities by downscaling MEMS and enabling disruptive NEMS devices with advantageous properties. Significant examples will be outlined in the following subsections. As a result of being the most attractive field in terms of time to market and potential market size, NEMS data storage will be covered in more detail than the other areas**.**

2.1 Storage

The downscaling of current memory devices like DRAM, SRAM,[2] hard disk, or flash is expected to slow down and involve only a few additional process technology nodes as each follows the path set by Moore's law. Additionally, the rapid increase of portable computing devices raises the demand for non-volatile memories with low power consumption. Due to its growing functionality, the mobile phone is the strongest driver in this segment. Hence, the semiconductor industry is searching for a new scalable low-cost technology. Ideally, it would be a "unified" memory combining the performance of SRAM, the cheapness and density of DRAM, together with the non-volatility of flash.

A variety of novel concepts are currently being developed to serve as next-generation storage technologies, including MRAM, holographic memory, molecular memory, and NEMS-based approaches. The price-per-bit of some NEMS technologies is not only already below that of flash but also expected to drop faster in the future, leveraging commercialization in this highly cost-sensitive business. Indeed a significant fraction of the overall market for non-volatile memory, which amounted to $\$19 \times 10^9$ in 2005, can be targeted by nanomemory concepts within two years.

Two complementary upcoming ideas for data storage relying on downsized MEMS technology can be identified: approaches based on *nanomechanical probes* and approaches based on *nanomechanical switches*.

2.1.1 NEMS memories based on scanning probe technology

Several companies are developing storage devices that use arrays of micro-/nanomechanical cantilevers with atomic force microscope (AFM) tips. The tips write and erase bits of data by manipulating a movable storage medium located beneath the array in a reversible manner. We describe the major proponents below.

IBM "Millipede" technology

The Millipede concept developed at the IBM Zurich Research Laboratory (CH) represents one of the first "real nanotechnology" mass data storage devices.

[2] DRAM, dynamic random access memory; SRAM, static random access memory.

Combining MEMS and scanning probe microscopy, it employs an array of micromachined cantilevers—64 × 64 or a total of 4096 in the recent design—equipped with an AFM tip, a reading sensor, and heating resistor. The cantilevers create structures of the order of 10 nm in a polymer film applied as the storage medium, therefore the method really is nanotechnology.

Each of the tiny depressions in the data medium represents one bit, enabling storage densities that far exceed those of magnetic storage media. To date 517 gigabits per square inch have been demonstrated, and more than one terabit per square inch is claimed as achievable.

Since many of the processes required for manufacturing mechanical structures are not compatible with CMOS fabrication, IBM developed a new "transfer-and-join" technology. This technique allows fabrication of the cantilevers and necessary CMOS control electronics on separate wafers and interconnects the components in a subsequent step, thereby eliminating a critical problem in NEMS manufacturing.

Superdense Millipede memory devices will offer a capacity of up to 100 GB at the size of a Secure Digital (SD) flash card. Featuring low power, high frequency, high capacity and extreme miniaturization, this novel NEMS-based storage technology is especially suited for mobile computing applications. It is designed to replace flash rather than hard disk memory.

While Millipede is still a research project, it is at an advanced stage. IBM presented a prototype at CeBIT 2005 and is in negotiations with potential partners for the commercialization of the technology.

Hewlett-Packard "Atomic Resolution Storage"

Similar to the Millipede concept, the "Atomic Resolution Storage" (ARS) programme from Hewlett-Packard (USA) builds on atomic probe microscopy in combination with a special polymer film serving as the storage medium. The current design features in excess of 8000 read/write probes poking and erasing nanoscale dents in the polymer surface.

HP's patented MEMS-based micro-mover technology allows positioning of the cantilever probes with respect to the polymer film with an accuracy down to 3 nm. Using such precise positioning, a centre-to-centre distance of single bits of less than 10 nm seems reachable, translating into a storage density of more than 6 terabits per square inch.

HP's concept is at a very advanced stage. Portable storage of up to 10 GB in the format of SD cards is the first market segment to be targeted. Commercialization is moving fast and claimed possible in under a year. However, the company decided against launching an internal commercialization programme, and is looking for partners and licensees to bring its ARS and micro-mover technologies to market.

Nanochip "Ovonic" memory

Nanochip (USA) combines scanning probe techniques with a phase-change memory medium to realize a Phase-change Random Access Memory (PRAM) or "ovonic" memory, a concept developed by Ovshinsky Electronics.

How does it work? An array of atomic force tips writes and erases data bits in a thin chalcogenide film. During the writing process, a current driven through a tip into the film locally heats and melts the storage medium. Depending on the subsequent cooling process, the melted chalcogenide is either frozen in an amorphous phase or adopts a crystalline structure. These two phases differ in resistivity, thereby allowing a data bit to be represented. For readout, the resistivity, i.e. the encoded bit value, is monitored by a small probe current. Applying HP's micro-mover technology, the chalcogenide-coated plotter can be precisely positioned beneath the probe array, enabling high storage densities.

Generally, the technology can serve as an alternative to DRAM, SRAM and flash and enable high capacity, low cost, non-volatile memory that is x,y-addressable. Nanochip licensed the ovonic phase-change technology for use in its nanoprobe storage device back in 2004 and is partnering with Intel in the USA for commercialization. The market segment of interest is standard removable memory cards such as compact flash, SD, memory sticks, etc. with a capacity of up to 100 GB.

STMicroelectronics

As a global independent semiconductor company that designs, develops, manufactures and markets a broad range of semiconductor integrated circuits (ICs) and discrete devices, STMicroelectronics (F/I) has started an internal development programme to develop probe storage MEMS-based memory devices.

While defining key European partners, STMicroelectronics (STM) is examining options for nanometer-scale non-volatile memory. Relying on a MEMS cantilever array, the company's approach is similar to that of the Millipede and ARS concepts. However, STM has not committed itself to a polymeric storage medium yet. Determining the best storage medium for commercialization—whether polymeric, chalcogenide or ferroelectric—is the current focus of the work.

2.1.2 NEMS memories based on switches

In addition to nanoprobe-based memory devices, there are notable concepts emerging making use of nanomechanical switches. Eliminating the need for a special storage medium and avoiding the moving and accurate positioning of large separated components makes these technologies highly flexible.

Two start-up companies have to be mentioned in this context: Cavendish Kinetics (NL) and Nantero (USA). Requiring only standard process equipment, the technologies developed by these companies offer new possibilities for highly dense data storage and could, if successful, replace existing mainstream memory products.

Cavendish Kinetics "Nanomech" technology

Cavendish Kinetics is harnessing MEMS techniques for its non-volatile storage technology called "Nanomech". Unlike IBM, HP and Nanochip, Cavendish is developing an *embedded* memory that can easily be implemented. Again, the basic idea is to use arrays of cantilevers to store information.

In contrast to scanning probe-based approaches, the cantilevers here act as nanoswitches. The switches are formed by conducting metal bars etched using MEMS processes that are supported and suspended above contact electrodes. Spatial dimensions approach the sub-100 nm range. By introducing a charge onto a contact electrode or onto a separate gate electrode the respective bar is attracted and deformed by electrostatic forces until it touches the contact. Able to adopt either a resistive or a conducting state, each structure represents one bit of memory. The programming of a single switch requires only 25 picojoules, giving rise to exceptionally low write/erase power requirements.

This novel concept enables faster and lower power on chip data storage. As a back-end process, Nanomech technology can be integrated with the top layer of a device. The mechanical elements are freely located within the existing interconnect process, so the method is fully compatible with CMOS and other technologies.

In principle, the approach is suitable for any type of memory. As a small company, Cavendish Kinetics bundles its activities and focuses on the replacement of embedded flash, the current mainstream technology for embedded non-volatile memory that is expected to be phased out in four to five years. Cavendish does not own a semiconductor fab,[3] but offers a process module as an IP package. Market entry is planned for 2007.

Nantero "NRAM" technology

Commercializing a technology invented at Harvard University,[4, 5] Nantero is developing "NRAM", a high-density non-volatile Random Access Memory (RAM) involving the use of suspended carbon nanotube (CNT) junctions as memory bits.

Prototype devices include arrays of 10^{10} "nano-relays" on a single silicon wafer. Each of the switches formed by some dozens of CNTs represents a single bit of data (cf. the Nanomech concept). After overcoming several technological challenges, especially the purification of the CNT material, Nantero is now the first company to use carbon nanotubes in a production CMOS fab. A 22 nm NRAM device has recently been fabricated and tested successfully, demonstrating the scalability of the technology to numerous process nodes.

NRAM memory is being developed as a potential universal memory. Nantero's ultimate goal is to use it as a replacement for any type of storage, including DRAM, SRAM, flash and hard drives. A first product is expected on the market by the end of 2007.

2.2 Sensors

In the field of sensing there are novel concepts emanating from the combination of MEMS and nanotechnology.

Cantion MEMS cantilevers

Cantion (DK) provides nanomechanical products for label-free detection and analysis of molecules.

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3 fab, fabrication facility (sometimes called a "foundry").

4 T. Rueckes et al., Carbon nanotube-based Nonvolatile Random Access Memory for molecular computing, *Science* **289** (2000) 94.

5 J.W. Ward et al., A non-volatile nanoelectromechanical memory element utilizing a fabric of carbon nanotubes, *IEEE NVMTech-Symp*. **29** (2004) 34.

Its technology is based on nanomechanical cantilevers produced by standard silicon microfabrication technology with dimensions in the nano- to micrometre range. Due to an application-dependent functionalization of the cantilever surface, the devices become sensitive to specific molecular targets. Immobilization of the target molecules on the cantilever surface makes the cantilever bend as a result of the surface stress induced by the interaction. Hence the cantilevers are used as nanomechanical stress sensors.

Piezoresistors integrated with the cantilevers allow for a complete electrical readout for monitoring of the bending, thus offering the possibility of creating handheld devices for decentralized analysis applications.

Cantion's technology is established and well-documented as a multifunctional, highly sensitive real-time method for a variety of sensor applications, including gas sensors for detecting volatile emissions from plastic explosives and sensors operating in liquids for detecting entire microorganisms, and in DNA and protein studies.

In December 2005, Cantion was acquired by NanoNord, a new Danish nanotechnology company cooperating closely with Aalborg University and Aarhus University. NanoNord has started a major redesign of Cantion's products and is intending to launch a new and improved generation of sensors based on Digital Signal Processing (DSP).

Basic research: suspended microchannels

The nanoscale sensing group at the Media Laboratory of the Massachusetts Institute of Technology (MIT) is developing a similar concept for a biochemical sensor particularly suited for sensing biomolecules found in aqueous environments (bacteria, viruses etc.).

By hollowing out a tiny cantilever, the researchers have manufactured a suspended microfluidic channel. Binding of the target molecules to appropriately functionalized inner walls shifts the resonance frequency of the cantilever, which can be monitored electronically. Since there is no surrounding fluid, the vibrations of the cantilever are not damped, resulting in better resolution.[6]

STMicroelectronics: NEMS inertial sensors

The Crolles-based branch of STMicroelectronics is investigating the downsizing of conventional MEMS within the MIMOSA European project (microsystem platform for ambient intelligence). Concerning sensors, STM is developing nano-accelerometers operating in the 10 *g* range with feature sizes down to 45 nm. The motivation is to completely integrate the sensor in the IC and thus save room and costs. NEMS fabrication technologies are extensions of the technologies used for (nano)electronics. For nano-accelerometers, the company makes use of thin silicon-on-insulators (SOI) to integrate the process.

2.3 Radio frequency (RF) resonators

High frequency applications constitute another area that will benefit from the impact of nanotechnology on MEMS. Since the resonance frequency of an oscillating structure is

[6] T.P. Burg & S.R. Manalis, Suspended microchannel resonators for biomolecular detection, *Appl. Phys. Lett.* **83** (2003) 2698.

inversely proportional to its size, reducing a mechanical resonators' dimensions enables the creation of devices operating in the GHz range, e.g. filters for cell phone applications.

STMicroelectronics: NEMS oscillators and filters

Again, it is STMicroelectronics that is active in this field in the context of MIMOSA. Using a silicon-on-nothing (SON) process, electro-mechanical resonators realized as beams or discs with feature sizes in the nanorange and resonance frequencies up to several GHz are developed and investigated in the Crolles-based branch of the company. Targeted applications are oscillators and RF filters.

As in the case of nano-accelerometers, this R&D work is still some way from the market; prototypes should be available at the end of the MIMOSA project (i.e. the beginning of 2008).

Basic research: quantum devices

NEMS resonators are primarily a subject of intense academic research. At ultra-low temperatures mechanical quantum effects, i.e. "quantum mechanics" in the literal sense, can be observed.

A team of researchers from the University of Maryland (USA), the University of Nottingham (UK), McGill University of Montreal (Canada), and Dartmouth College in Hannover (USA) recently demonstrated interactions between a superconducting single-electron transistor (SSET) and a radio-frequency nanomechanical resonator.[7] The SSET serves as a sensitive tool to monitor the position of the resonator. The authors claim that the reported measurements will have implications for nanomechanical readout of quantum information devices (e.g. for future quantum computers) and ultra-sensitive force microscopy techniques.

2.4 NEMS based on carbon nanotubes

Promising applications of carbon nanotubes for data storage have been described above in the form of Nantero's NRAM technology. Due to their high electrical conductivity, outstanding mechanical properties and nanometre dimensions, carbon nanotubes (CNTs) are predestined for a variety of NEMS applications. Several prototypes of CNT-based NEMS have been realized during the past years, including so-called nano-tweezers, actuators and electromechanical switches.[8]

Xintek: AFM tips

A well-established technique is the use of CNTs as high resolution nanosensors in AFM tips such as those developed by Xintek, an American company that has specialized in commercializing CNT-based products and technologies. Exploiting the mechanical properties of CNTs, and in particular their high aspect ratio and rigidity, such tips can enhance the performance of the various scanning probe microscopy techniques.

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7 A. Naik et al., Cooling a nanomechanical resonator with quantum back-action, *Nature* **443** (2006) 193.

8 J.P. Bourgoin et al., Carbon nanotubes for NEMS and RF NEMS, *Proc.* MEMSWAVE 2005, and references therein.

Basic research: switches, oscillators and mechanical sensors

Most activities in the CNT field still fall under the rubric of basic research and are unlikely to lead to interesting products in the near term. Besides scanning probe microscopy, electromechanical switches ("nanorelays") consisting of suspended nanotubes[9] in particular are considered to have great commercial potential, namely for memory devices and high frequency circuits.

In the case of high frequency components, those based on short (about 100 nm long) multiwall CNTs should easily approach a regime of several tens of GHz. Recently, a prototype tunable oscillator using CNTs has been demonstrated.[10]

Carbon nanotubes can also serve as ultra-sensitive mechanical sensors. Researchers from the Max-Planck-Institute in Stuttgart have fabricated nanotube-based torsion pendulums that act as a nano-force meter or nano-balance.[11]

A major remaining obstacle for CNT NEMS is the development of a CMOS-compatible fabrication process suitable for mass production. It is essential to find low-cost self-assembly techniques allowing for massive parallelism in manufacturing. Promising approaches have been reported in recent years.[12]

3. Conclusions

To answer our original question, there appears to be no general trend that would indicate transformation of MEMS into NEMS, and in many cases MEMS and nanotechnology will remain distinct fields. However, we note that there are several applications where NEMS are already of great importance, or will be shortly. The fields of storage, sensing, RF MEMS and CNT-based systems are emphasized in this context.

A number of motivations drive NEMS development: reduction of costs, increasing need for integration with CMOS, and inherent technological advantages (e.g. high surface to volume ratio allows highly sensitive sensors, small dimensions result in high resonance frequencies, to name but a few). In some instances, NEMS devices are likely to have a huge impact in mass markets, offering various business opportunities, in the main for semiconductor companies. Cavendish Kinetics, licensing an IP-protected product, and Nanochip, fabricating entire components in cooperation with big partners, represent some of the different business models.

Generally, we foresee that due to the impelling drive for integration, the market for individual NEMS components will be relatively small. For a while, stand-alone components will play an initial role. This is more the case for sensors than storage and high frequency applications.

In the case of fabrication, the commercialization of NEMS offers chances for materials and equipment suppliers alike. In particular, surface-related process steps like etching (e.g. DRIE[13]) and chemical-mechanical polishing technologies are becoming increasingly critical and require advanced equipment.

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[9] S.N. Cha et al., Fabrication of a nanoelectromechanical switch using a suspended carbon nanotube, *Appl. Phys. Lett.* **86** (2005) 083105.

[10] V. Sazonova et al., A tunable carbon nanotube electromechanical oscillator, *Nature* **431** (2004) 284.

[11] J.C. Meyer et al., Single-molecule torsion pendulum, *Science* **309** (2005) 1539.

[12] K.H. Choi et al., Controlled deposition of carbon nanotubes on a patterned substrate, *Surf. Science* **462** (2000) 195.

[13] DRIE, deep reactive ion etching.