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M^3: the Third Dimension of Silicon

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Abstract

Microsystems technology is a fascinating and exciting field that has played and will continue to play a very important role in building a bridge between science and society. Physical properties and material characteristics are translated into structures and devices that can have a large positive impact on people's lives. Silicon micromachining has been largely responsible for the expansion of sensors and actuators into more complex systems and into areas not traditionally related to microelectronics, such as medicine, biology and transportation. The shift to 3D microstructures has not only added a physical *third dimension* to silicon planar technology, it has also added a *third dimension* in terms of functionality and applications. In this chapter, the basic issues and fundamental aspects of this field are briefly introduced. A few examples that illustrate *the power of the small world* are given and possible ways to pursue further miniaturization and/or increase in functionality are discussed.

Keywords

microsystems technology; MEMS; silicon micromachining; 3D microstructuring.

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1.1

Introduction

The fascination for the small world has been a constant in the research in physics, biology and engineering. Many scientists share a great interest in miniaturization technologies and in studying the behavior of materials and structures in the micro- and nanometer range. The investigation of the small world of matter is crucial to understanding how things work and this knowledge can be used to create novel microstructures and devices, thus offering the necessary tools and components to realize applications of great societal importance.

Microsystems technology is a fascinating and exciting field that has played and will continue to play a very important role in building a bridge between science and society to translate physical properties and material characteristics into structures and devices that can have a large positive impact on people's lives. In this chapter, the basic issues and fundamental aspects of this field are briefly introduced and an attempt is made to indicate where we are now and where we are going and how the small world makes a big difference.

1.2

M^3: Microsystems Technology, MEMS and Micromachines

Microsystems technology (MST) generally refers to design, technology and fabrication efforts aimed at combining electronic functions with mechanical, optical, thermal and others and that employ miniaturization in order to achieve high complexity in a small space. Microsystems are thus intelligent microscale machines that combine sensors and actuators, mechanical structures and electronics to sense information from the environment and react to it. These tiny systems are or soon will be present in many industrial and consumer products and will have a huge impact on the way we live, play and work.

In addition to MST, there are a number of other terms and acronyms that are used to describe this field, referring either to technologies, design concepts or integration issues. The most frequently used or encountered terms come from the three major geographical areas involved in this field:

- Europe → Microsystems technology (MST);
- USA → Microelectromechanical systems (MEMS);
- Japan → Micromachines (MM).

Apparently in Europe the accent is placed on the miniaturization of the entire systems, in the USA on the mechanical components being brought into the microelectronic world and in Japan on the miniaturization of a machine. Maybe this reflects in some way the cultural backgrounds of the three regions.

Although the names are somewhat different, basically they all accentuate both the miniaturization and the multi-functionality and system character. Some groups consider the presence of a movable part in the system necessary to be able to talk about MEMS, but in most cases the multi-functional character and miniaturization are the essential ingredients or prerequisites.

In view of the truly global character of research and the many transnational cooperations in this area, a new way to address this field collectively is M^3:

$$\mathrm{MST} \cdot \mathrm{MEMS} \cdot \mathrm{MM} = M^3$$

The exponential factor 3 can also be seen in relation to the *third dimension*. In fact, it not only combines all definitions identifying this field, it also stresses and symbolizes the importance of the introduction of an active 'third dimension' to silicon, literally and figuratively, and the impact these truly three-dimensional (3D) microsystems have in applications ranging from health care to consumer products.

We could also see the M^3 as summarizing three key characteristics of this field: *M*ultidisciplinary, *M*iniaturization, *M*ankind needs:

$$M^3 = M \cdot M \cdot M$$

Each of these aspects will be addressed in the following sections. Let us now take a closer look at the general concept of microsystems (or MEMS or MM) technology.

1.2.1
Microsystem Technology

Microsystem technology (MST) has experienced about two decades of evolution, mainly driven by a few key applications. It is likely to drive the next phase of the information revolution, as microelectronics has driven the first phase. A multi-bil-

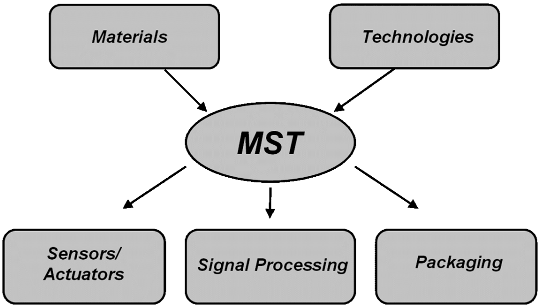

Fig. 1.1 Microsystems technology: the next phase in information evolution

lion dollar market by the middle of the next decade has been forecast and although there is some discrepancy in the figures presented by different bureaus and agencies, a common belief in a consistent growth is shared by all.

The general concept of MST, schematically depicted in Fig. 1.1, is to combine new materials with microprocessing technology (mostly well suited for low-cost mass production purposes) and micromachining technologies to form the three basic building blocks of every microsystem: sensing/actuation element, signal processing, package.

Advances in material science and processing are at the base of each MST product. Three main groups of materials are to be distinguished: materials for the package, materials for the actual device and the electronics and materials for the mechanical/electrical connection between these. Progress in semiconductor processing has evolved in a number of substrate materials predestined for use in microstructured devices, such as silicon, silicon-on-insulator, silicon carbide and gallium arsenide. Pricing and reliability considerations have led to the almost exclusive use of silicon-based micromachined devices. Packaging and assembly have focused on ceramics, printed circuit board (PCB) technology and multi-chip modules (MCMs) [1].

1.2.2
MST versus IC

The continuous advances in silicon-based integrated circuit (IC) technology, in terms of both processing and equipment, have definitely contributed to microsystems developments. At the same time the enormous growth in microsystems applications has stimulated the development of dedicated equipment and generated a larger knowledge of material and structure characteristics, especially in the mechanical area, which have been of great help to the IC world.

MST is often envisioned as being similar to semiconductor microelectronics and, although they possess many similarities, there are also some strong differences, as indicated in Tab. 1.1. Some of the most important ones are the lack of a 'unit cell' (no transistor-equivalent) and of a stable front-end technology (no CMOS equivalent). Moreover a multidimensional interaction space (not only elec-

Tab. 1.1 Important differences between MST and IC

	MST	*IC*
Unit cell	No unit cell	Transistor
Front-end technology	No single stable technology	CMOS
Interaction space	Multidimensional	Electrical
Basic disciplines	Multidisciplinary	Physics and engineering

trical connections) is present and it is a very multidisciplinary field as next to physics and engineering other disciplines such as chemistry, material science and mechanics play an important role.

Therefore, research is evolving toward a MST unit that is not a single unit cell, like the transistor, but small, specifically designed, components libraries that could be refined over time to become standard building blocks for each MST device domain.

1.3
M^3: Multidisciplinary, Miniaturization, Mankind Needs

Microsystems technology has a strong *multidisciplinary* character. Integration across several disciplines takes place. Next to physics and engineering, the basic disciplines of microelectronics, we find that chemistry and biology are becoming more and more a part of MST as new materials and phenomena play a major role in the development of new microsystems. Also, of course, as movable or flexible parts are often essential components of the system, the role of mechanics or rather micromechanics is much larger than it ever was in conventional microelectronics. Although the broad range of expertise and know-how that this field requires might make the path to problem solving and product development more difficult, it can also be seen as enrichment in the engineering world.

In fact, microelectronics is entering many industrial sectors that are becoming increasingly multidisciplinary environments, such as biotechnology, health care and telecommunication. Consequently, growing interest in an interdisciplinary educational program is observed as it will become extremely important to prepare a new generation of engineers capable of operating in such multi-disciplinary environments. Another positive aspect of the way in which research and development in this field is carried out is the development of important social skills such as dealing with people from different fields and speaking different languages (literally and figuratively), something that is more the norm than the exception. This learning process could be very useful in the global world in which we operate nowadays.

1.3.1
Miniaturization

Another key aspect of MST is *miniaturization*. Miniaturization is necessary

- to achieve increased functionality on a small scale;
- to utilize particular effects and phenomena that are of no specific relevance at the macroscale level;
- to increase performance in order to make new areas of application possible;
- to interface the nanoworld.

It is generally pursued by using silicon IC-based technologies, with proper modification or the addition of specifically developed modules. A key process is the 3D machining of semiconductor materials, leading to miniaturized structures constituting the sensing, actuating or other functional parts. The main processes are bulk micromachining (BMM) and surface micromachining (SMM).

1.3.1.1 Bulk micromachining

Bulk micromachining covers all techniques that remove significant amounts of the substrate (or bulk) material and the bulk is part of the micromachined structure [2]. Typical BMM structures are shown in Fig. 1.2. This microstructuring of the substrate is often done to form structures that can physically move, such as floating membranes or cantilever beams. Other types of structures that can be realized by bulk micromachining are wafer-through holes, often used for through wafers interconnects in chip stacks and very deep cavities or channels to form microwells or reservoirs for biochemical applications. The substrate (generally silicon) can be removed using a variety of methods and techniques. In addition to a number of processes using wet (or liquid) etchants, techniques using etchants in the vapor and plasma state (generally referred to as dry) are available.

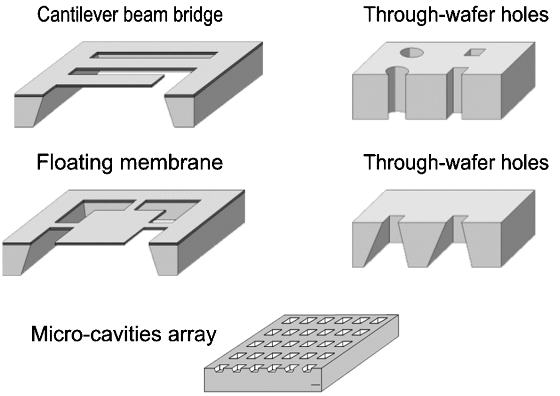

Fig. 1.2 Typical bulk micromachined structures

1.3.1.2 **Surface Micromachining**

Surface micromachining is a very different technology, which involves the deposition of thin films on the wafer surface and the selective removal of one or more of these layers to leave freestanding structures, such as membranes, cantilever beams, bridges and rotating structures [2]. Examples of typical SMM structures are shown in Fig. 1.3. In recent years, a number of new processes have been developed which use the upper few microns of the substrate (often an epitaxial layer) as a mechanical layer. The basic principle of surface micromachining shows two types of layers, the sacrificial layer and the mechanical layer. The sacrificial layer is removed during subsequent processing to leave the freestanding mechanical structure. The sacrificial layer is accessed from the side of the structure or through access holes.

Other processes or techniques relevant to microsystems fabrication are wafer-to-wafer bonding techniques, 3D lithography and some other high aspect ratio techniques such as LIGA and laser machining [3].

The choice of the 3D micromachining technology depends strongly on the application field and design of the MST product to be manufactured. The use of techniques compatible with standard semiconductor processing is often preferred as this permits batch fabrication, potential cost efficiency and system integration.

In Delft, the importance of integrating multi-elements on a single chip while focusing on the system aspects has been recognized for a long time [4]. Research has therefore focused on silicon (the major material for ICs) and silicon-related materials and the development of post-process modules following the approach shown schematically in Fig. 1.4. This approach allows on the one hand the addition of more functions on a chip, offering some flexibility and application-specific variations, and on the other hand preserves the compatibility with basic IC processes (Bipolar or CMOS), thus allowing the realization of complete systems (sensor + signal processing + actuator).

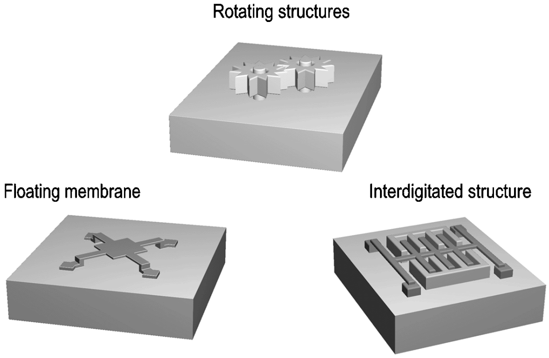

Fig. 1.3 Typical surface micromachined structures

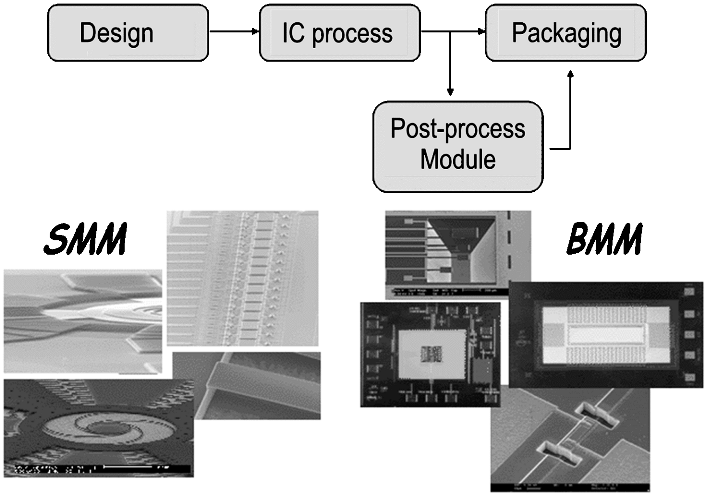

Fig. 1.4 IC-compatible post-process modules: the approach followed at DIMES and examples of structures realized with the developed BMM and SMM post-process modules

1.4
The Power of a Small World

Great progress has been made in the field of microsystems. Initially sensors or actuators built in bulk silicon with either simple dedicated processes or built-in conventional CMOS processes were introduced, more as an extension of the possibility of microelectronics than as a separate field. The real expansion into more complex systems and into areas not traditionally related to microelectronics, such as medicine, biology and optical telecommunication, came much later. Silicon micromachining has been crucial for this. In fact, the shift from planar, essentially 2D components, to vertical or 3D microstructures has added not only a physical *third dimension* to silicon planar technology, but also a *third dimension* in terms of functionality and applications (see Fig. 1.5).

Micromachining has also moved from silicon to other materials, such as glass, polymers and metals, thus creating an even larger pool of possible configurations. However, the level of maturity and the advantages related to the use of silicon are still predominant.

Let us examine a few examples that illustrate the 'power of the small world', i.e., the realization of applications, components and systems that would not be available or would not be as functional, as light or as small as they are now thanks to MST.

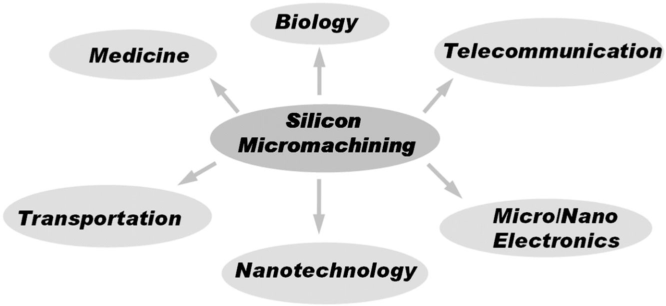

Fig. 1.5 Silicon micromachining: a crucial technology for an increase in functionality and application areas

1.4.1
MST in Transportation

An area where MST has made a major difference is transportation. Not only vehicles are equipped with an increasing amount of MST devices, creating smart cars, planes, boats, etc.; MST is also used in efforts to monitor highways, roads and bridges, leading to smart roads and safer skies. However, it has been the automotive industry, and thus the car, which has been and still is playing a key role in promoting MST technology and development.

It actually began with pressure sensors, with the introduction of the manifold air pressure sensor (MAP) for engine control in 1979, but one of the biggest commercial applications of MST is the accelerometer for air bags. In the case of a crash, the accelerometer sends the information to the inflation system. The bag is inflated by the large volume of gas created by an extremely rapid burning process. The bag then literally bursts from its storage site at up to 200 mph – faster than the blink of an eye. A second later, the gas quickly dissipates through tiny holes in the bag, thus deflating the bag so that driver and passengers can move.

At present, microsystems are most frequently used in safety applications, followed by engine and power train applications and on-board vehicle diagnostics. A major concern is reliability. Sensors working for safety features and leading to functions controlling at least part of the driving need to be of the highest quality. On the other hand, reliability in the automotive environment with temperatures up to 125 °C and aggressive media is an important cost issue. Packaging solutions and contactless sensors can help to reach the targets.

A revolution in this sector is starting to take place, implying a complete transition from the mechanically driven automobile system to a mechanically based but ICT-driven system. Microsystems are indispensable for fulfilling these ambitions. The current 7 Series BMW has a total of 70 MST devices installed in the car – a new milestone in the use of MST components in this application area [5].

1.4.2
MST in Medicine

MST developments have had and continue to have a remarkable impact on biology and medicine. Miniaturization on the one hand and system integration on the other are responsible for the presence or improvement of a number of applications that are all around us.

Biomedical sensors permit the reliable generation of essential physiological information required to provide therapeutic, diagnostic and monitoring care to patients. One example related to chronic cardiac disease is the pacemaker. This small apparatus, which has been implanted in more than two million people worldwide and is a true life saver, is based on a sensing and actuating unit, signal processing and a power source. In the newest generation of pacemaker-defibrillators, a MEMS accelerometer capable of tracking changes in motion, in this case the heart beat, sends the information to the processing unit and the proper amount of electric shock to restore the natural rhythm of the heart is delivered through the pacing lead [6]. The electronics of these microsystems, as for all implantable devices, must operate on low power. Novel powering alternatives to reduce further the size and weight of the apparatus and to prolong its lifetime are important research themes.

Microsurgery or minimally invasive surgery, an almost unknown notion a few years ago, is also an area where progress has been remarkable and tangible results are seen every day. Smart medical devices can be realized by embedding MST-based sensors at the most effective place on or within the device. Microsystems technology is the only method available that produces sensors small enough to be embedded in surgical devices without changing the basic function or form. MST-laden scalpels, needles and drills would give surgeons an unprecedented level of control or even the flexibility to perform entirely new procedures [7]. Tools such as the ‘smart’ scalpel schematically shown in Fig. 1.6, incorporate sensing and measuring devices to track and record information during surgery. The sensors, placed as close as possible to the edge of the cutting tool, for instance, can

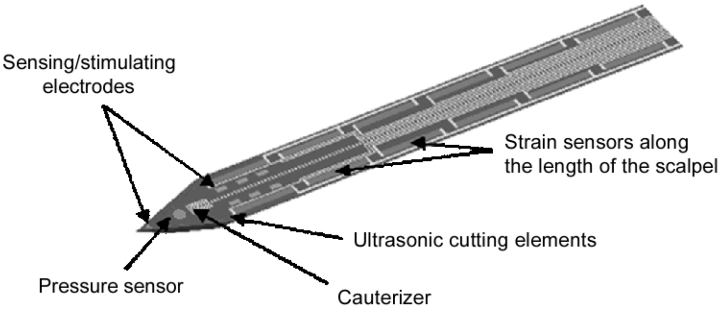

Fig. 1.6 The ‘data knife’ concept incorporates sensing and data-gathering capabilities on the edge of various surgical tools (adapted from [7])

tell how close a scalpel is to a blood vessel and shut the tool down if it approaches too close.

Using proven semiconductor manufacturing processes, microneedles to deliver small, precision dosages of drugs to localized areas are realized. A microneedle with a hollow core can easily fit into the bore of one of the smallest hypodermic injection needles commercially available today. Furthermore, the tip of the microfabricated microneedle is sharper and smoother than that of the steel needle. The smaller the diameter and the sharper the tip, the less pain and tissue damage occur during use. Initial tests have shown the microneedle to be nearly painless [7].

1.4.3
MST in Biology

Another area that is experiencing enormous development and where MST plays a crucial role is the miniaturization of (bio)chemical assays that are used for quality management in the biotechnology and food industry, medical diagnostics, drug development, environmental monitoring and high-throughput biochemical screening. In a successful multidisciplinary project [8], recently completed at our university, relevant progress has been achieved in the design and realization of an intelligent analytical system that measures many different molecular analytes simultaneously using specific molecular interactions on the surface of specially constructed microchips. Images of microchips containing arrays of microwells of different size and shape are shown in Fig. 1.7. Besides allowing a large number of different analyses simultaneously in a very short time, the system uses only extremely small amounts of reagents and samples.

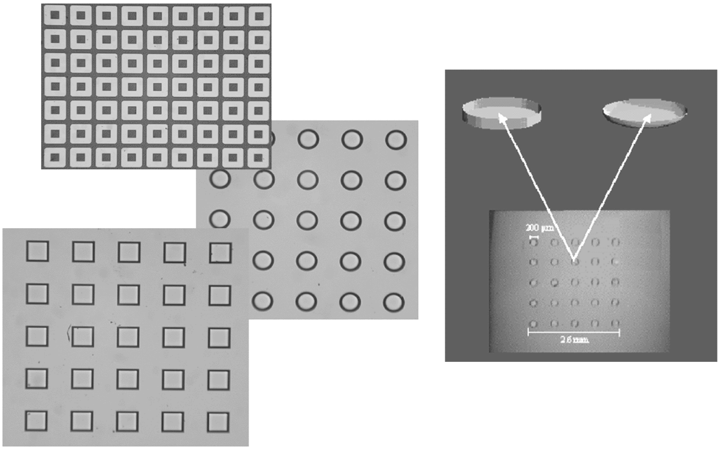

Fig. 1.7 Microchip containing picoliter reaction chambers developed in the DIOC-IMDS project [8]

1.4.4
MST in Telecommunication

Twenty-four hours a day, 365 days a year, data bits race through the optical fiber networks that span our globe. This vital link between people both for professional and private matters cannot afford any failure. Protection switches have a key role in guaranteeing network safety and in redirecting the data stream around a section that is not functioning. Switching in the optical domain is preferable because it avoids electro-optical conversion and is independent of data and encoding format. MST technology and specifically silicon micromachining have made it possible to realize fiber-optic switches that have many advantages over the conventional mechanical-relay type (no fatigue; miniaturization = faster switching time). Although the optical MEMS industry has not lived up to the high expectations with respect to implementation of photonic MEMS-based switching subsystems, the developed technology seems promising for other applications. Optical MEMS are, in fact, well suited for a variety of displays to be used in consumer electronics products, such as digital cameras and TVs, and also as medical instrumentation and car information systems [9].

However, by far the largest contribution that MST can offer is in wireless communication by providing more function and power with smaller parts. Radiofrequency (rf) systems for telecommunication are expected to be the next major application for MST [10]. Microsystems for rf applications, also known as rf MEMS, cover a large variety of devices, such as microswitches, tunable capacitors, micromachined inductors, micromachined antennas, microtransmission lines and mi-

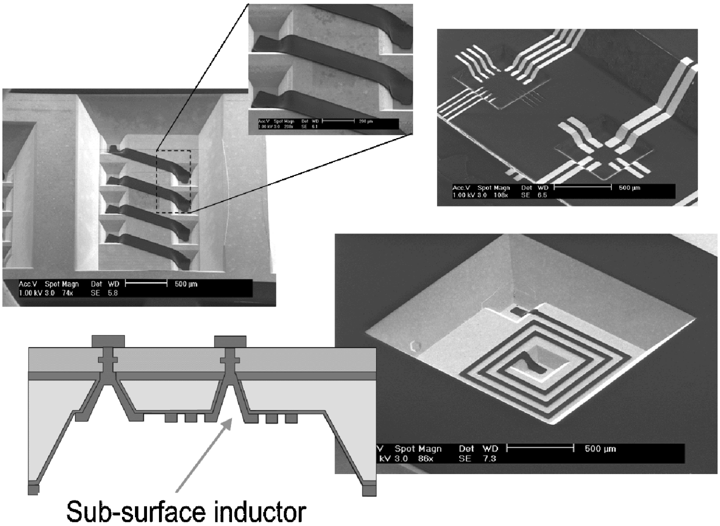

Fig. 1.8 Integrated rf components realized with the DIMES BMM post-process module

cromechanical resonators. Manufactured by conventional or novel 3D microstructuring techniques, they offer increased performance, such as lower power consumption, lower losses, higher linearity and higher Q factors.

The importance of silicon micromachining for rf applications has been recognized in DIMES. Novel post-process modules based on innovative techniques have been developed to address some of the limitations of planar silicon IC technology, making it possible to enhance the performance of integrated rf devices and systems [11]. Examples of integrated rf devices realized using BMM, such as sub-surface inductors, 3D solenoid inductors and through-chip transmission lines, are shown in Fig. 1.8.

1.5
Future Perspectives

MST has indeed had and continues to have a strong impact on almost every aspect of our lives. What are the challenges that lie ahead and which are the areas on which the microsystems community will focus? Let us look at some important aspects and mention some of the activities we are currently pursuing or intend to explore in our laboratory.

1.5.1
Autonomous Microsystems: More Intelligence in a Small Space

It is clear that the future generation of microsystems will have to satisfy challenging demands. These systems have to be capable of self-regulation and wireless communication, should be compact in size and should operate at low power, often in harsh environments. These systems will provide, among others, the future front-ends of information networks and links from microelectronics to the cellular world.

An integrated autonomous microsystem, schematically depicted in Fig. 1.9 a, needs to contain several basic functional modules to interact with its environment. It should be able to *sense* the perturbation in an environment (hearing or sight), and also to actuate perturbation to the environment for response (motion). It also needs to *communicate* with other microsystems and with a central point to establish collective and coordinated functions (Fig. 1.9 b). Many of the operations involve computing and control for complex information processing. Finally, the autonomous microsystems must contain a *power generation/conversion unit*. These functions of the autonomous microsystems can be potentially realized by integrating memory/microprocessors with MEMS in a power-efficient manner (system-on-a-chip).

The effective 3D microstructuring offered by MST together with the introduction of new materials into microelectronics will be essential for this future generation of integrated microsystems. In particular, attention should be paid to novel concepts and principles for power generation and/or conversion and for operation in harsh environments.

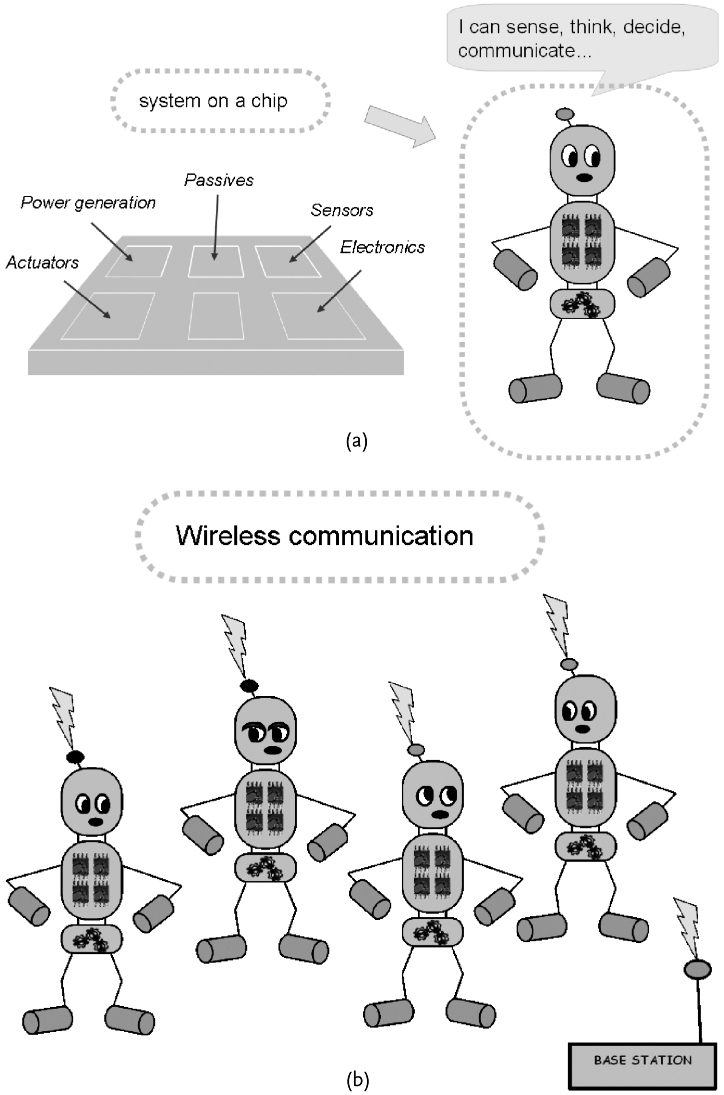

Fig. 1.9 Artist's impression of (a) an integrated autonomous microsystem and (b) wireless communication among autonomous microsystems (© P. M. Sarro, M. v. d. Zwan, 2003)

Applications can include any measurement requirements in remote locations or where access is difficult, from monitoring weather patterns to tracking human movement. After space applications, where reliability, power consumption and size are very critical, a large application area can be envisioned in implantable sensors for medical applications and home monitoring systems for the elderly. Through these systems, for example, patients could be sent home earlier and monitored via the Internet and elderly people could continue living in their homes, with direct connections to a central point. Besides improving the quality of life and extending independence, this will lead to considerable saving in health costs.

1.5.2
Top Down or Bottom Up: the Next Phase in Miniaturization

Although much progress has been made and exciting results have been achieved, there is still, as Richard Feynman wisely said about half a century ago, '*Plenty of room at the bottom*' [12]. After application-specific issues, a more generic discussion addresses the approach to follow in order to pursue further miniaturization: top down or bottom up?

The top down method focuses on downscaling to miniaturize devices and systems to the nanometer scale. The 'conventional' microsystems technology/MEMS belong to this approach. The bottom up approach relies on rather different technologies and materials to generate novel miniature systems. Atoms and molecules are integrated to form devices, shaping the system atom by atom.

These two approaches can also be combined to create a new converging technology, thus further increasing future perspectives. As illustrated in Fig. 1.10, we are at the point where both approaches can be used to create new systems, devices and even new materials.

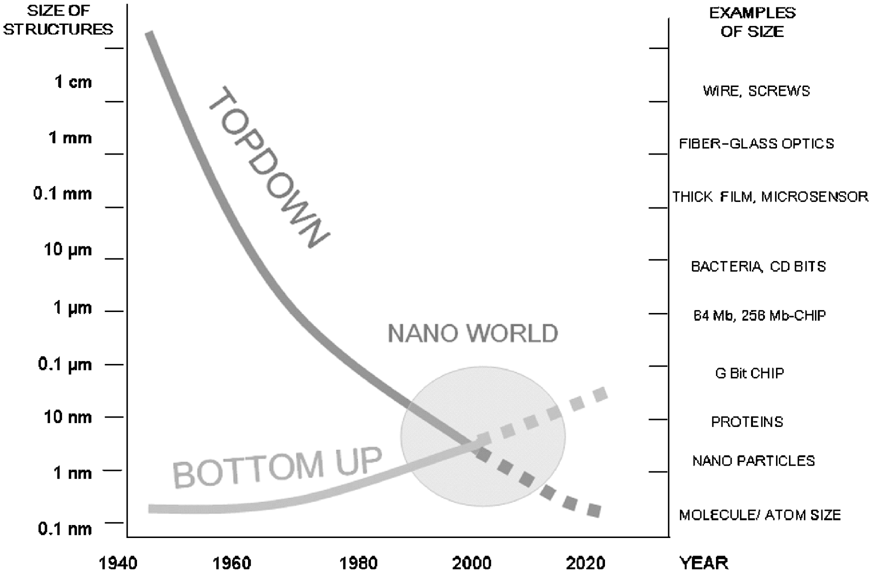

Fig. 1.10 History of nanotechnology: status of top down and bottom up approaches (adapted from [13])

1.5.2.1 Top down

Top down mostly means shrinking dimensions either to improve functionality or to create complex systems in a small space. In order to achieve this, novel micromachining technologies are required. These include various etching techniques (DRIE, laser ablation), resulting in well-controlled, accurate definition of the microstructures; specific lithographic processes (spray coating or electrodeposition of resist, front-to-back alignment (FTBA), direct write) to transfer fine patterns onto multi-level, truly 3D microstructures and coating or plating techniques (electroplating, electroless plating, vapor deposition) to deposit insulating, sensing or conducting layers on these large topography (highly non-planar) surfaces. The *M* from microsystems, MEMS or micromachine can slowly become an *N*, i.e. Nanosystems technology, nanoelectromechanical systems, nanomachines:

$$M^3 \rightarrow N^3$$

1.5.2.2 Bottom Up

In the *bottom up* approach, the focus is on other materials (polymers, carbide, diamond, organic materials), new 'building' techniques and the use of different effects. Inspired by biology, where the precise (self) organization of molecules permits the many functions carried out in living cells, scientists have started to explore means to build molecular machines, wires and other devices in a very precise manner, by stacking individual atoms or molecules. Research into methods for such assembly is still in its infancy, but its promise is great. Moreover, the potential use of DNA – with its ability for 'programmed self-assembly' – for biomolecular electronic devices (nanowires, molecular memories) in combination with advanced microsystems technology, various protein molecules and nanoparticles is also a challenging and promising future development.

Combination of both approaches is also possible. Our group participated in a European project that aims at developing an enabling technology for 3D computer structures, such as a fault-tolerant, 3D, retina-cortex computer (CORTEX) [14]. One objective of this project is to demonstrate the feasibility of very high-density, 3D molecular 'wires' (bottom up approach) between electrical contacts on separate, closely spaced, semiconductor chips or layers, as illustrated in Fig. 1.11. The high-density array of through-wafer interconnects with a very high aspect ratio is a good example of the top down approach, whereas the building of molecular wires for chip-to-chip connections well represents the bottom up method. Whether a top down or a bottom up approach is used (or a combination of both), major developments are envisioned for the coming decades.

1.5.3
The Link Between Nanoscience and the Macro World

Although remaining on the micron or submicron scale, MST will continue to be of significant importance for nanotechnology and nanoscience. In fact, microsystems,

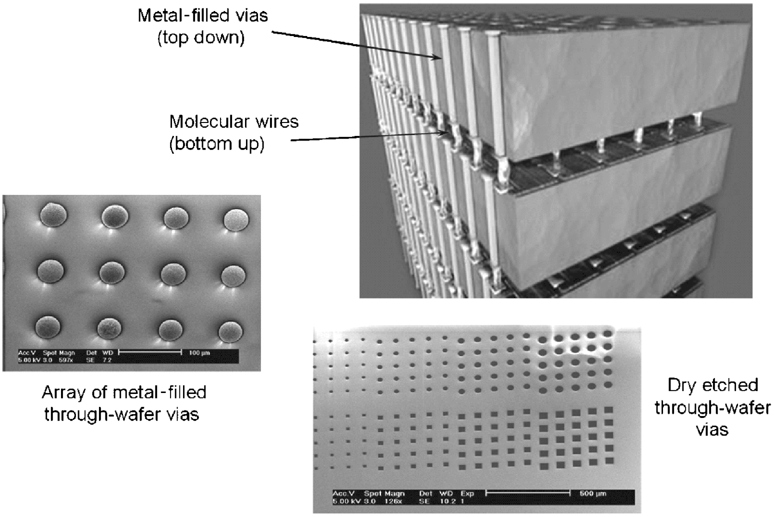

Fig. 1.11 The CORTEX project: a combination of top down and bottom up approaches

either sensors, actuators or mechanical microstructures with the necessary interfacing, are often the unavoidable bridge between the atom or molecular structure and the macro-world. Moreover, specific tools that are indispensable for building molecular systems or investigating phenomena at the atomic level heavily rely on MST.

The use of silicon-based technologies or derivatives can have an extreme impact on studying phenomena or realizing crucial tools for complex molecular systems. A good example is atom optics on a chip (atomic laser). At the University of Colorado, USA, a very active group involved in atom optics is investigating the use of Bose-Einstein condensates (BEC) to make practical devices [15]. An essential component of the system is the MOT (magneto-optic trap), the largest physical structure of most BEC and atom guiding systems. It is highly desirable to miniaturize this component. MST technology can play a crucial role here by offering small, truly 3D structures. The possibility of using the third dimension is fundamental to acquiring full control over the magnetic field applied to the atoms.

Another example is related to 3D atomic resolution microscopes, the scanning tunneling microscope (STM) and the atomic force microscope (AFM). Scanning probe microscopy is a key technology for nanotechnology research and fundamental in studying phenomena at the atomic/molecular level. Scanning probe microscopes also allow the manipulation of atoms and molecules for the creation of nanodevices. Very often the tips of these tools, see Fig. 1.12, a recognized symbol for nanotechnology, are realized with the help of silicon-based microsystem technologies [16].

New developments in MST will further contribute to building the necessary interface between nanodevices or nanostructures and microinstrumentation and will help in studies of phenomena at the nanoscale level. On the other hand, future develop-

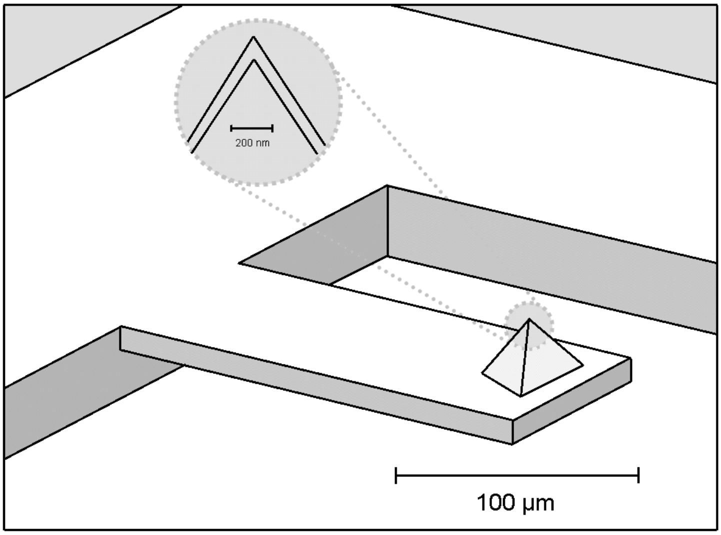

Fig. 1.12 The tip of a scanning probe microscope fabricated by silicon micromachining

ments in nanotechnology will permit the realization of highly sophisticated microsystems, such as miniaturized drug-delivery systems and miniaturized computers.

1.6
Conclusions

MST research activities continue to focus on innovative technological processes and material findings to create the necessary environment to address the many challenges in areas currently recognized to be of strategic importance and of high societal relevance. In particular, increasing the autonomous and wireless character of microsystems will be intensively pursued. Mostly a top down approach will be followed to realize truly 3D microstructures, essential to many microsystems. Research on silicon-related/compatible materials such as SiC, polymers and alternative metals to expand application areas further or improve system performance will also be carried out. The potential of the bottom up approach will be increasingly explored as this approach can offer more possibilities and proper solutions in new areas as well as stimulating new developments.

Whatever the approach followed or the application area targeted, research in microsystems technology will continue to provide further developments in many scientific disciplines and at the same time make a tangible contribution to society.

1.7
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1.8
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