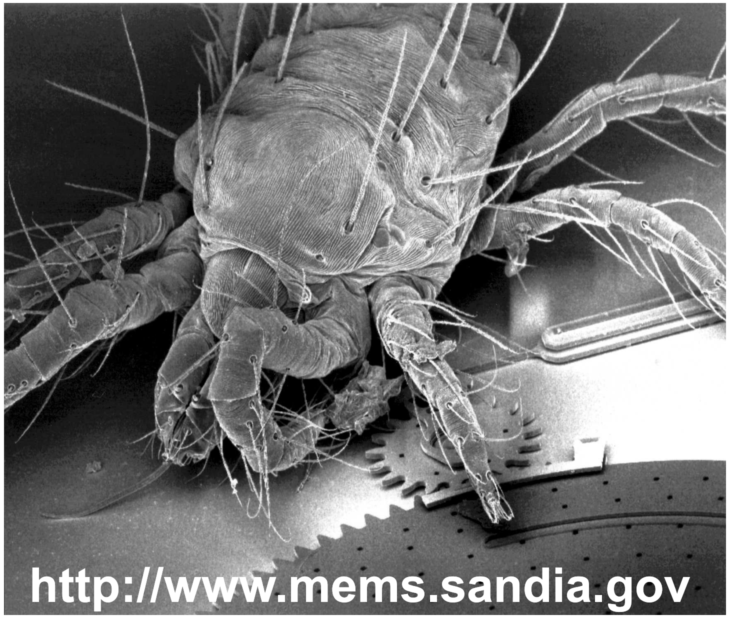
SAND2007-4521C

Introduction to MEMS

(MicroElectroMechanical Systems)



Sandia National Laboratories

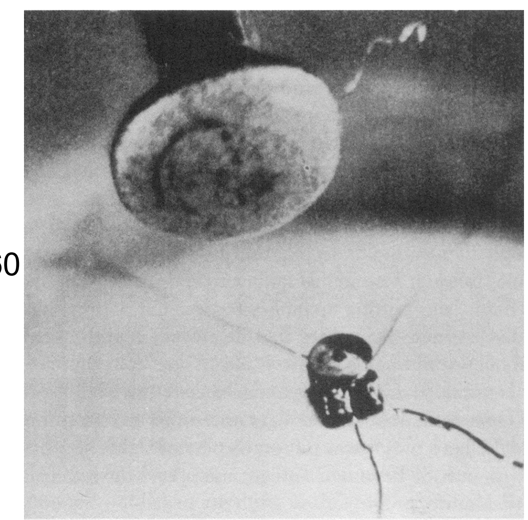
Topics

- Historical perspective
- Issues of Scale
- Micro-System Timeline
- Commercial Applications
- Fabrication Technologies

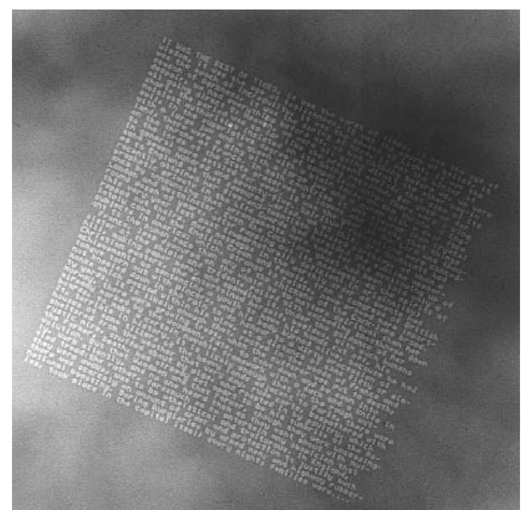
Vision of Micro-Systems

- "There's Plenty of Room at the Bottom", 1959, California Institute of Technology
  - 2 Challenges:
    - Construct a working electric motor able to fit in a 1/64 inch cube
    - Print text at a scale that the Encyclopedia Britannica could fit on the head of a pin

Richard P. Feynman
(1918-1988)



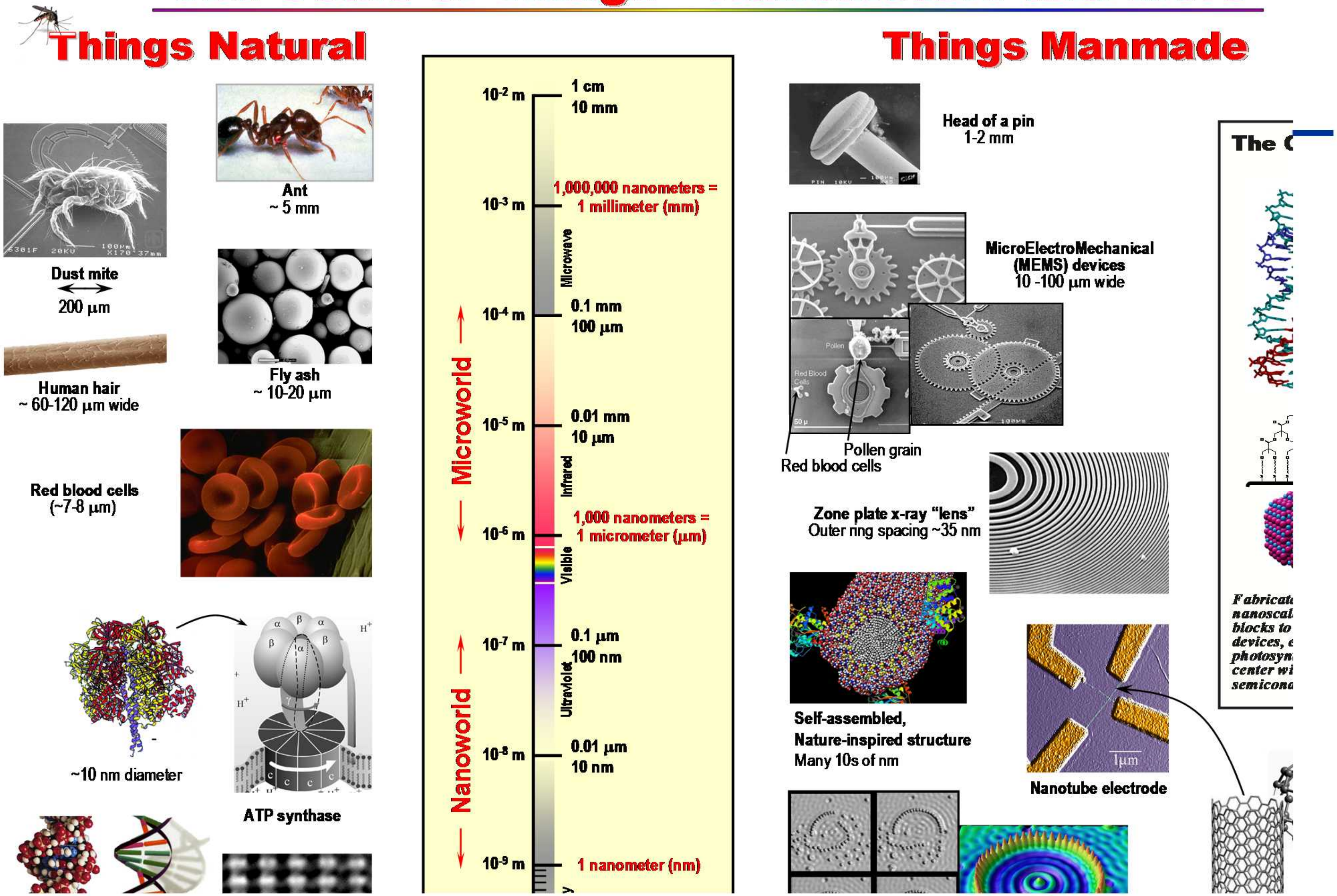
William McLellan, 1960



T. Newman,
R.F.W. Pease,
1985

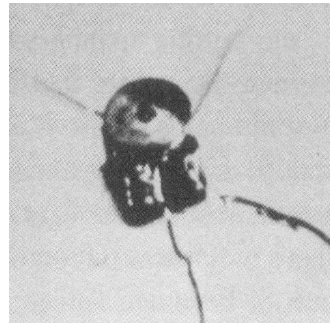
Sandia National Laboratories

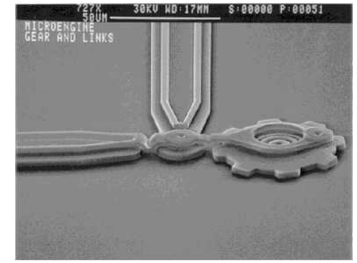
The Scale of Things – Nanometers and More



Sandia National Laboratories

Effect of Reduction in Scale





Why does a change is scale matter?

- Entering different physics regimes at a particular scale.
- Physical phenomena scale at different rates which changes their relative importance.

Sandia National Laboratories

Physical Phenomena Scale at different rates

Forces	Scaling (S=1→ 0.001)
• Casmir	$\propto$ $1/S^4$
• Van der Waals	$\propto$ $1/S^3$
• Surface Tension	$\propto$ $1/S^3$
• Electrostatic	$\propto$ $1/S^2$
• Magnetic	$\propto$ S^0
• Elastic stiffness	$\propto$ S
• Inertia	$\propto$ S^3
• Gravity	$\propto$ S^3

Nano Domain

Micro Domain

Macro Domain

Physical Phenomena Change: The breakdown of Continuum Model

- Mean Free Path of air at STP - 65 nM
- Material crystal sizes in polycrystalline material ~300-500 nM
- Magnetic Domains ~10-25 micron
- Silicon lattice constant 5.43 A

Sandia National Laboratories

Newly Relevant Phenomena

- **Brownian Noise: (thermal noise, Johnson noise) atomic vibrations. Significant for MEMS sensors**
- **Paschen's Effect: Breakdown voltage increases as the pressure*gap product decreases.**
- **Electron Tunneling: Quantum mechanical effect in which entities such as electrons can "tunnel" across small (~nm). Displacement transduction technique**

Ref: Ch 4, Scaling Issues for MEMS, "Micro Electro Mechanical System Design," J. J. Allen, CRC Press, 2005

Timeline of Key Micro-System Developments

Time	Event	Company
1947	ENIAC (electronic numerical integrator and computer)	University of Pennsylvania
1947	Invention of the bipolar transistor	
1954	Piezoresistive effect in germanium and silicon	
1958	First commercial bare silicon strain gages	Kulite Semiconductor
1959	"There's plenty of room at the bottom"	
1959	Planar Silicon Transistor	
1959	Planar fabrication process for microelectronics	
1960	Feynman Prize awarded for electric motor no larger than a 1/64-in. cube	
1961	Silicon pressure sensor demonstrated	Kulite Semiconductor
1965	Moore's law	
1967	Resonant gate transistor	
1974	First high-volume pressure sensor	National Semiconductor
1977–1979	Micromachined ink-jet nozzle:	International Business Machines, Hewlett-Packard
1982	Silicon as a mechanical material	
1982	Disposable blood pressure transducer	Foxboro/ICT, Honeywell
1985	Feynman prize awarded for producing text at a 1/25,000 scale	
1983	Surface micromachining process	
1987	Digital micromirror device (DMD) invented	Hornbeck
1988	Micromechanical elements	
1986	LIGA process	
1989	Lateral comb drive	
1991	Polysilicon hinge	
1993	ADXL50 accelerometer commercially sold.	Analog Devices Inc.
1996	Digital light processor (DLP™) containing DMD commercially sold	Texas Instruments
2002	Analog Devices ADXRS gyroscope introduced	Analog Devices Inc.

Feynman's Visionary Talk

Beginnings of Microelectronic Technology

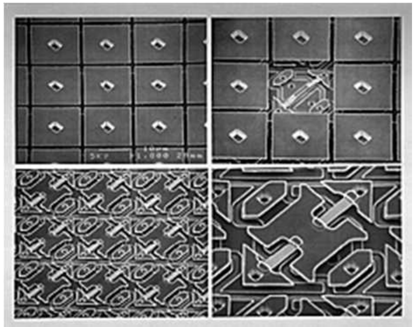
Early Products based upon the Piezoresistive properties of Silicon

MEMS Commercial Products

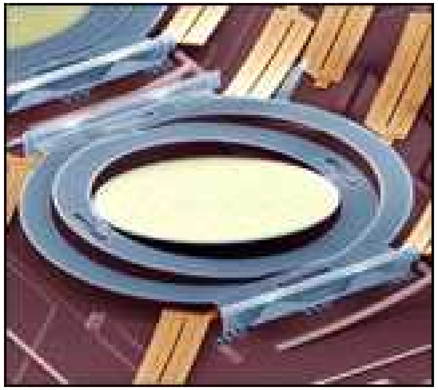
Adapted from: *Micro Electro Mechanical System Design*, J. Allen, CRC Press, 2005

Sandia National Laboratories

MEMS Commercial Applications

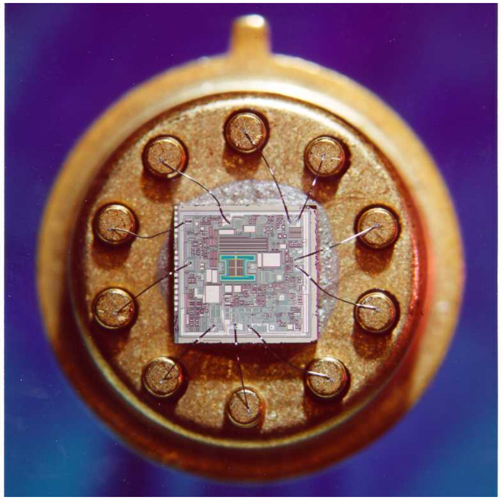


Digital Mirror Device
Texas Instruments

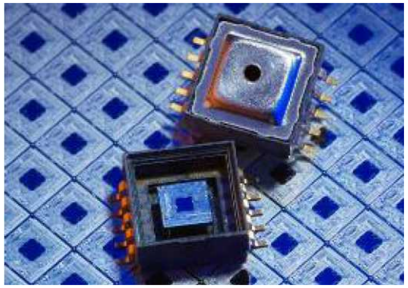


Micromirror switch
Lucent Technologies

Ink Jet Cartridge
Hewlett Packard



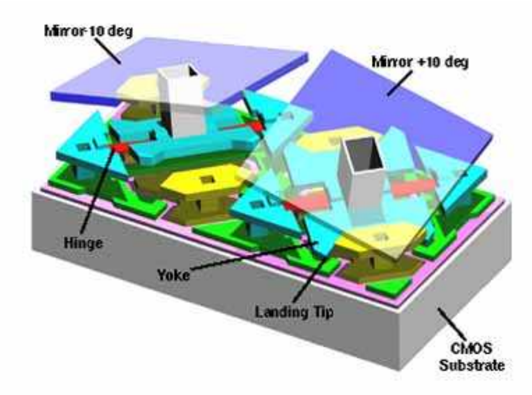
Accelerometer
Analog Devices



Pressure Sensor
Bosch MEMS

TI DMD Light Switch

- Each light switch has an aluminum mirror (16 μm square) that can reflect light in two directions
- Rotation of the mirror occurs from an electrostatic attraction between the mirror and underlying memory cell
- System occupies 90% of projected image – mirrors separated by only 1 μm

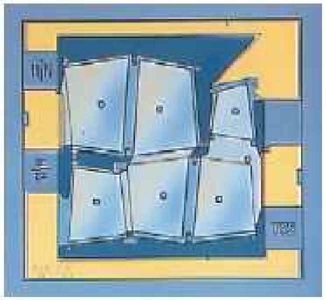


Sandia National Laboratories

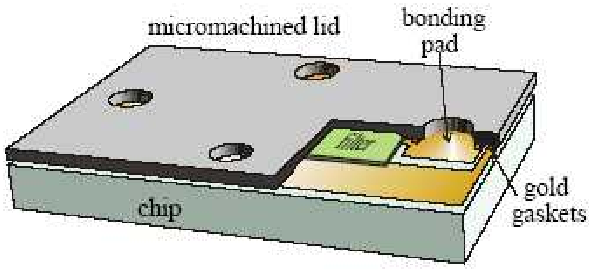
Agilent Technologies RF MEMS

Recent MEMS developments

- **FBAR Technology (over 1,000,000 sold!)**
  - A revolutionary acoustic radio frequency filter technology for mobile appliances

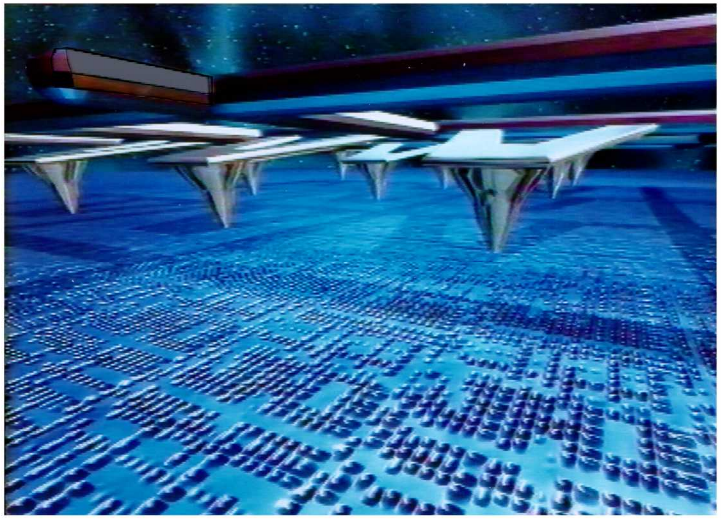


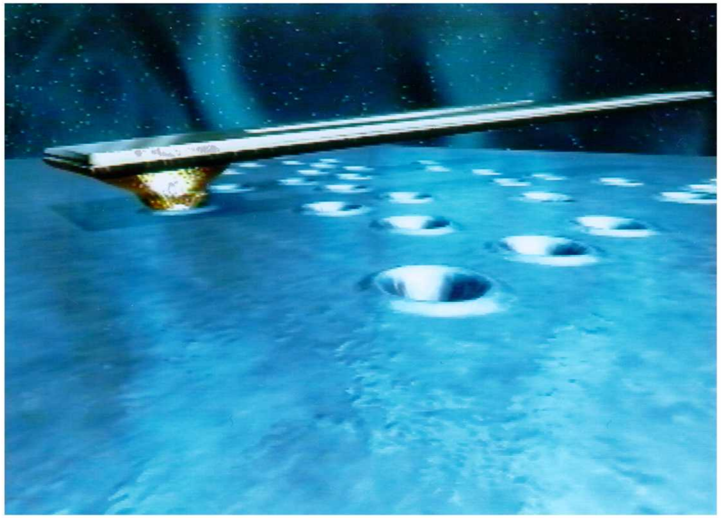
- **Microcap**
  - A miniature, wafer-scale, silicon packaging technology



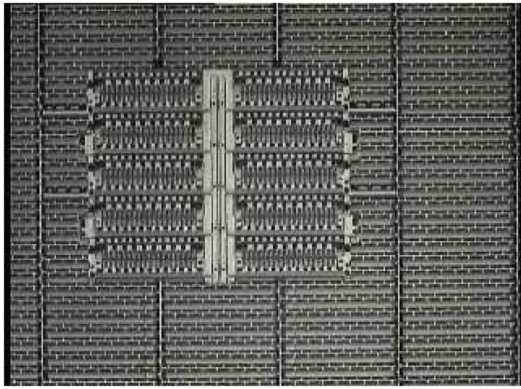
IBM Millipede Storage System

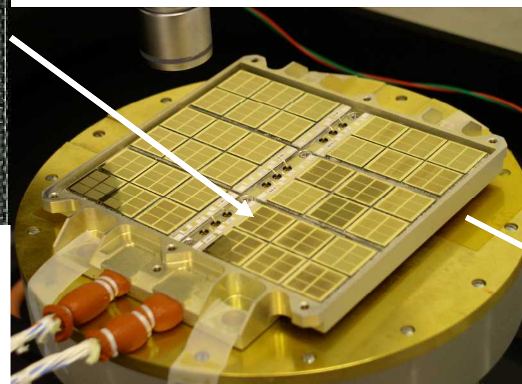
- High density data storage (100 Gb/in^2)
- AFM tip writes and reads data
- Bit set by melting depression into polymer medium
- X-Y stroke for tip array of 100 μm





MESA-Fabricated MEMS
"First in Space"





4x4" Johns Hopkins/APL Thermal Regulator

2592 SUMMiT V™ die w/ Buried Interconnects

3 NASA/Goodard ST5 Microsats Launched 3/22/06

"This is the first time a fully space-qualified device of this type has ever been flown, and the first to be flown on the outside of a satellite."
- Ann Darrin
Applied Physics Laboratory
Program Manager

Experimental satellites monitor space weather

Sandia National Laboratories

A Continuum of Microsystems Fabrication Technologies

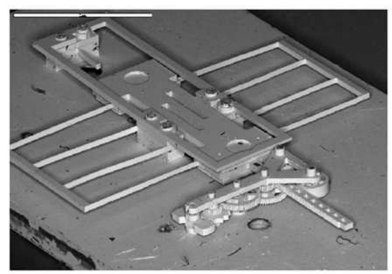
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} **Lateral Dimension (m)**

Depth (m): 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}

Surface Micro-Machining

- **Materials: mostly silicon based and metal coatings**
- **Processing: Many Parts produced at wafer level**
- **Assembly: Pre-assembled through standard processing**
- **Geometry: Two-dimensional, multi-level**

LIGA
Bulk Micro-Machining



- **Materials: Limited metals, ceramics, and polymers**
- **Processing: Parts produced at wafer level**
- **Assembly: Precision assembly or non-standard processing for multi-levels**
- **Geometry: Deep two-dimensionality or multi-level**

Precision Machining

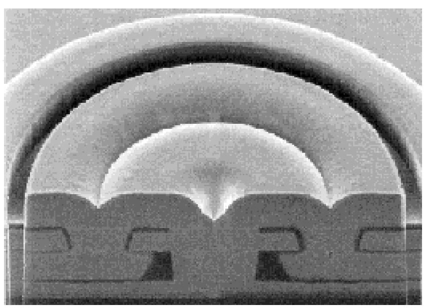
- **Materials: Most metals, alloys, and superalloys & most polymers and ceramics**
- **Processing: One piece at a time**
- **Assembly: Assembly required**
- **Geometry: Full three-dimensionality**

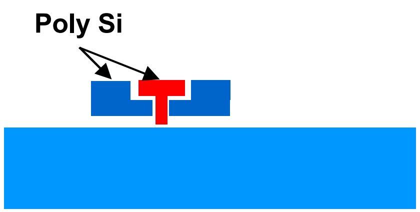
Sandia National Laboratories

Three Dominant MEMS Fabrication Technologies

Surface Micromachining

structures formed by deposition and etching of sacrificial and structural thin films.

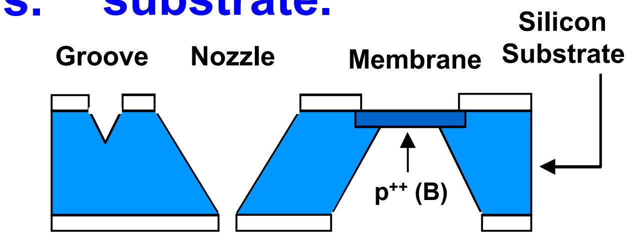




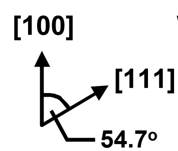
Silicon Substrate

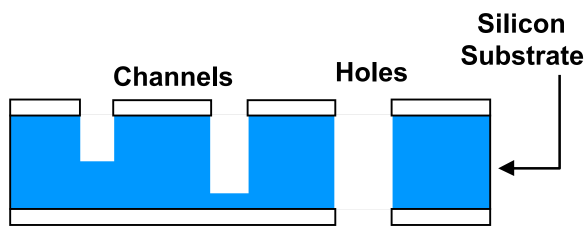
Bulk Micromachining

3D structures formed by wet and/or dry etching of silicon substrate.



Wet Etch Patterns

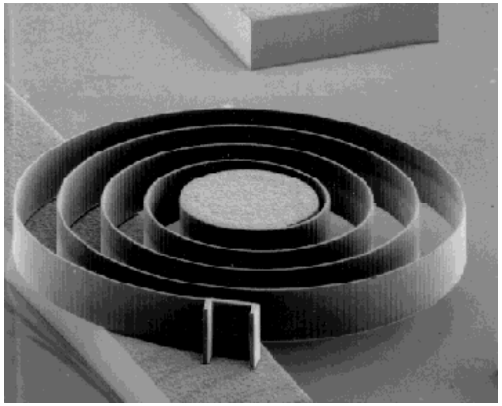


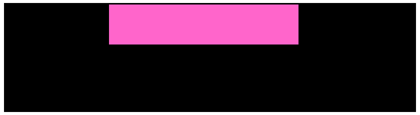


Dry Etch Patterns

LIGA

3D structures formed by mold fabrication, followed by injection molding/electroplating



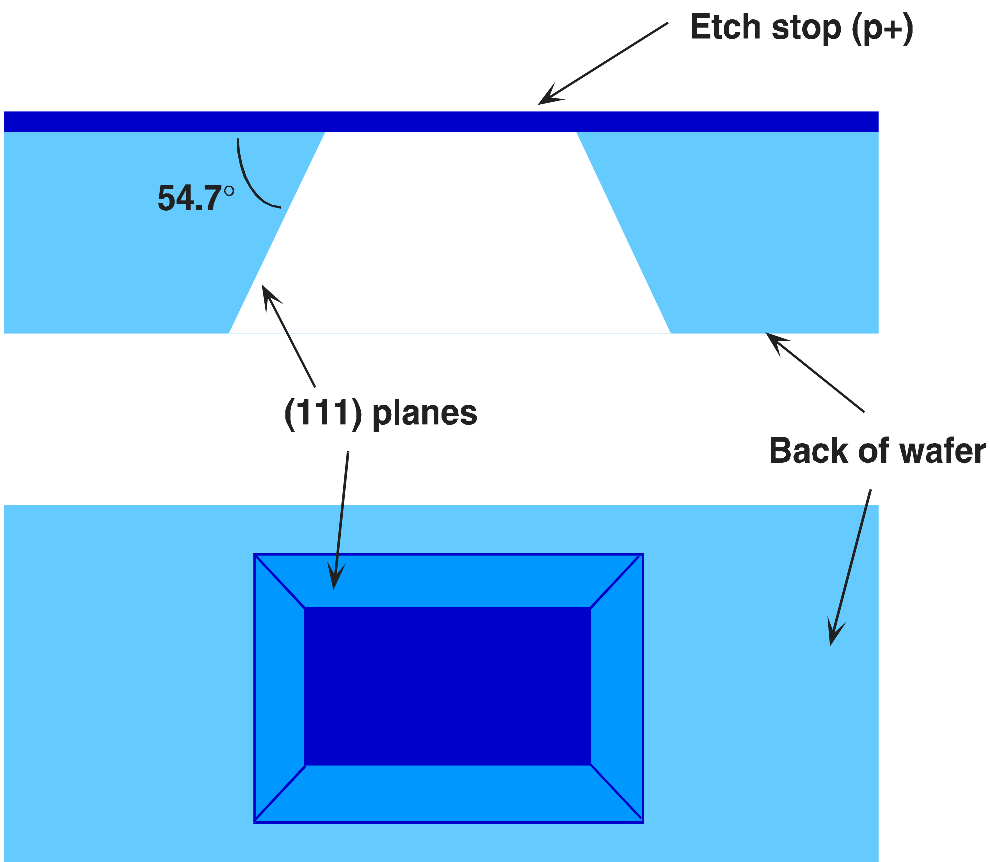


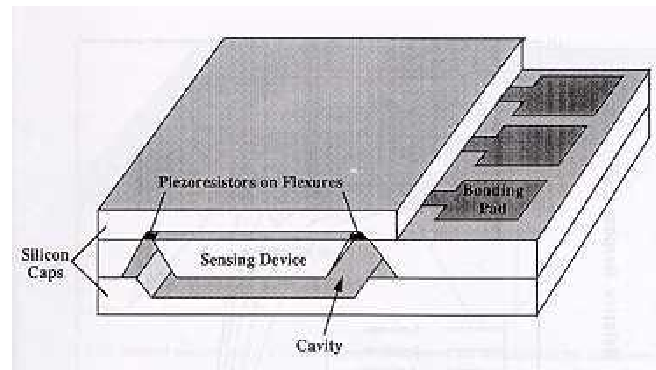
Mold

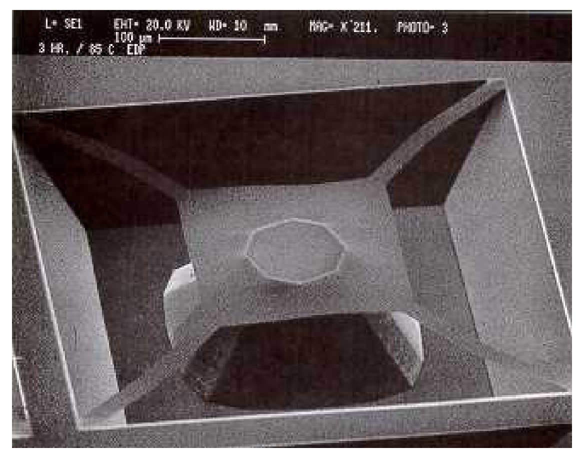
Sandia National Laboratories

Bulk Micromachining

- **Key concept: Mechanical part is formed out of the substrate material**
- **Example: Bulk-micromachined pressure sensor etched w/KOH or EDP**



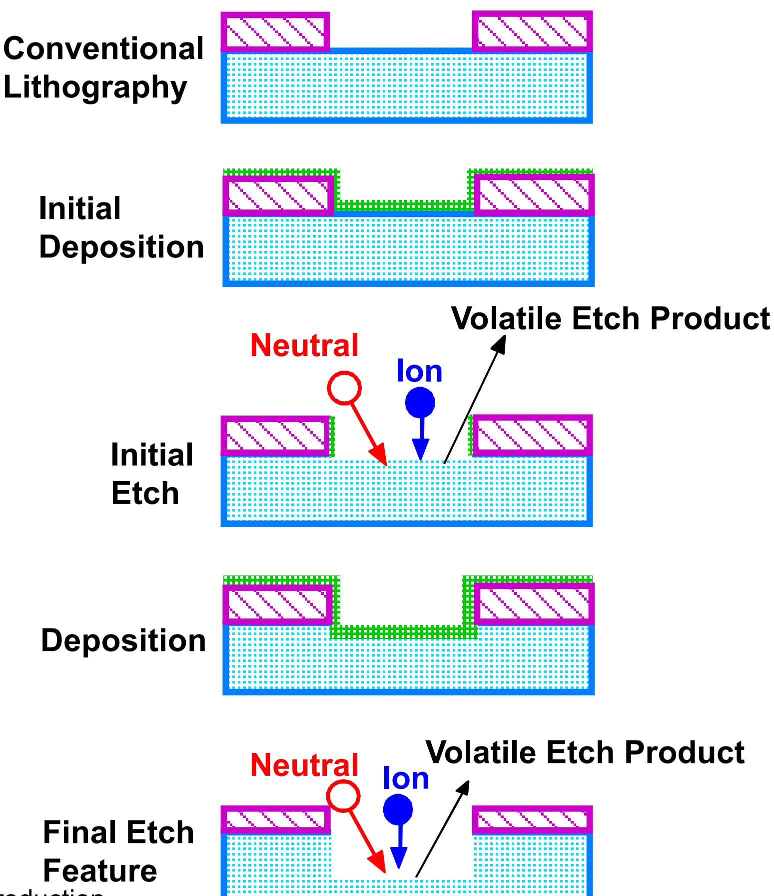


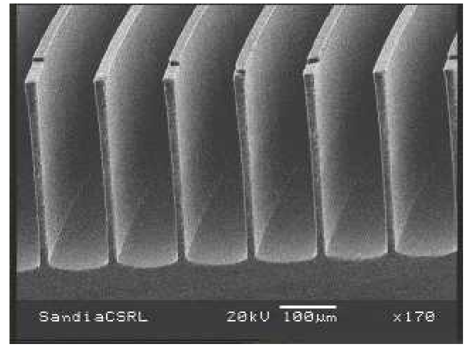


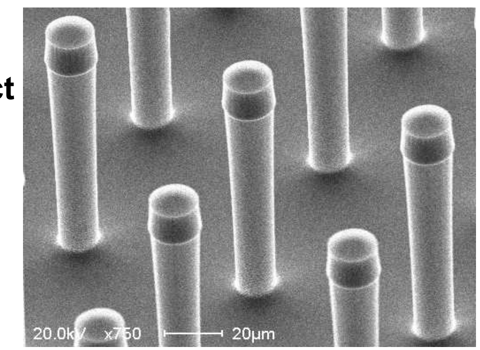
Sandia National Laboratories

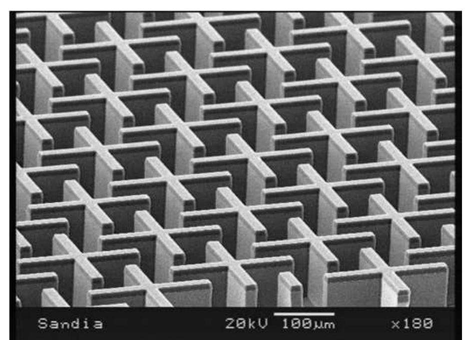
Bulk Micromachining: Deep Reactive Ion Etch (DRIE

Basic Process









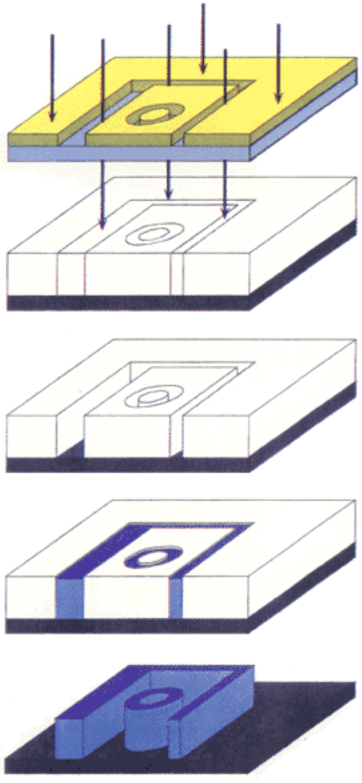
- **High-aspect ratio Si etching**
- **Anisotropic profiles**
- **Smooth sidewalls**
- **Smooth surface morphology**
- **Deep structures**

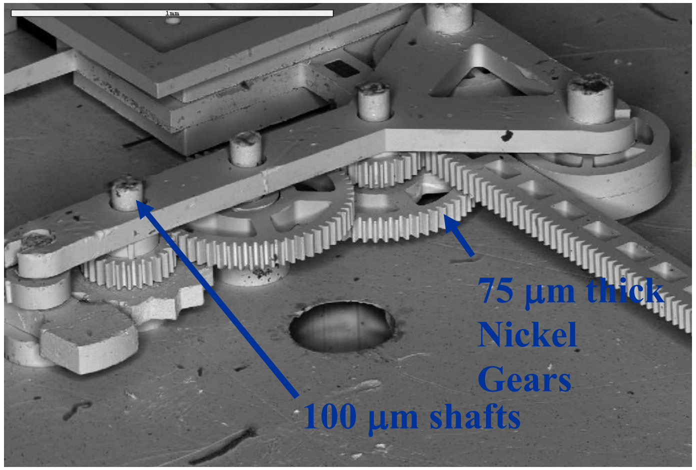
- **Standard resist patterning**
- **Room temperature etching**
- **High etch selectivity to resist**

Sandia National Laboratories

LIGA Processing Steps

- X-rays from a synchrotron are incident on a mask pattered with high Z absorbers.
- X-rays are used to expose a pattern in PMMA, normally supported on a metallized substrate.
- The PMMA is chemically developed create a high aspect ratio, parallel wall mold.
- A metal or alloy is electroplated in the PMMA mold to create a metal micropart.
- The PMMA is dissolved leaving a three dimensional metal micropart. This micropart can be separated from the base plate if desired.



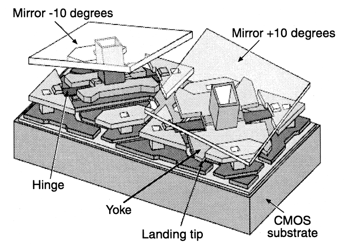


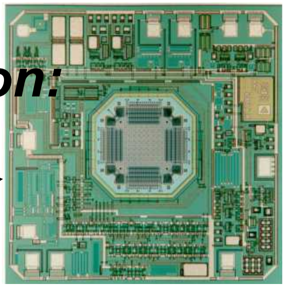
* PMMA - polymethylmethacrylate

Integration of Electronics and MEMS Technology (IMEMS)

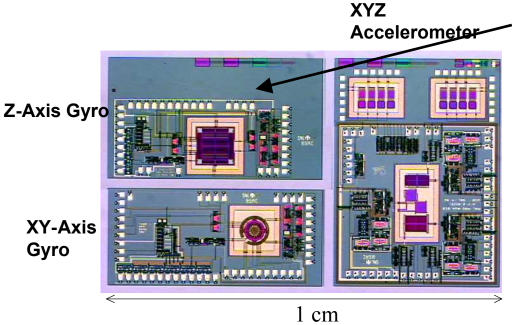
- **Issues for Integration of μelectronics & MEMS**
  - **Large vertical topologies**
  - ***High Temperature Anneals***
- ***Strategies for IMEMS processes***
  - ***Microelectronics first*: (ex. TI DMD™)**
  - ***Interleave the Microelectronics and MEMS fabrication:* (ex. Analog Devices ADXL)**
  - **MEMS fabrication first: (ex. Sandia IMEMS Process)**

Digital Micromirror Device
Texas Instruments





Analog Devices ADXL Accelerometer



Fabricated: Sandia National Laboratories

Designed: University of California, Berkeley Sensor & Actuator Center