
History of MEMS

Primary Knowledge

Participant Guide

Description and Estimated Time

This learning module provides a timeline of the progression of microtechnology through a series of innovations that starts with the first Point Contact Transistor built in 1947 and ends with the optical network switch in 1999. Activities provide the opportunity to build on this timeline and to identify innovations of the 21st century that have contributed to current advancements in both micro and nanotechnology.

With this unit you will become familiar with the major milestones involved in the emergence of Microelectromechanical Systems (MEMS). The following topics are discussed:

- A timeline of major milestones in the history of Microelectromechanical Systems (MEMS)
- Brief descriptions of some of the major milestones in the history of MEMS

Estimated Time to Complete

Allow approximately 45 minutes

Introduction

Microelectromechanical Systems (MEMS) are miniature systems present in our every day lives. They are manufactured from a variety of materials and manufacturing methods. Materials used include semiconductors, plastics, ceramics, ferroelectric, magnetic, and biomaterials. MEMS are used as sensors, actuators, accelerometers, switches, game controllers and light reflectors, just naming a few applications. MEMS are currently used in automobiles, aerospace technology, biomedical applications, ink jet printers, wireless and optical communications. New applications are emerging every day.

MEMS components range in size from a millionth of a meter (micrometer) to a thousandth of a meter (millimeter). They are also referred to as micromachines, microsystems, micromechanics, or Micro Systems Technology (MST).

In 1965 Gordon Moore made an observation: since the invention of the transistor in the late 1940s the number of transistors per square inch on integrated circuits had doubled every 18 months since the integrated circuit was invented in the late 1950's, early 1960's. This observation was the basis for "Moore's Law". With this statement, Moore indicated that technology has and will for the foreseeable future concentrate on smaller, not bigger.

As with the transistor, there have been many efforts in trying to make electromechanical systems smaller and smaller. In 1959, a man named Richard Feynman said it best in his now famous talk entitled: "There's Plenty of Room at the Bottom". He was interested in exploring how to manipulate and control things on a small scale. Feynman said, "They tell me about electric motors that are the size of the nail on your small finger. It is a staggeringly small world that is below."

Gordon Moore and Richard Feynman are only two examples of scientists who predicted the emerging technology of smaller and smaller electromechanical systems. This SCO will discuss the major milestones and technologies that have emerged in the field of MEMS.



*Three MEMS blood pressure sensors on a head of a pin
[Photo courtesy of Lucas NovaSensor, Fremont, CA]*

Objectives

The objectives of this lesson are:

- Name three major MEMS technology processes which have emerged in Microsystems history.
- Name at least three major MEMS milestones which have occurred throughout MEMS history.

Key Terms (Definitions of Key Term in Glossary at the end of this unit.)

Sensors
Actuators
Accelerometers
Moore's Law
Transistors
Piezoresistive Effect
Nanotechnology
surface micromachining
isotropic etch
anisotropic etch
bulk micromachining
LIGA
SCREAM

Major MEMS Milestones

The inception of MEMS devices occurred in many places and through the ideas and endeavors of several individuals. And of course, new MEMS technologies and applications are being developed every day. Following is a timeline which includes many efforts leading to MEMS development. This lesson by no means includes all the efforts put forth in developing MEMS technology and applications. It gives a broad look at some of the milestones which have contributed to the development of Microelectromechanical Systems as we know them today.

- 1948 Invention of the Germanium transistor at Bell Labs (William Shockley)
- 1954 Piezoresistive effect in Germanium and Silicon (C.S. Smith)
- 1958 First integrated circuit (IC) (J.S. Kilby 1958 / Robert Noyce 1959)
- 1959 "There's Plenty of Room at the Bottom" (R. Feynman)
- 1959 First silicon pressure sensor demonstrated (Kulite)
- 1967 Anisotropic deep silicon etching (H.A. Waggener et al.)
- 1968 Resonant Gate Transistor Patented (Surface Micromachining Process) (H. Nathanson, et.al.)
- 1970's Bulk etched silicon wafers used as pressure sensors (Bulk Micromachining Process)
- 1971 The microprocessor is invented
- 1979 HP micromachined ink-jet nozzle
- 1982 "Silicon as a Structural Material," K. Petersen
- 1982 LIGA process (KfK, Germany)
- 1982 Disposable blood pressure transducer (Honeywell)
- 1983 Integrated pressure sensor (Honeywell)
- 1983 "Infinitesimal Machinery," R. Feynman
- 1985 Sensor or Crash sensor (Airbag)
- 1985 The "Buckyball" is discovered
- 1986 The atomic force microscope is invented
- 1986 Silicon wafer bonding (M. Shimbo)
- 1988 Batch fabricated pressure sensors via wafer bonding (Nova Sensor)
- 1988 Rotary electrostatic side drive motors (Fan, Tai, Muller)
- 1991 Polysilicon hinge (Pister, Judy, Burgett, Fearing)
- 1991 The carbon nanotube is discovered
- 1992 Grating light modulator (Solgaard, Sandejas, Bloom)
- 1992 Bulk micromachining (SCREAM process, Cornell)
- 1993 Digital mirror display (Texas Instruments)
- 1993 MCNC creates MUMPS foundry service
- 1993 First surface micromachined accelerometer in high volume production (Analog Devices)
- 1994 Bosch process for Deep Reactive Ion Etching is patented
- 1996 Richard Smalley develops a technique for producing carbon nanotubes of uniform

diameter

- 1999 Optical network switch (Lucent)
- 2000s Optical MEMS boom
- 2000s BioMEMS proliferate
- 2000s The number of MEMS devices and applications continually increases
- 2000s NEMS applications and technology grows

1947 Invention of the Point Contact Transistor (Germanium)

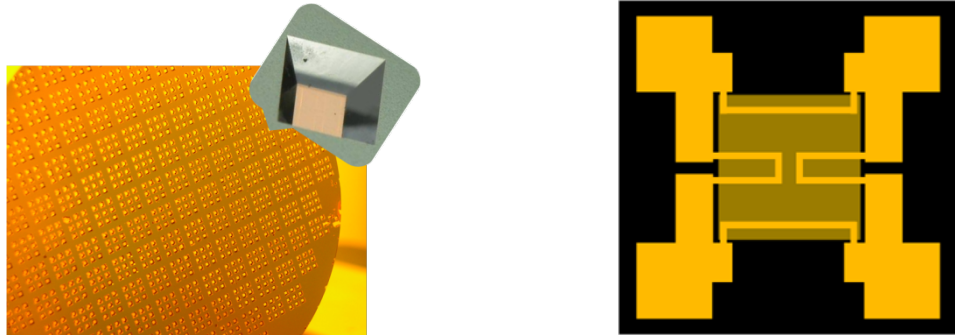


First Point Contact Transistor and Testing Apparatus (1947)
[Photo Courtesy of The Porticus Centre]¹

In 1947, William Shockley, John Bardeen, and Walter Brattain of Bell Laboratories succeeded in building the first point-contact transistor.² This transistor utilized germanium, a semiconductive chemical element. This invention demonstrated the capability of building transistors with semiconductive materials, allowing for better control of voltage and current. It also opened the door to building smaller and smaller transistors. The patent for the germanium NPN grown junction transistor was filed by William Shockley in 1948.³

This first transistor was approximately half an inch high, which is huge compared to today's standards. Today, scientists can build nanotransistors which measure approximately 1 nm in diameter.⁴ For reference, a single human hair is approximately 60 – 100 micrometers.

1954 Discovery of the Piezoresistive Effect in Silicon and Germanium

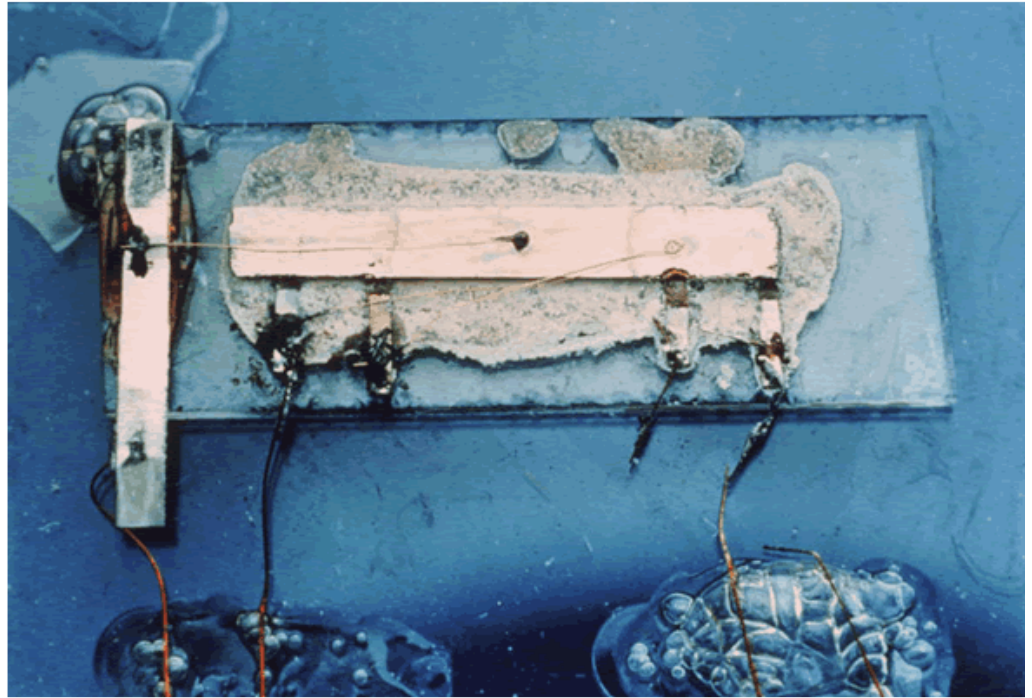
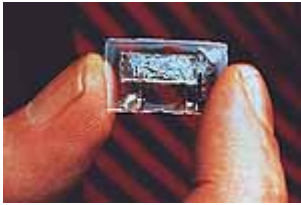


*An example of a pressure sensor utilizing the piezoresistive effect of a metal (gold)
[MTTC Pressure Sensor]*

In 1954, C. S. Smith discovered the piezoresistive effect in semiconductor material such as silicon and germanium. This piezoresistive effect of semiconductor can be several magnitudes larger than the geometrical piezoresistive effect in metals. This discovery was important to MEMS because it showed that silicon and germanium could sense air or water pressure better than metal.

As a result of the discovery of the piezoresistive effect in semiconductors, silicon strain gauges began to be developed commercially in 1958. In 1959 Kulite was founded as the first commercial source of bare silicon strain gages.

1958 Invention of the First Integrated Circuit (IC)

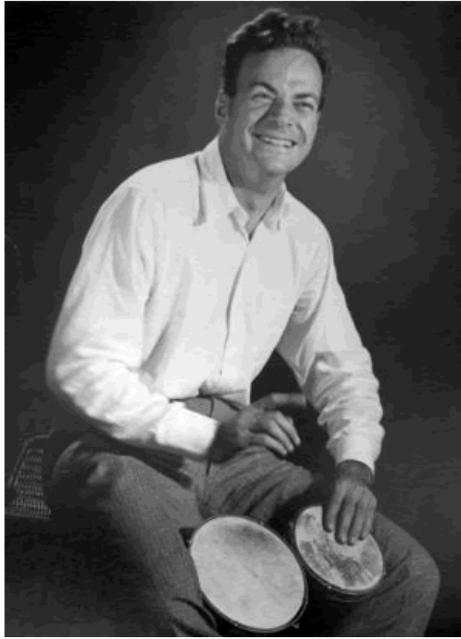


Texas Instrument's First Integrated Circuit⁵
[Photos Courtesy of Texas Instruments]

When the transistor was invented, there was a limit to how small each transistor could actually be because it had to be connected to wires and other electronics. As a result, the shrinking of transistors reached a standstill until the "integrated circuit". An integrated circuit would include the transistors, resistors, capacitors, and wires needed to serve a particular application. If an integrated circuit could be made all together on one substrate, then the whole device could be made smaller.

Two people independently developed an integrated circuit at almost the same time. In 1958, Jack Kilby who worked for Texas Instruments built a working model of a "Solid Circuit". This circuit consisted of one transistor, three resistors, and one capacitor all on one germanium chip. Shortly after, Robert Noyce from Fairchild Semiconductor made the first "Unitary Circuit". This integrated circuit was made on a silicon chip. The first patent was awarded in 1961 to Robert Noyce.

1959 "There's Plenty of Room at the Bottom"



Richard Feynman on his bongos⁶

Photo credit: Tom Harvey

[There's Plenty of Room at the Bottom An Invitation to Enter a New Field of Physics by Richard P. Feynman]

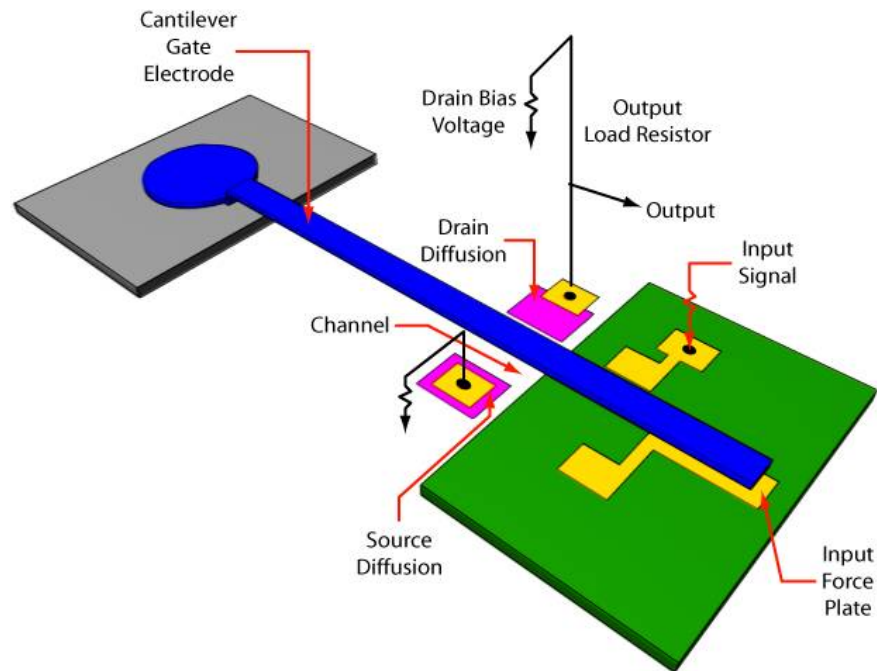
In 1959, at a meeting of the American Physical Society, a man named Richard Feynman popularized the growth of micro and nano technology with a notable seminal talk entitled "There's Plenty of Room at the Bottom". In his talk he posed the question, "Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin?" He proposed methods of how to write so much text in such a small area, as well as how it could be read.

Feynman introduced the possibility of manipulating matter on an atomic scale. He was especially interested in denser computer circuitry, and microscopes which could see things much smaller than is possible with scanning electron microscopes. He suggested the possibility of building tiny robots which could be swallowed to perform surgical procedures.

Feynman talked about the new physical challenges that would occur when working at the atomic scale. Gravity would become less important, while surface tension and Van der Waals attraction would become more important.

At the end of this famous speech, he challenged his audience to design and build a tiny motor and to write the information from a page of a book on a surface $1/25,000$ smaller in linear scale. For each challenge, he offered prizes of \$1000. He awarded the prize for a tiny motor within one year and in 1985 a student at Stanford University collected the prize for reducing the first paragraph of "A Tale of Two Cities", by $1/25,000$. Continuing the challenge, The Foresight Nanotech Institute has been issuing the Feynman Prize in Nanotechnology each year since 1997 to researchers who have most advanced the achievement of Feynman's goal for nanotechnology.

1968 The Resonant Gate Transistor Patented

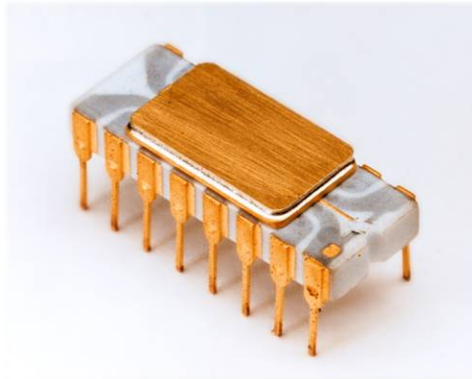


Resonant Gate Transistor⁷

In 1964, a team from Westinghouse led by Harvey Nathanson produced the first batch fabricated MEMS device. This device joined a mechanical component with electronic elements and was called a resonant gate transistor (RGT). The RGT was a gold resonating MOS gate structure. It was approximately one millimeter long and it responded to a very narrow range of electrical input signals. It served as a frequency filter for integrated circuits by transmitting only those signals within the designed range to an output circuit while ignoring all other frequencies.

The RGT was unlike conventional transistors in that it was not fixed to the gate oxide. Instead, it was movable and cantilevered with respect to the substrate. Electrostatic attractive forces controlled the distance between the gate and the substrate. The RGT was the earliest demonstration of micro electrostatic actuators. It was also the first demonstration of surface micromachining techniques.⁷

1971 The Invention of the Microprocessor



The Intel 4004 Microprocessor and the Busicom calculator⁸
[Photos Courtesy Intel Corporation]

In 1971, a company called Intel publicly introduced the world's first single chip microprocessor, the Intel 4004. The 4004 powered the Busicom calculator and was Intel's first microprocessor. This invention paved the way for the personal computer. As noted below, MEMS capitalized on semiconductor manufacturing technologies.

1960's and 1970's Proliferation of Bulk-Etched Silicon Wafers Used as Pressure Sensors

In the early 1960s, the fabrication of silicon transistors brought about the process of isotropic etching of silicon. Isotropic etching removes material from a substrate using a chemical process. The material is equally removed in all directions due to the etch rate being uniform in all directions.

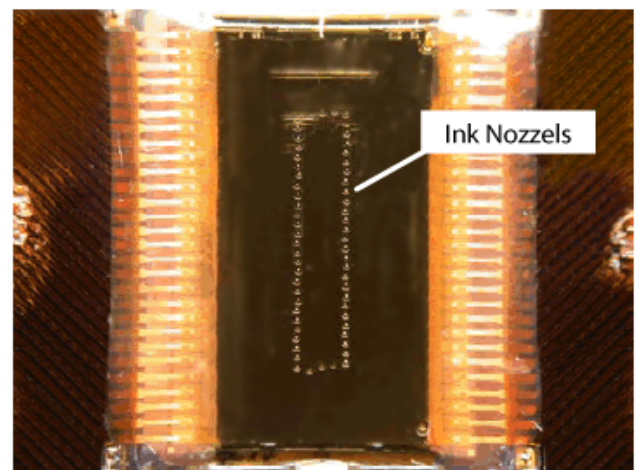
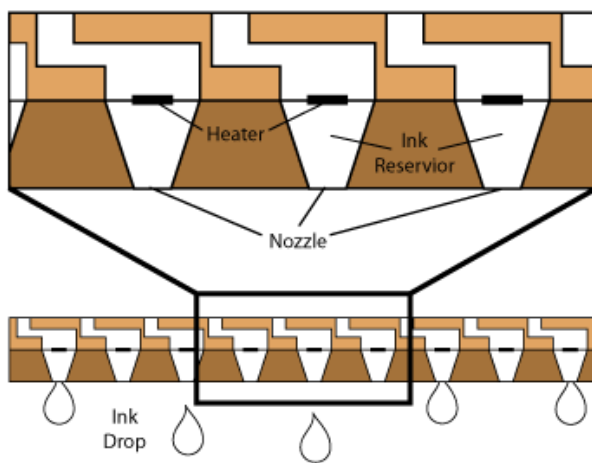
In the late 1960's early 1970's, a paper by H. A. Waggener was published entitled, "Electrochemically Controlled Thinning of Silicon".⁹ This illustrated the anisotropic wet etching of silicon. Wet anisotropic etching differs from wet isotropic etching in that the electrochemical removal of material is dependent on the crystallographic orientation of the silicon crystal. The etch rate (the amount of material removed per unit of time) varies greatly for the different crystal planes. The silicon can then be etched away selectively creating a variety of structures including v-shaped grooves, pyramid-shaped mesas and micro-chambers.

Electrochemical anisotropic etching is important in microsystems fabrication because it is the basis of the bulk micromachining process. Bulk micromachining etches away relatively large portions of the silicon substrate leaving behind the desired structures. Since its inception, bulk micromachining has remained a very powerful method for fabricating micromechanical elements such as micro-fluidic channels, nozzles, diaphragms, suspension beams and other moving or structural elements.

In the 1970's, a micromachined pressure sensor using a silicon diaphragm was developed by Kurt Peterson from IBM research laboratory. The thin diaphragm allowed for a greater deformation, thus greater sensitivity compared to other membrane type pressure sensors at that time. These thin diaphragm pressure sensors have proliferated in blood pressure monitoring devices which can be considered to be one of the earliest commercial successes of microsystems devices.¹⁰

1979 HP Micromachined Inkjet Nozzles

In 1979, Hewlett Packard came up with an alternative to dot matrix printing called Thermal Inkjet Technology (TIJ). This printing technique rapidly heats ink, creating a tiny bubble. When the bubble pops, the ink droplet squirts through a nozzle; an array of these nozzles are part of the complete inkjet print head and allows the rapid creation of an image onto paper and other media. Silicon micromachining technology is used to manufacture the nozzles. The nozzles are made very small and are densely packed for high resolution printing. Since HP first came up with the TIJ, improvements have been made to make the nozzles smaller and more densely packed to improve resolution. Many printers available today use the thermal ink jet technology.



(left) Schematic of an array of inkjet nozzles

(right) Close-up view of a commercial inkjet printer head illustrating the nozzles [Hewlett Packard]

1982 LIGA Process Introduced



LIGA-micromachined gear for a mini electromagnetic motor [Sandia National Labs]

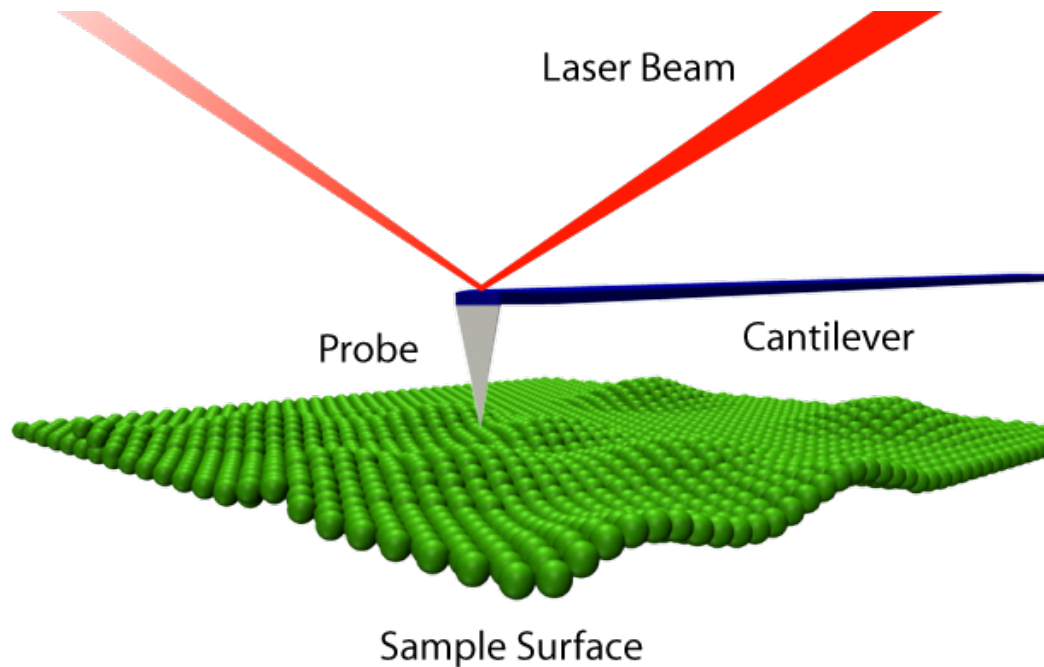
In the early 1980s a team at the Karlsruhe Nuclear Research Center in Germany, developed a new process called LIGA. LIGA is a German acronym for X-ray lithography (X-ray Lithographie), Electroplating (Galvanoformung), and Molding (Abformung).

This process is important in microsystems manufacturing because it allows for manufacturing of high aspect ratio microstructures. High aspect ratio structures are very thin, or narrow, and tall, such as a channel. LIGA can achieve ratios as high as 100:1 and LIGA structures have precise dimensions and low surface roughness.

1982 “Silicon as a Mechanical Material”

In 1982 a paper written by Kurt Petersen was published in an Institute of Electrical and Electronics Engineers (IEEE) publication. It was entitled "Silicon as a Mechanical Material". The paper provided information on material properties and etching data for silicon and was instrumental in enticing the scientific community into exploration of these areas. It is one of the most referenced articles in the MEMS field.

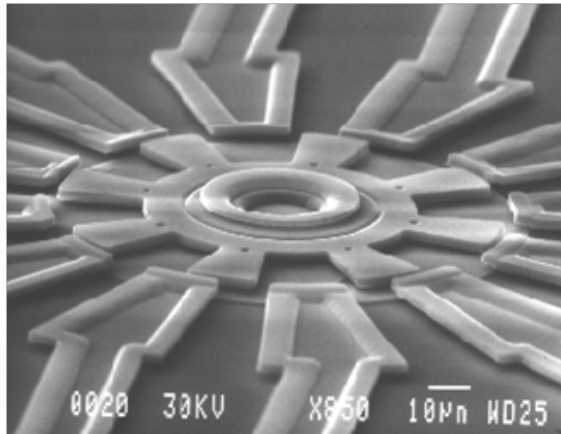
1986 Invention of the Atomic Force Microscope (AFM)



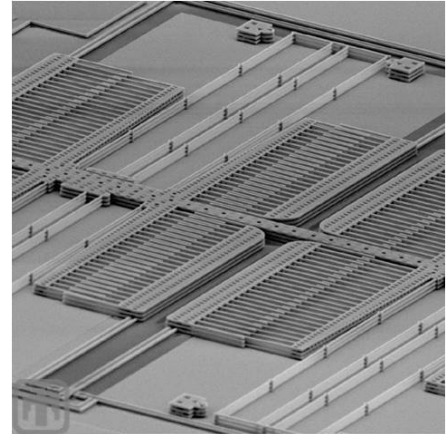
Cantilever on an Atomic Force Microscope

In 1986 scientists from IBM developed a microdevice called the atomic force microscope (AFM).¹¹ The AFM is a device that maps the surface of an atomic structure by measuring the force acting on the tip of a microscale cantilever with a sharp tip or probe at its end. The cantilever is usually silicon or silicon nitride. The ultimate resolution of the AFM is down to about 10 \AA .¹⁵

Other Developments in Microsystems in the 1980's



(left) First Rotary Electrostatic Side Drive Motor [Richard Muller, UC Berkeley]



(right) Lateral Comb Drive [Sandia National Labs]

There were many developments and new applications that emerged in the 1980's.

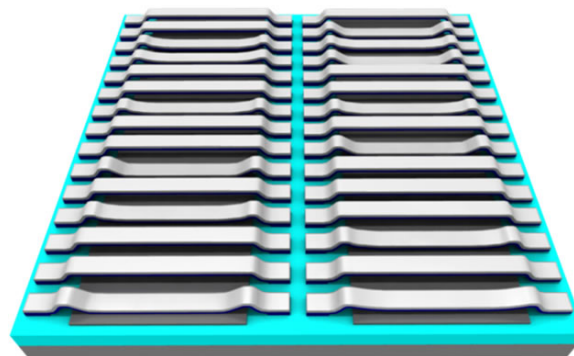
In 1988 the first rotary electrostatic side drive motors were made at UC Berkeley.¹²

In 1989 a lateral comb drive emerged where structures move laterally to the surface.¹²

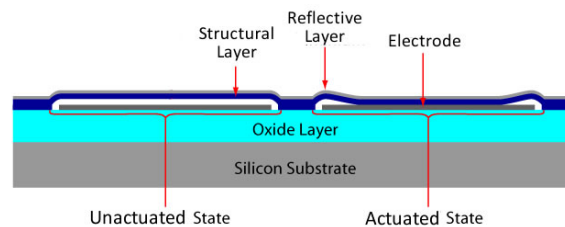
1992 SCREAM Process (Cornell)

In 1992 at Cornell University, a bulk micromachining process was developed called Single Crystal Reactive Etching and Metallization (SCREAM).¹³ It was developed to fabricate released microstructures from single crystal silicon and single crystal Gallium Arsenide (GaAs).

1992 Grating Light Modulator



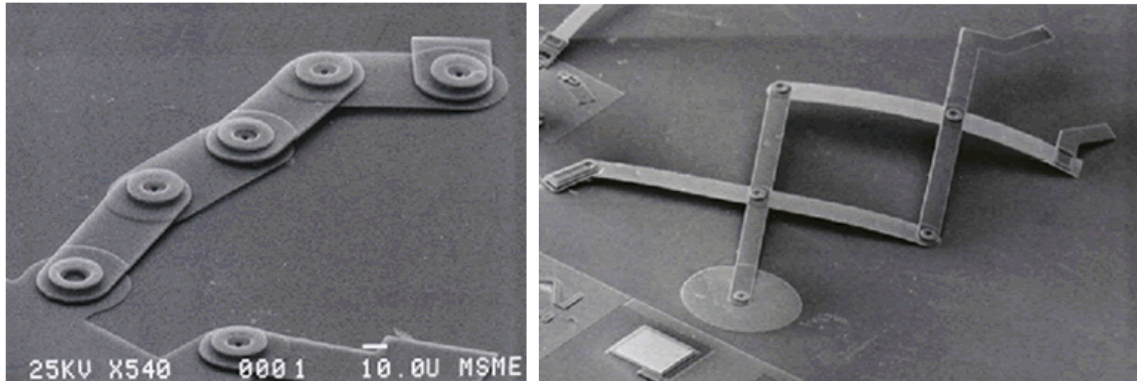
Cross-section of GLV fabrication and actuation



Grating Light Valve

The deformable grating light modulator (GLM) was introduced by O. Solgaard in 1992.¹⁴ It is a Micro Opto Electromechanical System (MOEMS). Since it was introduced, it has been developed for uses in various applications such as in display technology, graphic printing, lithography and optical communications.

1993 MUMPs Emerges



Two simple structures using the MUMPs process
[Photos Courtesy of Justin Black, UC Berkeley]

In 1993 Microelectronics Center of North Carolina (MCNC) created a foundry which was meant to make microsystems processing highly accessible and cost effective for a large variety of users. It developed a process called MUMPs (MultiUser MEMS Processes) which is a three layer polysilicon surface micromachining process. Since its inception, several modifications and enhancements have been made to increase the flexibility and versatility of the process for the multi-user environment.



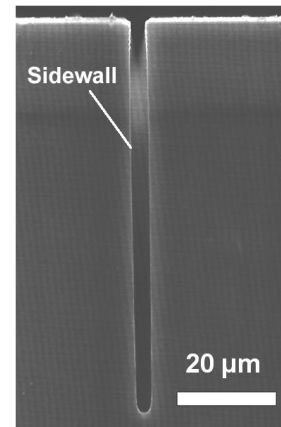
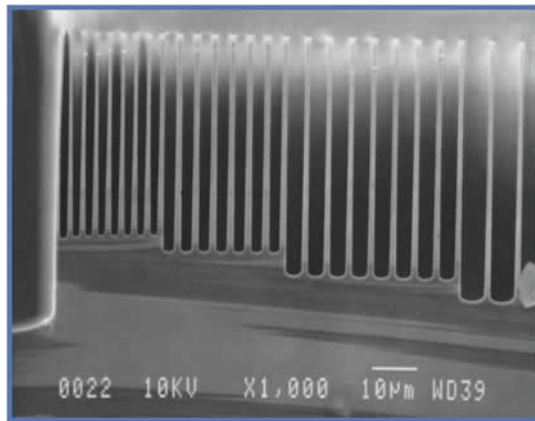
*A MEMS device built using SUMMiT IV
[Sandia National Labs]*

In 1998, another surface micromachining foundry began. This one was started at Sandia National Laboratories and the process was called SUMMiT IV. This process later evolved into the SUMMiT V which is a five-layer polycrystalline silicon surface micromachining process. SUMMiT is an acronym for “Sandia Ultra-planar, Multi-level MEMS Technology.”

1993 First High Volume Manufactured Accelerometer

In 1993 Analog Devices was the first to produce a surface micromachined accelerometer in high volume. Previously, in the 1980's, TRW produced a sensor which sold for about \$20 each. The automotive industry used the Analog Devices' accelerometer in airbags and it was sold for about \$5 each. This was about a cost reduction in airbag electronics of about 75%.¹⁶ It was highly reliable, very small, and very inexpensive. It was sold in record breaking numbers which increased the availability of airbags in automobiles. Today, accelerometers are found in a wide variety of consumer products including safety and navigation automotive systems, game controllers, mobile cell and computer systems.

1994 Deep Reactive Ion Etching is Patented



Trenches etched with DRIE

[SEM images courtesy of Khalil Najafi, University of Michigan]

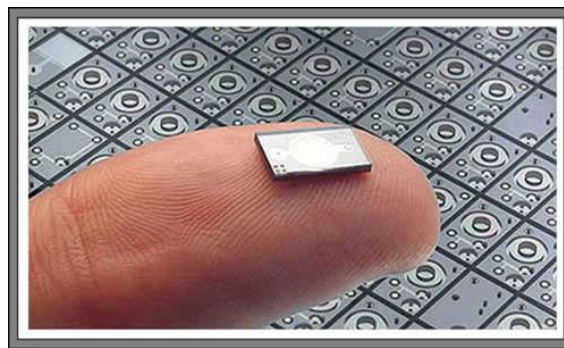
In 1994, Bosch, a company from Germany, developed a special Deep Reactive-Ion Etching (DRIE) process. DRIE is a highly anisotropic etch process used to create deep, steep-sided holes and trenches in wafers. It was developed for micro devices which require these features but is also used to excavate trenches for high-density capacitors for Dynamic Random Access Memory (DRAM)

Late 1990's, Early 2000's Optics Technology Proliferates

In 1999 Lucent Technologies developed the first MEMS optical network switch. Optical switches are optoelectric devices, consisting of a light source and a detector that produces a switched output. It provides a switching function in a data communications network.

These MEMS optical switches utilize micromirrors to switch or reflect an optical channel or signal from one location to another depending on the relative angle of the micromirror. There are several different design configurations. Growth in this area of technology is still progressing.

Late 1990's, Early 2000's BioMEMS Technology Proliferates



Insulin pump [Printed with permission from Debiotech SA]

Scientists are still discovering new ways to combine MEMS sensors and actuators with emerging bioMEMS technology. Applications include drug delivery systems, insulin pumps, DNA arrays, lab-on-a-chip (LOC), glucometers, neural probe arrays, and microfluidics, just to name a few. The area of bioMEMS has only just begun to be explored. Research and development at this time is occurring at a very rapid pace.

Summary

Since the invention of the transistor, scientists have been trying to improve and develop new microelectromechanical systems. MEMS devices have been used in so many commercial products. New applications and better technologies are emerging every day. The first MEMS devices measured such things as pressure in engines and motion in cars. Today, MEMS elements are controlling our communications networks. They are saving lives by inflating automobile air bags. They are placed in the human body to monitor blood pressure and used to administer drugs when and directly where they are needed.

Microsystems continue getting smaller, creating a new technology called nanoelectromechanical systems (NEMS). The applications and growth for MEMS and NEMS are endless and will continue to find their way into so many aspects of our everyday lives.

Glossary of Key Terms

Accelerometers: A device that uses a suspended inertial mass to measure acceleration.

Actuator: A device to convert an electrical control signal to a physical action. Actuators may be used for flow-control valves, pumps, positioning drives, motors, switches, relays and meters.

Anisotropic etch: An etch process that proceeds in one direction only; the result is a vertical feature that is the same size as the mask.

Bulk micromachining: A process to form microdevices by etching into the substrate.

DRIE: Deep Reactive-Ion Etching: A highly anisotropic etch process used to create deep, steep-sided holes and trenches in wafers, with aspect ratios of 20:1 or more.

Isotropic etch: An etch process that proceeds equally in all directions; the result is an etched feature that is larger than the mask.

LIGA: A German acronym for (X-ray) lithography (Lithographie), Electroplating (Galvanoformung), and Molding (Abformung). It is a process used to create high-aspect-ratio structures (structures that are much taller than wide) with lateral precision below one micrometer.

MOEMS: Micro-Optical-Electro-Mechanical systems

Moore's Law: The power of microprocessor technology doubles and its costs of production decreases every 18 months.

Nanotechnology: Technology involved with design and fabrication of devices and thin films with dimensions in the nanometer range ($1\text{E-}9\text{ m}$).

Piezoresistive Effect: The piezoresistive effect describes the changing electrical resistance of a material due to applied mechanical stress.

SCREAM: Single Crystal Reactive Etching and Metallization: A bulk micromachining process developed to fabricate released microstructures from single crystal silicon and single crystal Gallium Arsenide (GaAs).

Sensors: A device that responds to a stimulus, such as heat, light, or pressure, and generates a signal that can be measured or interpreted.

Surface micromachining: An additive fabrication technique which involves the building of a device on the top surface of a supporting substrate. This technique is relatively independent of substrate.

Transistors: An electronic device used to control the flow of electricity.

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Related SCME Units and Learning Modules

- History of MEMS Activity
- History of MEMS Final Assessment
- MEMS Applications Learning Module
- BioMEMS Applications Learning Module

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