SAND2007-4156C

Challenges of MEMS Design, Fabrication and Design Verification

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy under contract DE-AC04-94AL85000.

Topics

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

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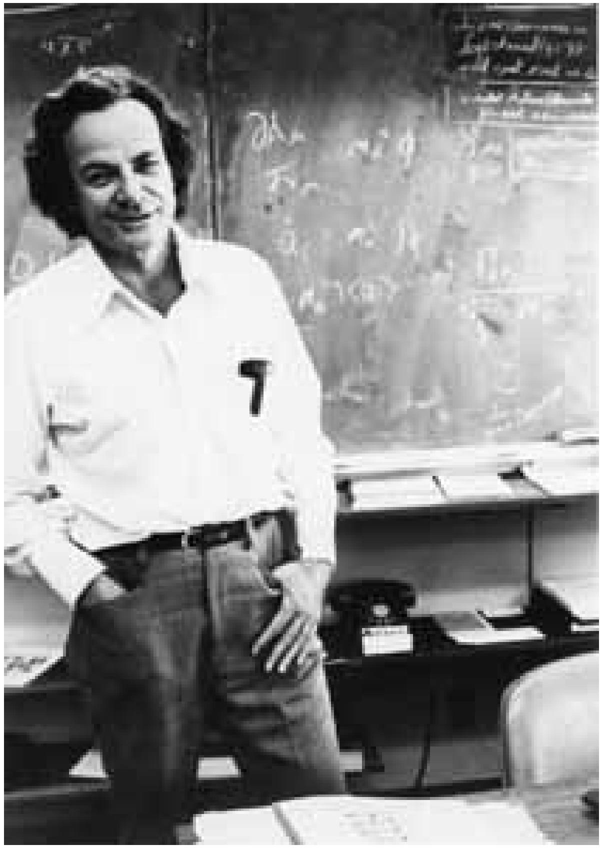
Feynman – A Vision of Microsystems



Dr. Richard P. Feynman (1918 – 1988)
Nobel Prize in Physics (Quantum Electrodynamics) – 1965

- **I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle. … What I want to talk about is the problem of manipulating and controlling things on a small scale.**
- **It would be interesting in surgery if you could swallow the surgeon**
- **Atoms on a small scale behave like *nothing* on a large scale**

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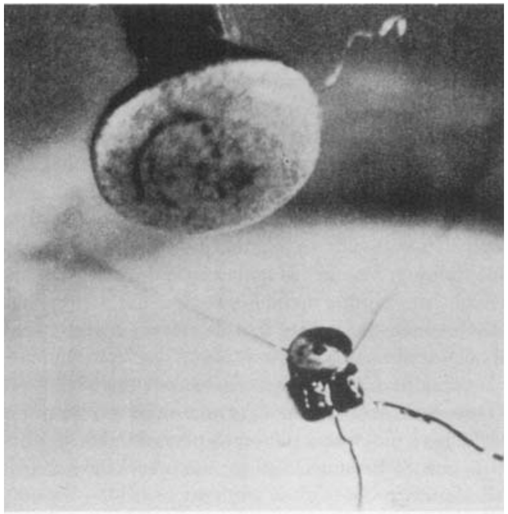
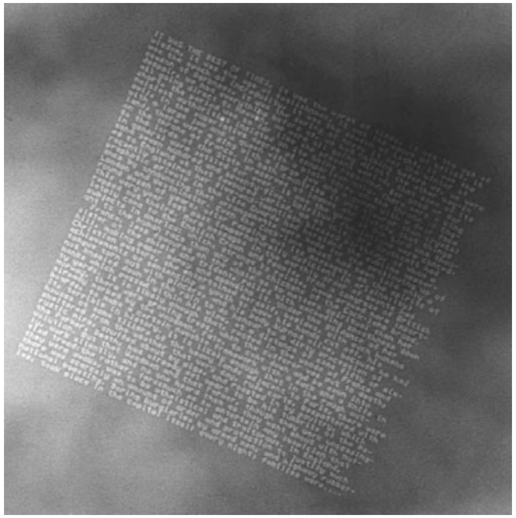
Vision of Micro-Systems

- "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)

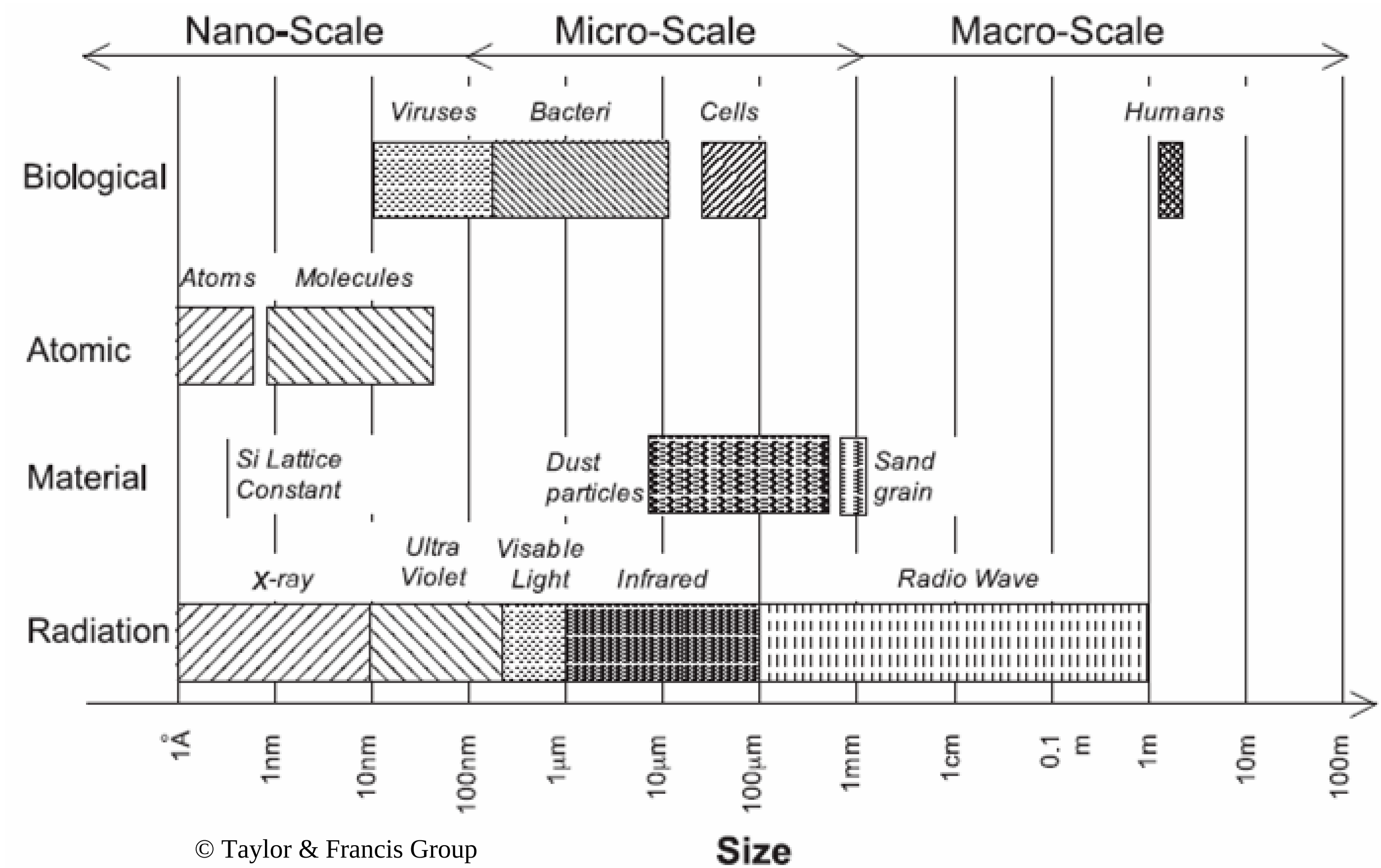


William McLellan, 1960



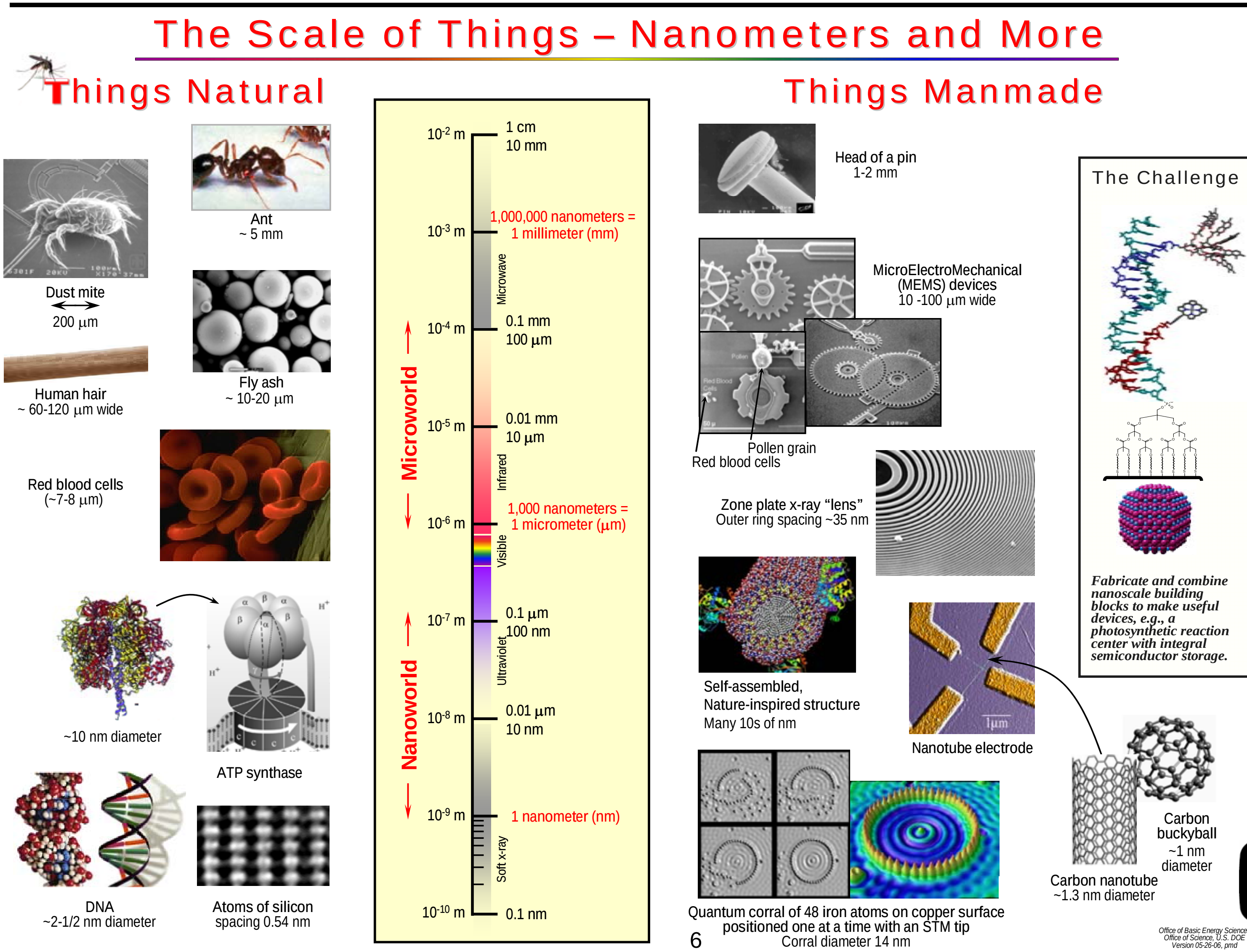
T. Newman, R.F.W. Pease, 1985

A Perspective of Size



"Micro Electro Mechanical System Design," J. J. Allen, CRC Press, 2005

The Scale of Things



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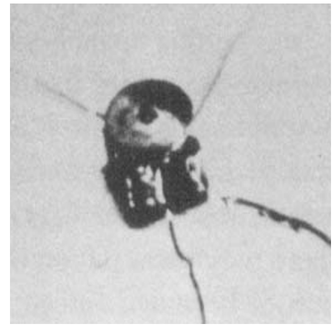
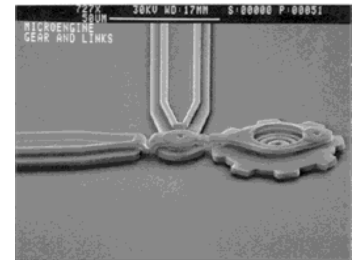
Effect of Reduction in Scale





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.

Physical Phenomena Scale at different rates

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

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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**

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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

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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 (1959)

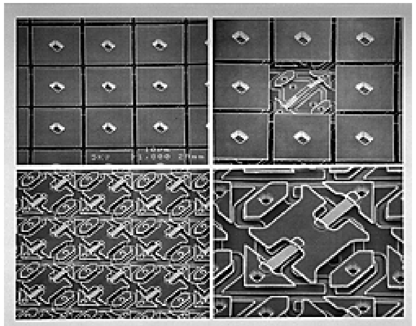
Beginnings of Microelectronic Technology (1959)

Early Products based upon the Piezoresistive properties of Silicon (1954, 1958, 1961)

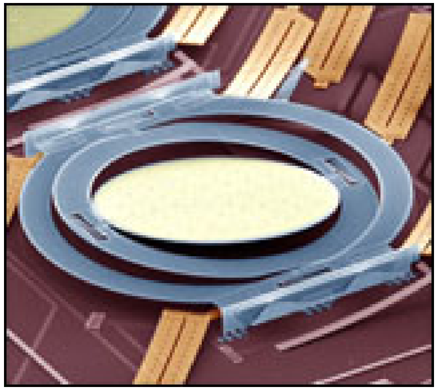
MEMS Commercial Products (1977–1979, 1982, 1987, 1993–2002)

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

MEMS Commercial Applications

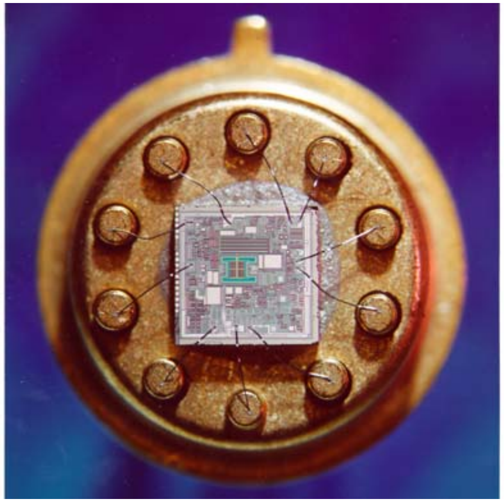


Digital Mirror Device
Texas Instruments

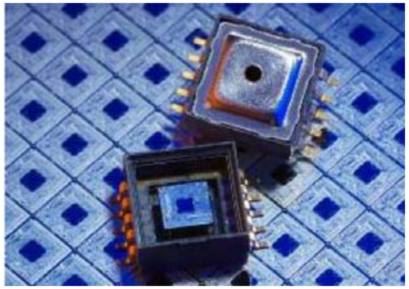


Micromirror switch
Lucent Technologies

Ink Jet Cartridge
Hewlett Packard



Accelerometer
Analog Devices



Pressure Sensor
Bosch MEMS

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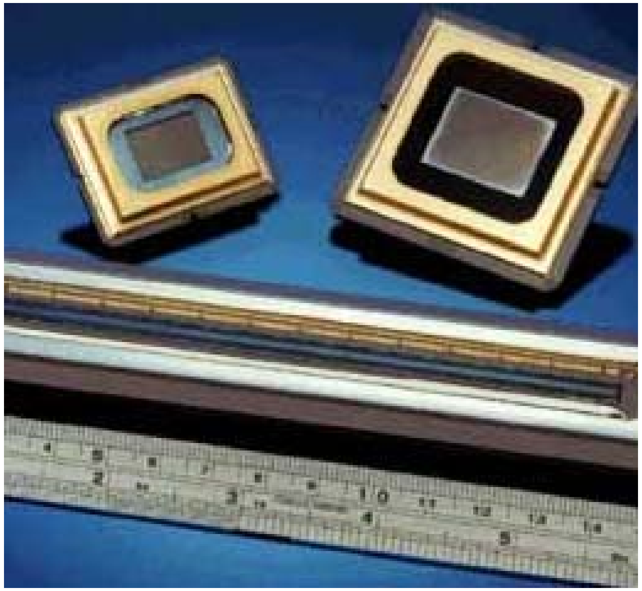
Texas Instruments Digital Mirror Display

- DLP Technology was invented in 1987 at Texas Instruments.
- DLP Technology is based on a micro-electromechanical system (MEMS) device known as the Digital Micromirror Device (DMD).
- DMD is a semiconductor-based array of fast, reflective digital light switches that precisely control a light source using a binary pulse width modulation technique.
- Consists of 480,000-1.3million mirrors (800x600 – 1280x1024)



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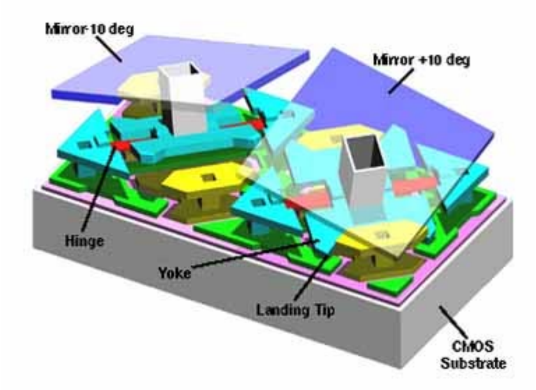
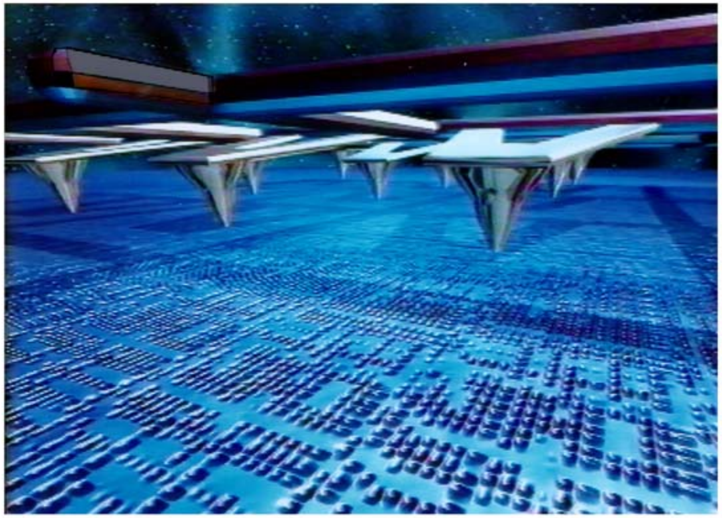
TI DMD Light Switch

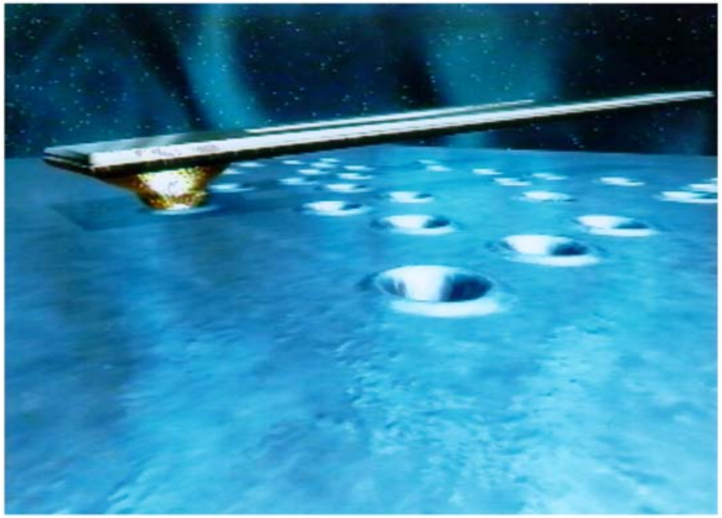
- **Each light switch has an aluminum mirror (16 μm square) that can reflect light in two directions**
- **Rotation of the mirror occurs from an electrostatic attraction between the mirror and underlying memory cell**
- **System occupies 90% of projected image – mirrors separated by only 1 μm**



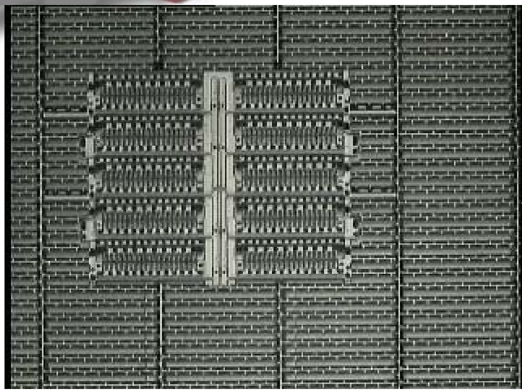
IBM Millipede Storage System

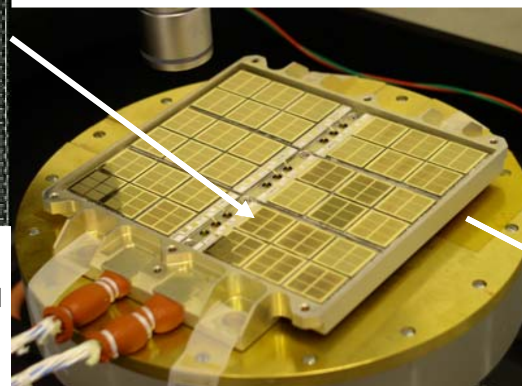
- **High density data storage (100 Gb/in^2)**
- **AFM tip writes and reads data**
- **Bit set by melting depression into polymer medium**
- **X-Y stroke for tip array of 100 μm**





MESA-Fabricated MEMS “First in Space”



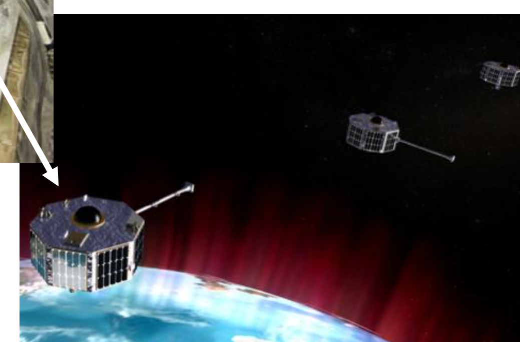


4x4” Johns Hopkins/APL Thermal Regulator

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

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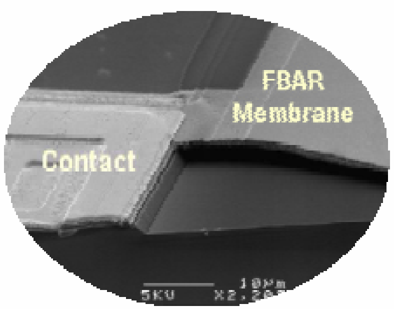
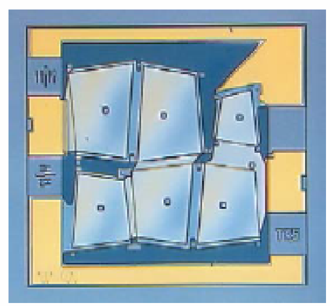
Agilent Technologies RF MEMS

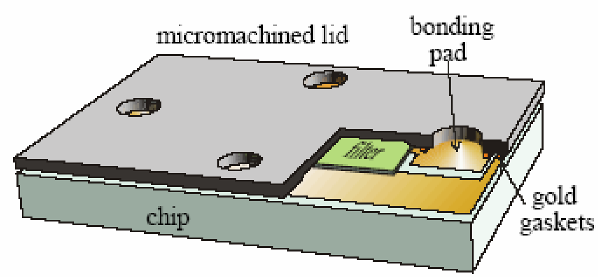
Recent MEMS developments

- **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



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

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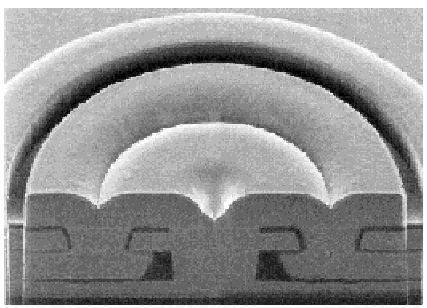
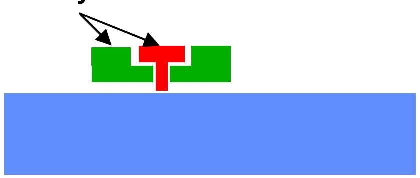
Three Dominant MEMS Fabrication Technologies

Surface Micromachining

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

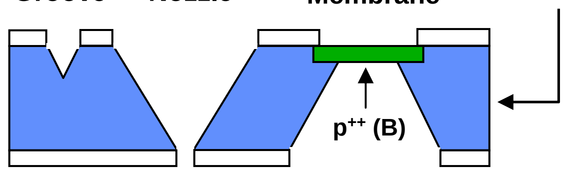




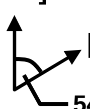
Silicon Substrate

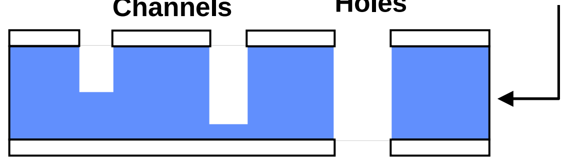
Bulk Micromachining

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



Wet Etch Patterns

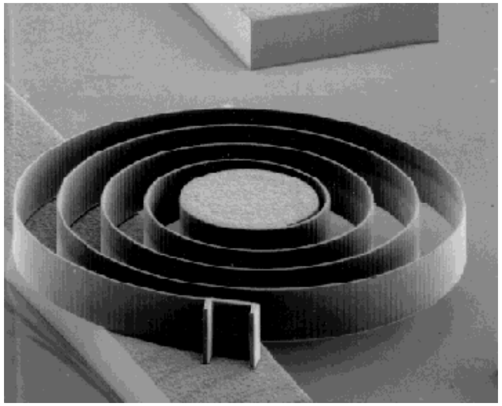


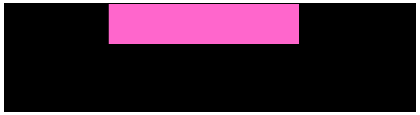


Dry Etch Patterns

LIGA

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





Mold

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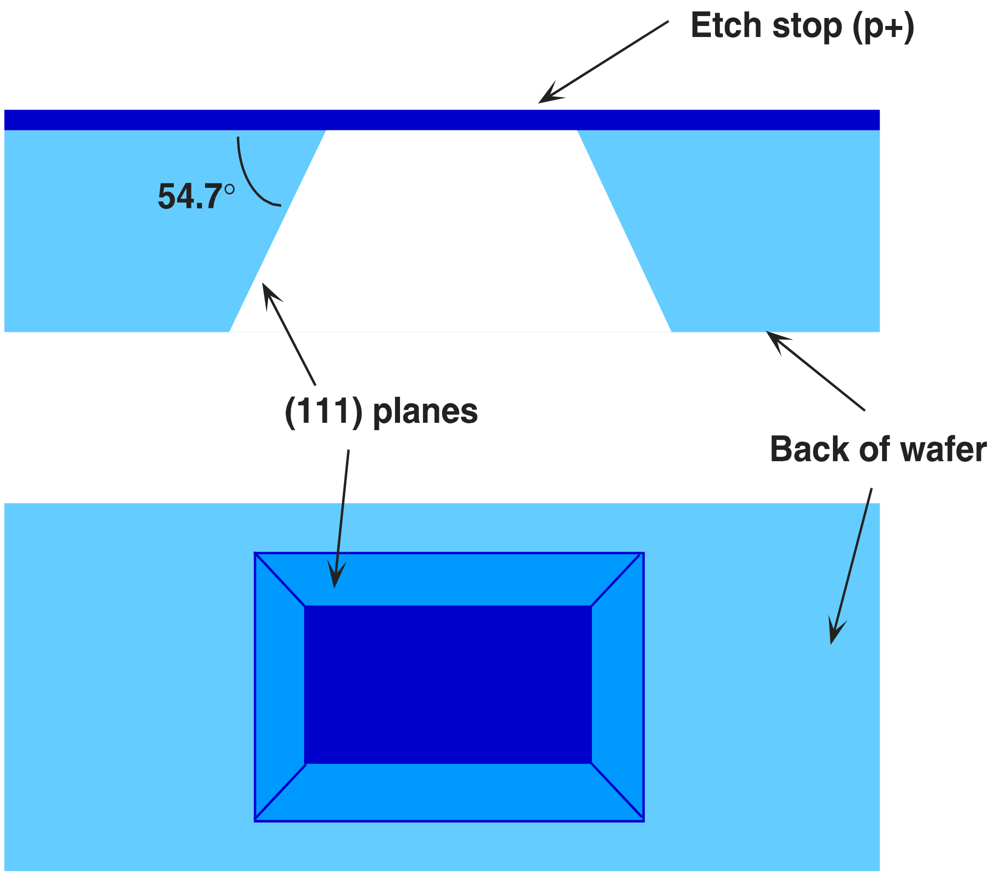
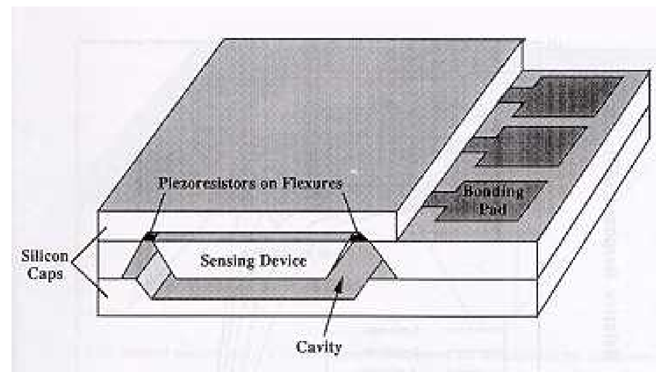
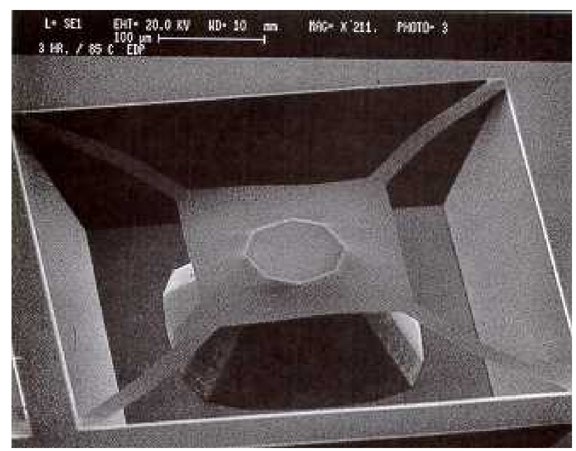
Bulk Micromachining

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

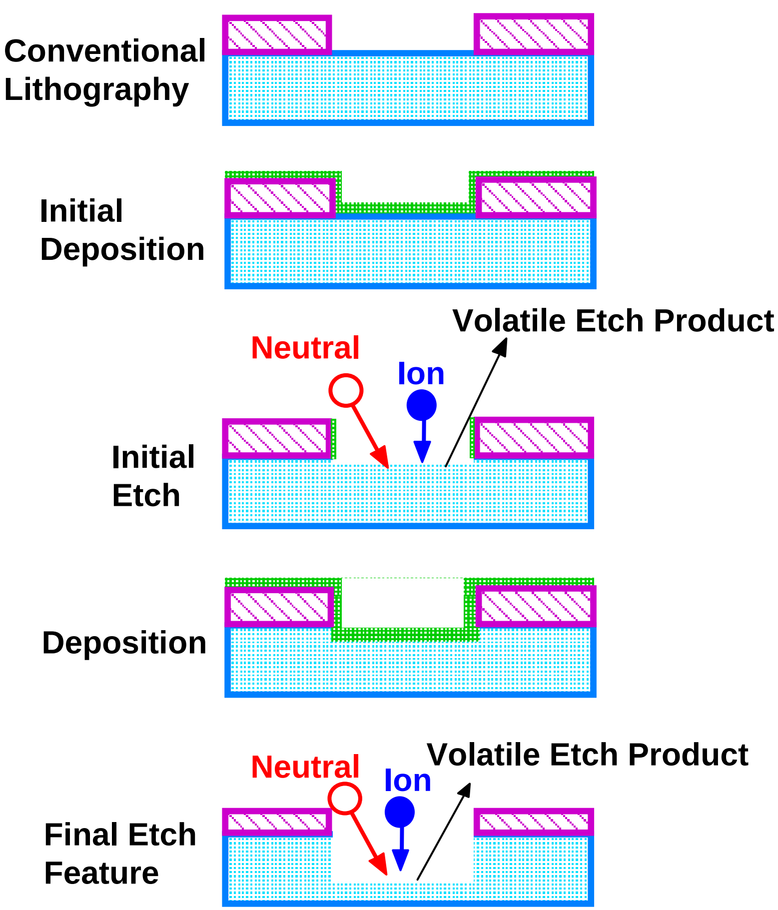


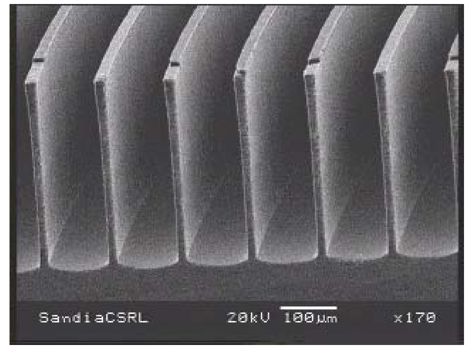


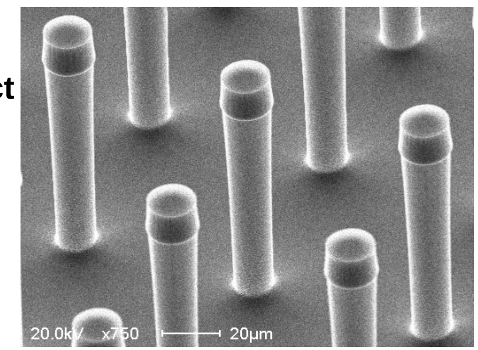


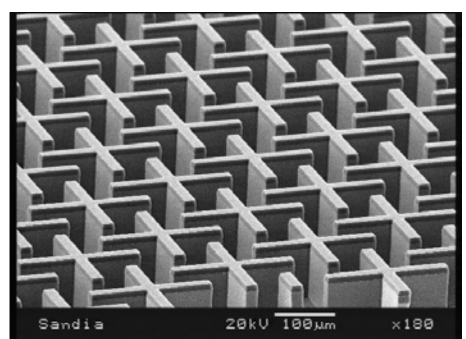
Bulk Micromachining: Deep Reactive Ion Etch (DRIE

Basic Process



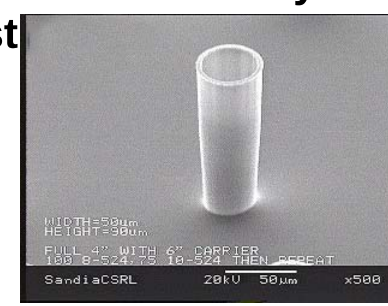






- High-aspect ratio Si etching
- Anisotropic profiles
- Smooth sidewalls
- Smooth surface morphology
- Deep structures

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



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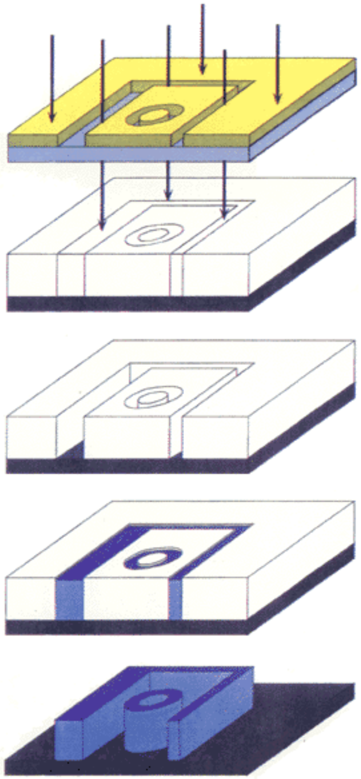
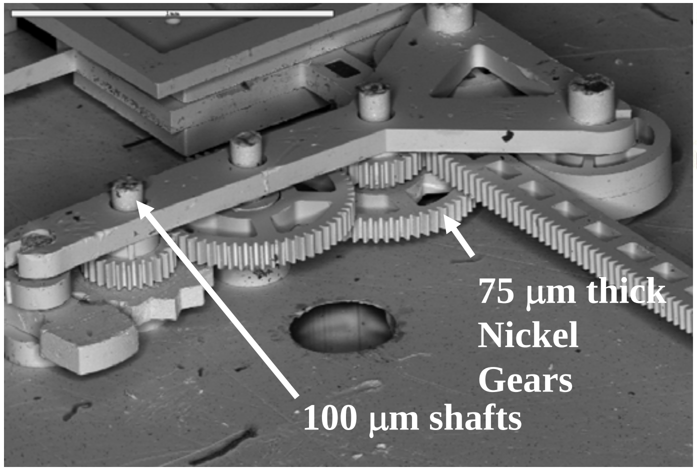
LIGA Processing Steps

- 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.



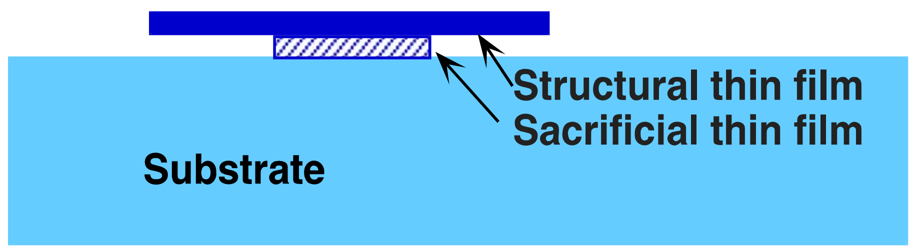


* PMMA - polymethylmethacrylate

Surface Micromachining

Material system requirements:

- **Structural film must have desirable mechanical and electrical properties (low stress, conductivity, etc.)**
- **Sacrificial film must be stable under structural film deposition conditions and etch readily in an etchant that doesn't attack the mechanical film or the substrate**
- **Both films must be compatible with fabrication environment (generally silicon IC fab)**



Examples from the literature:

Structural	**Sacrificial**
Polysilicon	SiO_2 (most common), porous Si
Low-stress (Si rich) SiN_X	Polysilicon
Tungsten	SiO_2
Aluminum	Resist

SUMMiT V™ is an example of Surface Micromachining Technology

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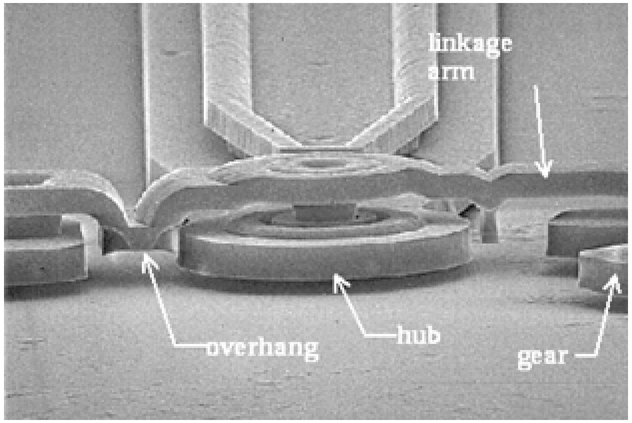
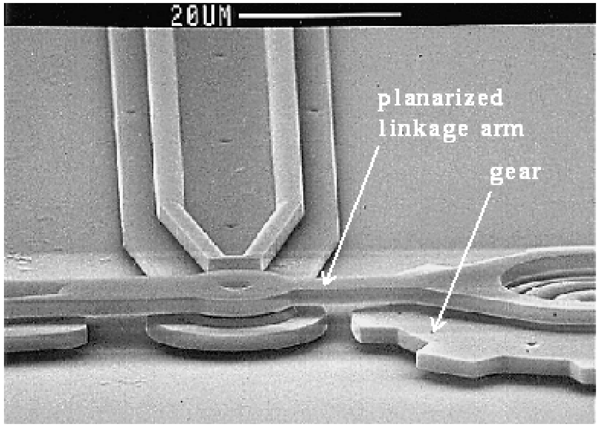
MEMS Technology
Surface Micromachining

Chemical Mechanical Polishing used in SUMMiT™



a) Example of a conformable Layer



b) Example of topography removed by Chemical Mechanical Polishing

Table 1. Example Surface Micromachining Technologies Material Systems

Structural	Sacrificial	Release	Application
polySi	SiO_2	HF	SUMMiT V™
SiN	polySi	XeF_2	GLV™
Al	resist	plasma etch	TI DMD™
SiC	PolySi	XeF_2	MUSIC™

Note: SUMMiT™ - Sandia Ultra-planar, Multi-level MEMS Technology
GLV™ - Grating Light Valve (Silicon Light Machines)
DMD™ - Digital Mirror Device (Texas Instruments)
MUSIC™ - Multi User Silicon Carbide (FLX micro)

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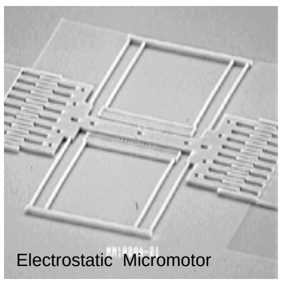
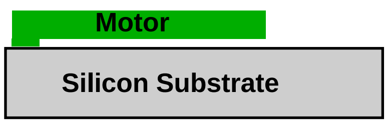
Planarization Enables the Design of Complex Micromachines

2-Level

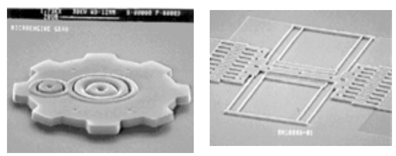




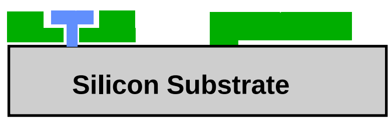
- Polysilicon Level #1

Sensors

3-Level



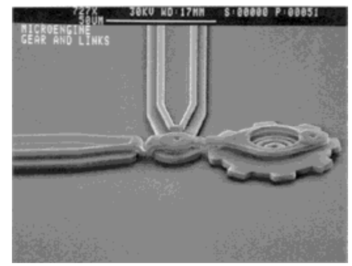
Gear Bearing Motor

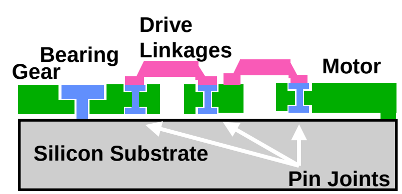


- Polysilicon Level #1
- Polysilicon Level #2

Advanced Sensors
Simple Actuators

4-Level

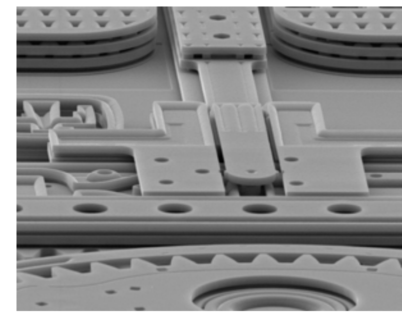


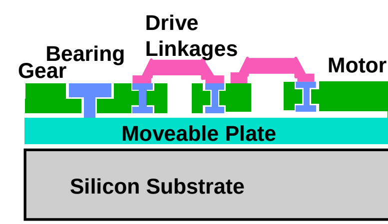


- Polysilicon Level #1
- Polysilicon Level #2
- Polysilicon Level #3

Advanced Actuators

5-Level





- Polysilicon Level #1
- Polysilicon Level #2
- Polysilicon Level #3
- Polysilicon Level #4

Complex Systems

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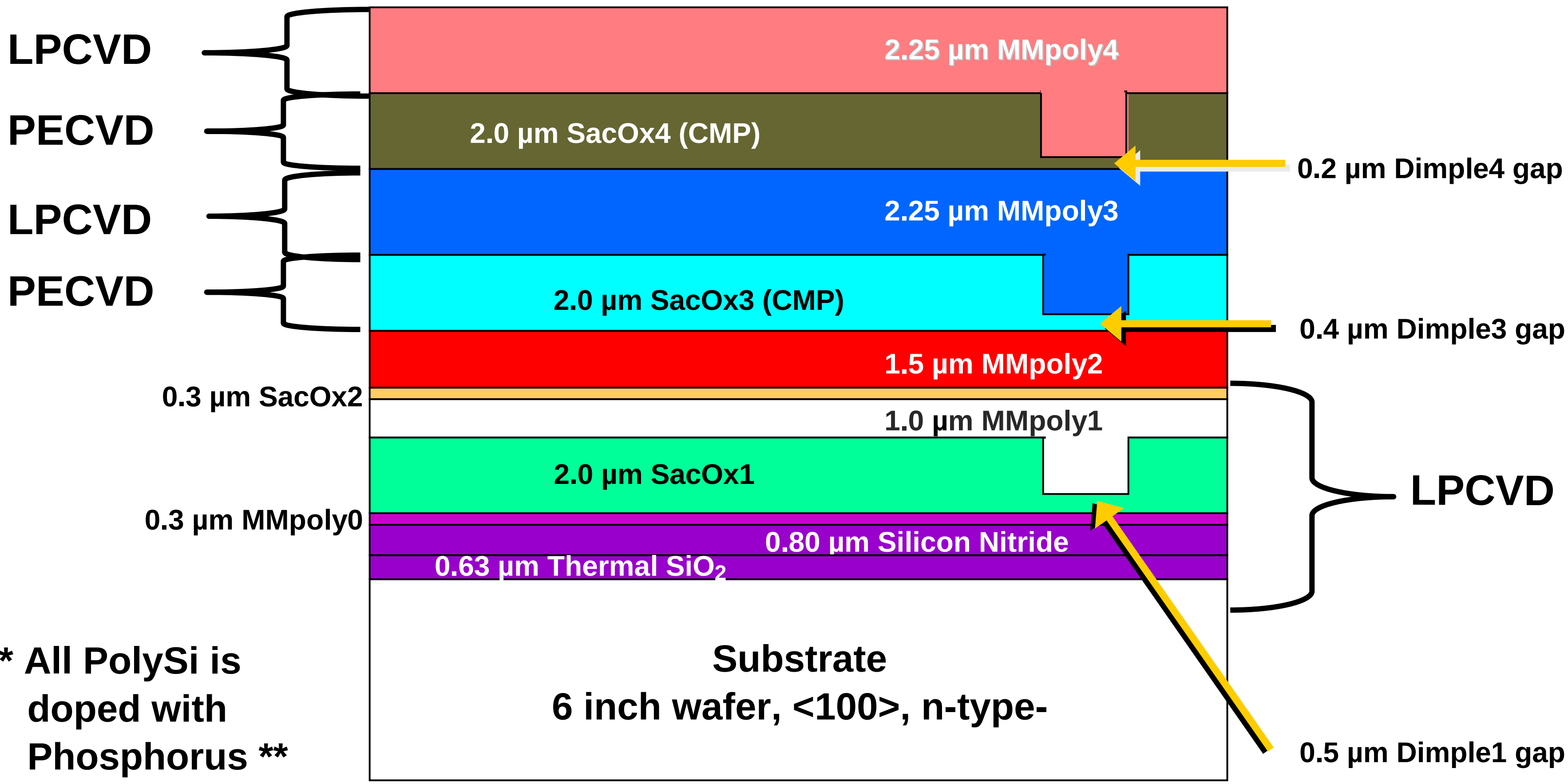
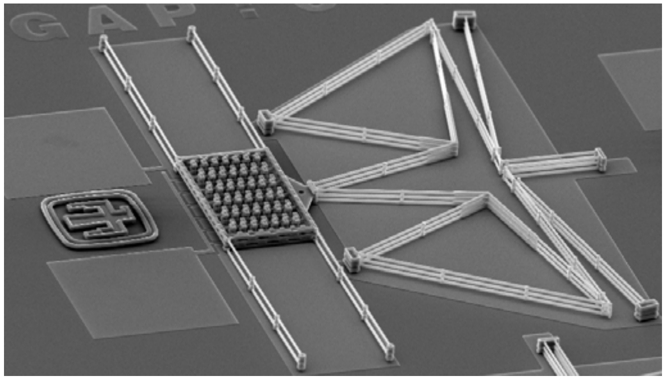
SUMMiT™
Sandia's Ultra-planar Multi-level MEMS Technology

SUMMiT™ Layer Descriptions

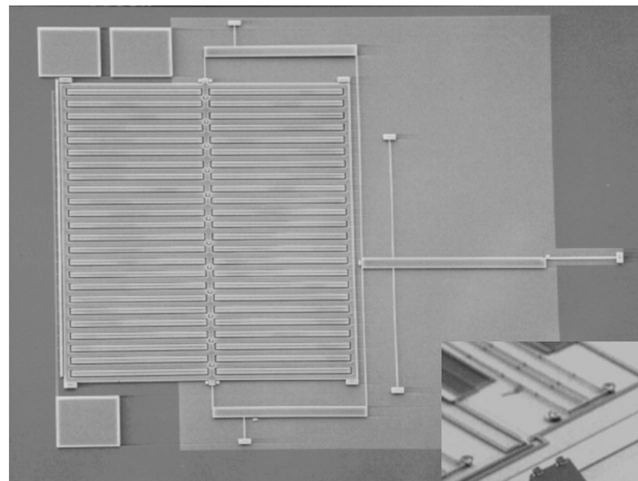


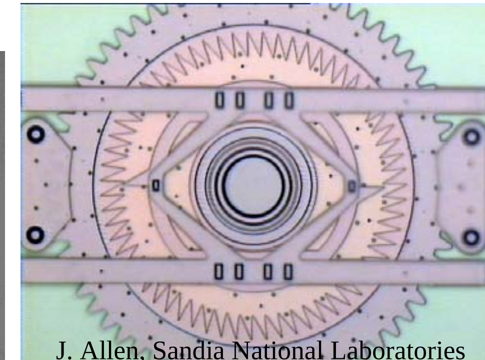
** All PolySi is doped with Phosphorus **

A Variety of Micro Mechanisms are required for Microdevice Applications

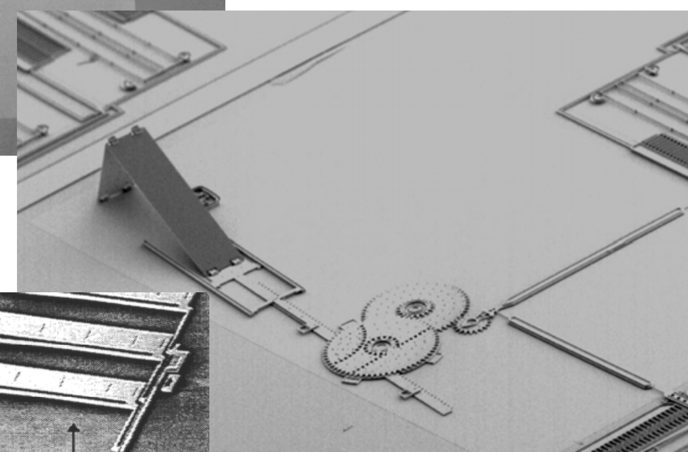


Dr. Kota, U of Michigan, S. Rogers, Sandia National Laboratories

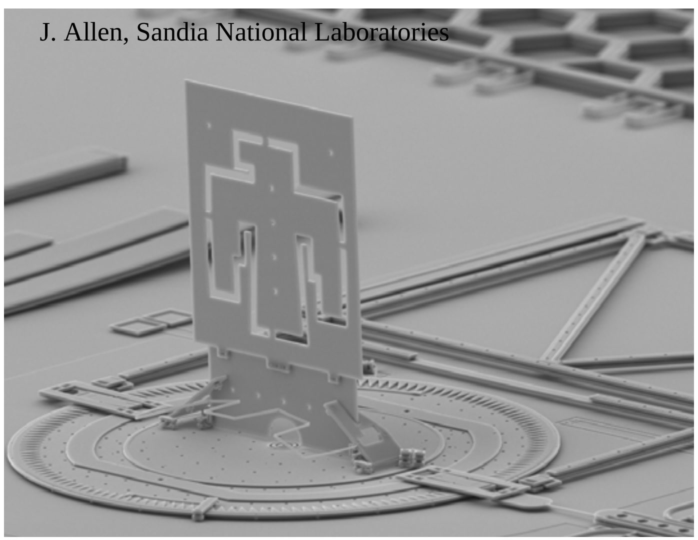




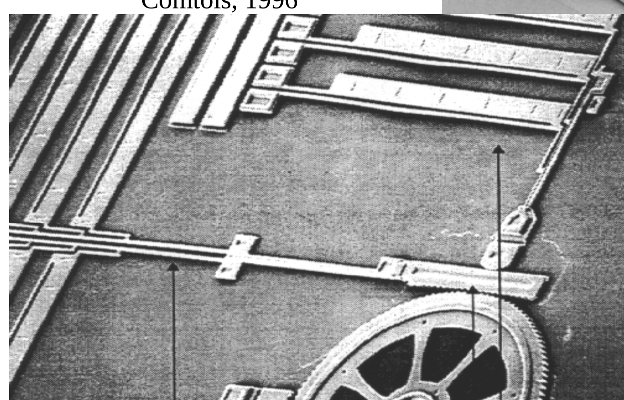
J. Allen, Sandia National Laboratories



J. Allen, Sandia National Laboratories



Comtois, 1996



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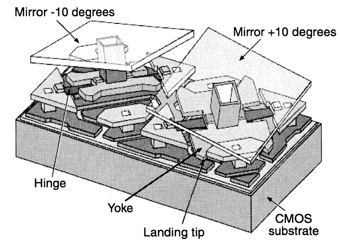
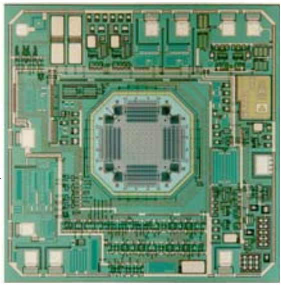
Integration of Electronics and MEMS Technology (IMEMS)

- **Issues for Integration of μelectronics & MEMS**
  - **Large vertical topologies**
  - ***High Temperature Anneals***
- ***Strategies for IMEMS processes***
  - ***Microelectronics first*: (ex. TI DMD™)**

Digital Micromirror Device
Texas Instruments

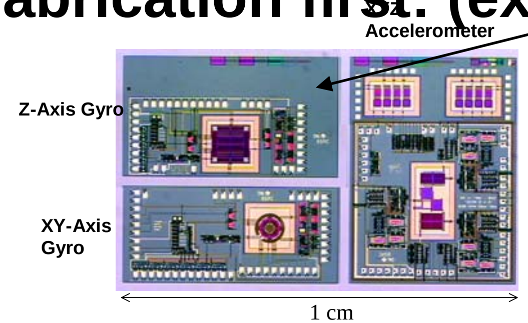


  - ***Interleave the Microelectronics and MEMS fabrication:* (ex. Analog Devices ADXL)**



Analog Devices ADXL Accelerometer

  - **MEMS fabrication first: (ex. Sandia IMEMS Process)**



Fabricated: Sandia National Laboratories

Designed: University of California, Berkeley Sensor & Actuator Center

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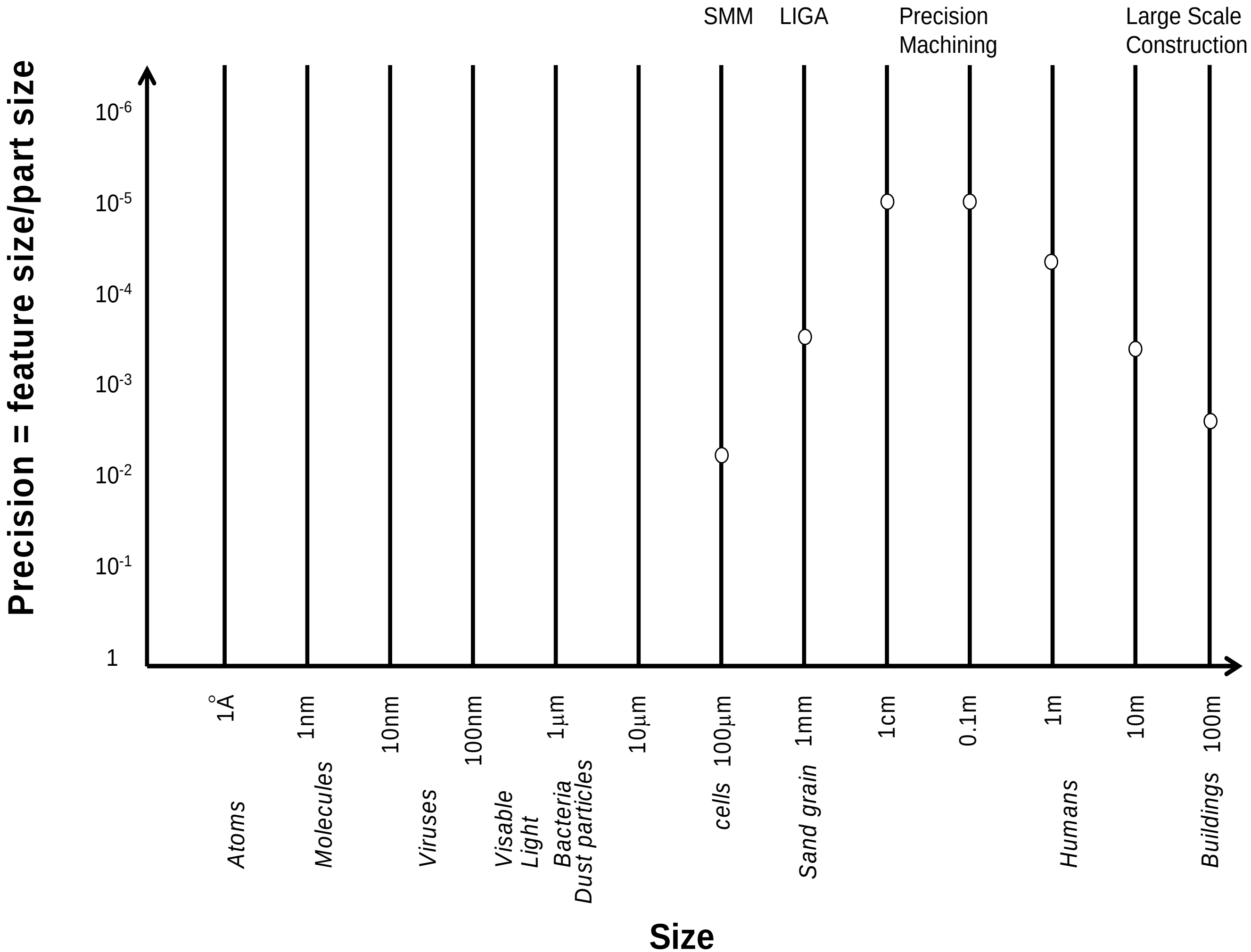
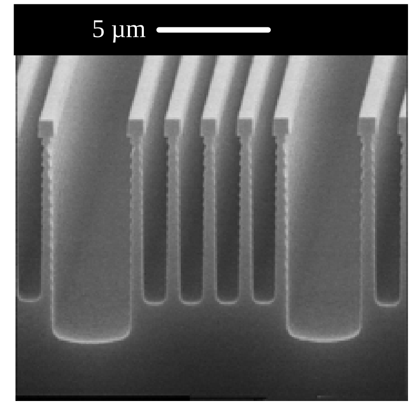
Precision versus Size

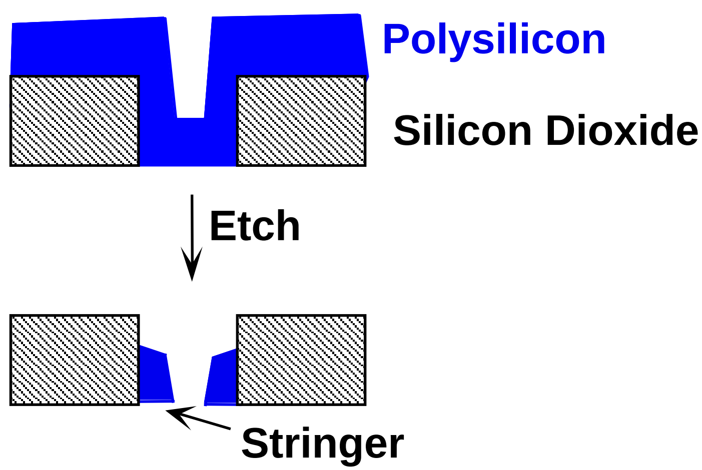


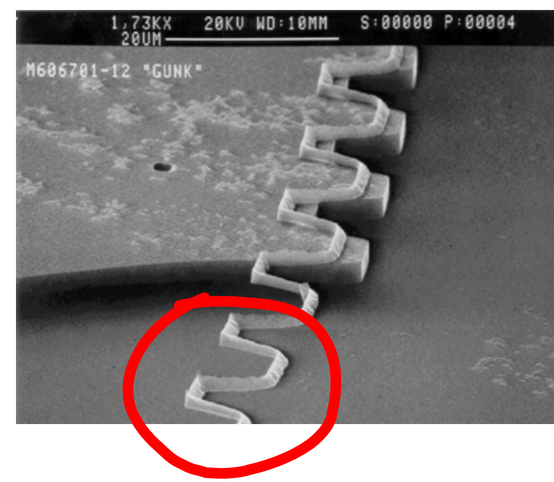
Manufacturing Processes Impose constraints on Design

- **Bulk Micromaching Example:**
  - Aspect ratio of etches

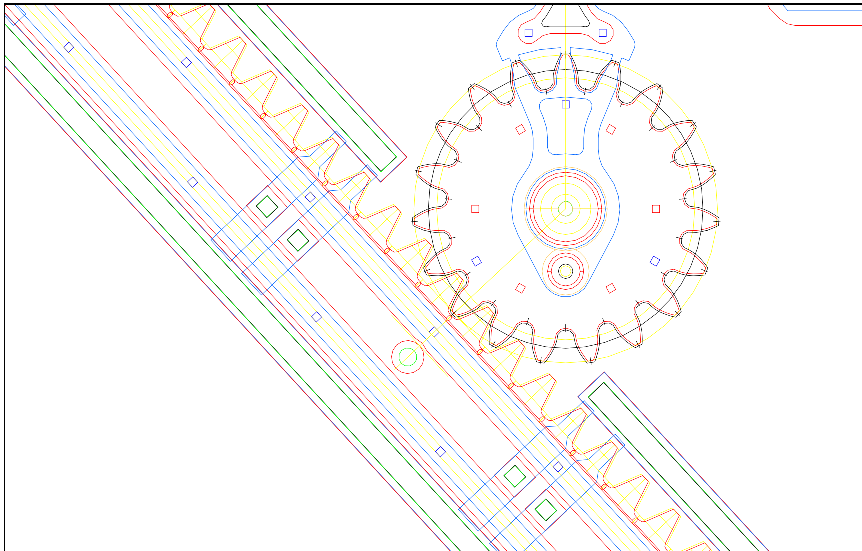


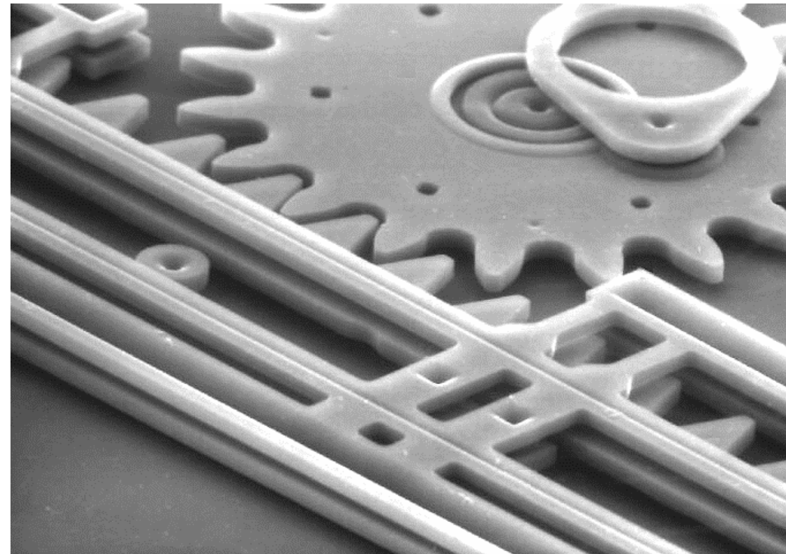
- **Surface Micromachining Example**
  - Stringers





Design Realization Challenges





2-D mask layers
+
fabrication process

→

difficult-to-visualize
3-D systems with
complex shapes

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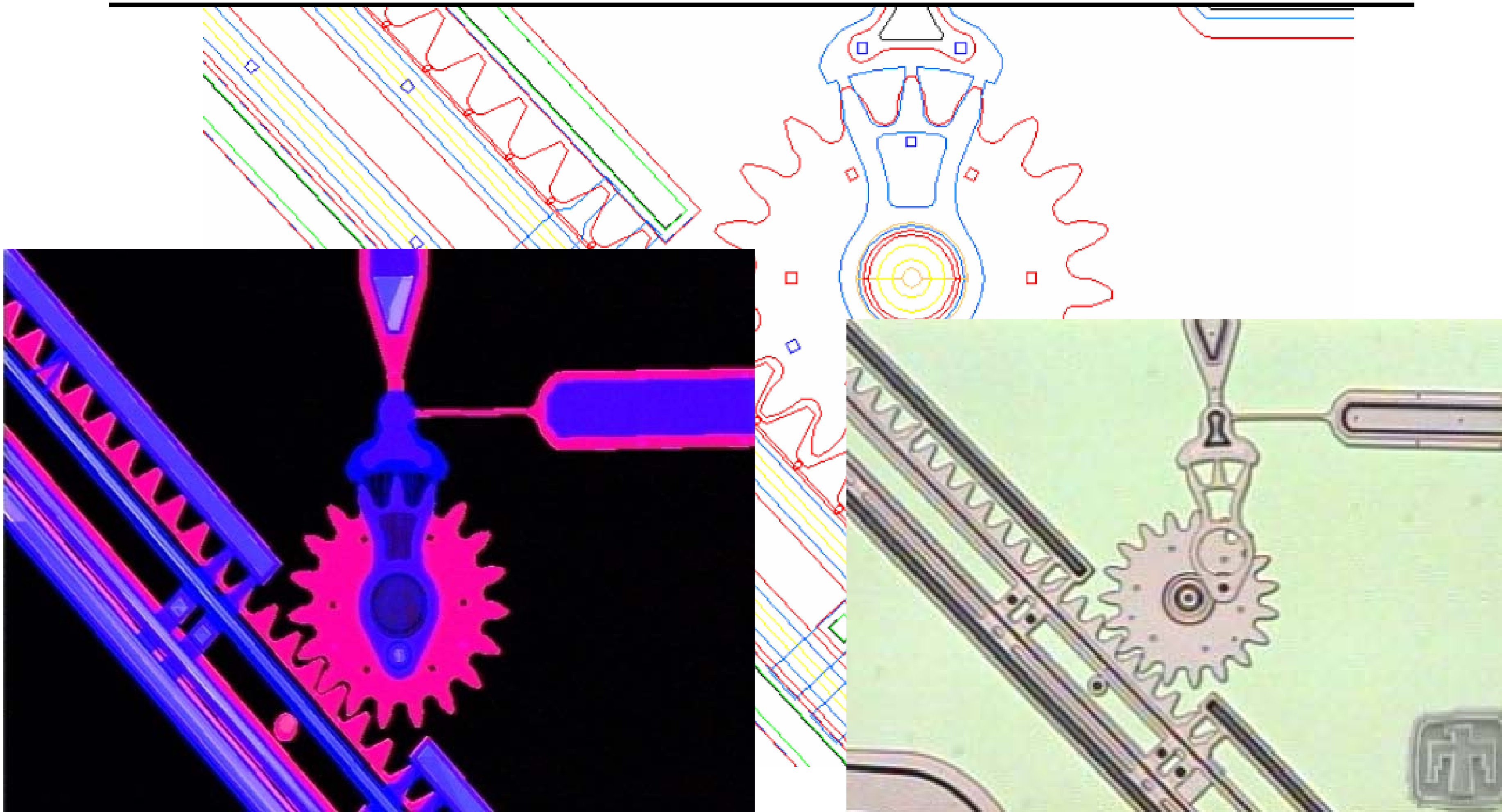
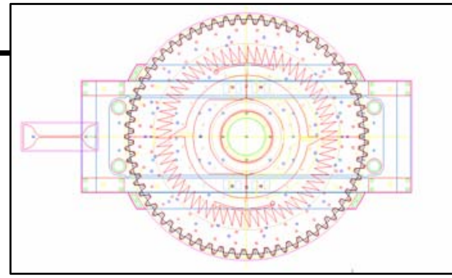
MicroSystem Design



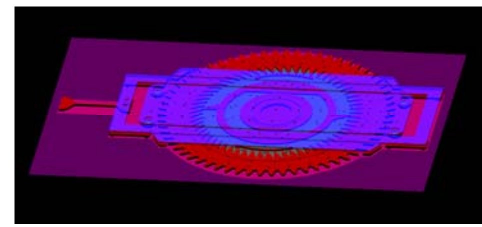
CAD Tools are Essential to the Design of Microsytems

Initial Design



Layout

3D Modeler



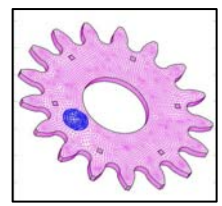
Visualization

2D Process Visualizer

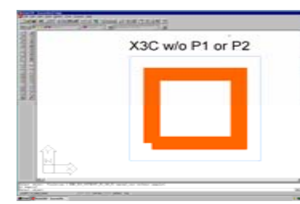
Design Validation

Analysis

Mesh

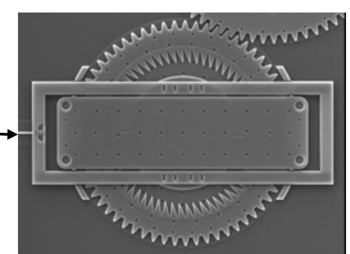


Design Rule checking



Verification

Fabrication Time & Expense demand the availability of these tools



Final Product

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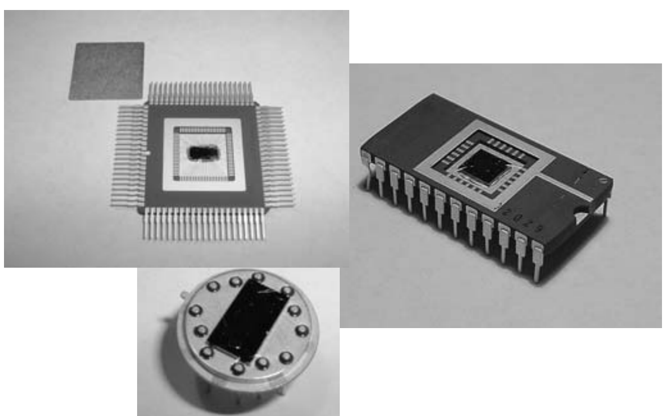
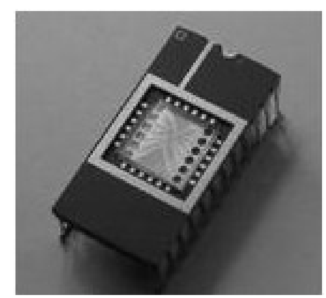
Packaging

- The MEMS die resulting from fabrication are *rarely the end product.*
- They need to assembled, protected and tested
- There are a number of packaging steps which need to be done after the MEMS fabrication is complete to produce a deliverable product.
- Packaging is frequently the most costly portion of product development.



Standard Microelectronic Packaging

Texas Instruments DLP Package



Sandia Microfluidic Package

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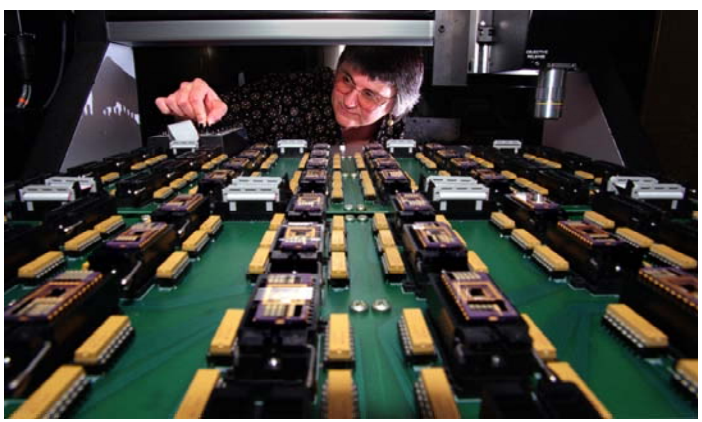
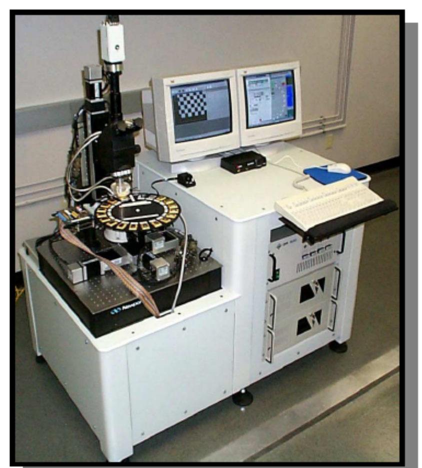
Reliability

- ***Reliability*** **is the *ability of a device or system to perform a required function for a specified amount of time*.**
- **This assessment takes methodical approach and a statistically significant amount of data**
- **Any "true" product will have this capability**



The Sandia SHiMMeR system for MEMS reliability testing.



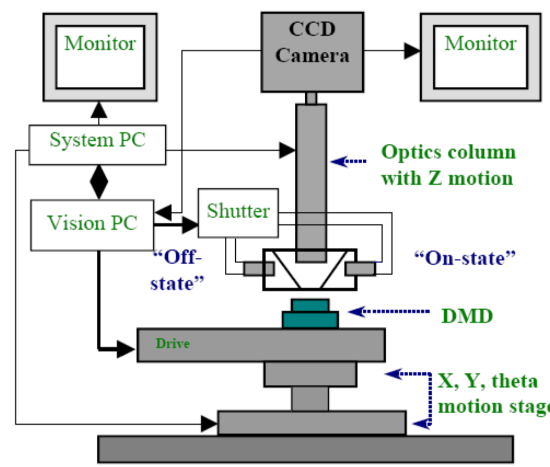


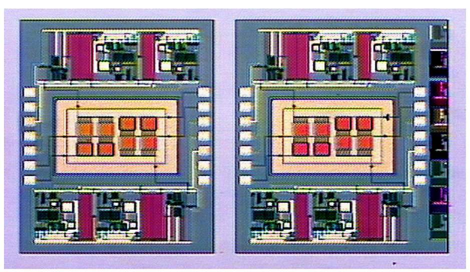
Figure 4 - DMD Test System

M. R. Douglass, "DMD reliability: a MEMS success story," Proc. of SPIE, Vol.4980, pp. 2-11, 2003.

Taxonomy For MEMS Reliability:

Class I

No Moving parts

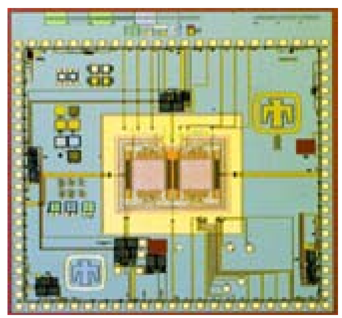


Pressure Sensors
Ink Jet Print Heads
Strain Gauge

Class II

Moving parts;

No rubbing or impacting surfaces

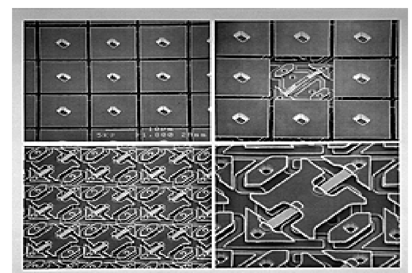


Accelerometers
Gyros
Comb Drives
Resonators
Filters

Class III

Moving parts;

Impacting surfaces

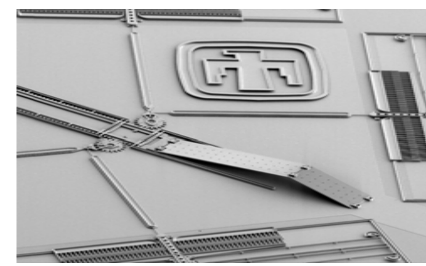


TI DMD
Relays
Valves
Pumps

Class IV

Moving parts;

Impacting and rubbing surfaces



Optical Switches
Corner Cube Refl.
Shutters
Scanners

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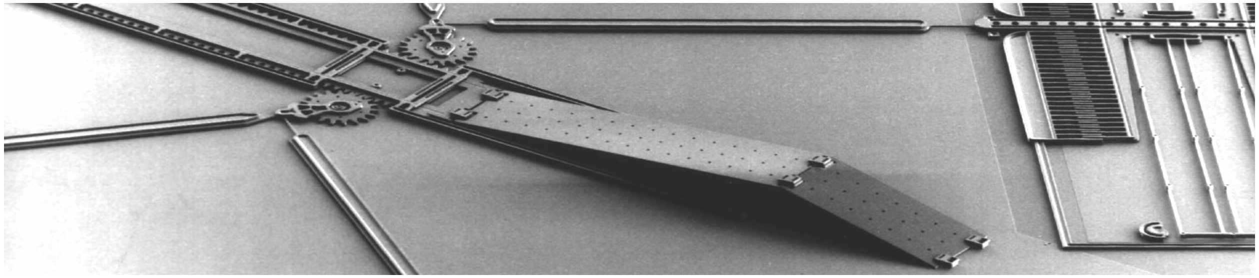
MEM Performance Measurement Issues

- These are small devices (microns)
- Structures may move very fast (>1 kHz, >100000 rpm)
- Small displacements can occur (angstroms - microns)
- Displacements can be in plane or out of plane
- High voltages may be required (many 10s of volts)
- Complex control signals may be necessary
- Direct electrical measurements are not typical



Scope of MEMS Performance Measurement

Basic Functionality

- Apply simple signals
- Verify operation occurs

Operational Performance

- Apply model-based signals
- Make quantitative measurements
- Perform quantitative analysis
- Apply results to improve designs and operational methods

Reliability

- Acquire/analyze statistical data
- Identify and model failure modes
- Apply results to improve designs and operational methods
- Develop qualification methods

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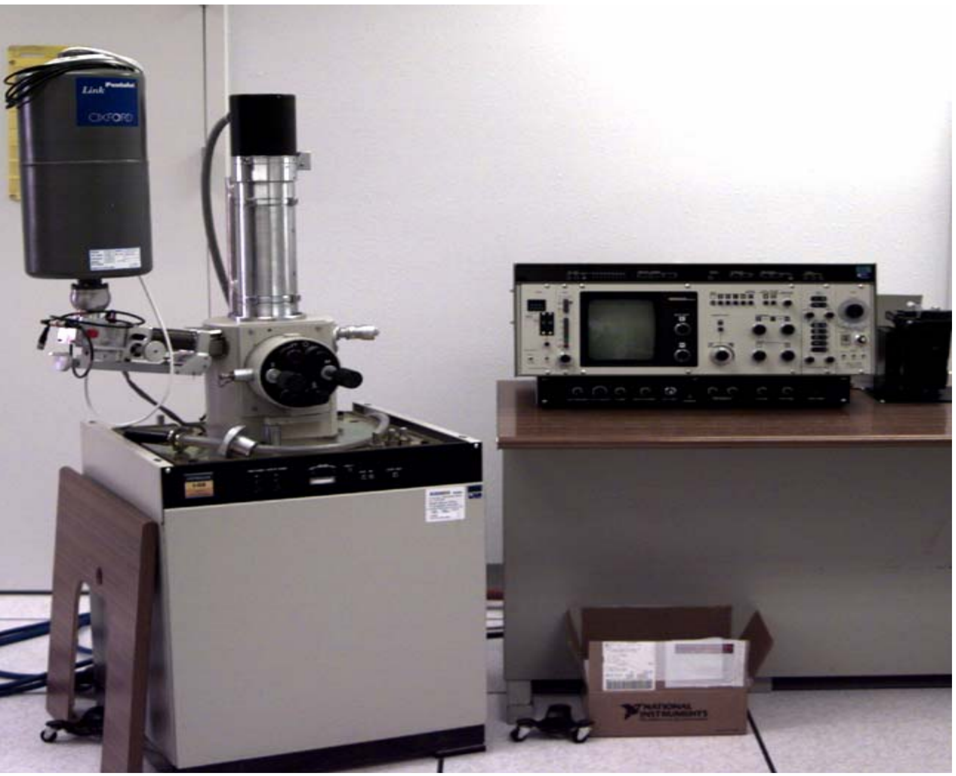
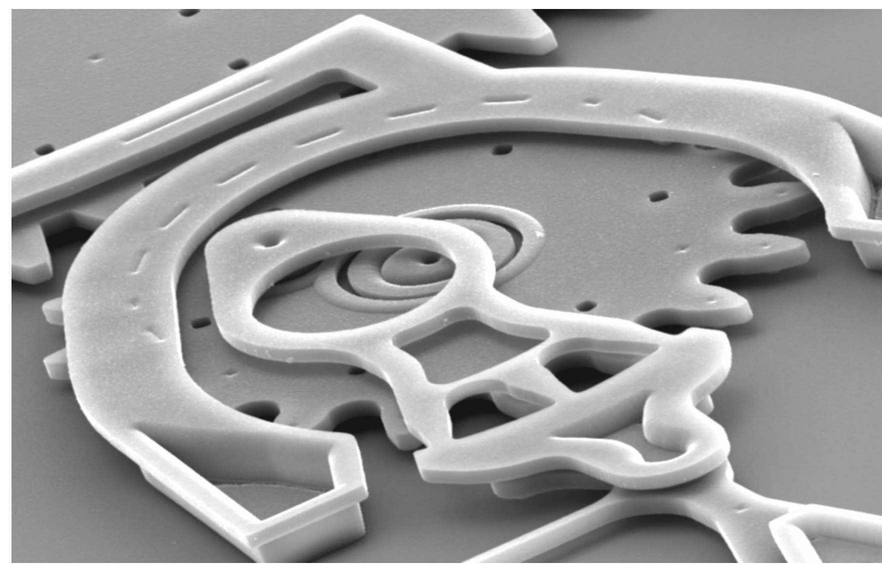
Observation Methods

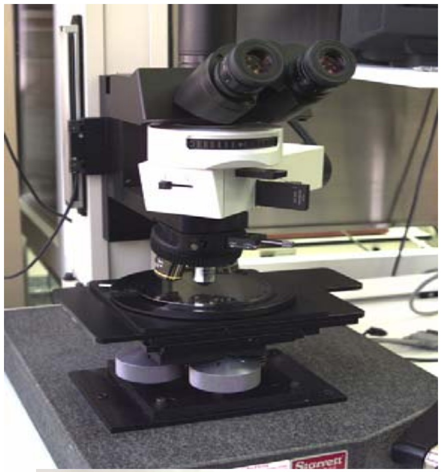


Scanning Electron Microscope (SEM)



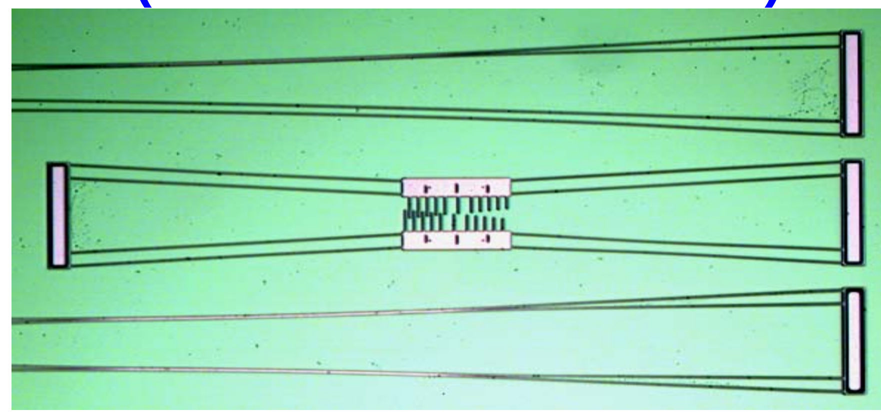
SEM

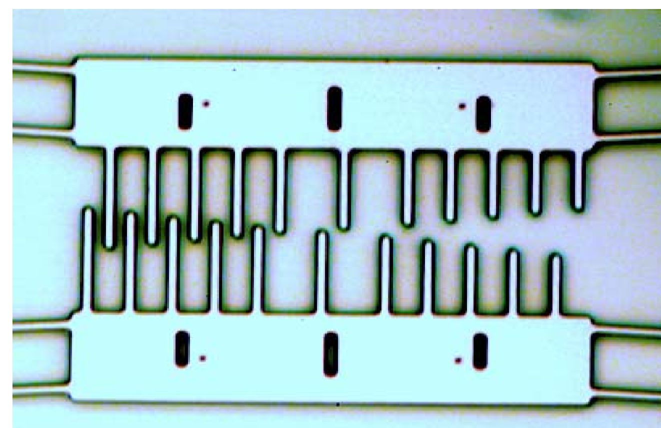
Observation Methods



Optical Microscope

Lateral deflection (calibration marks useful)





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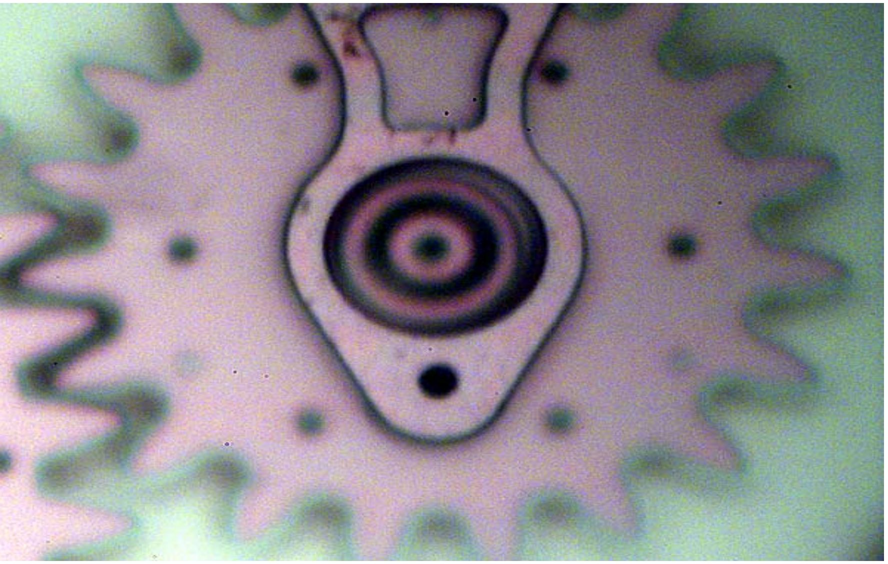
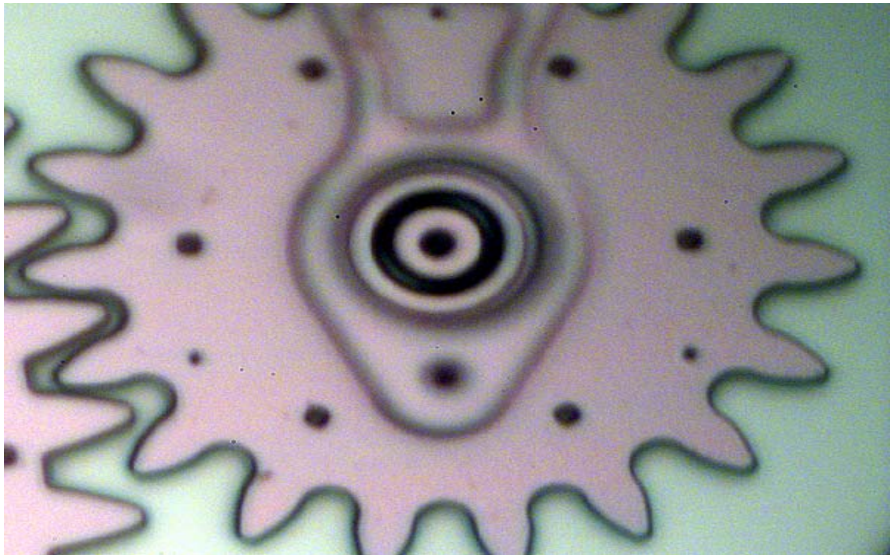
Observation Methods

Vertical position (focus)



focus on top

focus on bottom



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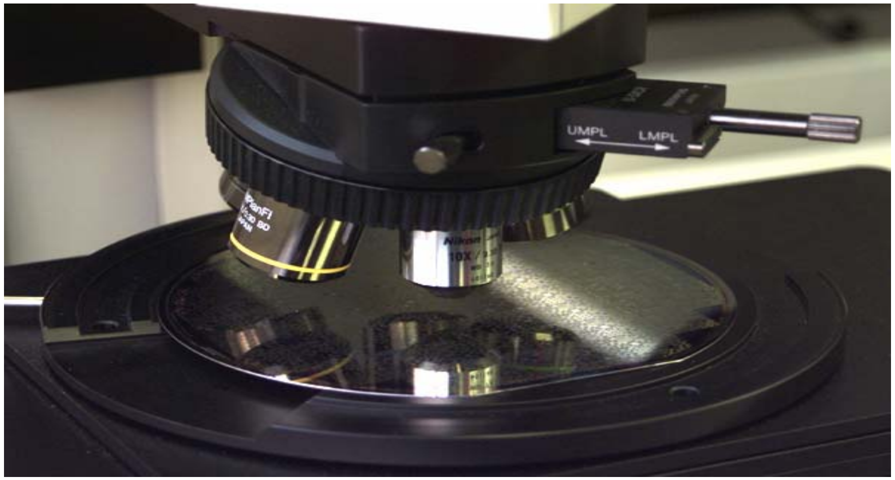
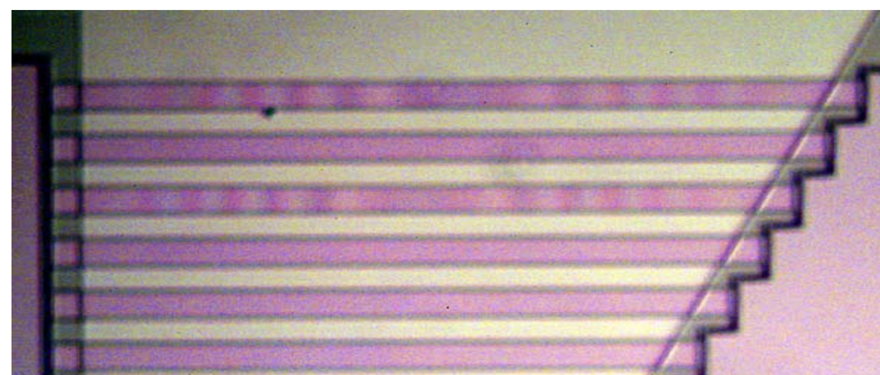
Observation Methods



Interferometer

Vertical deflection
(interference fringes)



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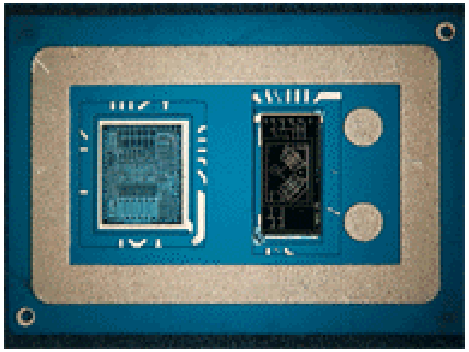
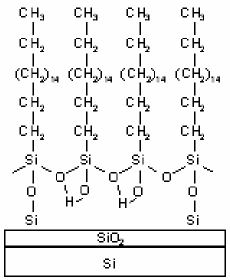
MEMS Performance & Reliability

Industry-compatible manufacturing processes and equipment

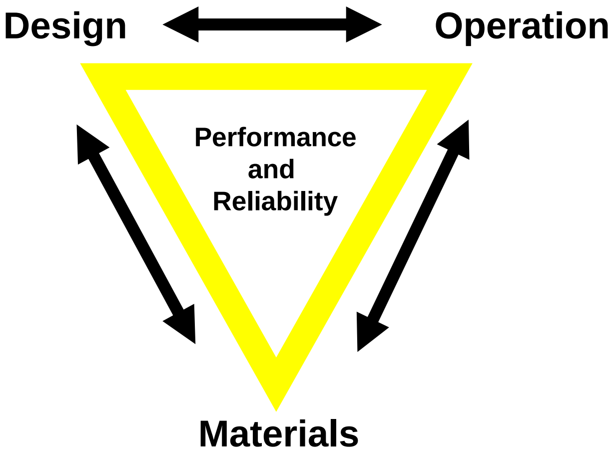
Design and visualization tools

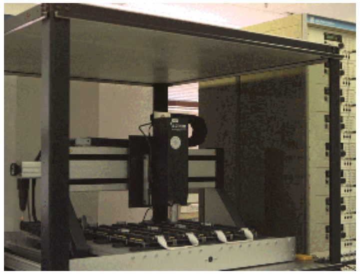


Packaging



Scientific Support





Environmental Testing

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Factors in MEMS Design

- Scaling Issues (Advantage, Disadvantages)
- Fabrication Processes, Relative Tolerances, Constraints.
- MEMS CAD Tools are a necessity.
- MEMS Performance Measurement Techniques require significant development.
- Design with Reliability Issues in Mind
- Design, Performance and Reliability are intertwined.

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