The Challenges of Micro-System Product Development

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Topics

- MEMS Products
- History
- Issues of Scale
- Fabrication Processes
- Reliability & Problems to be solved
- New Applications –Approaches – Problems to be solved

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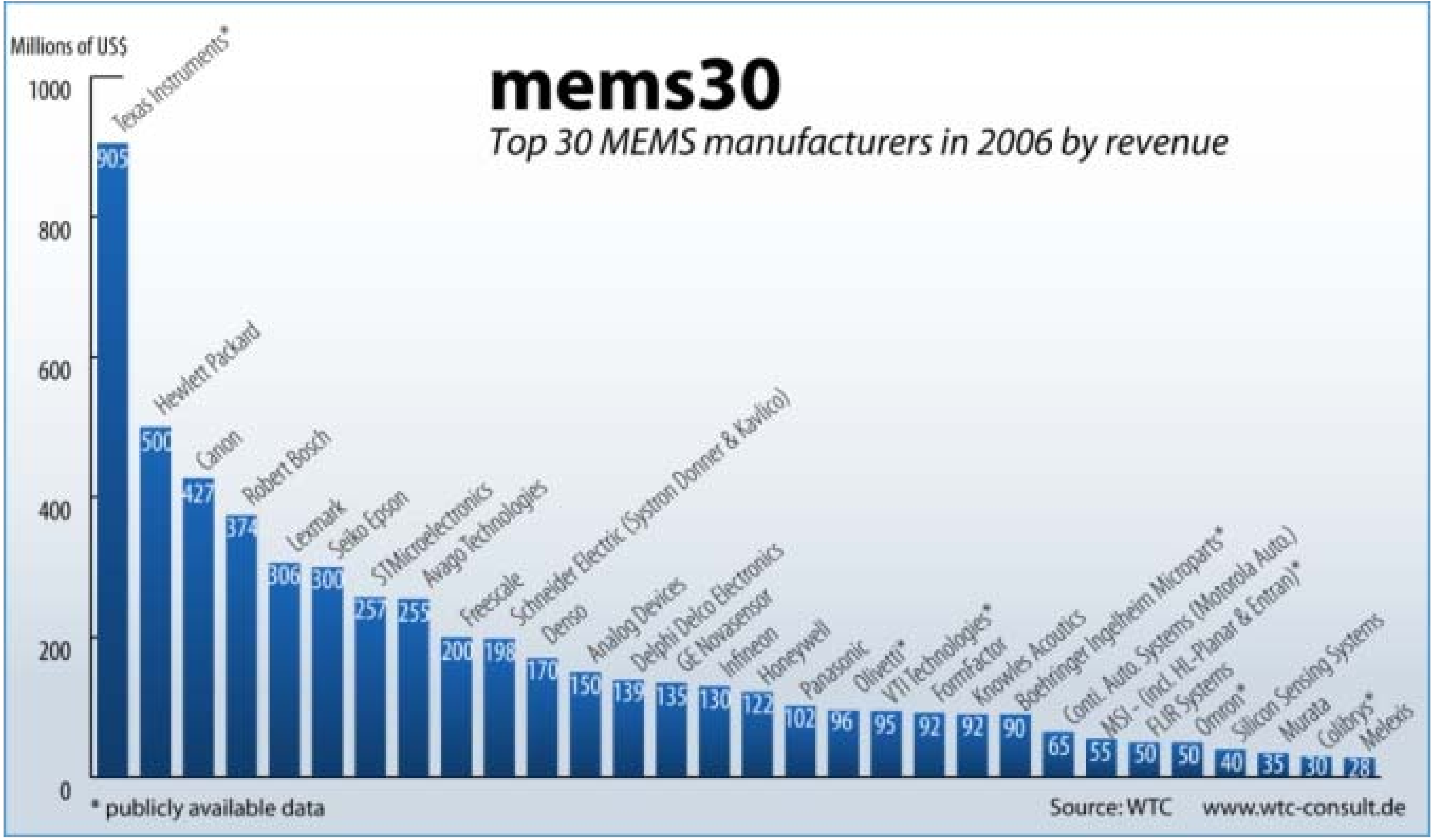
MEMS are everywhere!

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Top MEMS Manufacturers in 2006



* publicly available data

Source: WTC www.wtc-consult.de

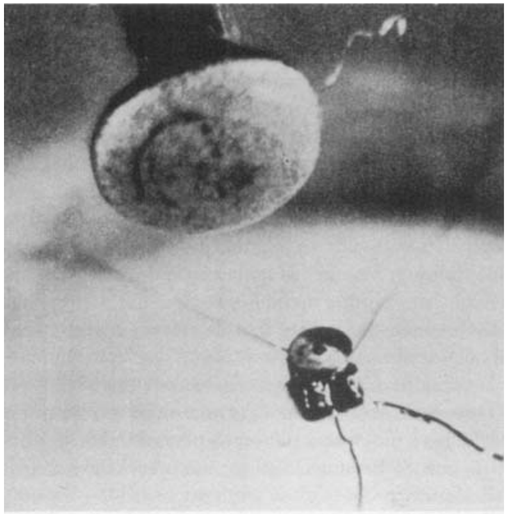
- http://www.memsinvestorjournal.com/2007/04/ranking_of_top_.html#more

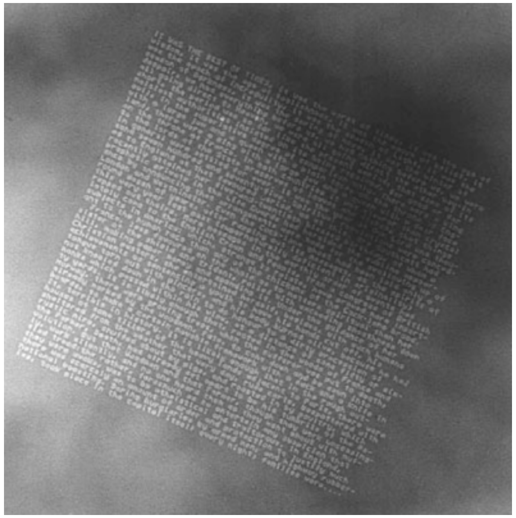
Vision of Microsystems

- "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

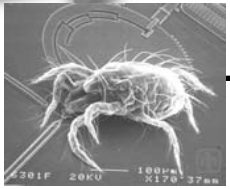




T. Newman,
R.F.W. Pease,
1985

The Scale of Things – Nanometers and More

Things Natural



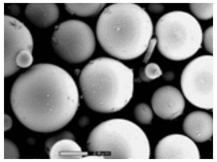
Dust mite

↔

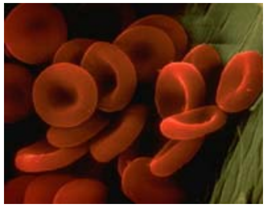
200 µm

Ant
~ 5 mm

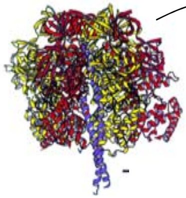
Human hair
~ 60-120 µm wide



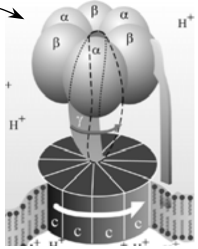
Fly ash
~ 10-20 µm



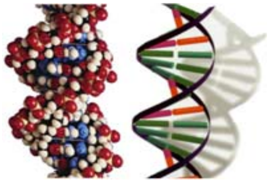
Red blood cells
(~7-8 µm)



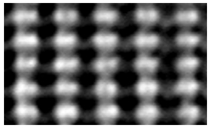
~10 nm diameter



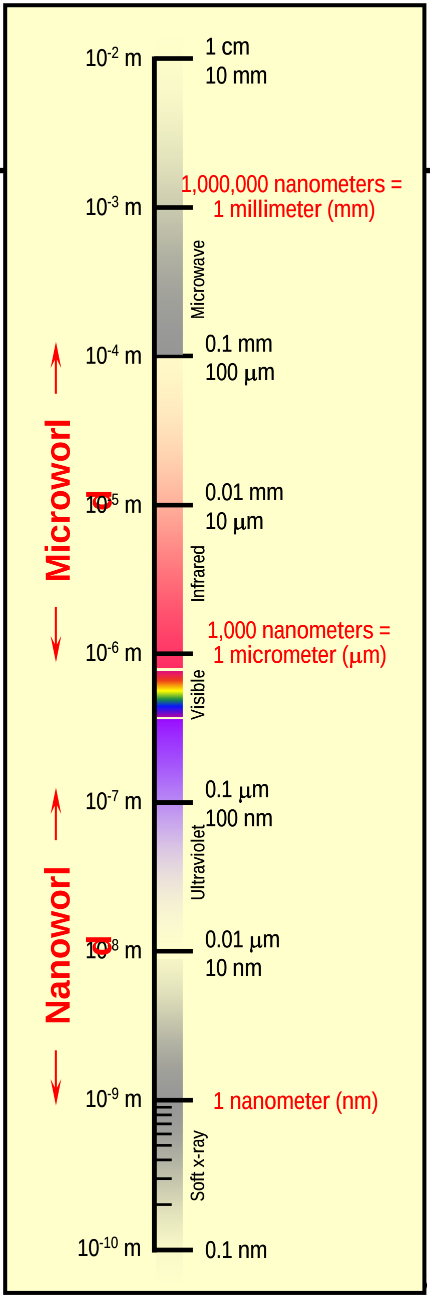
ATP synthase



DNA
~2-1/2 nm diameter



Atoms of silicon
spacing 0.078 nm



10^{-2} m — 1 cm
10 mm

10^{-3} m — 1,000,000 nanometers =
1 millimeter (mm)

Microwave

10^{-4} m — 0.1 mm
100 µm

Microworld

10^{-5} m — 0.01 mm
10 µm

Infrared

10^{-6} m — 1,000 nanometers =
1 micrometer (µm)

Visible

Ultraviolet

10^{-7} m — 0.1 µm
100 nm

Nanoworld

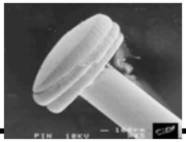
10^{-8} m — 0.01 µm
10 nm

10^{-9} m — 1 nanometer (nm)

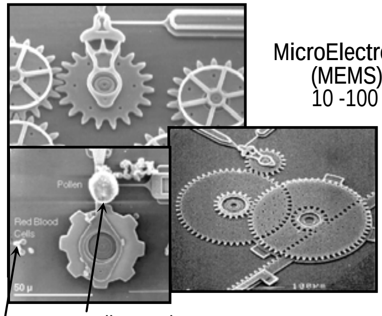
Soft x-ray

10^{-10} m — 0.1 nm

Things Manmade



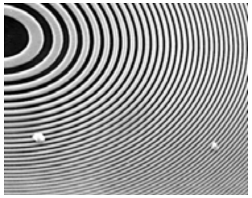
Head of a pin
1-2 mm



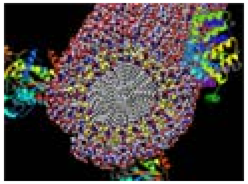
MicroElectroMechanical
(MEMS) devices
10 -100 µm wide

Pollen grain

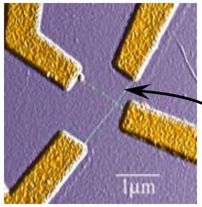
Red blood cells



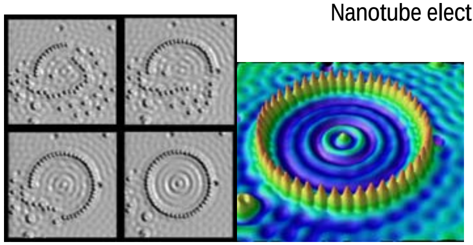
Zone plate x-ray "lens"
Outer ring spacing ~35 nm



Self-assembled,
Nature-inspired structure
Many 10s of nm

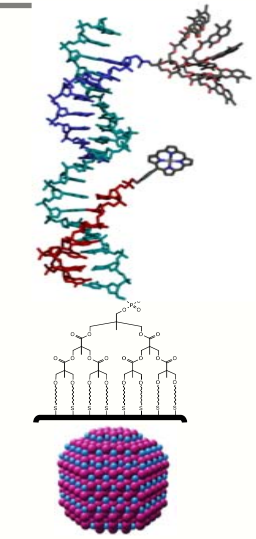


Nanotube electrode

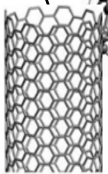


Quantum corral of 48 iron atoms on copper surface
positioned one at a time with an STM tip
Corral diameter 14 nm

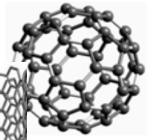
The Challenge



Fabricate and combine nanoscale building blocks to make useful devices, e.g., a photosynthetic reaction center with integral semiconductor storage.



Carbon nanotube
~1.3 nm diameter



Carbon
buckyball
~1 nm
diameter

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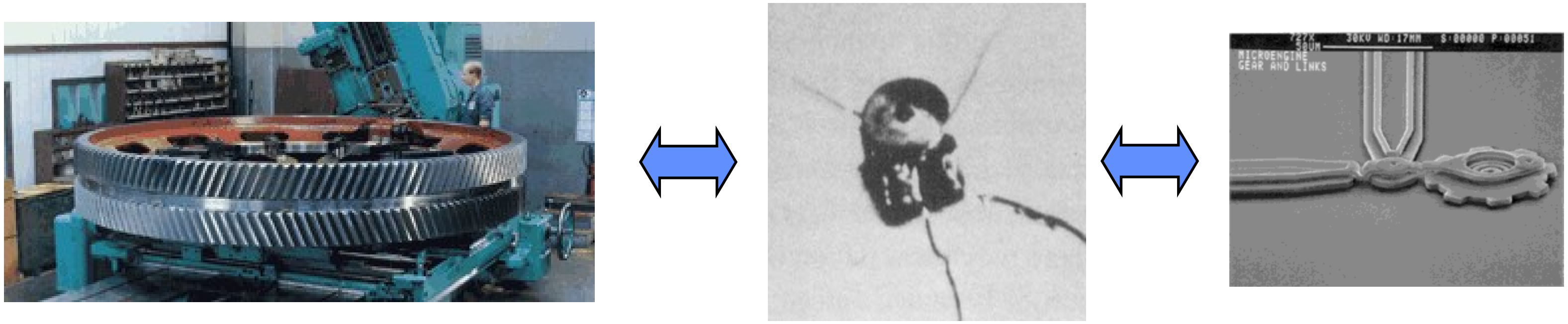
Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 05-26-06, pmd

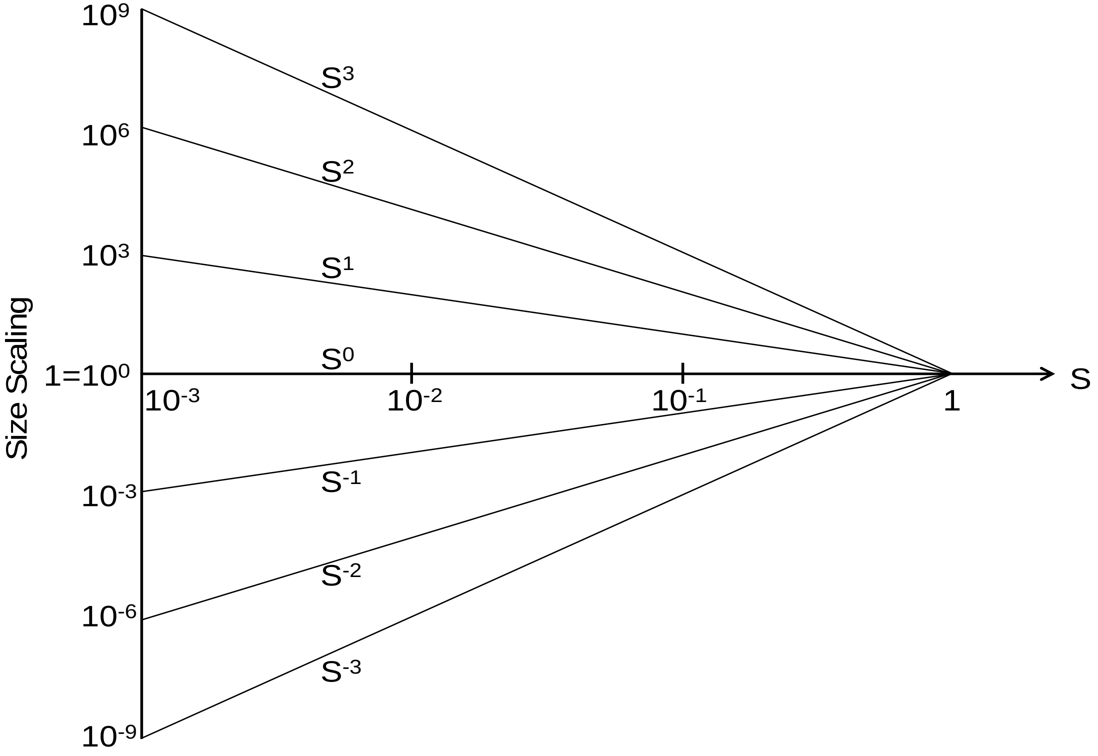
Effect of Reduction in Scale

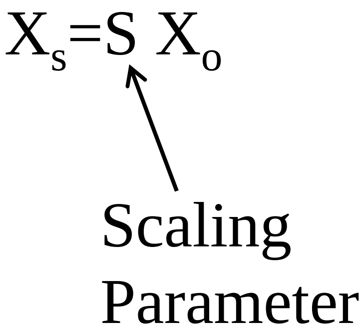


Why does a change is scale matter?

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

Use a Scaling Parameter to evaluate Scale effects





$$X_s = S\,X_o$$

Scaling Parameter

Geometric Scaling

GEOMETRY SCALING

$X_s = S\, X_o$

$A_s = X_s Y_s = S^2 X_o Y_o = S^2 A_o$

$V_s = X_s Y_s Z_s = S^3 X_o Y_o Z_o = S^3 V_o$ →

Things that depend on Volume are going to decrease dramatically

AREA – VOLUME RATIO SCALING

$A_s/V_s = 1/S\, (A_o/V_o)$ →

Things that depend on this ratio will increase in importance

Mechanical Scaling

Mass: cubically reduced

$$M_s = \rho S^3 V_o = S^3 M_o$$

Stiffness: Linearly reduced

$$K_{bending} \propto \frac{EI}{L^3} \propto \frac{Ewt^3}{L^3} \propto S$$

$$K_{axial} \propto \frac{EA}{L} \propto \frac{Ewt}{L} \propto S$$

Natural Frequency: increases

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \propto \sqrt{\frac{K}{M}} \propto \sqrt{\frac{S}{S^3}} \propto \frac{1}{S}$$

Thermal Scaling

Thermal Mass: *proportional to volume*

$$mc_p \Delta T = \rho V c_p \Delta T$$

Thermal Conductivity: *Proportional to Area*

$q = KA\nabla T$ conduction

$q = hA(T_w - T_\infty)$ convection

$q = A\sigma T^4$ radiation

Thermal Diffusivity (time constant): *Proportional to Vol/Area*

$$\tau = \frac{mc_p}{\kappa A} = \left(\frac{\rho c_p}{\kappa}\right)\left(\frac{V}{A}\right) \propto S$$

Fluidic Scaling

Reynolds Number: A measure of the transition between laminar and turbulent flow

Laminar flow: Re<2000

Turbulent Flow: Re>4000

$$\mathrm{Re} = \frac{\rho V D}{\mu} \propto S$$

Micro Domain is dominated by laminar flow.

Scaling of Electrical and Magnetic Fields

Energy Density:

$$U_{electric} = \frac{1}{2}\varepsilon E^2$$

$E_{breakdown}$=3MV/M $\Rightarrow$ $U_{electric}$=40 J/M^3

$$U_{magnetic} = \frac{1}{2}\frac{B^2}{\mu}$$

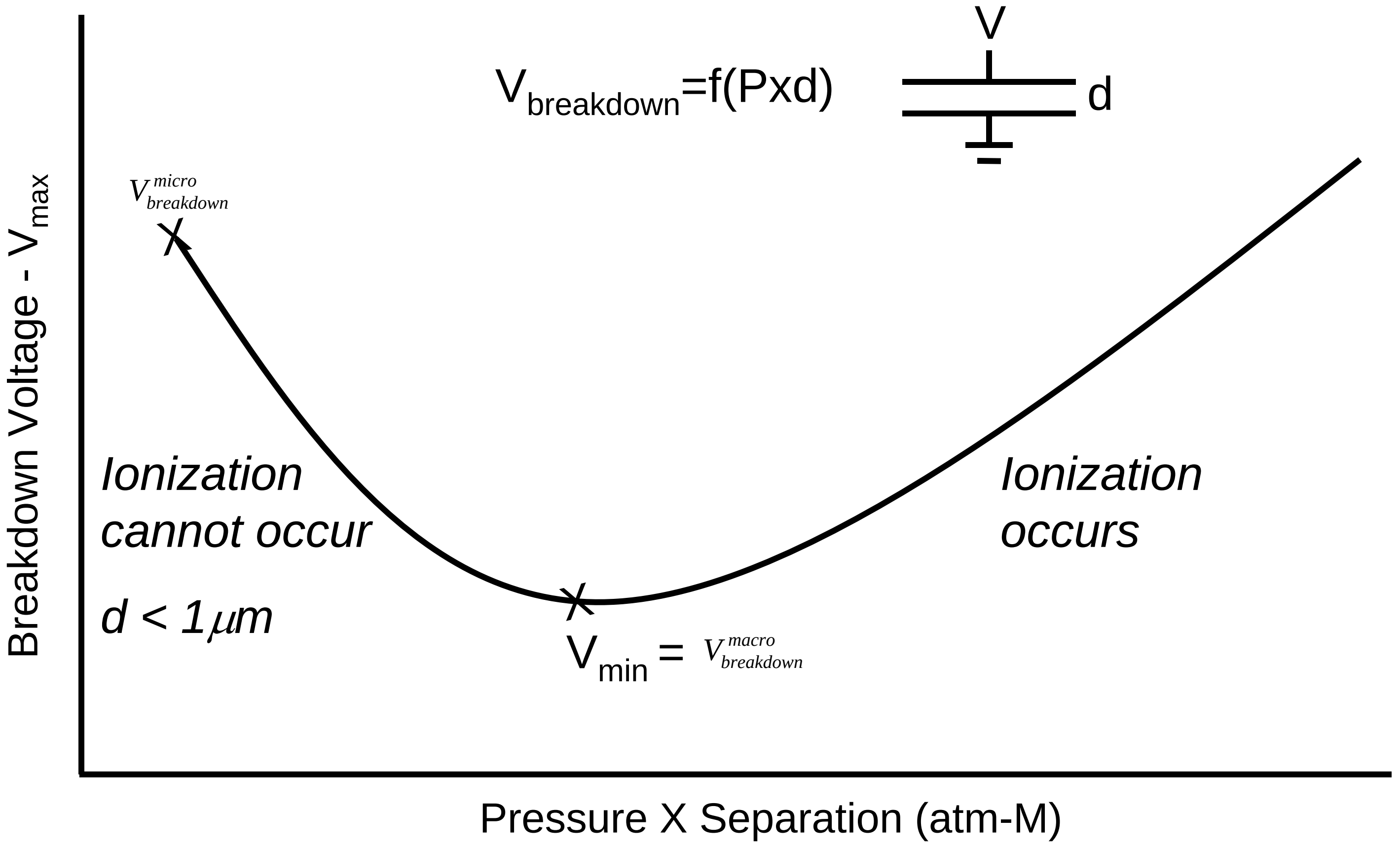
B_{sat}=1T $\Rightarrow$ U_{mag}=4x10^5 J/M^3

Magnetic actuation dominates in the Macro world due to the calculations above.

But Magnetics **does not** dominate in the Micro world. Why?

Paschen’s Law

$V_{breakdown}$=f(Pxd)



F. Paschen, Wied. Ann., 37, 69, 1889

Scaling of Electrical and Magnetic Fields

$E_{breakdown} = 3\text{x}10^{8}$ V/M for small gap of ~ 1 μm or less

$\therefore \Rightarrow$ $U_{electric} = 4\text{x}10^{5}$ J/M^3

which is now comparable to magnetics

However,

* Magnetics has fabrication issues at the microscale

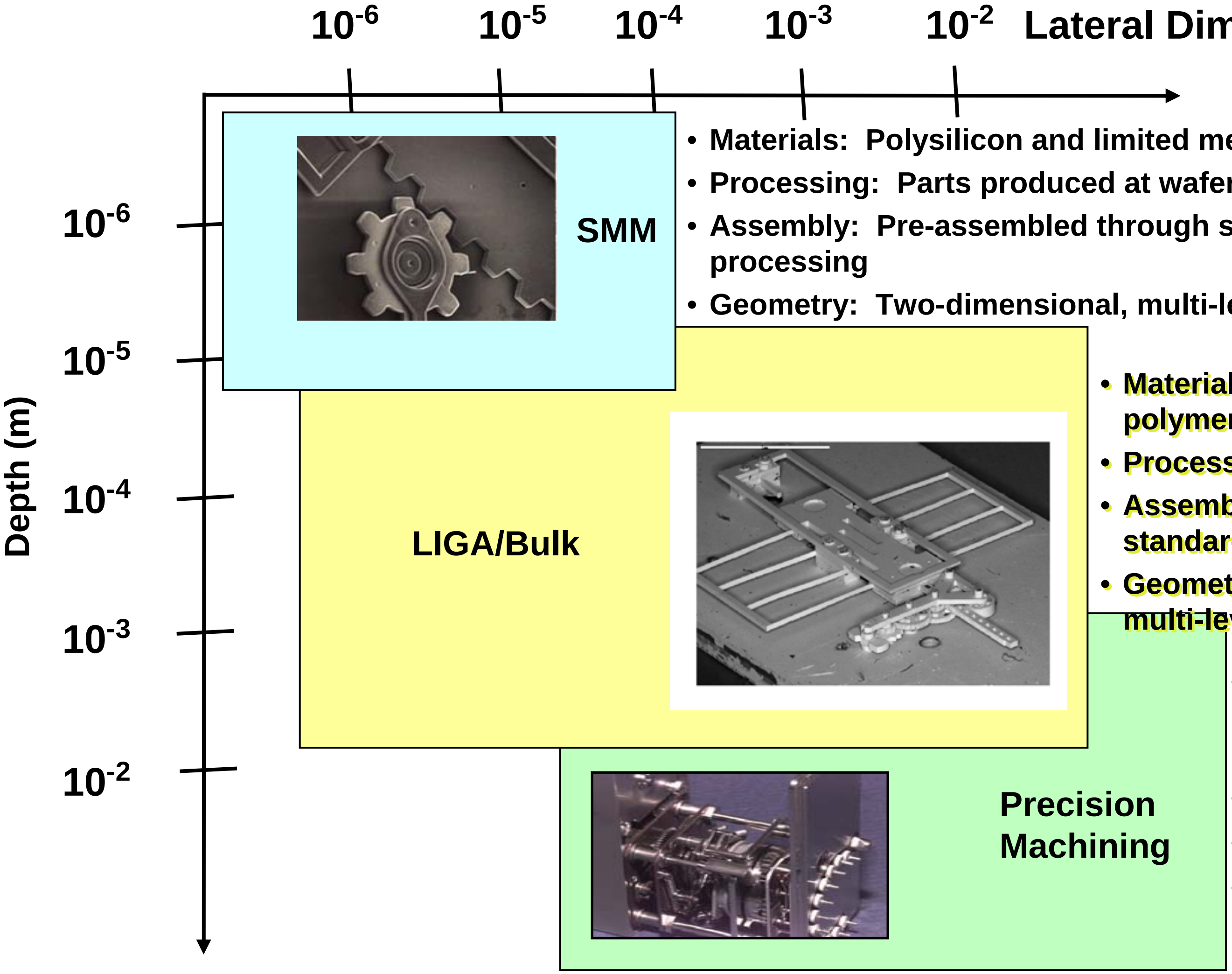
•For magnetic field constant $B = B_{sat}$

•Electric Field increases with decreasing gap ($E \propto \frac{1}{S}$) up to the breakdown voltage.

Physical Phenomena Change The breakdown of the continuum

- **Paschen Effect**
- **M.F.P 0.1 μM of air at STP**
- **Material crystal sizes in polycrystalline material ~0.1 μM**
- **Magnetic Domains ~10-25 micron**

A Continuum of Microsystems Fabrication Technologies



SMM

- Materials: Polysilicon and limited metal coatings
- Processing: Parts produced at wafer level
- Assembly: Pre-assembled through standard processing
- Geometry: Two-dimensional, multi-level

LIGA/Bulk

- 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: Hand assembly
- Geometry: Full three-dimensionality

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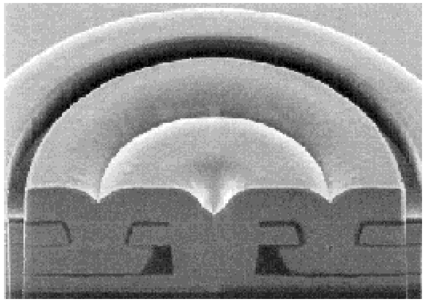
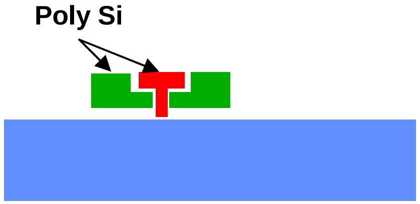
Three Dominant MEMS Fabrication Technologies

Surface Micromachining

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

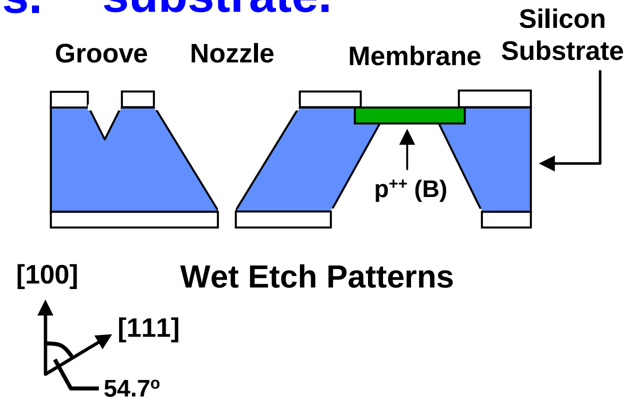




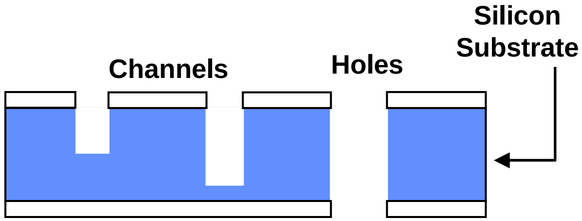
Silicon Substrate

Bulk Micromachining

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



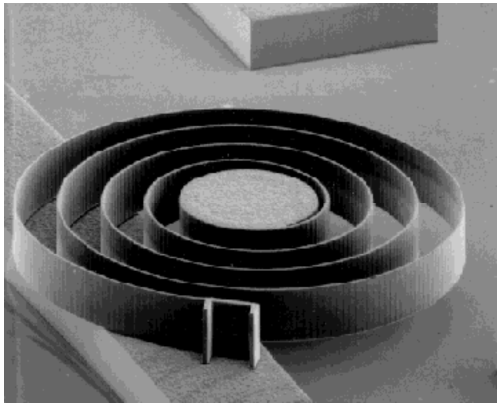
Wet Etch Patterns

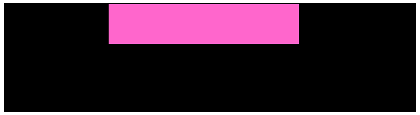


Dry Etch Patterns

LIGA

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





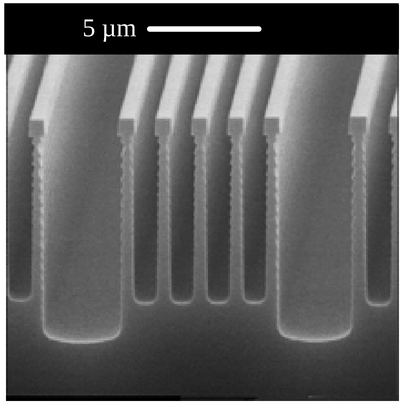
Mold

Manufacturing Effect of Reduction in Scale

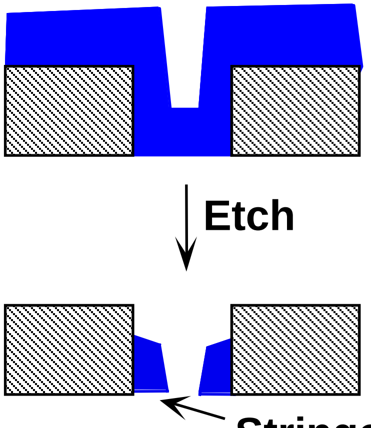
- **Size ↓ Relative Manufacturing Precision ↓**
  - **Dimensional Tolerance/Nominal Dimension**
    - **Micro Scale (1-100μm) ≈ 0.1% - 1%**
    - **Macro Scale (1cm – 1m) ≈ 0.001%**

Manufacturing Processes Impose constraints on Design

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



- **Surface Micromachining Example**
  - **Stringers**

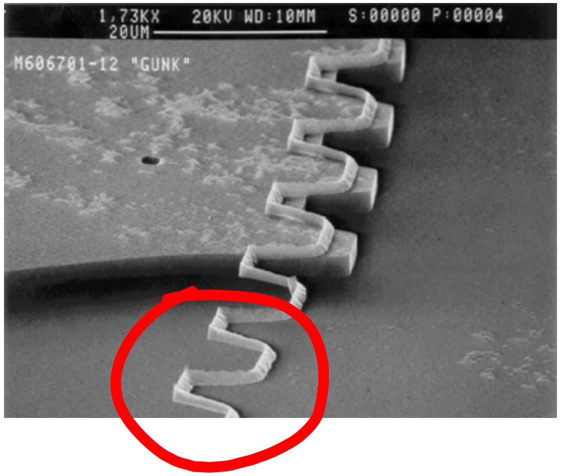


Polysilicon

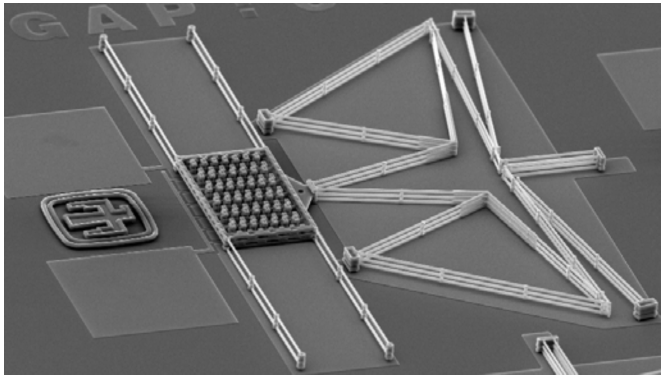
Silicon Dioxide

Etch

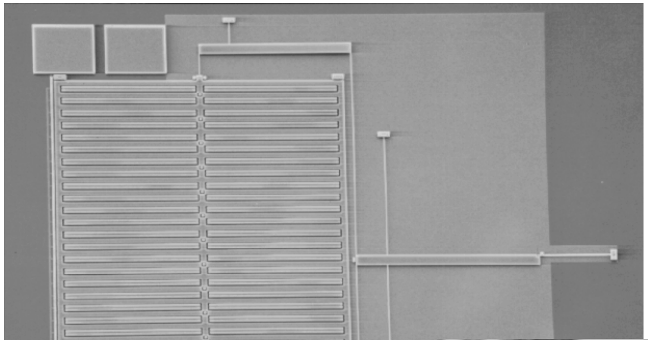
Stringer

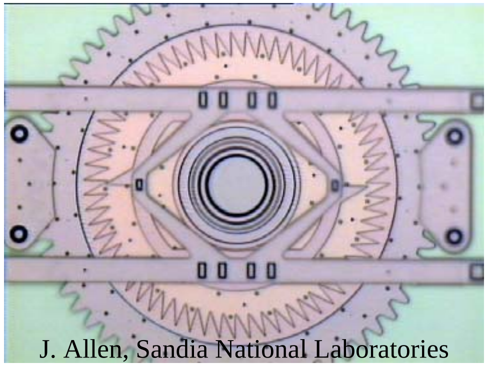


A Variety of Micro Mechanisms are required for Microdevice Applications



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





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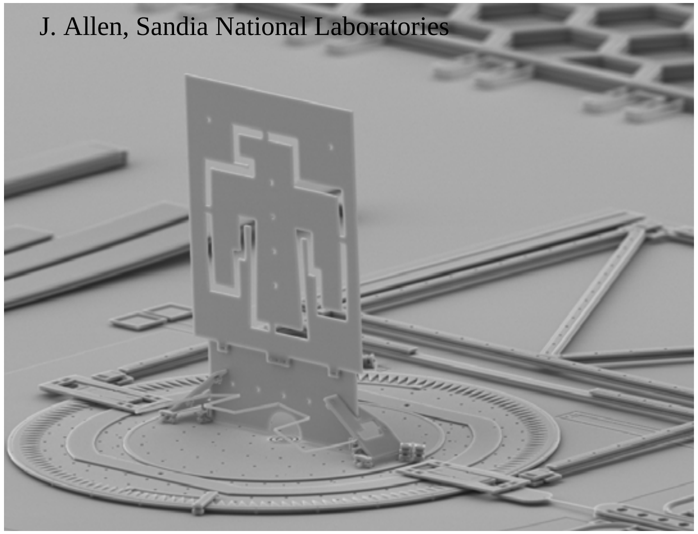
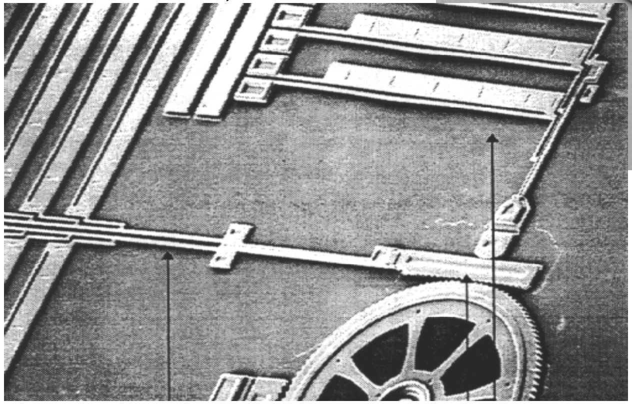


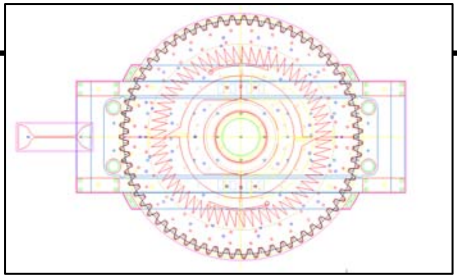
J. Allen, Sandia National Laboratories

Comtois, 1996



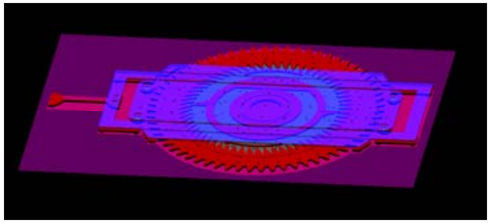
CAD Tools are Essential to the Design of Microsytems

Initial Design

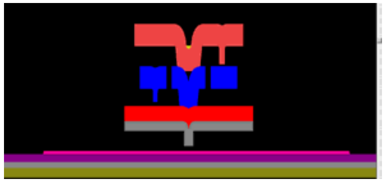


Layout

3D Modeler

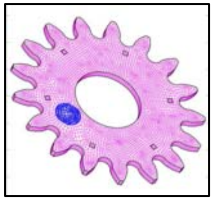


2D Process Visualizer

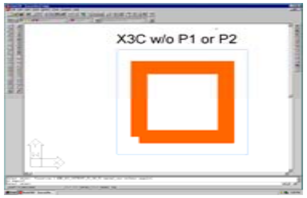


Visualization

Mesh



Design Rule checking



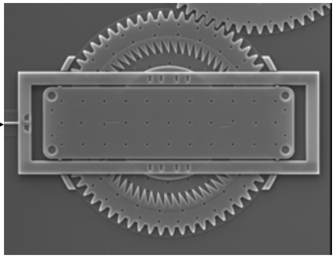
X3C w/o P1 or P2

Design Validation

Analysis

Verification

Fabrication Time & Expense demand the availability of these tools



Final Product

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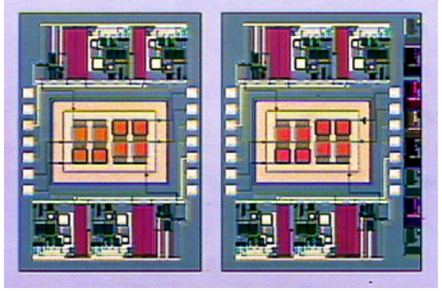
Reliability Concerns Increase With Complexity

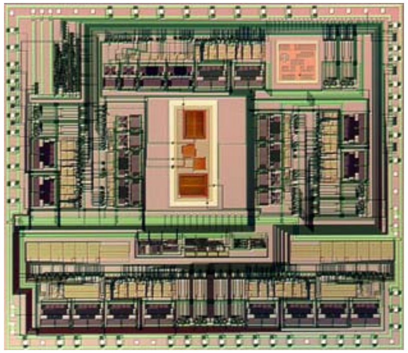
Class I
- No Moving Parts

e.g., Pressure Sensors



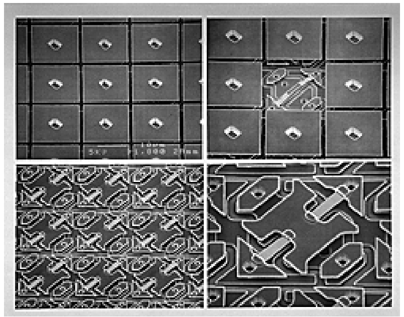
Class II
- Moving Parts

e.g., Accelerometers



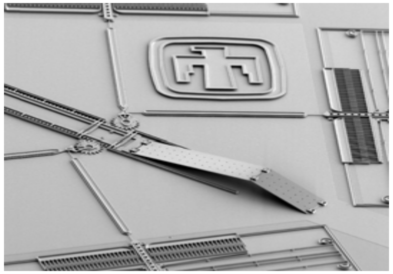
Class III
- Moving Parts
- Impacting Surfaces

e.g., Tilting Mirrors

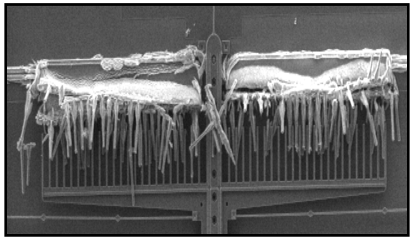


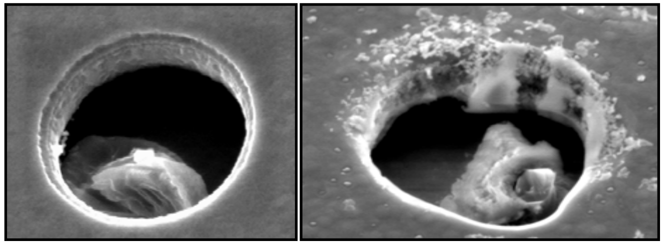
Class IV
- Moving Parts
- Impacting Surfaces
- Rubbing Surfaces

e.g., Gears



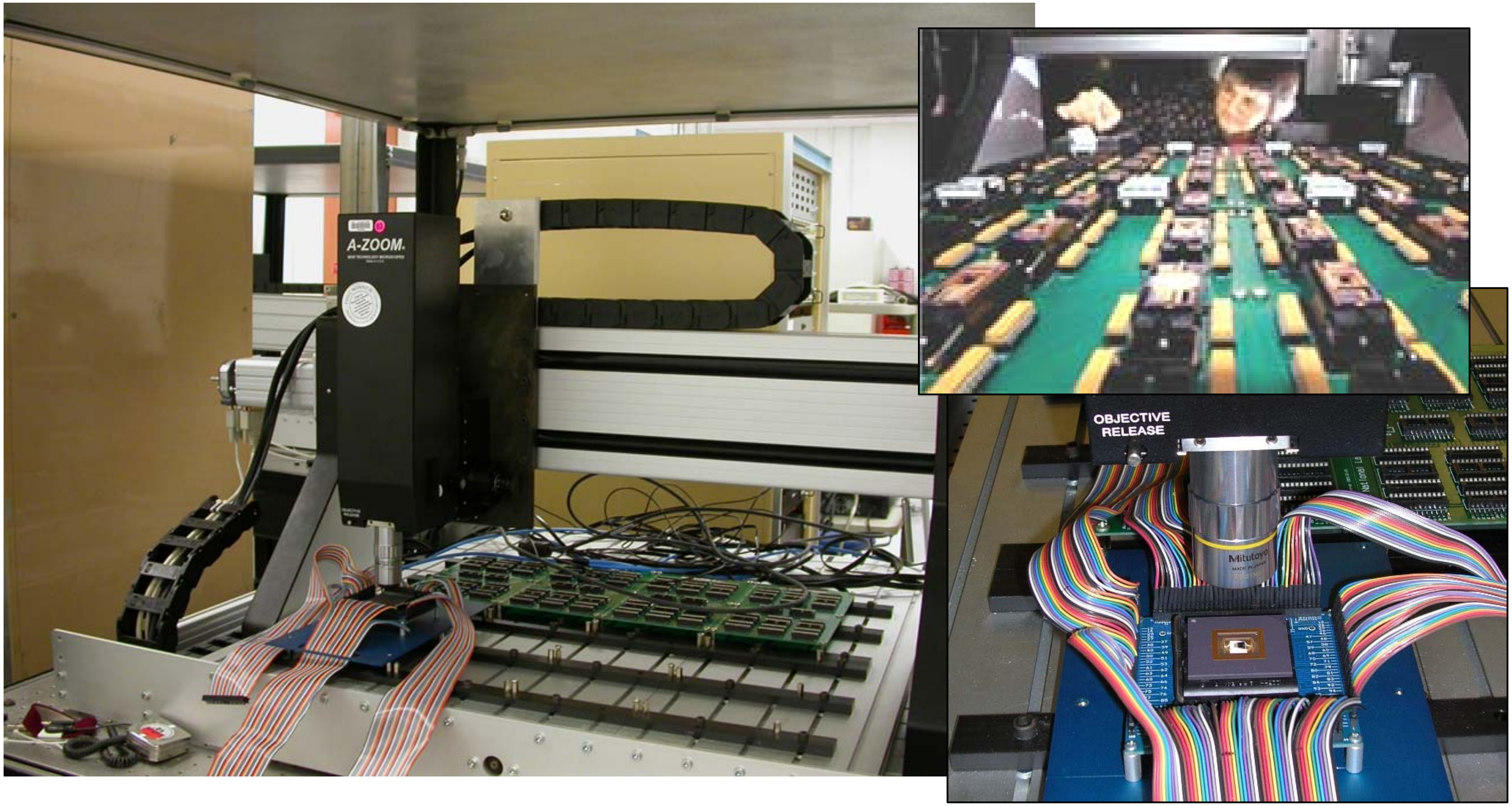
Understand the science of reliability





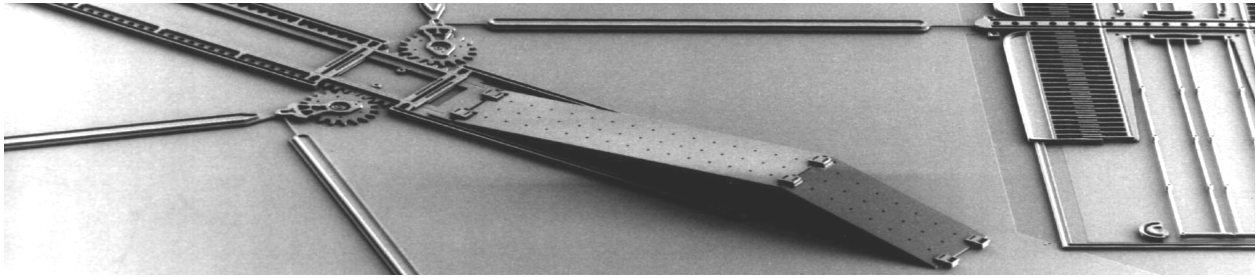
Reliability Testing

Sandia High-volume Micromachine Measurement of Reliability



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



MEMS Electrical Contacts

- **Contact Resistance is a function of Contact Force**
  - **An issue at Microscale**
- **Materials issues**
  - **Contact Stiction**
  - **Contact Resistance change with age and repeated actuation**

l Actuators 73 (1999) 138–143

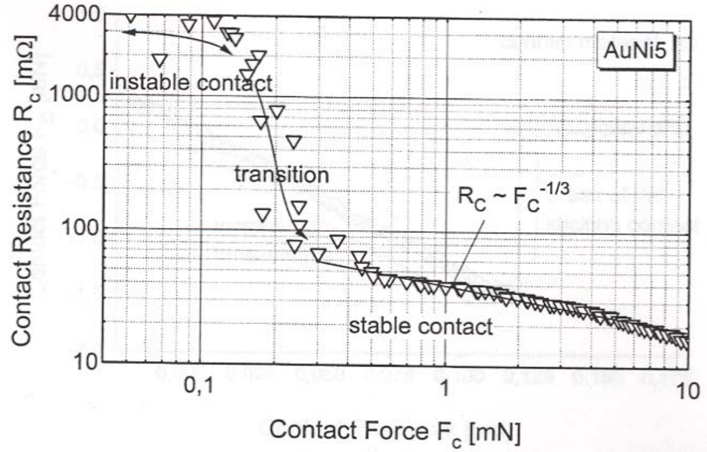
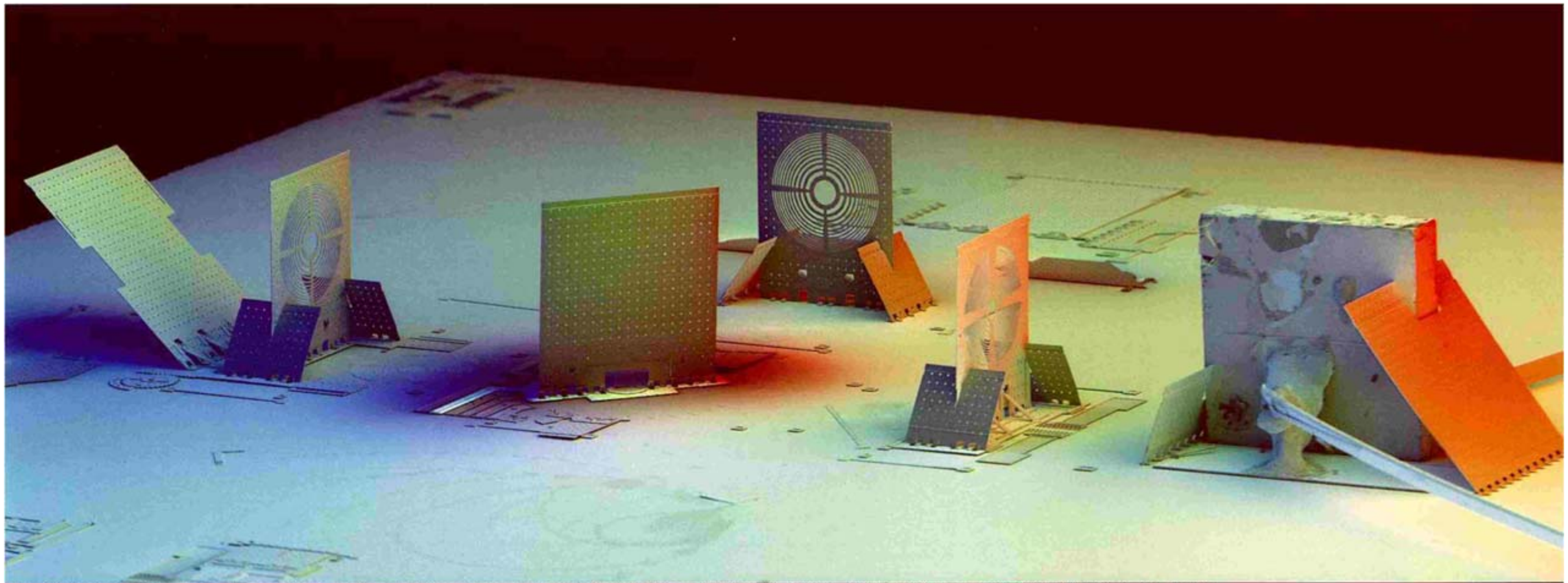


Fig. 4. $R_c - F_c$ characteristics of closing AuNi5 contacts: unstable contact at very low force, transition to lower resistance and the domain of stable contact with the measured resistance force characteristic compared to theoretical relationship according to Holm's model, from Ref. [6].

Optical Bench Example

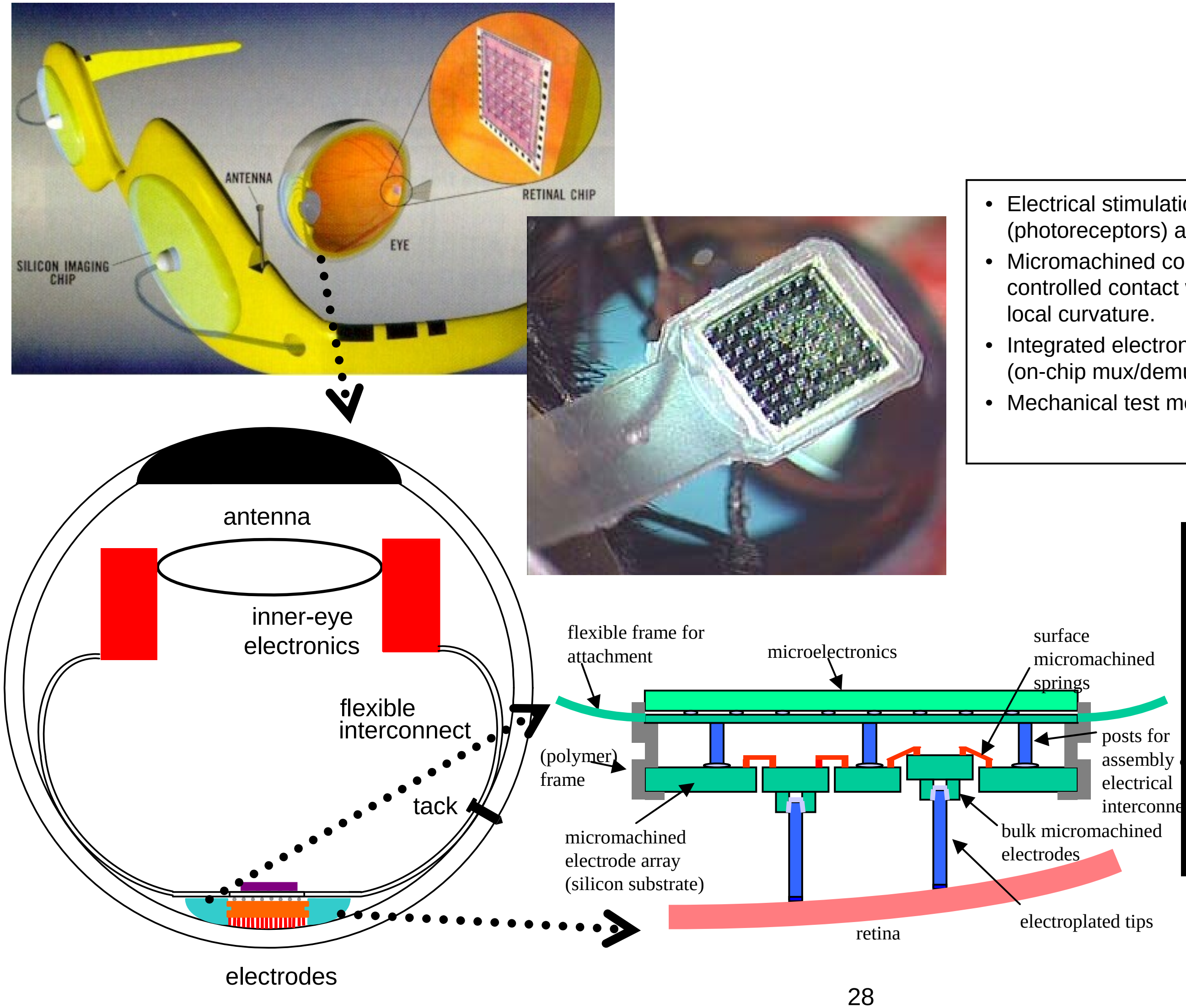


Micro Optics (laser, 3 fresnel lenses, beam splitter, & 45 deg. mirror) Nano-fabrication Micromachining (Fabricated by Ming Wu, L. Y. Lin, J. L. Shen, S. S. Lee, and C. R. King @ U.C.L.A. , E.E. Dept.)
50X @ 4"x5" size. © David Scharf, 1996. All rights reserved. (9605-009a)

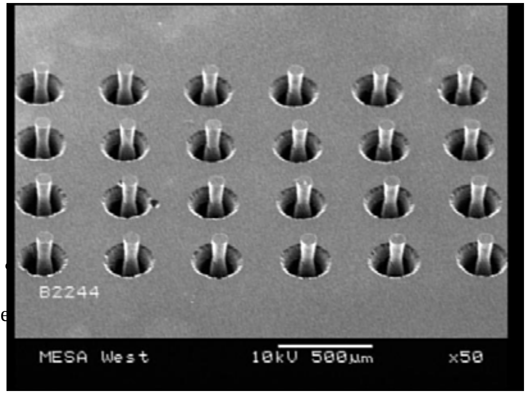
Laser, 3 Fresnel lenses, beam splitter, 45 degree mirror

Dr. Wu, U. of California, Berkley

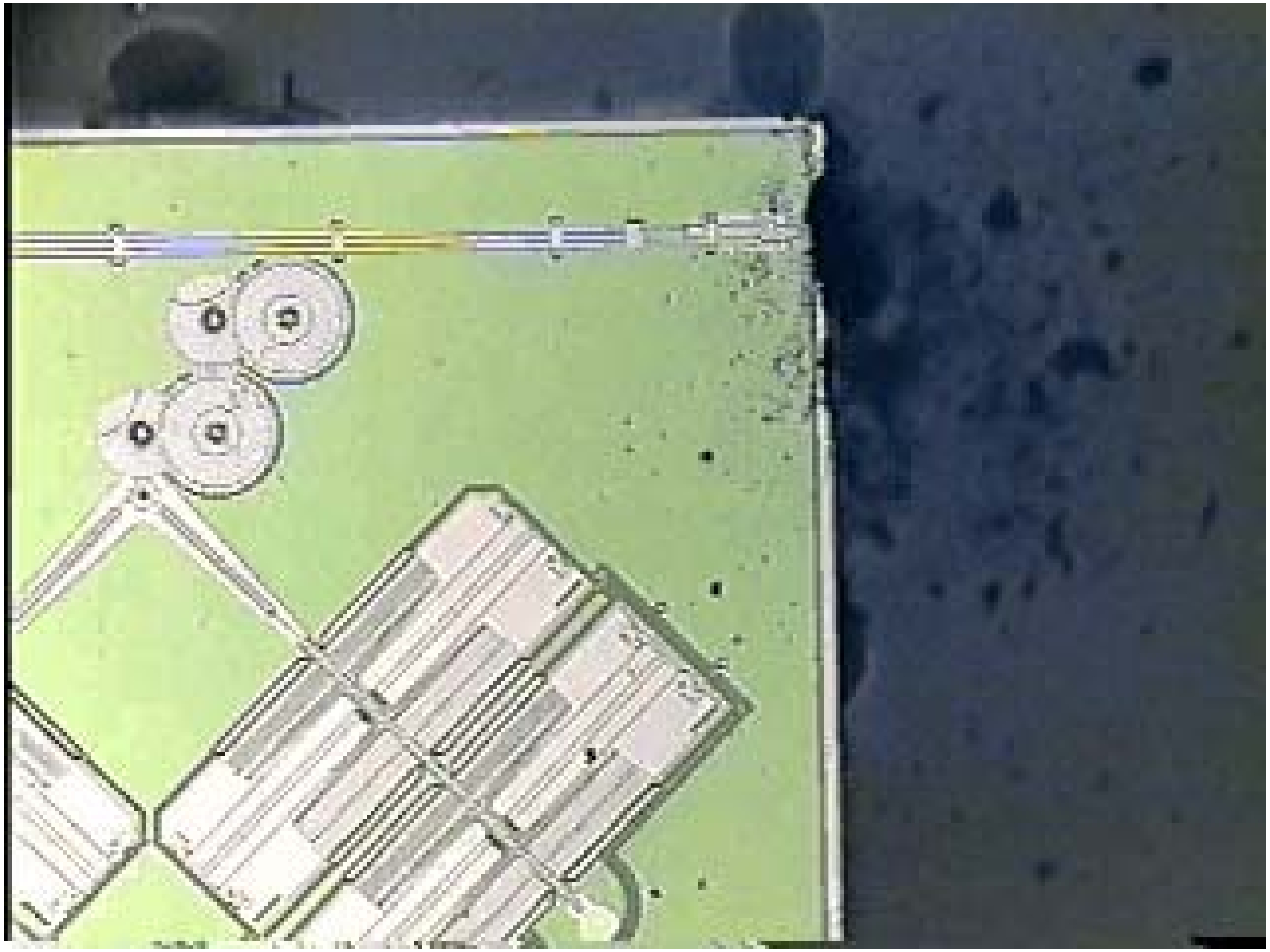
Retinal Implant



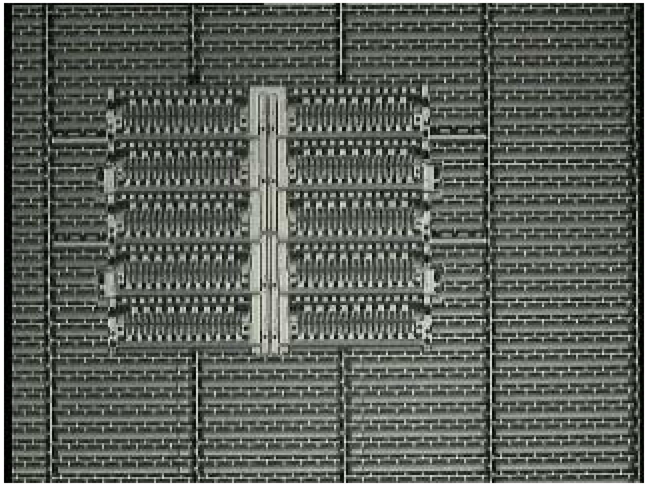
- Electrical stimulation of retinal neurons after light sensitive cells (photoreceptors) are lost.
- Micromachined conformal electrode array provides positive controlled contact with tissue (retina), accommodating overall and local curvature.
- Integrated electronics essential for high electrode count system (on-chip mux/demux for 100+).
- Mechanical test modules in animal tests.



Neural Probes

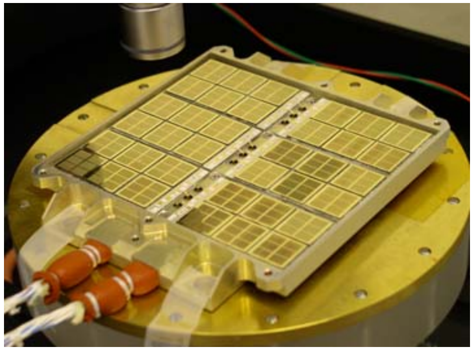


MEMS Variable Emittance Louvers

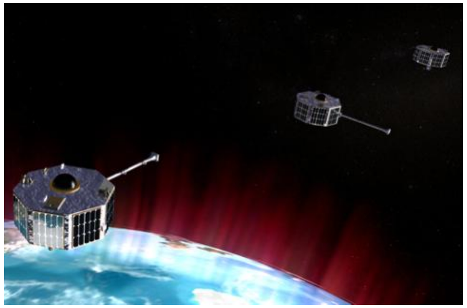


2592 SUMMiT V™ die
with Buried Interconnects

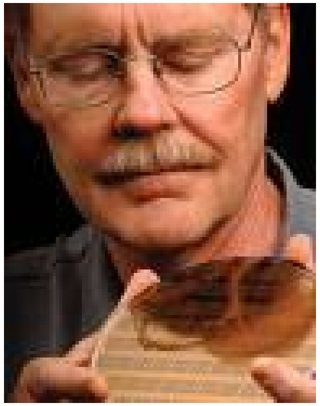
4”x4” Johns Hopkins/APL
Experimental Thermal
Regulator



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

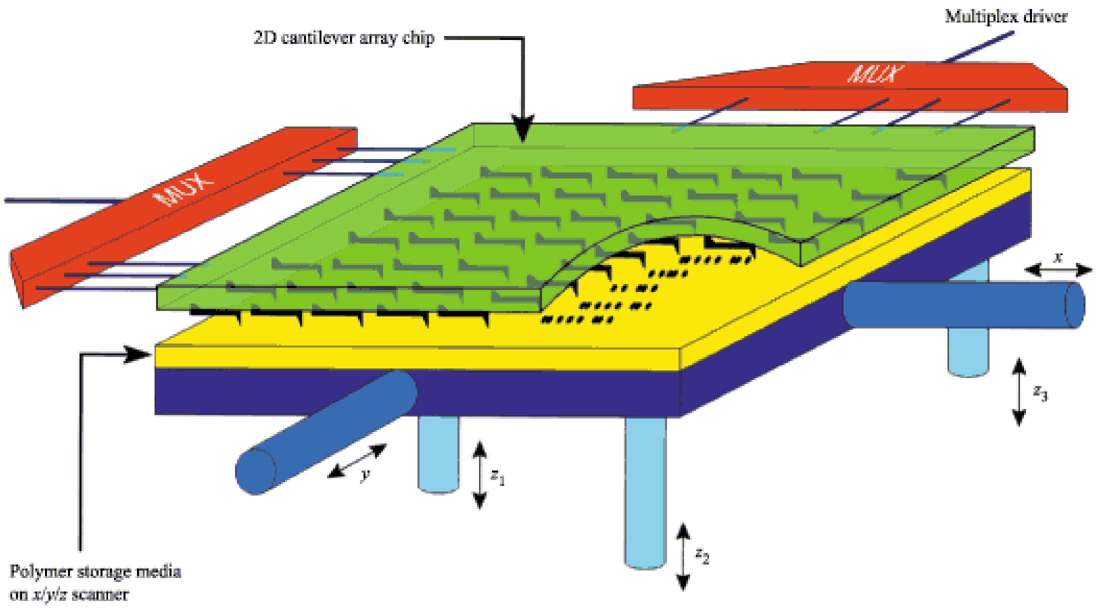


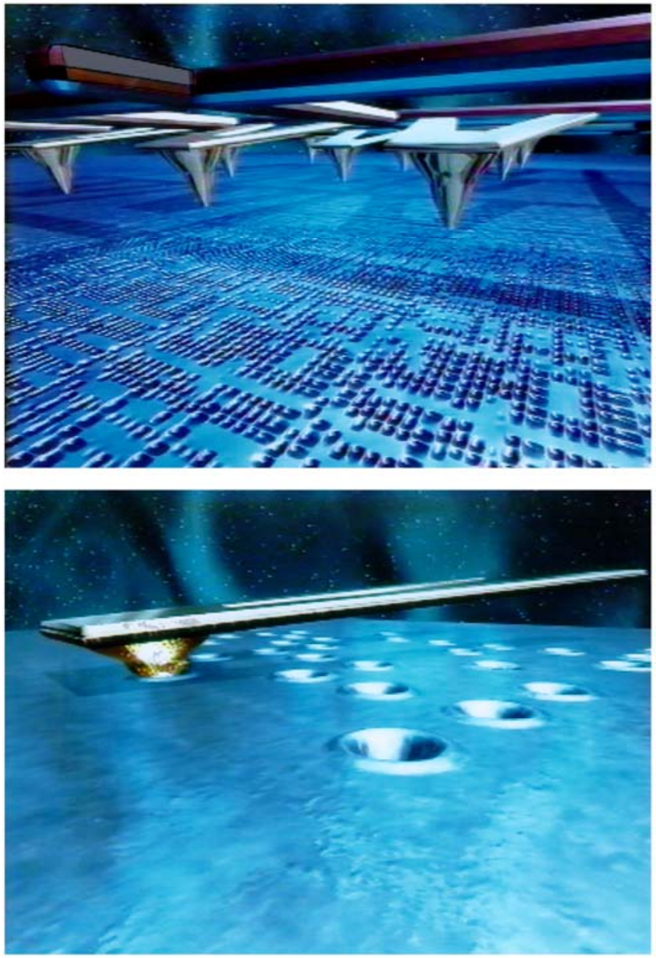
Experimental satellites
monitor space weather



IBM Millipede Storage System

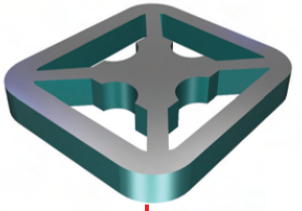
- **High density data storage possible(Tb/in^2)**
- **4x Magnetic Media**
- **AFM tip writes and reads data**
- **Bit set by melting depression into polymer medium**



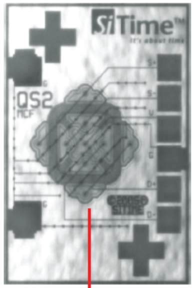


SiTime Resonators

SiRes™

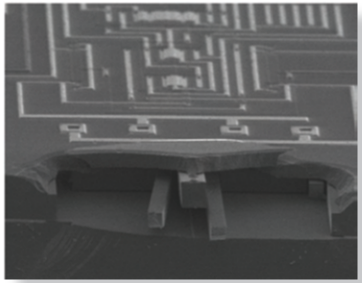


SiTime's revolutionary MEMS First™ technology allows ultra stable mechanical resonators to be integrated into standard silicon chips with performance as good as or better than traditional quartz-based systems.



SiRes™ mechanical resonator vibrating.

Single crystal Si encapsulation layer allows CMOS integration



PRISM Center can greatly Impact Microsystem Development

- **Improve understanding MEMS reliability**
- **Provide the capability for analysis based design versus empirical or design of experiments approach**
- **Provide the ability to include uncertainty of fabrication process and materials in MEMS designs**
- **Increased understanding of the physics of phenomena.**

Sandia
National
Laboratories