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MICRO & NANO TECHNOLOGIES – APPLICATIONS, DESIGN AND INTEGRATION

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Rezumat. *Ştiinţa micro-nano tehnologiilor reprezintă un domeniu de cercetare multidisciplinară, care provoacă o participare activă a specialiştilor din mai multe domenii (fizică, chimie, biologie, matematică, electronică, medicină, ş.a.). Nanotehnologia este un domeniu de ştiinţe aplicate focalizând proiectarea, sinteza şi caracterizarea materialelor şi dispozitivelor de pornind de la nivelul atomilor şi molecule până la nivelul supramolecular de tulpini de molecule cu 100 diametre moleculare. Operaţiunile la aceste dimensiuni presupune înţelegerea noilor principii ştiinţifice şi proprietăţile noilor materiale, care au loc la nivel micro şi scară nano şi sunt folosite în dezvoltarea materialelor, dispozitivelor şi sistemelor cu funcţii noi şi performanţe îmbunătăţite. Proprietăţile şi funcţiile de bază ale structurilor şi ale sistemelor materiale la scară nano se pot schimbat în funcţie de organizarea materiei vii pe interacţiunile moleculare "slabe" (legături cu hidrogenul, dipoli electrostatici, forţe Van der Waals, forţele de suprafaţă, forţele electro-fluidice, ş.a.).*

Abstract. *The science of micro-nano technologies represents a multidisciplinary research domain, which provokes active participation of specialist from multiple domains (physics, chemistry, biology, mathematics, electronics, medicine, a.o.). Nanotechnology is an applied science domain focusing the design, synthesis and characterization of materials and devices starting from individual atoms and molecules level up to supramolecular level of strains of molecules with 100 molecular diameters. Operations at this dimensions implies the understanding of new scientific principles and new materials properties, which take place at micro and nano scale and are used in the development of materials, devices and systems with new and improved functions and performances. The properties and basic functions of structures and material systems at nano scale may be changed based on the organization of the living mater on molecular "weak" interactions (hydrogen binds, electrostatic dipole, Van der Waals forces, surface forces, electro-fluidic forces, a.o.).*

Keywords: MEMS, market, application, design, integration

1. Introduction

In many respects, MEMS technology development parallels that of solid state electronics. However, it lacks the definitive pedigree of that more extensive topic, which started with the invention of the transistor in 1947, followed by the integrated circuit in 1959. The closest analogy for MEMS was the 1954 discovery

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of the piezoelectric effect in silicon, which enabled strain in micromechanical structures to be measured. Subsequent developments in high gain, low noise amplifier technology made capacitance based sensors and actuators feasible. MEMS products based on piezoelectric and capacitance sensing now include pressure and flow sensors, accelerometers, gyroscopes, microphones, digital light projectors, oscillators, and RF switches. Development continues on a plethora of new devices, but significant effort is also being devoted to improving the performance and packaging of existing devices.

MEMS based products produced in 2005 had a value of $8 billion, 40% of which was sensors. The balance was for products that included micro machined features, such as ink jet print heads, catheters, and RF IC chips with embedded inductors. Growth projections follow a hockey stick curve, with the value of products rising to $40 billion in 2015 and $200 billion in 2025! Growth to date has come from a combination of technology displacement, as exemplified by automotive pressure sensors and airbag accelerometers, and new products, such as miniaturized guidance systems for military applications and wireless tire pressure sensors. Much of the growth in MEMS business is expected to come from products that are in early stages of development or yet to be invented. Some of these devices include disposable chips for performing assays on blood and tissue samples, which are now performed in hospital laboratories, integrated optical switching and processing chips, and various RF communication and remote sensing products.

The key to enabling the projected 25 fold growth in MEMS products is development of appropriate technologies for integrating multiple devices with electronics on a single chip. At present, there are two approaches to integrating MEMS devices with electronics. Either the MEMS device is fabricated in polysilicon, as part of the CMOS wafer fabrication sequence, or a discrete MEMS device is packaged with a separate ASIC chip. Neither of these approaches is entirely satisfactory, though, for building the high value, system-on-chip products that are envisioned. A combination of self-assembly techniques in conjunction with wafer stacking, will offer a viable path to realizing ubiquitous, complex MEMS systems.

2. Market for MEMS

Between 2000 and 2004 the largest growth in MEMS applications occurred in the automotive market. Sales in this period climbed from $1.26 billion to $2.35 billion, while applications expanded to the point that a typical automobile contains between 25 and 70 MEMS devices. Even though the quantity of MEMS devices sold into the automotive market is expected to continue climbing steadily, the automotive percentage of the total MEMS market is actually expected to decline, as consumer product applications expand.

Demand for ink jet print heads is expected to remain strong, but relatively constant. The large growth in the consumer products area is expected from demand in three areas, large screen, high definition television, read write heads for high density storage systems, and mobile phone sets. The first two of these applications are essentially single products, digital light projectors and high precision positioning devices. Mobile phones are expected to incorporate an increasing number of MEMS devices. The two most significant of these devices, in terms of dollar value, are clocks and microphones.

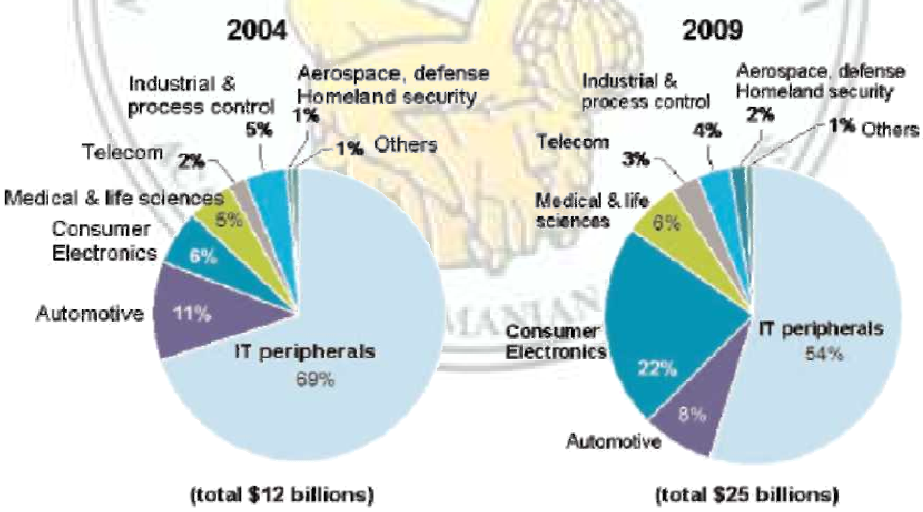

Fig. 1. Trends in MEMS products markets

The medical market for MEMS devices is expected to more than double from $660M in 2004 to $1.6B in 2009. Much of the current volume is in pressure sensors, but many new applications are emerging such as blood analysis chips. There is considerable potential for revolutionary products in which MEMS sensors are integrated with highly miniaturized electronics for in-vivo remote monitoring. Two such examples are capsule camera and injectable capsules, for monitoring the health of livestock.

3. MEMS applications

Science and technology continue to move forward in making the fabrication of micro/nanodevices and systems possible for a variety of industrial, consumer, and biomedical applications. A range of MEMS devices have been produced, some of which are commercially used. A variety of sensors are used in industrial, consumer, and biomedical applications. Various microstructures or micro-components are used in micro-instruments and other industrial applications, such as micro-mirror arrays. Two of the largest "killer" industrial applications are accelerometers (about 85 million units in 2002) and digital micro-mirror devices (about $400 million in sales in 2001). Integrated capacitive type, silicon accelerometers have been used in airbag deployment in automobiles since 1991.

Accelerometer technology was about a billion-dollar-year industry in 2001, dominated by Analog Devices followed by Motorola and Bosch. Commercial digital light processing (DLP) equipment using digital micro-mirror devices (DMD) were launched in 1996 by Texas Instruments for digital projection displays in portable and home theater projectors, as well as table-top and projection TVs. More than 1.5 million projectors were sold before 2002. Other major industrial applications include pressure sensors, inkjet printer heads, and optical switches. Silicon-based piezoresistive pressure sensors for manifold absolute pressure sensing for engines were launched in 1991 by Nova-Sensor, and their annual sales were about 25 million units in 2002. Annual sales of inkjet printer heads with microscale functional components were about 400 million units in 2002. Capacitive pressure sensors for tire pressure measurements were launched by Motorola.

Other applications of MEMS devices include chemical sensors; gas sensors; infrared detectors and focal plane arrays for earth observations; space science and missile defense applications; pico-satellites for space applications; and many hydraulic, pneumatic, and other consumer products. MEMS devices are also being pursued in magnetic storage systems, where they are being developed for super-compact and ultrahigh recording-density magnetic disk drives. Several integrated head/suspension microdevices have been fabricated for contact recording applications. High-bandwidth, servo-controlled microactuators have been fabricated for ultrahigh track-density applications, which serve as the fine-position control element of a two-stage, coarse/fine servo system, coupled with a conventional actuator. Millimeter-sized wobble motors and actuators for tip-based recording schemes have also been fabricated.

BIOMEMS are increasingly used in commercial and defense applications. Applications of BIOMEMS include biofluidic chips (otherwise known as microfluidic chips, bioflips, or simply biochips) for chemical and biochemical analyses (biosensors) in medical diagnostics (e.g., DNA, RNA, proteins, cells, blood pressure and assays, and toxin identification) and implantable pharmaceutical drug delivery.

The biosensors also referred to as lab-on-a-chip, integrate sample handling, separation, detection, and data analysis onto one platform. Biosensors are designed to either detect a single or class of (bio) chemicals or system-level analytical capabilities for a broad range of (bio) chemical species known as micro total analysis systems (μTAS). The chips rely on microfluidics and involve the manipulation of tiny amounts of fluids in microchannels using microvalves for various analyses.

Examples of NEMS include nanocomponents, nanodevices, nanosystems, and nanomaterials, such as microcantilever with integrated sharp nanotips for STM and atomic force microscopy (AFM), AFM array (millipede) for data storage, AFM tips for nanolithography, dip-pen nanolithography for printing molecules, biological (DNA) motors, molecular gears, molecularly thick films (e.g., in giant magneto-resistive or GMR heads and magnetic media), nanoparticles, (e.g., nanomagnetic particles in magnetic media), nanowires, carbon nanotubes, quantum wires (QWRs), quantum boxes (QBs), and quantum transistors.

BIONEMS include nanobiosensors – a microarray of silicon nanowires, roughly a few nm in size, to selectively bind and detect even a single biological molecule, such as DNA or protein, by using nanoelectronics to detect the slight electrical charge caused by such binding, or a microarray of carbon nanotubes to electrically detect glucose, implantable drug-delivery devices – e.g., micro/nanoparticles with drug molecules encapsulated in functionized shells for a site-specific targeting application, and a silicon capsule with a nanoporous membrane filled with drugs for long term delivery, nanodevices for sequencing single molecules of DNA in the Human Genome Project, cellular growth using carbon nanotubes for spinal cord repair, nanotubes for nanostructured materials for various applications, such as spinal fusion devices, organ growth, and growth of artificial tissues using nanofibers.

Nanoelectronics can be used to build computer memory, using individual molecules or nanotubes to store bits of information, as well as molecular switches, molecular or nanotube transistors, nanotube flat-panel displays, nanotube integrated circuits, fast logic gates, switches, nanoscopic lasers, and nanotubes as electrodes in fuel cells.

4. MEMS design principles

A typical micro electro mechanical system is a monolithically integrated system or subsystem consisting of micro sensors, micro actuators and microelectronic circuits, as schematically shown in Figure 2. The bold arrows in the figure indicate the mechanical interaction between the device and the outside world, and the thin arrows indicate the electrical or other non-mechanical signals among the components of the device, and between the device and the outside world. Note that not every MEMS device makes use of all the components and operations indicated in the figure, but each involves a micro mechanical structure of some kind.

The movement of mechanical structures is detected by mechanical sensors. The other parameters (say, temperature, pressure, acceleration, and so on) can be sensed either by mechanical sensors or by solid-state sensors. Obviously, the sensors for the state of mechanical structure are more essential than those for other parameters.

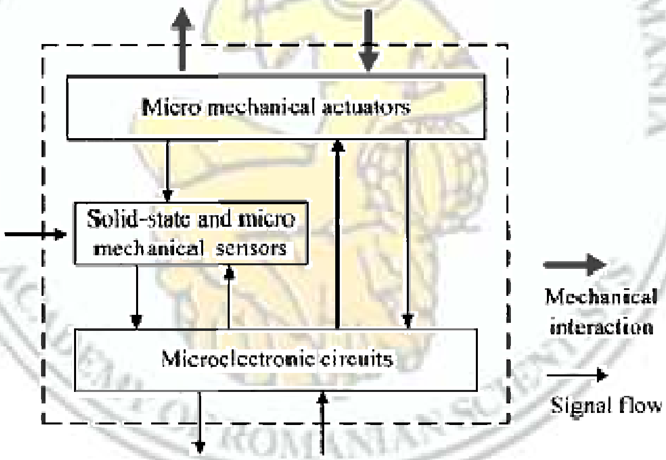

Fig. 2. Basic configuration of a MEMS device

The micro mechanical actuators are driven and controlled by a variety of means. However, electrostatic driving is the most commonly used one nowadays. Electronic circuits are widely used for signal detection, signal processing, the control of the system and providing electrostatic driving force for mechanical actuators.

Based on the description above, the analysis and design principles of the MEMS device fall into three basic categories: the dynamics of micro mechanical structure (or, the microdynamics), the sensing schemes and microelectronics, as illustrated in Figure 3.

Micro mechanical technology has been under development for several decades. So far a variety of MEMS devices have been developed and many of them have been mass produced. However, the analysis and design principles on MEMS devices are still widely scattered in literatures of different disciplines, such as mechanics, electrostatics, hydrodynamics, solid-state physics, microelectronics, etc. This situation is not convenient for the researchers and engineers who are developing MEMS devices and for students who are studying in this interesting area.

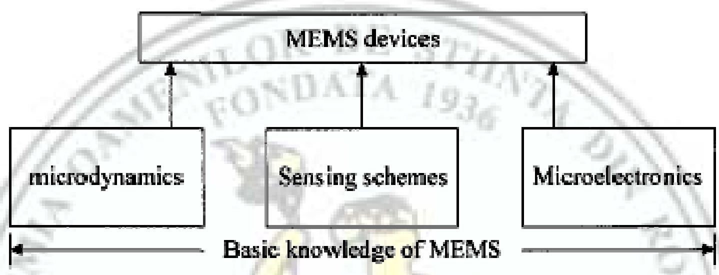

Fig. 3. Basic analysis and design principles of MEMS

The essential theories for the analysis and design of MEMS need more materials study and understanding for MEMS practical applications to be made more easily. Microdynamics must be treated more thoroughly including the basic principles of mechanics of beam and diaphragm structures, air damping and its effect on the motion of mechanical structures, and the electrostatic driving of mechanical structures. For sensing schemes, the following are the most common: Frequency sensing thats naturally related to mechanical structures and promising for its high resolution, high stability and digital compatibility. Capacitive sensing is the sensing scheme most compatible with MEMS devices and the most popular sensing scheme currently used in MEMS. Piezoresistive sensing is the first sensing scheme that led to the development of micro mechanical transducers since the 1960s and is now still widely used in MEMS.

5. MEMS integration

The integration of electronics for control and sense circuitry and MEMS technology becomes essential for sensing applications, which require increased sensitivity (e.g., Analog Devices ADXL accelerometers), or actuation applications that require the control of large arrays of MEMS devices (e.g., TI DMD™). For sensor applications, the packaging integration of a MEMS device and an electronic ASIC becomes unacceptable when the parasitic capacitances and wiring resistances have an impact on sensor performance (i.e., RC time constants of the integrated MEMS system are significant). For actuation applications such as a large array of optical devices that require individual actuation and control circuitry, a packaging solution becomes untenable with large device counts.

Surface micromachining is the most amenable to integration with electronics to form an IMEMS process. The development of an IMEMS process faces some challenges:

• Large vertical topologies. Microelectronic fabrication requires planar substrates due to the use of precision photolithographic processes. Surface micromachine topologies can exceed 10 μm due to the thickness of the various layers.

• High-temperature anneals. The mitigation of the residual stress of the surface micromachine structural layers can require extended periods of time at high temperatures (such as several hours at 1100°C for polysilicon). This would have adverse effects due to a thermal budget of microelectronics that is limited because of dopant diffusion and metalization.

Usually there are three strategies for the development of an IMEMS process:

• Microelectronics first. This approach overcomes the planarity restraint imposed by the photolithographic processes by building the microelectronics before the nonplanar micromechanical devices. The need for extended high-temperature anneals is mitigated by the selection of MEMS materials (e.g., aluminum, amorphous diamond) and/or selection of the microelectronic metallization (e.g., tungsten instead of aluminum); these make the MEMS and microelectronic processing compatible. Examples of this IMEMS approach include an all-tungsten CMOS process developed by researchers at Berkeley Sensor and Actuator Center, and the Texas Instruments' process used to fabricate the DMD (Figure 4), which utilizes aluminum and photoresist as the device structural layer and sacrificial layer, respectively.

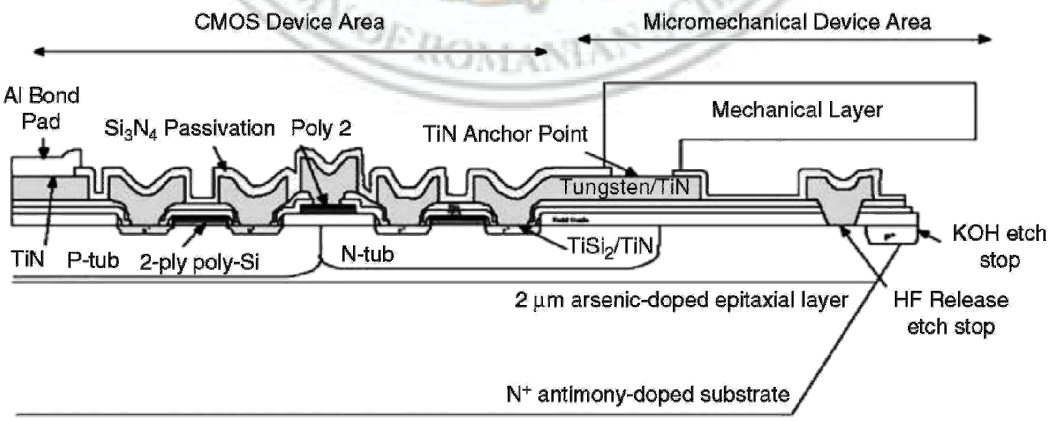

Fig. 4. Microelectronics first approach to MEMS-microelectronic process integration

• Interleave the microelectronics and MEMS fabrication. This approach may be the most economical for large-scale manufacturing because it optimizes and combines the manufacturing processes for MEMS and microelectronics. However, this requires extensive changes to the overall manufacturing flow in order to accommodate the changes in the microelectronic device or the MEMS device. Analog Devices has developed and marketed an accelerometer and gyroscope that illustrate the viability and commercial potential of the interleaving integration approach.

• MEMS fabrication first. This approach fabricates, anneals, and planarizes the micromechanical device area before the microelectronic devices are fabricated, thus eliminating the topology and thermal processing constraints. The MEMS devices are built in a trench that is then refilled with oxide, planarized, and sealed to form the starting wafer for the CMOS processing. This technology was targeted for inertial sensor applications.

Conclusions

Even though the field of MEMS has experienced significant growth over the past decade, many challenges still remain. In broad terms, these challenges can be grouped into three general categories: (1) fabrication, (2) packaging, and (3) application. Challenges in these areas will, in large measure, determine the commercial success of a particular MEMS device, both in technical and economic terms.

Conclusion (1).

MEMS are currently dominated by planar processing techniques, which find their roots in silicon IC fabrication. However, modular process integration of micromachining with standard IC fabrication is not straightforward and represents a great challenge in terms of processing material compatibility, thermal budget requirements, etc. Furthermore, planar processing places significant geometric restrictions on device designs, especially for complex mechanical components requiring high-aspect ratio three-dimensional geometries, which are certain to increase as the application areas for MEMS continue to grow. Along the same lines, new applications will likely demand materials other than silicon that may not be compatible with the conventional microfabrication approach, posing a significant challenge if integration with silicon microelectronics is required.

Conclusion (2).

Packaging tends to negate the effects of miniaturization based upon microfabrication, especially for MEMS devices requiring protection from certain environmental conditions. Moreover, packaging can cause performance degradation of MEMS devices, especially in situations where the environment exerts mechanical stresses on the package, which, in turn, results in a long-term device performance drift. To address many of these issues, wafer-level packaging schemes that are customized to the device of interest will likely become more common. In essence, packaging of MEMS will move away from the conventional IC methods, which utilize independently manufactured packages, toward custom packages, which are created specifically for the device as part of the batch fabrication process.

Conclusion (3).

The advancement of MEMS will open many new potential application areas to the technology. In most cases, MEMS will be one of several alternatives available for implementation. For cost sensitive applications, the trade off between technical capabilities and cost will challenge those who desire to commercialize the technology. The biggest challenge to the field will be to identify application areas that are well suited for MEMS/NEMS technology and have no serious challengers. As MEMS technology moves away from the component level and towards microsystems solutions, it is likely that such application areas will come to the fore.

Conclusion (4).

Micro-assembly technique can become an attractive solution to lessen all above issues. Multifunctional Microsystems can be implemented by assembling various MEMS devices and electronic building blocks fabricated through disparate processing technologies. Microsystem on a common substrate will likely become the ultimate solution. Development of sophisticated modeling programs for device design and performance will become increasingly important as fabrication processes and device designs become more complex. In terms of NEMS, the most significant challenge is likely the integration of nano- and microfabrication techniques into a unified process, since NEMS devices are likely to consist of both nanoscale and microscale structures. Integration will be particularly challenging for nanoscale devices fabricated using a bottom-up approach, since no analog is found in microfabrication. Nevertheless, hybrid systems consisting of nanoscale and microscale components will become increasingly common as the field continues to expand.

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