CHAPTER

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# MEMS: A Technology from Lilliput

… And I think to myself, what a wonderful world … oh yeah!

*Louis Armstrong*

## The promise of technology

The ambulance sped down the Denver highway carrying Mr. Rosnes Avon to the hospital. The flashing lights illuminated the darkness of the night, and the siren alerted those drivers who braved the icy cold weather. Mrs. Avon's voice was clearly shaking as she placed the emergency telephone call a few minutes earlier. Her husband was complaining of severe heart palpitations and shortness of breath. She sat next to him in the rear of the ambulance and held his hand in silence, but her eyes could not hide her concern and fear. The attending paramedic clipped onto the patient's left arm a small, modern device from which a flexible cable wire led to a digital display that was showing the irregular cardiac waveform. A warning sign in the upper right-hand corner of the display was flashing next to the low blood pressure reading. In a completely mechanical manner reflecting years of experience, the paramedic removed an adhesive patch from a plastic bag and attached it to Mr. Avon's right arm. The label on the discarded plastic package read "sterile microneedles." Then with her right hand, the paramedic inserted into the patch a narrow plastic tube while the fingers of her left hand proceeded to magically play the soft keys on the horizontal face of an electronic instrument. She dialed in an appropriate dosage of a new drug called Nocilis™. Within minutes, the display was showing a recovering cardiac waveform and the blood pressure warning faded into the dark green color of the screen. The paramedic looked with a smile at Mrs. Avon, who acknowledged her with a deep sigh of relief.

Lying in his hospital bed the next morning, Mr. Avon was slowly recovering from the disturbing events of the previous night. He knew that his youthful days were behind him, but the news from his physician that he needed a pacemaker could only cause him anguish. With an electronic stylus in his hand, he continued to record his thoughts and feelings on what appeared to be a synthetic white pad. The pen recognized the pattern of his handwriting and translated it to text for the laptop computer resting on the desk by the window. He drew a sketch of the pacemaker that Dr. Harte showed him in the morning; the computer stored an image of his lifesaving instrument. A little device barely the size of a silver dollar would forever remain in his chest and take control of his heart's rhythm. But a faint smile crossed Mr. Avon's lips when he remembered the doctor saying that the pacemaker would monitor his level of physical activity and correspondingly adjust his heart rate. He might be able to play tennis again, after all. With his remote control he turned on the projection screen television and slowly drifted back into light sleep.

This short fictional story illustrates how technology can touch our daily lives in so many different ways. The role of miniature devices and systems is not immediately apparent here because they are embedded deep within the applications they enable. The circumstances of this story called for such devices on many separate occasions. The miniature yaw-rate sensor in the vehicle stability system ensured that the ambulance would not skid on the icy highway. In the event of an accident, the crash acceleration sensor guaranteed that the airbags would deploy just in time to protect the passengers. The silicon manifold absolute pressure (MAP) sensor in the engine compartment helped the engine's electronic control unit maintain, at the location's high altitude, the proper proportions in the mixture of air and fuel. As the vehicle was safely traveling, equally advanced technology in the rear of the ambulance saved Mr. Avon's life. The modern blood pressure sensor clipped onto his arm allowed the paramedic to monitor blood pressure and cardiac output. The microneedles in the adhesive patch ensured the immediate delivery of medication to the minute blood vessels under the skin, while a miniature electronic valve guaranteed the exact dosage. The next day, as the patient lay in his bed writing his thoughts in his diary, the microaccelerometer in the electronic quill recognized the motion of his hand and translated his handwriting into text. Another small accelerometer embedded in his pacemaker would enable him to play tennis again. He could also write and draw at will because the storage capacity of his disk drive was enormous, thanks to miniature read and write heads. And finally, as the patient went to sleep, an array of micromirrors projected a pleasant high-definition television image onto a suspended screen.

Many of the miniature devices listed in the above story, particularly the pressure and acceleration microsensors and the micromirror display, already exist as commercial products. Ongoing efforts at many companies and laboratories throughout the world promise to deliver, in the not-too-distant future, new and sophisticated miniature components and microsystems. It is not surprising, then, that there is widespread belief in the technology's future potential to penetrate far-reaching applications and markets.

## What are MEMS—or MST?

In the United States, the technology is known as *microelectromechanical systems* (MEMS); in Europe it is called *microsystems technology* (MST). A question asking for a more specific definition is certain to generate a broad collection of replies, with few common characteristics other than "miniature." But such apparent divergence in the responses merely reflects the diversity of applications this technology enables, rather than a lack of commonality. MEMS is simultaneously a toolbox, a physical product, and a methodology all in one:

- It is a portfolio of techniques and processes to design and create miniature systems;
- It is a physical product often specialized and unique to a final application—one can seldom buy a generic MEMS product at the neighborhood electronics store;
- "MEMS is a way of making things," reports the Microsystems Technology Office of the United States Defense Advanced Research Program Agency (DARPA) [1]. These "things" merge the functions of sensing and actuation with computation and communication to locally control physical parameters at the microscale, yet cause effects at much grander scales.

Although a universal definition is lacking, MEMS products possess a number of distinctive features. They are miniature *embedded* systems involving one or many *micromachined* components or structures. They *enable* higher level functions, although in and of themselves their utility may be limited—a micromachined pressure sensor in one's hand is useless, but under the hood it controls the fuel-air mixture of the car engine. They often *integrate* smaller functions into one package for greater utility—for example, merging an acceleration sensor with electronic circuits for self-diagnostics. They can also bring *cost benefits*, directly through low unit pricing, or indirectly by cutting service and maintenance costs.

Although the vast majority of today's MEMS products are best categorized as components or subsystems, the emphasis in MEMS technology is on the "systems" aspect. True microsystems may still be a few years away, but their development and evolution rely on the success of today's components, especially as these components are integrated to perform functions ever increasing in complexity. Building microsystems is an evolutionary process. We spent the last thirty years learning how to build micromachined components. Only recently have we begun to learn about their seamless integration into subsystems, and ultimately into complete microsystems.

One notable example is the evolution of crash sensors for airbag safety systems. Early sensors were merely mechanical switches. They later evolved into micromechanical sensors that directly measured acceleration. The current generation of devices integrates electronic circuitry with a micromechanical sensor to provide self-diagnostics and a digital output. It is anticipated that the next generation of devices will also incorporate the entire airbag deployment circuitry that decides whether to inflate the airbag. As the technology matures, the airbag crash sensor may be integrated one day with micromachined yaw-rate and other inertial sensors to form a complete microsystem responsible for passenger safety and vehicle stability (Table 1.1).

Examples of future microsystems are not limited to automotive applications. Efforts to develop micromachined components for the control of fluids are just beginning to bear fruit. These could lead one day to the integration of micropumps with microvalves and reservoirs to build new miniature drug delivery systems.

**Table 1.1**
Examples of Present and Future Application Areas for MEMS

| **Commercial Applications** | **Military Applications** |
|---|---|
| Invasive and noninvasive biomedical sensors | Inertial systems for munitions guidance and personal navigation |
| Miniature biochemical analytical instruments | Distributed unattended sensors for asset tracking, environmental and security surveillance |
| Cardiac management systems (e.g., pacemakers, catheters) | Weapons safing, arming, and fuzing |
| Drug delivery systems (e.g., insulin, analgesics) | Integrated micro-optomechanical components for identify-friend-or-foe systems |
| Neurological disorders (e.g., neurostimulation) | Head- and night-display systems |
| Engine and propulsion control | Low-power, high-density mass data storage devices |
| Automotive safety, braking, and suspension systems | Embedded sensors and actuators for condition-based maintenance |
| Telecommunication optical fiber components and switches | Integrated fluidic systems for miniature propellant and combustion control |
| Mass data storage systems | Miniature fluidic systems for early detection of biochemical warfare |
| Electromechanical signal processing | Electromechanical signal processing for small and low-power wireless communication |
| Distributed sensors for condition-based maintenance and monitoring structural health | Active, conformable surfaces for distributed aerodynamic control of aircraft |
| Distributed control of aerodynamic and hydrodynamic systems | |

## What is micromachining?

Micromachining is the set of design and fabrication tools that precisely machine and form structures and elements at a scale well below the limits of our human perceptive faculties—the microscale. Micromachining is the underlying foundation of MEMS fabrication; it is the toolbox of MEMS.

Arguably, the birth of the first micromachined components dates back many decades, but it was the well-established integrated circuit industry that indirectly played an indispensable role in fostering an environment suitable for the development and growth of micromachining technologies. As the following chapters will show, many tools used in the design and manufacturing of MEMS products are "borrowed" from the integrated circuit industry. It should not then be surprising that micromachining relies on silicon as a primary material, even though the technology was certainly demonstrated using other materials.

## Applications and markets

Present markets are primarily in pressure and inertial sensors and inkjet print heads, with the latter dominated by Hewlett Packard Company of Palo Alto, California. Future and emerging applications include high-resolution displays, high-density data storage devices, valves, and fluid management and processing devices for chemical microanalysis, medical diagnostics, and drug delivery. While estimates for MEMS markets vary considerably, they all show significant present and future growth, reaching aggregate volumes in the many billions of dollars by the year 2004 [2–4]. The expected growth is driven by technical innovations and acceptance of the technology by an increasing number of end users and customers.

However, because of the lack of a single dominant application—the "killer app"—and the diverse technical requirements of end users, there is no single MEMS market, but rather a collection of markets, many of which are considered niche markets—especially when compared to their kin semiconductor businesses. It is true that unit volumes in a few segments, including automotive, are substantial, running in the tens of millions, but the corresponding dollar volumes tend to be modest. Furthermore, occasional poor forecasting of emerging applications poses additional risks and difficulties to companies engaged in the development and manufacture of MEMS products. For instance, the worldwide market for airbag crash sensors—thought by many to be a considerable market—is estimated today at $150,000,000, even as these components become standard on all 50,000,000 vehicles manufactured every year around the globe. Market studies conducted in the early 1990s incorrectly estimated the unit asking price of these sensors, neglecting the effect of competition on pricing, and artificially inflating the size of the market to $500,000,000 (Table 1.2).

## To MEMS or not to MEMS?

Like many other emerging technologies with significant future potential, MEMS is subject to a rising level of excitement and publicity. As it evolves and end markets develop, this excessive optimism is gradually

**Table 1.2**
Analysis and Forecast of U.S. MEMS Markets (in Millions of U.S. Dollars)[1]

| **Year** | **Automotive**[2] ($ 000,000) | **Medical** ($ 000,000) | **Information Technology & Industrial**[3] ($ 000,000) | **Military & Aerospace** ($ 000,000) | **Total** ($ 000,000) |
|---|---|---|---|---|---|
| 1994 | 255.7 | 129.5 | 438.3 | 49.1 | 872.5 |
| 1995 | 298.0 | 146.1 | 459.0 | 54.8 | 957.9 |
| 1996 | 355.0 | 164.4 | 492.8 | 62.2 | 1,074.3 |
| 1997 | 419.0 | 187.0 | 527.0 | 71.6 | 1,204.6 |
| 1998 | 491.5 | 216.7 | 575.3 | 79.6 | 1,363.1 |
| 1999 | 562.0 | 245.7 | 645.9 | 95.8 | 1,549.4 |
| 2000 | 645.7 | 291.3 | 733.3 | 110.7 | 1,781.0 |
| 2001 | 758.5 | 354.8 | 836.0 | 133.3 | 2,082.5 |
| 2002 | 879.6 | 444.7 | 995.1 | 156.9 | 2,476.3 |
| 2003 | 1,019 | 562.9 | 1,222 | 176.7 | 2,980.4 |
| 2004 | 1,172 | 716.0 | 1,514 | 202.7 | 3,604.5 |
| CAGR | 16% | 21% | 16% | 16% | 17% |

[1] Data prior to 1997 is actual. (The projected compound annual growth rate (CAGR) averages 17% across the dominant market sectors. Source: Frost & Sullivan [4].)

[2] Airbag systems and MAP sensors constitute 90% of the automotive MEMS market.

[3] In 1998, the market division was: inkjets 75.6%, displays 5.4%, and industrial 19%.

moderated with a degree of realism reflecting the technology's strengths and capabilities.

Any end user considering developing a MEMS solution or incorporating one into a design invariably reaches the difficult question of "Why MEMS?" The question strikes at the heart of the technology, particularly in view of competing methods, such as conventional machining or plastic molding techniques that do not have recourse to micromachining. For applications that can benefit from existing commercial MEMS products (e.g., pressure or acceleration sensors), the answer to the above question relies on the ability to meet required specifications and pricing. But the vast majority of applications require unique solutions that often necessitate the funding and completion of an evaluation or development program. In such situations, a clear-cut answer is seldom easy to establish.

In practice, a MEMS solution becomes attractive if it enables a new function, provides significant cost reduction, or both. For instance, medical applications generally seem to focus on added or enabled functionality and improved performance, whereas automotive applications often seek cost reduction. Size reduction can play an important selling role, but is seldom sufficient as the sole reason unless it becomes enabling itself. Naturally, reliability is always a dictated requirement. The decision-making process is further complicated by the fact that MEMS is not a single technology, but a set of technologies (e.g., surface vs. bulk micromachining). At this point, it is beneficial for the end user to become familiar with the capabilities and the limitations of any particular MEMS technology selected for the application in mind. The active participation of the end user allows for the application to drive the technology development, rather than the frequently occurring opposite situation.

Companies seeking MEMS solutions often contract a specialized facility for the design and manufacture of the product. Others choose first to evaluate basic conceptual designs through existing foundry services. A few companies may decide to internally develop a complete design. In the latter case, there is considerable risk that manufacturing considerations are not properly taken into account, resulting in significant challenges in production.

Regardless of how exciting and promising a technology may be, its ultimate realization is invariably dependent on economic success. The end user will justify the technology on the basis of added value, increased productivity, and/or cost competitiveness, and the manufacturer must show revenues and profits. On both tracks, MEMS technology is able to deliver within a set of realistic expectations that may vary with the end application. A key element in cost competitiveness is "batch fabrication," which is the practice of simultaneously manufacturing hundreds or thousands of identical parts, thus diluting the overall impact of fixed costs, including the cost of maintaining expensive cleanroom and assembly facilities. This is precisely the same approach that has resulted, over the last few decades, in a dramatic decrease in the price of computer memory chips. Unfortunately, the argument works in reverse too: Small manufacturing volumes will bear the full burden of overhead expenses, regardless of how "enabling" the technology may be (Figure 1.1).

## Standards

Few disagree that the burgeoning MEMS industry traces many of its roots to the integrated circuit industry. However, the two market dynamics differ greatly with severe implications, one of which is the lack of standards in MEMS. Complementary metal-oxide semiconductor (CMOS) technology has proven itself over the years to be a universally accepted manufacturing process for integrated circuits, driven primarily by the insatiable consumer demand for computers and digital electronics. In contrast, the lack of a dominant MEMS high-volume product, or family of products, combined with the unique technical requirements of

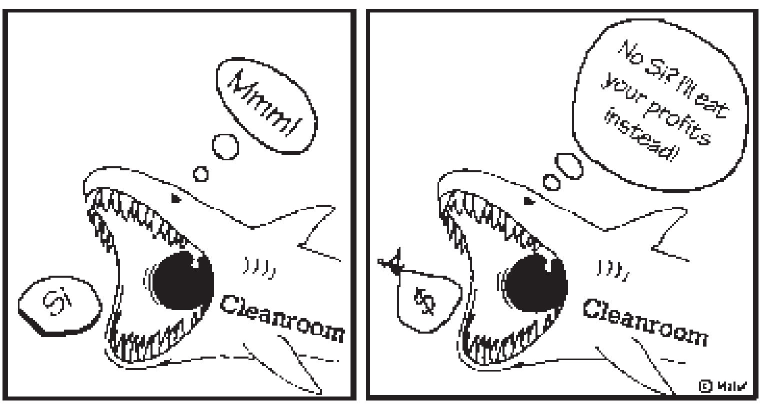


**Figure 1.1** Volume manufacturing is essential for maintaining profitability.

each application have resulted in the emergence of multiple fabrication and assembly processes. The following chapters will introduce these processes. Standards are generally driven by the needs of high-volume applications, which are few in MEMS. In turn, the lack of standards feeds into the diverging demands of the emerging applications.

## The psychological barrier

It is human nature to cautiously approach what is new because it is foreign and untested. Even for the technologically savvy or the fortunate individual living in high-tech regions, there is a need to overcome the comfort zone of the present before engaging the technologies of the future. This cautious behavior translates to slow acceptance of new technologies and derivative products as they are introduced into society. MEMS acceptance is no exception. For example, demonstration of the first micromachined accelerometer took place in 1979 at Stanford University. Yet it took nearly fifteen years before it became accepted as a device of choice for automotive airbag safety systems. Naturally, in the process, it was designed and redesigned, tested and qualified in the laboratory and the field before it gained the confidence of automotive suppliers. The process can be lengthy, especially for embedded systems (see Figure 1.2).

Today, MEMS and associated product concepts generate plenty of excitement, but not without skepticism. Companies exploring for the first time the incorporation of MEMS solutions into their systems do so with trepidation, until an internal “MEMS technology champion” emerges to educate the company and raise the confidence level. With many micromachined silicon sensors embedded in every car and in numerous critical medical instruments, and with additional MEMS products finding their way into our daily lives, the height of this hidden psychological barrier appears to be declining.

## Journals, conferences, and Web sites

The list of journals and conferences focusing on micromachining and MEMS continues to grow every year. There is also a growing list of on-

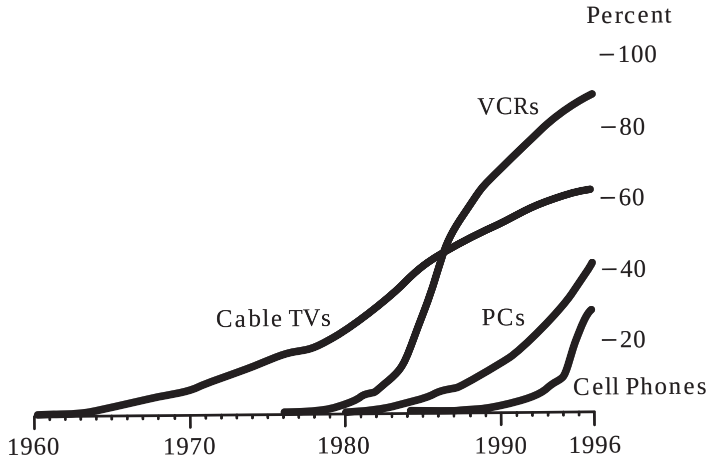


Figure 1.2 Chart illustrating the percent household penetration of new electronic products. It takes 5 to 15 years before new technologies gain wide acceptance [5].

line Web sites, most notably the MEMS Clearinghouse hosted by the Information Sciences Institute (ISI), Marina del Rey, California, and the European Microsystems Technology On-line (EMSTO), Berlin, Germany, sponsored by the ESPRIT program of the European Commission. The sites provide convenient links and maintain relevant information directories (Table 1.3).

### List of journals and magazines

Several journals and trade magazines published in the U.S. and Europe cover research and advances in the field. Some examples are:

- *Sensors and Actuators* (A, B & C): a peer-reviewed scientific journal published by Elsevier Science, Amsterdam, The Netherlands.
- *Journal of Micromechanical Systems* (JMEMS): a peer-reviewed scientific journal published by the Institute of Electrical and Electronic Engineers (IEEE), Piscataway, New Jersey, in collaboration with the American Society of Mechanical Engineers (ASME), New York, New York.
- *Journal of Micromechanics and Microengineering* (JMM): a peer-reviewed scientific journal published by the Institute of Physics, Bristol, United Kingdom.

**Table 1.3**
List of a Few Government and Nongovernment Organizations With Useful On-line Resources

| Organization | Address | Description | Web Site |
|---|---|---|---|
| MEMS ISI Clearinghouse | Marina del Rey, CA | U.S. Clearinghouse | mems.isi.edu |
| EMSTO | Berlin, Germany | European Clearinghouse | www.nexus-emsto.com |
| VDI/VDE – IT | Teltow, Germany | Association of German Engineers | www.vdivde-it.de/MST |
| DARPA | Arlington, VA | Sponsored U.S. government projects | web-ext2.darpa.mil/MTO |
| NIST | Gaithersburg, MD | Sponsored U.S. government projects | www.atp.nist.gov |
| Institute of Defense Analyses | Alexandria, VA | Insertion in military applications | www.ida.org/MEMS |
| AIST – MITI | Tokyo, Japan | The “Micromachine Project” in Japan | www.aist.go.jp |

- *Sensors Magazine*: a trade journal with an emphasis on practical and commercial applications published by Helmers Publishing Inc., Peterborough, New Hampshire.
- *MST news:* an international newsletter on microsystems and MEMS published by VDI/VDE Technologiezentrum Informationstechnik GmbH, Teltow, Germany.
- *Micromachine Devices*: a publication companion to *R&D Magazine* with news and updates on MEMS technology published by Cahners Business Information, Des Plaines, Illinois.

### List of conferences and meetings

Several conferences cover advances in MEMS or incorporate program sessions on micromachined sensors and actuators. The following list gives a few examples:

- International Conference on Solid-State Sensors and Actuators (Transducers): held on odd years and rotates sequentially between North America, Asia, and Europe.

- Solid-State Sensor and Actuator Workshop (Hilton Head): held on even years in Hilton Head Island, South Carolina, and sponsored by the Transducers Research Foundation, Cleveland, Ohio.
- MicroElectroMechanical Systems Workshop (MEMS): an international meeting held annually and sponsored by the Institute of Electrical and Electronics Engineers (IEEE), Piscataway, New Jersey.
- International Society for Optical Engineering (SPIE): regular conferences held in the United States and sponsored by SPIE, Bellingham, Washington.
- MicroTotalAnalysis Systems (MTAS): a conference focusing on microanalytical and chemical systems. This conference was held on alternating years, but will become annual beginning in the year 2000. It alternates between North America and Europe.

## Summary

Microelectromechanical structures and systems are miniature devices that enable the operation of complex systems. They exist today in many environments, especially automotive, medical, consumer, industrial, and aerospace. Their potential for future penetration into a broad range of applications is real, supported by strong developmental activities at many companies and institutions. The technology consists of a large portfolio of design and fabrication processes (a toolbox), many borrowed from the integrated circuit industry. The development of MEMS is inherently interdisciplinary, necessitating an understanding of the toolbox as well as the end application.

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