Microelectromechanical Systems (MEMS) Tutorial

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Introduction

As information systems increasingly leave fixed locations and appear in our pockets and palms, they are getting closer to the physical world, creating new opportunities for perceiving and controlling our machines, structures and environments. To exploit these opportunities, information systems will need to *sense* and *act* as well as *compute*. Investing engineered systems with superior capabilities to sense and act is the driving force for the development of microelectromechanical systems (MEMS).

Using the fabrication techniques and materials of microelectronics as a basis, MEMS processes construct both *mechanical* and electrical components. Mechanical components in MEMS, like transistors in microelectronics, have dimensions that are measured in microns and numbers measured from a few to millions. MEMS is not about any one single application or device, nor is it defined by a single fabrication process or limited to a few materials. More than anything else, MEMS is a fabrication approach that conveys the advantages of miniaturization, multiple components and microelectronics to the design and construction of integrated *electromechanical* systems.

MEMS devices have applications in areas ranging from automobiles and telecom switching to printers and inertial guidance systems. While MEMS devices will be a relatively small fraction of the cost, size and weight of these systems, MEMS will be critical to their operation, reliability and affordability. MEMS devices, and the smart products they enable, will increasingly be the performance differentiator for a wide variety of commercial products.

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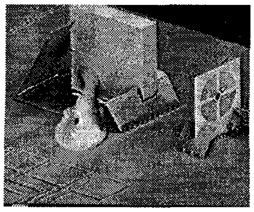
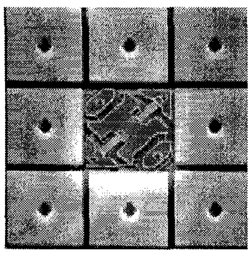
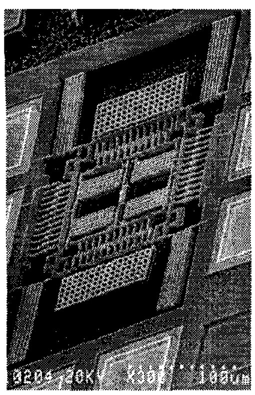
Applications of MEMS



MEMS will create new capabilities, make high-end functionality affordable to low-end systems, and extend the operational performance and lifetimes of existing products and systems. For example, MEMS will enable complete inertial navigation units on a chip, composed of multiple integrated MEMS accelerometers and gyroscopes. The inertial navigation systems of today, however, are large, heavy, expensive, power-consumptive, precision instruments affordable only in high-end systems. Inertial navigation on a chip would not only make it possible to augment global positioning satellite receivers for tracking of individuals and equipment, but would also provide inertial measurement capability for high-volume products that are currently unmeasured. MEMS inertial navigation units on a chip will achieve performance comparable to or better than existing inertial navigation systems and be no larger, costlier, or more power consumptive than microelectronic chips.



In addition to single-chip inertial navigation units, there are many opportunities for MEMS insertion across a number of technologies and products that include



- *distributed unattended sensors* for asset tracking, border control, environmental monitoring, security surveillance and process control,
- *integrated fluidic systems* for miniature analytical instruments, chip-based DNA processing & sequencing, propellant and combustion control, chemical factories on chip,
- *low-power, high-resolution, small-area displays* for workstation and portable, personal information systems,
- *embedded sensors and actuators* for condition-based maintenance of machines & structures and on-demand amplified structural strength in lower-weight systems and disaster-resistant building,
- *mass data storage devices* using magnetic and atomic scale patterning for storage densities of terabytes per square centimeter,
- *integrated microoptomechanical components* for low-power optical communication, displays and fiber-optic switches/modulators, and
- *radio frequency and wireless* for relay & switching matrices, reconfigurable antennas, switched filter banks, electromechanical front-end RF filtering and demodulation

MEMS Market and Industry Structure

MEMS Market

Forecasts for MEMS products throughout the world show rapid growth for the foreseeable future. Early market studies projected an eight-fold growth in the nearly $1 billion 1994 MEMS market by the turn of the century. More recent estimates are forecasting growth of nearly twelve to fourteen times today's market, reaching $12-14 billion by the year 2000 (Figure 1). While sensors (primarily pressure and acceleration) are the principal MEMS products today, no one product or application area is set to dominate the MEMS industry for the foreseeable future, with the MEMS market growing both in the currently dominant sensor sector and in the actuator-enabled sectors. Furthermore, because MEMS products will be embedded in larger, non-MEMS systems (e.g., automobiles, printers, displays, instruments, and controllers), they will enable new and improved systems with a projected market worth approaching $100 billion in the year 2000.

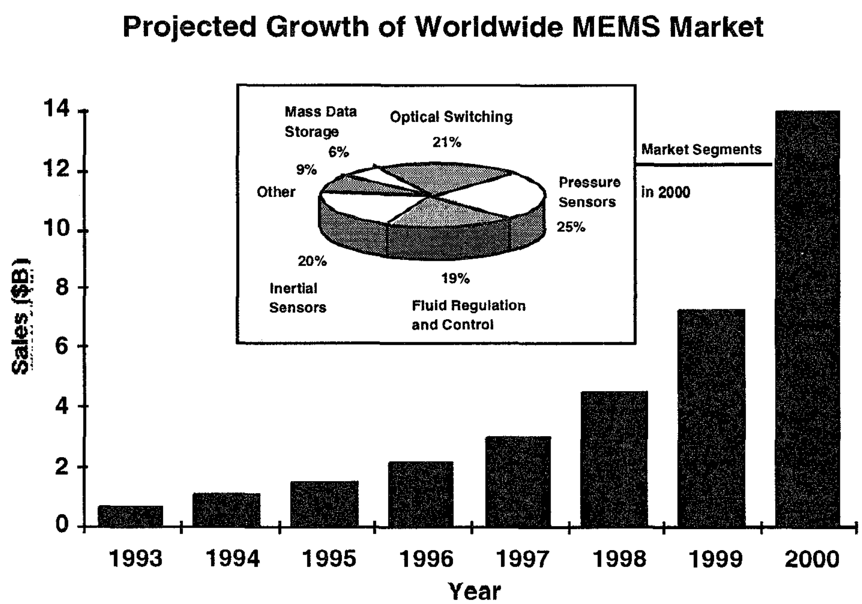


FIGURE 1. Projected worldwide MEMS market. Note inset pie chart that shows the non-sensor market segments in fluid regulation and control, optical systems and mass data storage are projected to be about half of the total market by the year 2000.

MEMS Industry Structure

Those companies which have so far been directly involved in producing MEMS devices and systems are manufacturers of sensors, industrial and residential control systems, electronic components, computer peripherals, automotive and aerospace electronics, analytical instruments, biomedical products, and office equipment. Examples of companies manufacturing MEMS products worldwide include Honeywell, Motorola, Hewlett-Packard, Analog Devices, Siemens, Hitachi, Vaisala, Texas Instruments, Lucas NovaSensor, EG&G-IC Sensors, Nippon Denso, Xerox, Delco, and Rockwell. Of the roughly 80 US firms currently identified as being involved in MEMS (Figure 2), more than 60 are small businesses with less than ten million dollars in annual sales. The remaining 20 firms are large corporations distributed across different industry sectors with varying degrees of research activities and products in MEMS (the front cover of the 1993 annual shareholders' report for Hewlett-Packard featured a MEMS flow-valve).

MEMS Technology

Using the fabrication processes and materials of microelectronics as a basis, MEMS processes construct both *mechanical* and electrical components. Mechanical components in MEMS, like electronic components in microelectronics, have dimensions that are measured in microns and numbers measured in millions. MEMS is not about any one single application or device, nor is it defined by a single fabrication process or limited to a few materials. More than anything else, MEMS is a fabrication approach that conveys the advantages of miniaturization, multiple components and microelectronics to the design and construction of integrated *electromechanical* systems.

Characteristics of MEMS Fabrication Technologies

Regardless of the specific type of micromachining fabrication process used, all MEMS fabrication approaches share certain key characteristics: *miniaturization*, *multiplicity* and *microelectronics.*

Miniaturization is an important but not the sole characteristic of MEMS. There are many advantages to the performance of electromechanical devices and systems that come from miniaturization. Structures that are relatively small and light lead to devices which have relatively high resonant frequencies. These high resonant frequencies in turn mean higher operating frequencies and bandwidths for sensors and actuators. Thermal time constants, the rate at which structures absorb and release heat, are shorter for smaller, less massive structures. But miniaturization is not the principal driving force for MEMS that it is for microelectronics. Because MEMS devices are by definition interacting with some aspect of the physical world (e.g., pressure, inertia, fluid flows, light), there is a size below which further miniaturization is *detrimental* to device and system operation. For example, reducing the size (and consequently the mass) of an accelerometer makes it harder to detect low-g accelerations. This minimum size is different for different applications, but for most MEMS applications, the size limits are a factor of 3 to 5 larger than the smallest microelectronic device features.

As important as miniaturization, *multiplicity* or the batch fabrication inherent in photolithographic-based MEMS processing, provides two important advantages to electromechanical devices and systems. Multiplicity makes it possible to fabricate 10,000 or a million components as easily, quickly, and at the same time as one component. This advantage of MEMS fabrication is critical for reducing the unit cost of devices and the semiconductor industry has proven the benefits of such economies of scale. The second, equally important advantage enabled by multiplicity is the additional flexibility in the design of massively-parallel, interconnected electromechanical systems.

Rather than designing components, the emphasis can shift to designing the pattern and form of interconnections (interactions or coordinated action) among thousands or millions of components. This approach to design has been standard operating procedure in microelectronic systems design for nearly three decades. When integrated circuit engineers design and lay out a new circuit, they don't design new components, but instead design the pattern of interconnections among millions of relatively simple and identical components. The diversity and complexity of function in integrated circuits is a direct result of the diversity and complexity of the interconnections and it is the differences in the interconnections that differentiate a microprocessor from a memory. The multiplicity characteristic of MEMS has already been exploited in the development and recent demonstration of a digital micromirror display. In an array about the size of two standard postage stamps, over a million mirrors, each the size of a red blood cell, collectively generate a complete, high-resolution video image. Trying to build and operate such a display using conventional methods of mechanical component manufacturing and assembly would be nearly impossible and certainly not affordable.

Finally, neither the miniaturization nor the multiplicity characteristics of MEMS could be fully exploited were it not for the *microelectronics* that is merged with the electromechanical components. Whether the electronics processing and micromachining steps are interleaved, the electronics processing precedes the micromachining steps, or the microelectronics processing and the micromachining are done separately and later flip-chip or wire-bonded does not matter. The integrated microelectronics provides the intelligence to MEMS and allows both the closed-loop feedback systems, localized signal conditioning, and the control of massively-parallel actuator arrays. Furthermore, the considerable and historic investments in microelectronics materials, processing and expertise will accelerate not only the development of MEMS devices, but will also accelerate the acceptance of MEMS devices by systems designers and integrators.

Fabrication Methods and Materials

Common processing techniques that are used to sculpt mechanical structures include bulk micromachining, wafer-to-wafer bonding, surface micromachining, and high-aspect ratio micromachining. While the objective of all these techniques is the fabrication of integrated mechanical and electrical structures, some techniques are best suited for MEMS with robust mechanical parts and structure, some for high-precision components, and others for high levels of integrated electrical-mechanical components.

Bulk micromachining is the term applied to a variety of etching procedures that selectively remove material, typically with a chemical etchant whose etching properties are dependent on the crystallographic structure of the bulk material.

Wafer-to-wafer bonding is a strategy commonly employed to get around the restrictions in the type of structures that can be fabricated using bulk micromachining. Because anisotropic etching, by definition, only *removes* material, bonding of wafers allows for the *addition* of material to the bulk micromachining repertoire.

High-aspect ratio micromachining is an even newer machining technique, developed (originally in Germany) to allow the fabrication of thick (usually greater than hundreds of microns and up to centimeters thick), precision, high-aspect ratio MEMS structures (structures with near-vertical sides). Bulk micromachined structures are typically limited to thicknesses of a few hundred microns. Surface micromachined structures, with their deposited structural films are much thinner, usually limited to thicknesses of no more than five to ten microns. Like all the other micromachining techniques reviewed so far, high-aspect ratio micromachining uses photolithographic processes, but the photoresists layers are hundreds of microns to centimeters thick rather than the one to two microns typical in bulk and surface micromachining.

Surface micromachining, like bulk micromachining, also starts with a wafer of material. But unlike bulk micromachining where the wafer itself serves as the stock from which material is removed to define mechanical structures, in surface micromachining the wafer is the substrate--the workin surface--on which multiple, alternating layers of structural and sacrificial material are deposited and etched (Figure 2).

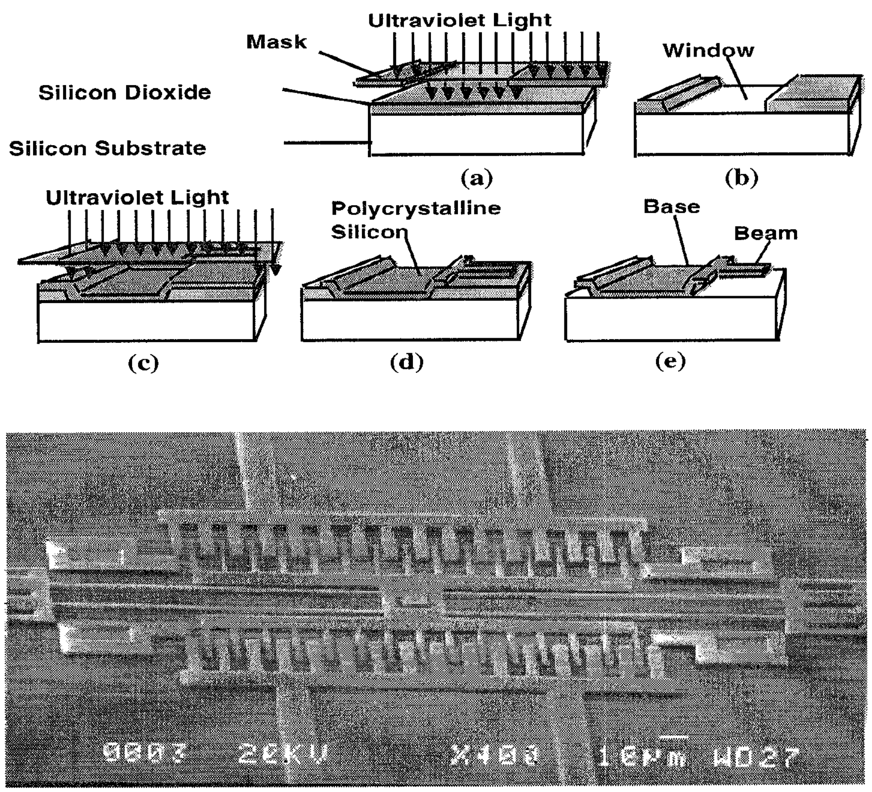


FIGURE 2.A single cycle in a common surface micromachining process. The process to build a single cantilever beam begins with the sacrificial material layer (silicon dioxide) being patterned and etched (a, b). Next, the structural material (polysilicon) is deposited over the entire surface. The polysilicon is then patterned and etched in the shape of the cantilever beam and base (c, d). Finally, the polysilicon is released by removing the remaining and underlying silicon dioxide (e). A portion of the patterned polysilicon is attached to the substrate forming the base (where the silicon dioxide was removed) and portions are suspended above the substrate and free to move (where the silicon dioxide had remained). The scanning electron microscope picture is a side-view of a comb-drive resonator fabricated with such a sequence. Note the two tri-indented square anchors that are the base holding the rest of the central folded beam and comb structures suspended above the substrate.

Because of the laminated structural and sacrificial material layers and the etching of material done by a process that is insensitive to crystalline structure (either because of the etch or because the material itself is non-crystalline), surface micromachining enables the fabrication of free-form, complex and multi-component integrated electromechanical structures, liberating the MEMS designer to envision and build devices and systems that are impossible to realize with bulk or bonded processes. Surface micromachining also frees the process developer and device designer to choose any material system that has complementary structural and sacrificial materials (structural materials that are unaffected by the etching of the sacrificial material). Examples of other material pairs include metals as structural materials paired with polyimides as sacrificial materials. It is this freedom to fabricate devices and systems without constraints on materials, geometries, assembly and interconnections that is the source for the richness and depth of MEMS applications that cut across so many areas. *More than any other factor, it is surface micromachining that has ignited and is at the heart of the current scientific and commercial activity in MEMS.*

Trends in MEMS Technology

By merging the capabilities of sensors and actuators with information systems, MEMS is extending and increasing the ability to both perceive and control the physical world. In order to quantitatively measure and track this ability and compare MEMS developments across diverse application areas, Figure 3 illustrates a map of electromechanical integration. The ordinate is a log plot of the number of transistors ranging from one to one billion. Similarly, the abscissa is a log plot of the number of mechanical components ranging from one to one billion. To first order, the number of transistors are a measure of information processing ability and the number of mechanical components are a measure of perception and control ability. Plotted on this graph is the region containing the ratios for many historic and current MEMS devices, ratios for some recent advanced MEMS devices, and regions of ratios required for future MEMS technologies and applications.

The higher levels of integrated electronics and the greater number of integrated mechanical components represented by the ADXL-50 (the 50G accelerometer fabricated by Analog Devices, Inc.) and the digital micromirror device, DMD (fabricated by Texas Instruments, Inc.) quantify the degree of recent MEMS technology advancements. In the context of the entire graph, the two points also illustrate the opportunity in MEMS represented by the regions of processing, perception and actuation integration yet to be explored. These unexplored regions are not only guides for advances in integration, but are also a guide to the capabilities that will be enabled at those integration levels. For example, to develop inertial navigation units on a chip will likely require nearly two orders of magnitude increase in both the number of transistors and mechanical components to reach the sensitivity and stability necessary in those devices. In contrast, the development of some fluid pumps or microoptomechanical devices will likely require greater numbers of mechanical components, but at lower levels of integrated electronics than other MEMS applications.

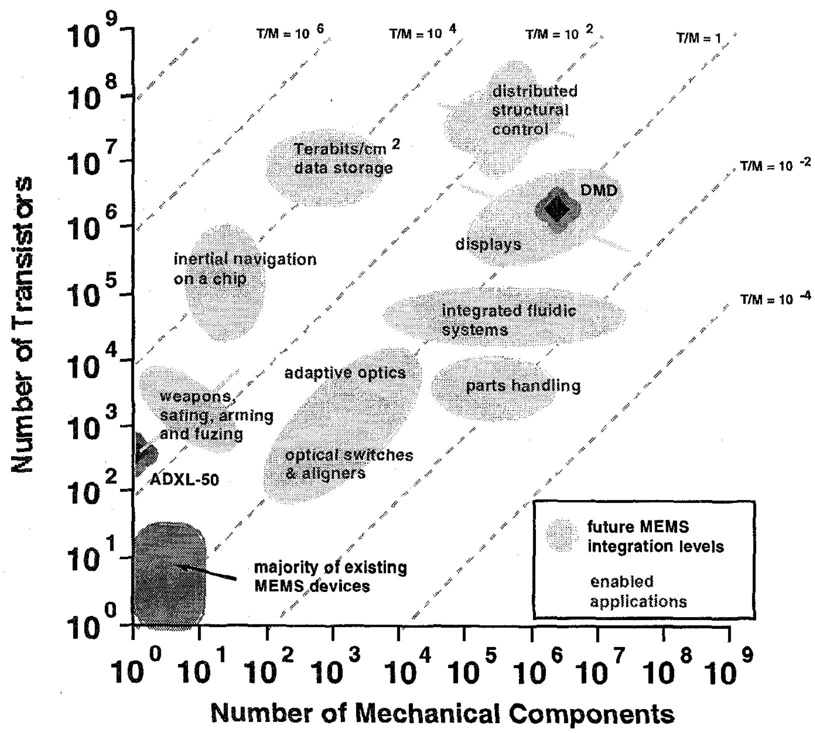


FIGURE 3. Log-log plot of number of transistors merged with number of mechanical components for MEMS devices and systems. Contours of equal transistors-to-mechanical-components ratios (T/M) are lines of 45° slope. Lines representing T/M ratios ranging from 10^{-4} to 10^{6} are shown for reference. The resulting map represents a quantitative way to measure and track MEMS technology advances across different application areas.

Future MEMS applications will be driven by processes that enable greater functionality through higher levels of electronic-mechanical integration and greater number of mechanical components. These process developments in turn will be paced by investments in the development of new materials, device and systems design, fabrication techniques, packaging/assembly methods, and test and characterization tools.

Reference List

(1) 39th Annual Fuze Conference, American Defense Preparedness Association. April 26 and 27, 1995.

(2) "ADI Accelerates Opportunities for MEMS and Micromachined Sensors." *Sensor Business Digest,* October, 1994.

(3) *AMCCOM Final Report on CMS and Operation Desert Sweep,* (DRAFT) CMS, Inc. 1992.

(4) Bryzek, Janusz; Peterson, Kurt; McCulley, Wendell. "Micromachines on the March." *IEEE Spectrum*, May 1994.

(5) *Building U.S. Capabilities in Flat Panel Displays*, U.S. Department of Defense, October 1994.

(6) Burgess, Lisa and Munro, Neil. "Microscopic Warriors, Weapons May Reshape War." *Defense News,* February 21, 1994

(7) Browne, Malcolm W. "Micro-Machines Help Solve Intractable Problem of Turbulence." *New York Times*, January 3, 1995.

(8) *Conventional Weapons Detailed Technology Area Plan - Draft*, U.S. Department of Defense, 1994.

(9) Core, Thomas A; Tsang, W.K.; and Sherman, Steven J. "Fabrication Technology for an Integrated Surface-Micromachined Sensor." *Solid State Technology,* October 1993.

(10) Fujita, H. and Gabriel, K.J., "Future Directions in Microactuators", Plenary Paper, *Transducers'91, IEEE Solid-State Sensors and Actuators Workshop*, San Francisco, 1991.

(11) Gabriel, Jurgen and Gessner, Wolfgang. "Government Promotion of Microsystems Technology in Europe." *International Working Papers No. 1*, VDI/VDE Technologiezentrum Informationstechnik GmbH, October 1992.

(12) Gabriel, Kaigham, "Microelectromechanical Systems Program: Summary of Research Activities." Advanced Research Projects Agency, July 1994.

(13) Howe, R.T., et al., "Micromotor on a Chip", *IEEE Spectrum*, July 1990.

(14) *JTEC Panel Report on Microelectromechanical Systems in Japan*. Japanese Technology Evaluation Center, Sep

(15) Mehregany, Mehran. "Introduction to Microelectromechanical Systems and the Multiuser MEMS Processes Activities." *Case Western Reserve University / MCNC Short Course Handbook*, 1993.

(16) *Microelectromechanical Systems Market Study,* System Planning Corporation. July 1994.

(17) *Microelectromechanical Systems Military Applications*, System Planning Corporation, December 1994.

(18) *The National Technology Roadmap for Semiconductors,* Semiconductor Industry Association, 1994.

(19) Santo, Brian. "U.S., Japan Gear Up For Micromachines." *Electronics Engineering Times*, November 23, 1993.

(20) Scott, William B. "Micro-Machines Hold Promise for Aerospace." *Aviation Week and Space Technology,* March 1, 1993.

(21) Stix, Gary. "Micro Machinations." *Scientific American*, November 1992.

(22) Younse, Jack M. "Mirrors on a Chip." *IEEE Spectrum,* November 1993.

(23) *Integrated Micro Motion Systems,* Third Toyota Conference, Nissin Aichi, Japan, October 22-25, 1989.

(24) Technical Digest, *Transducers'91, IEEE Solid-State Sensors and Actuators Workshop*, San Francisco, 1991.

(25) Technical Digest, *Transducers'93, IEEE Solid-State Sensors and Actuators Workshop*, Yokohama, Japan, 1993.

(26) Technical Digest, *Hilton Head Solid-State Sensors and Actuators Workshop,* 1992 & 1994.

(27) Gabriel, Kaigham. "Engineering Microscopic Machines." *Scientific American*, September 1995.