SAND2008-6246P

The Challenges of Micro-System Product Development

James J. Allen Ph.D, P.E.
Advanced MEMS Technologies
Sandia National Laboratories
Albuquerque, NM 87185-1080

http://www.mems.sandia.gov/

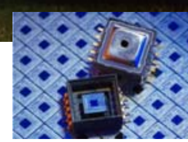
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy under contract DE-AC04-94AL85000.

Topics

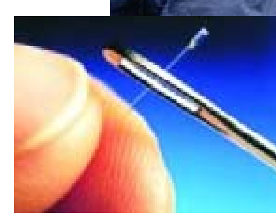
- MEMS Products
- History
- Issues of Scale
- Fabrication Processes
- Reliability & Problems to be solved
- New Applications –Approaches – Problems to be solved

Sandia National Laboratories

MEMS are everywhere!

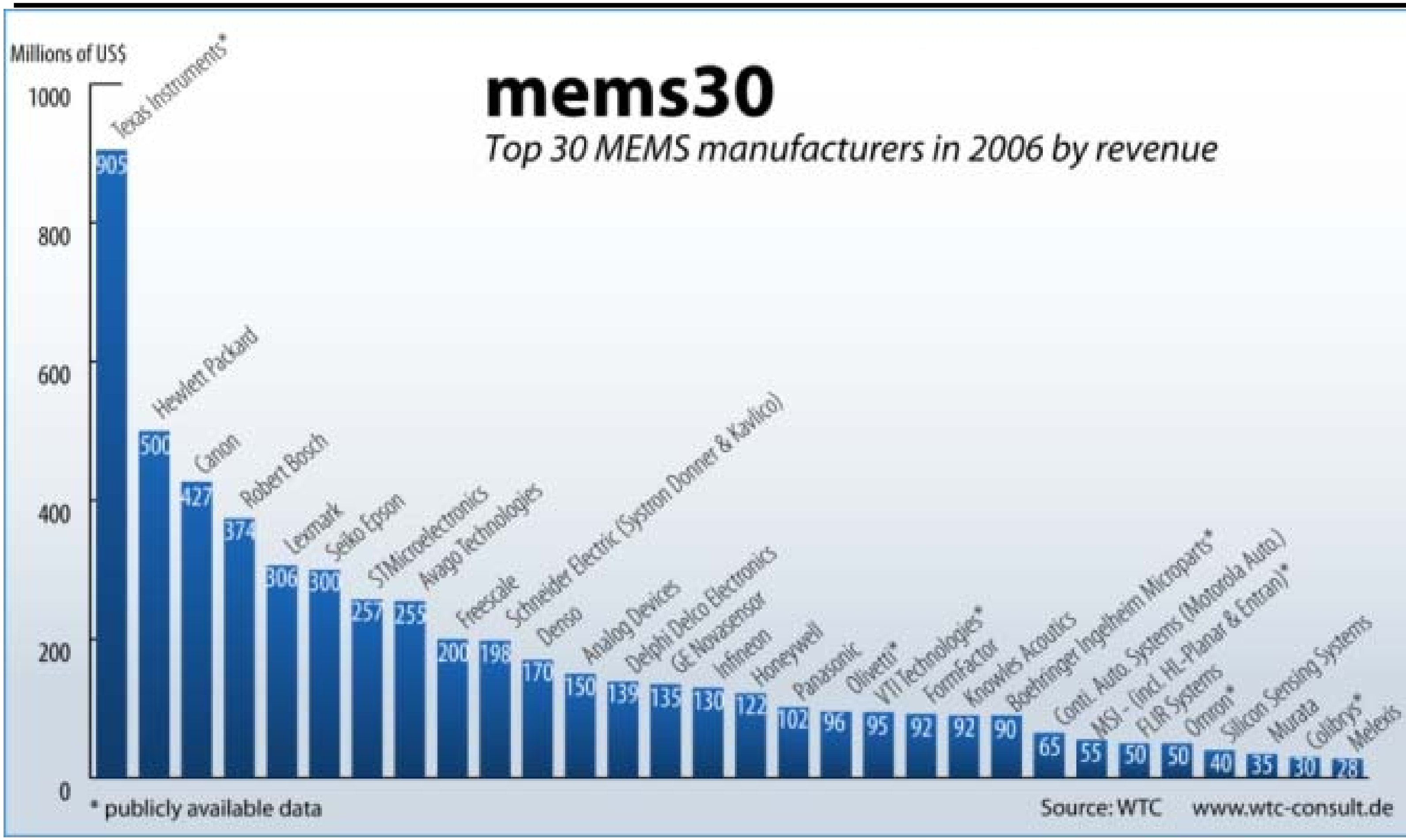


QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



Sandia
National
Laboratories

Top MEMS Manufacturers in 2006



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

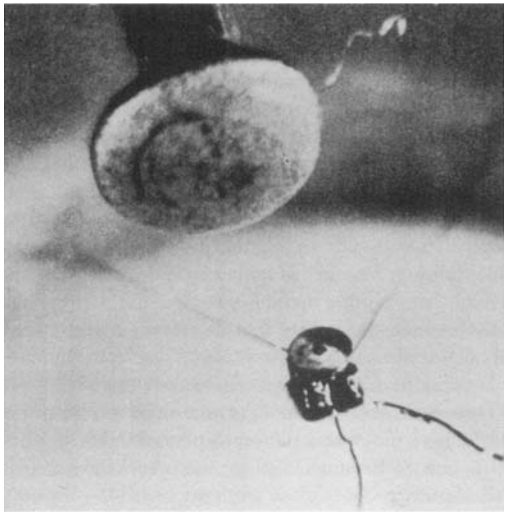
Sandia National Laboratories

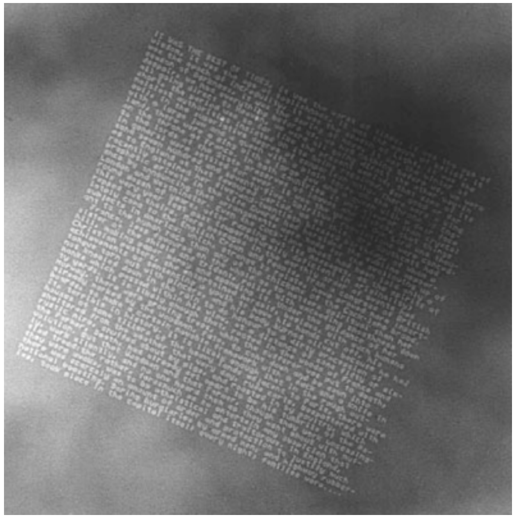
Vision of Micro-Systems

- **“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**

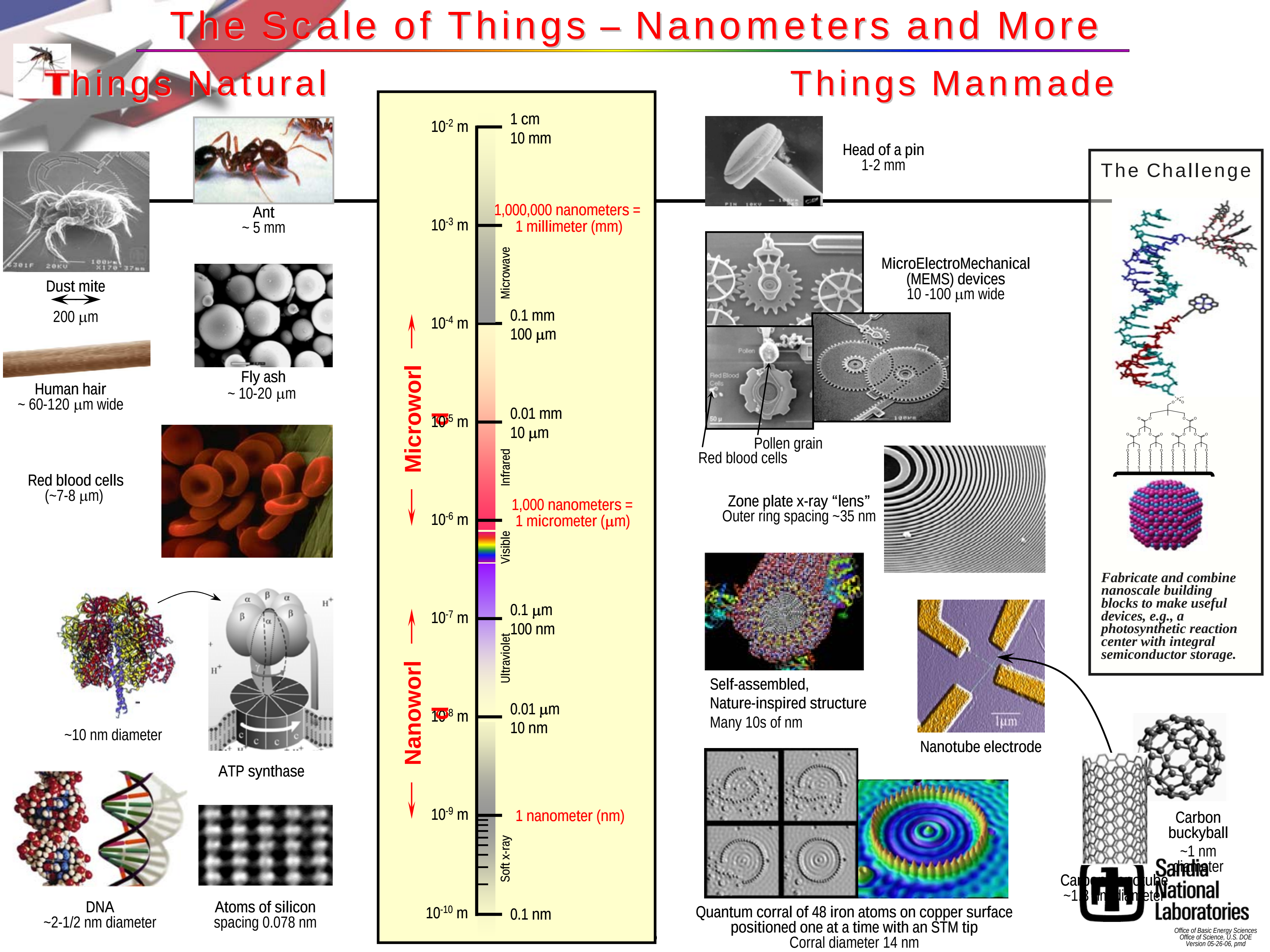
Richard P. Feynman (1918-1988)

William McLellan, 1960



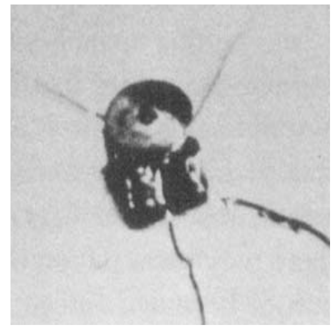


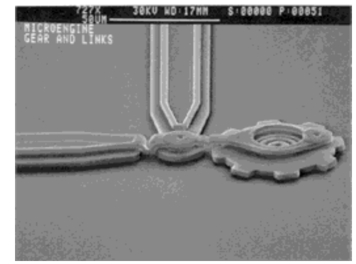
T. Newman, R.F.W. Pease, 1985



The Scale of Things – Nanometers and More
Things Natural
Things Manmade
Ant
~ 5 mm
Dust mite
200 µm
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
10^-7 m
0.1 µm
100 nm
Ultraviolet
Nanoworld
10^-8 m
0.01 µm
10 nm
10^-9 m
1 nanometer (nm)
Soft x-ray
10^-10 m
0.1 nm
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
buckyball
~1 nm
Sandia National Laboratories
Office of Basic Energy Sciences
Office of Science, U.S. DOE
Version 05-26-06, pmd

Effect of Reduction in Scale



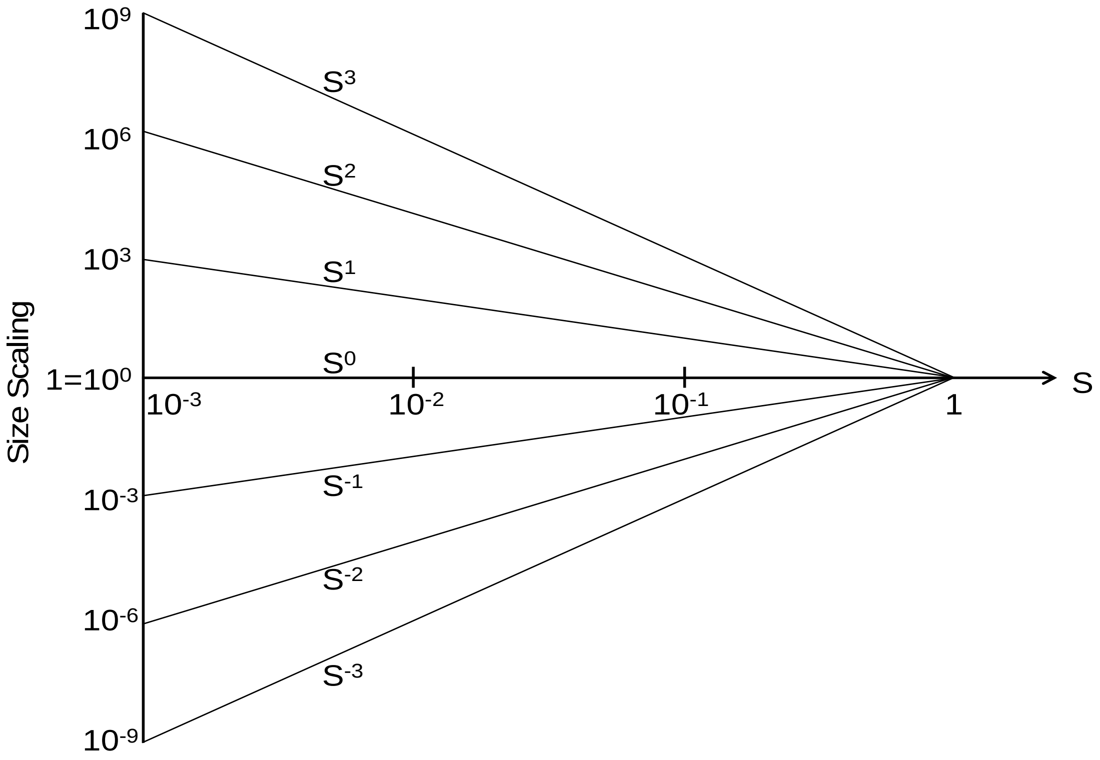


Why does a change is scale matter?

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

Sandia National Laboratories

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

Sandia National Laboratories

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

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

Sandia National Laboratories

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*

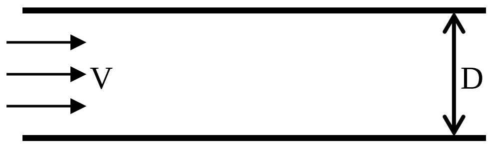
$$\tau = \frac{mc_p}{\kappa A} = \left(\frac{\rho c_p}{\kappa}\right)\left(\frac{V}{A}\right) \propto S$$

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:

$$U_{electric} = \frac{1}{2}\varepsilon E^2 \qquad E_{breakdown}=3MV/M \Rightarrow U_{electric}=40\ J/M^3$$

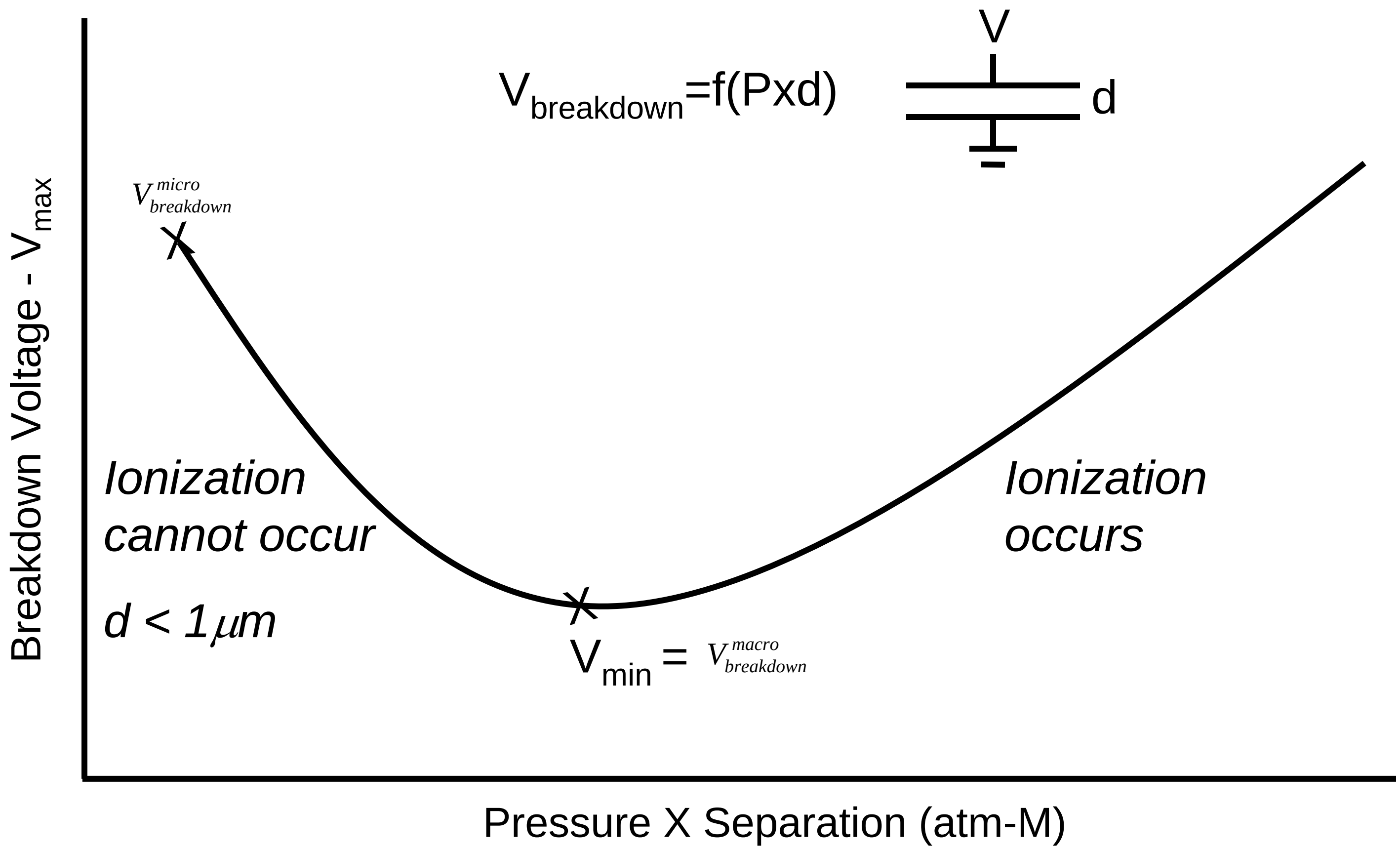
$$U_{magnetic} = \frac{1}{2}\frac{B^2}{\mu} \qquad B_{sat}=1T \Rightarrow U_{mag}=4x10^5\ J/M^3$$

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

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

Sandia National Laboratories

Paschen's Law



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

Scaling of Electrical and Magnetic Fields

$E_{breakdown} = 3x10^8$ V/M for small gap of ~ 1 μm or less

$\therefore \Rightarrow$ $U_{electric} = 4x10^5$ 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

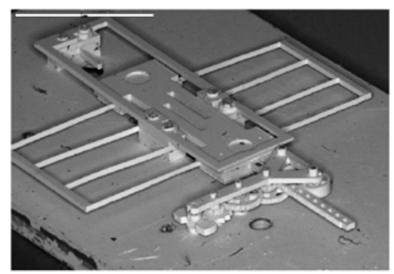
Lateral Dimension (m): 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}

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

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

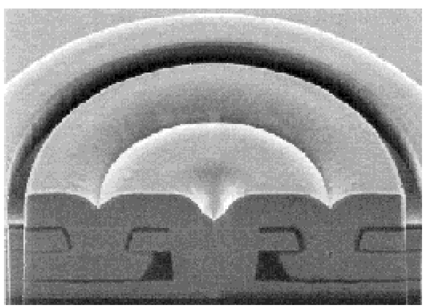
- Materials: Most metals, alloys, and superalloys & most polymers and ceramics
- Processing: One piece at a time
- Assembly: Hand assembly
- Geometry: Full three-dimensionality

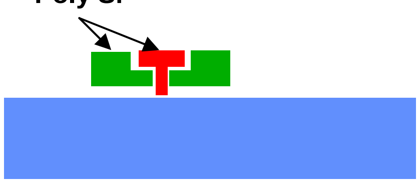
Sandia National Laboratories

Three Dominant MEMS Fabrication Technologies

Surface Micromachining

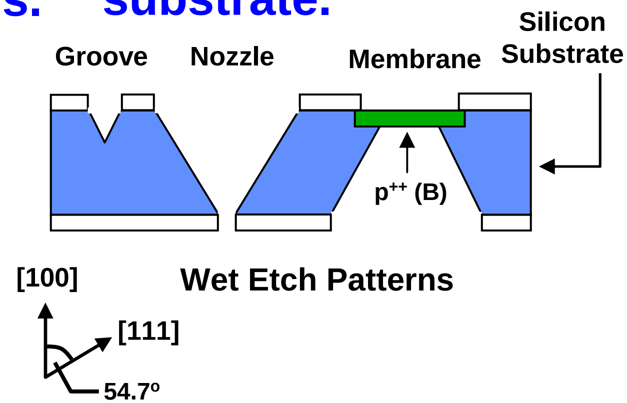
structures formed by deposition and etching of sacrificial and structural thin films.



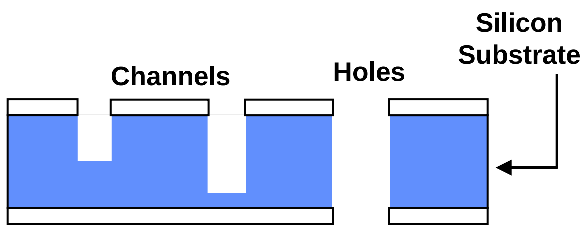


Bulk Micromachining

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



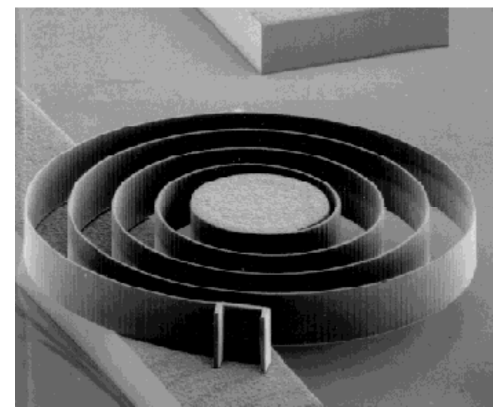
Wet Etch Patterns

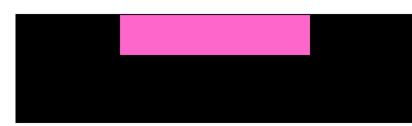


Dry Etch Patterns

LIGA

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





Mold

Sandia National Laboratories

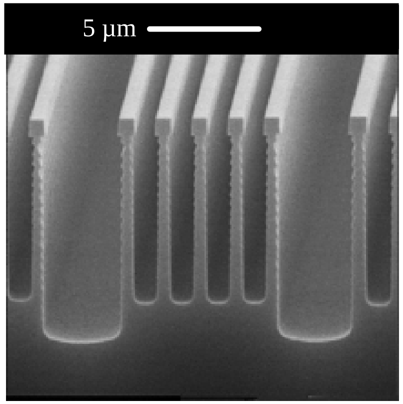
Manufacturing Effect of Reduction in Scale

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

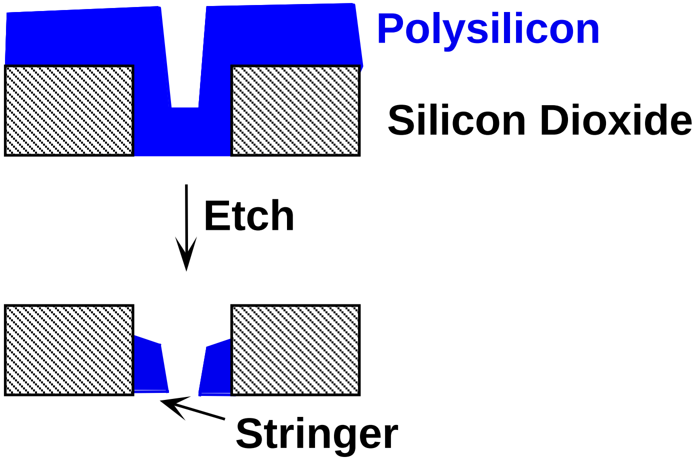
Sandia National Laboratories

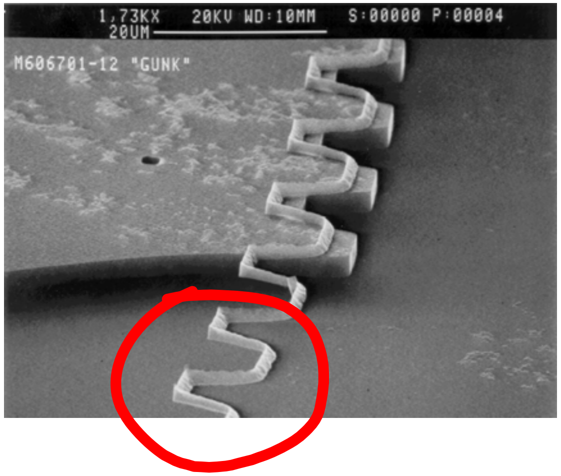
Manufacturing Processes Impose constraints on Design

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

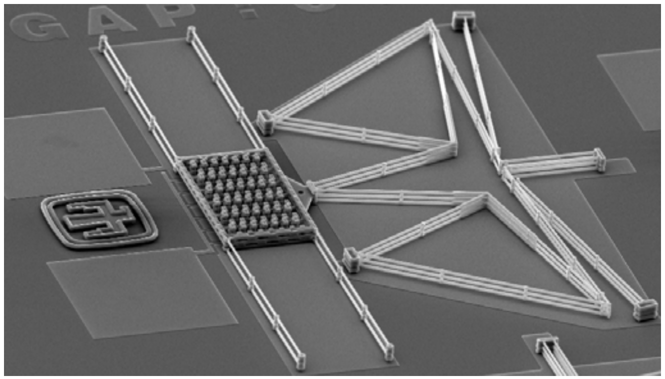


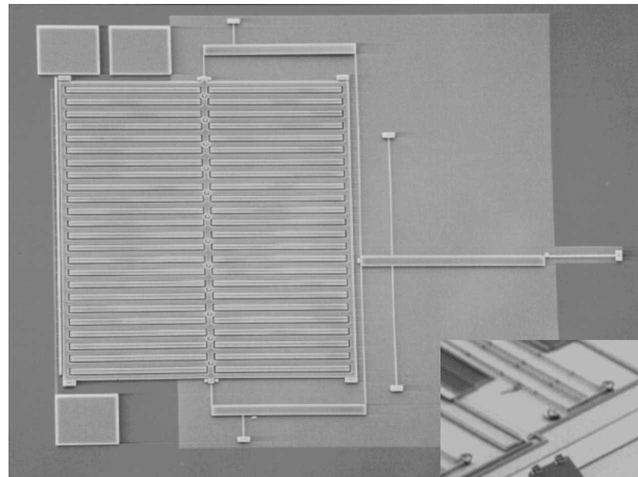
- **Surface Micromachining Example**
  - Stringers

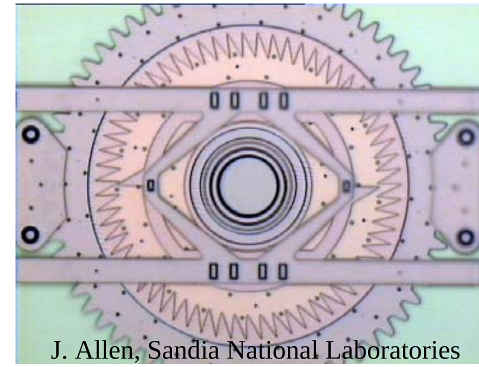


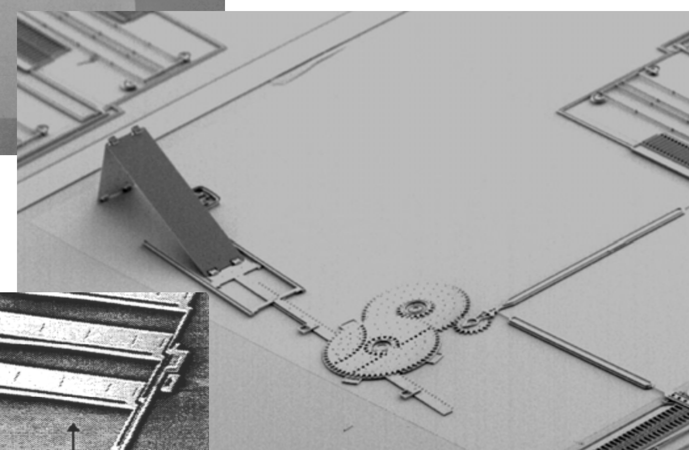


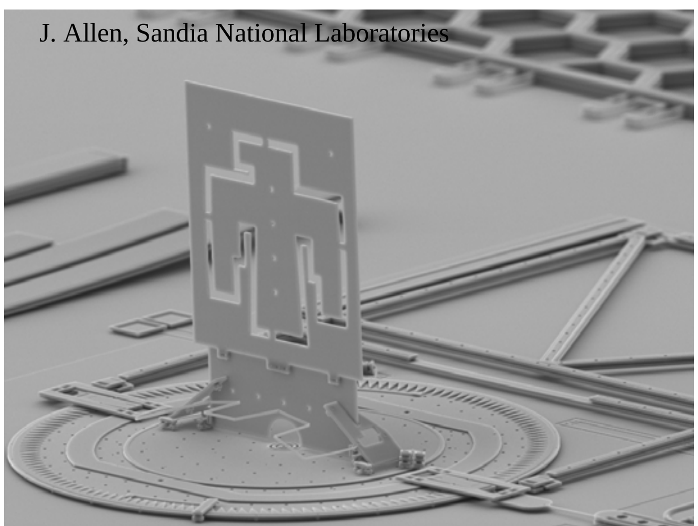
A Variety of Micro Mechanisms are required for Microdevice Applications


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

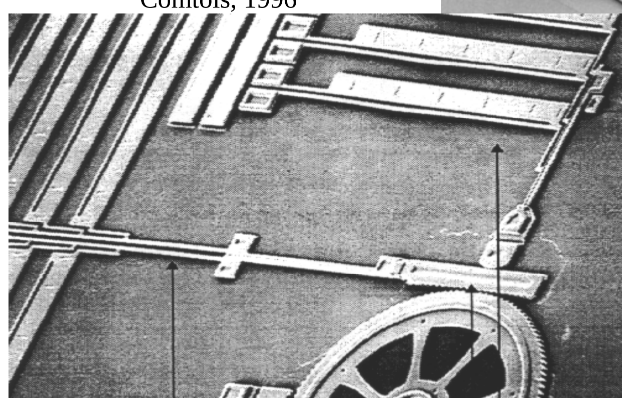



J. Allen, Sandia National Laboratories



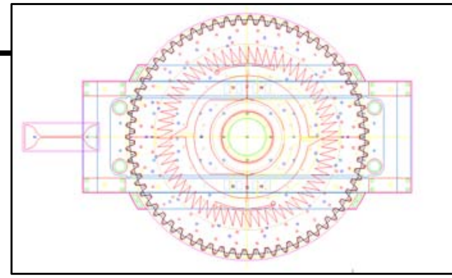

J. Allen, Sandia National Laboratories

Comtois, 1996



Sandia National Laboratories

CAD Tools are Essential to the Design of Microsytems



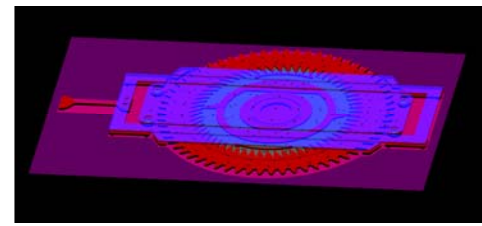
Layout

Initial Design

Visualization

2D Process Visualizer

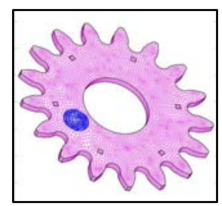
3D Modeler



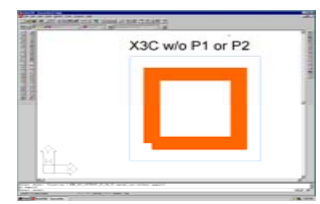
Design Validation

Analysis

Mesh



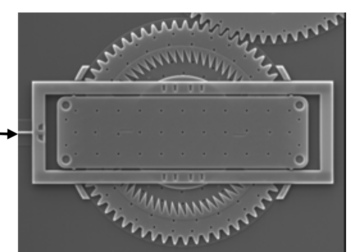
Design Rule checking



Verification

Fabrication Time & Expense demand the availability of these tools

Final Product



Sandia National Laboratories

Reliability Concerns Increase With Complexity

Class I
- No Moving Parts

e.g., Pressure Sensors

Class II
- Moving Parts

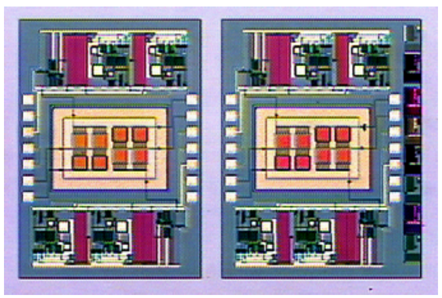
e.g., Accelerometers

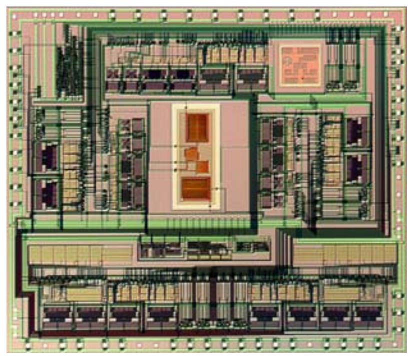
Class III
- Moving Parts
- Impacting Surfaces

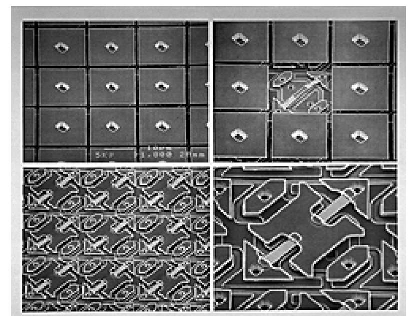
e.g., Tilting Mirrors

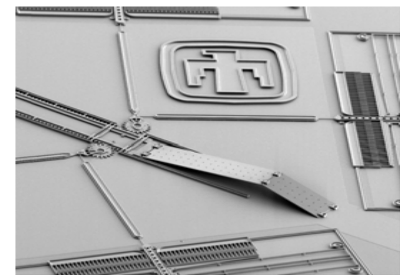
Class IV
- Moving Parts
- Impacting Surfaces
- Rubbing Surfaces

e.g., Gears

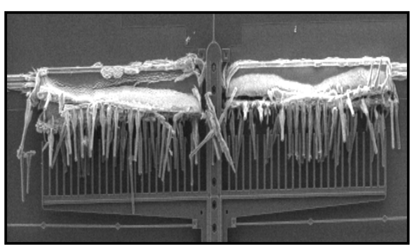


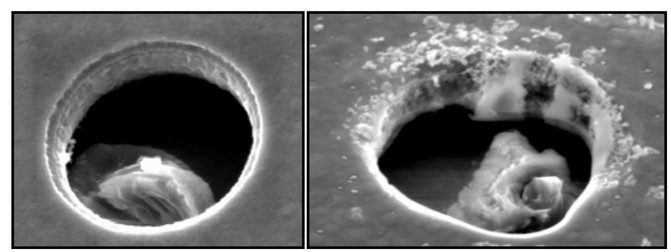






Understand the science of reliability

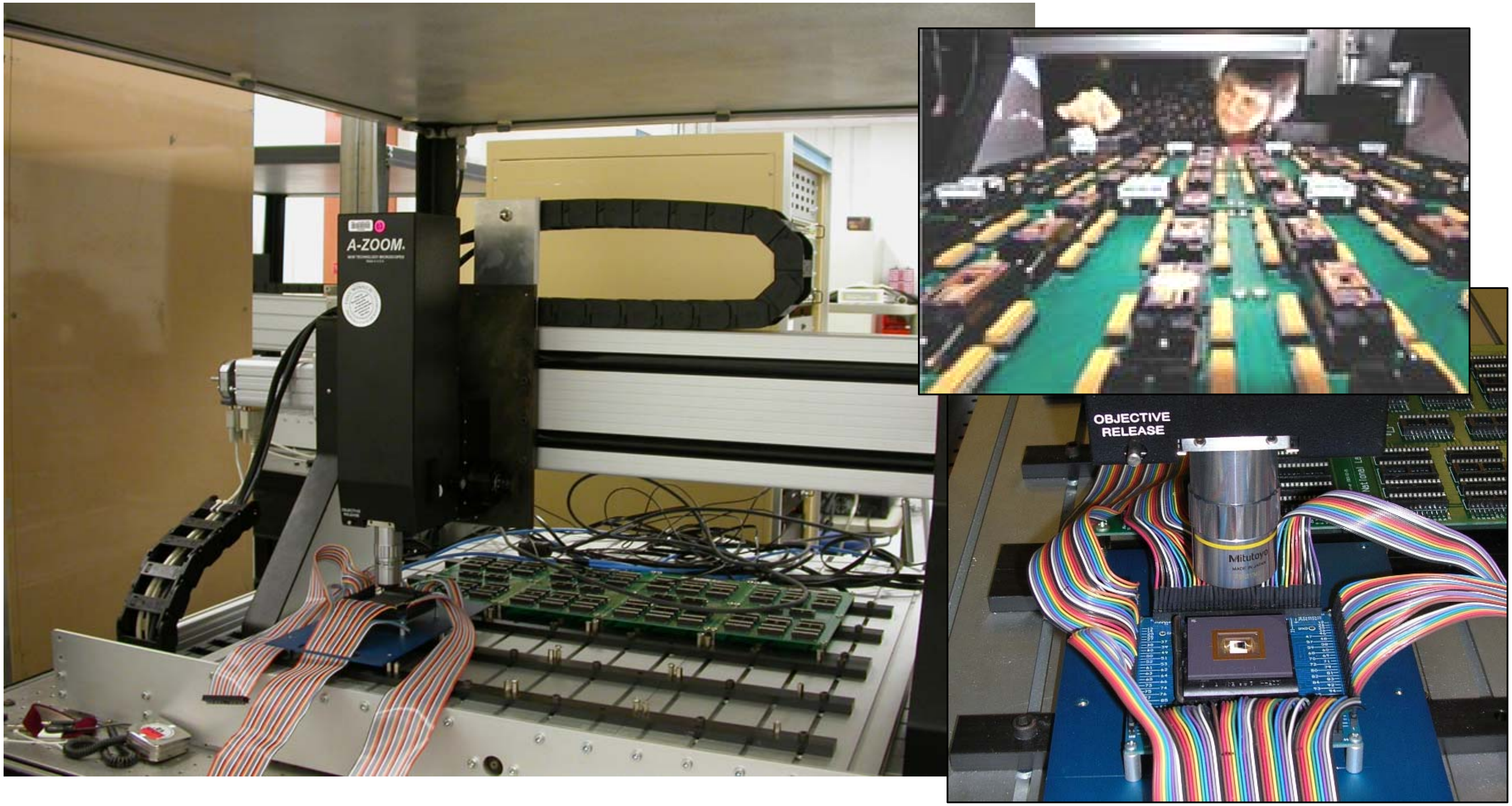




Sandia National Laboratories

Reliability Testing

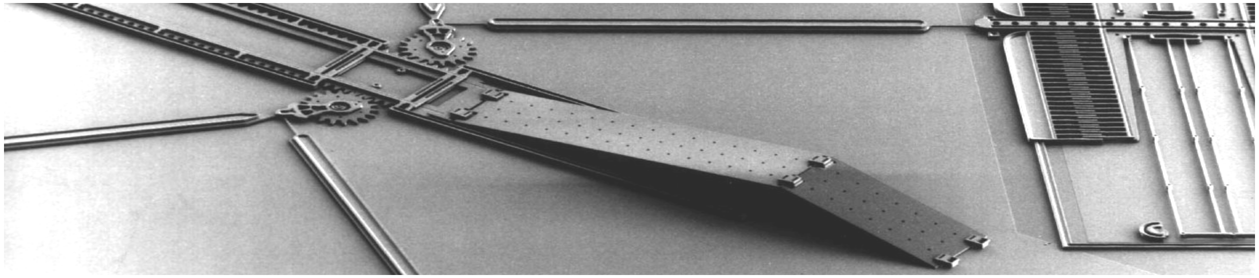
Sandia High-volume Micromachine Measurement of Reliability



Sandia
National
Laboratories

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



Sandia National Laboratories

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

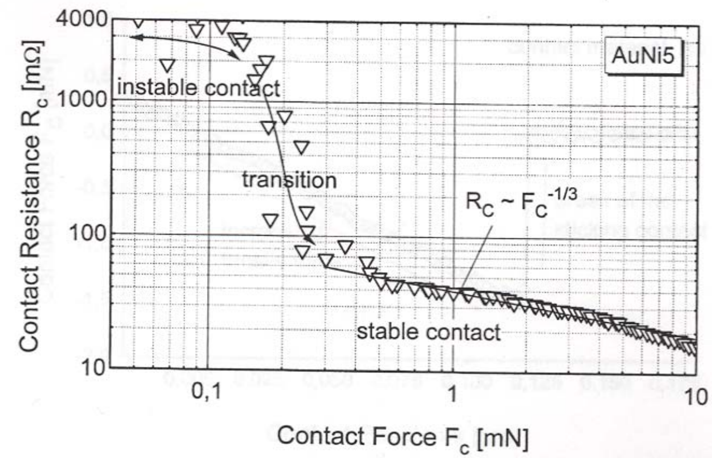
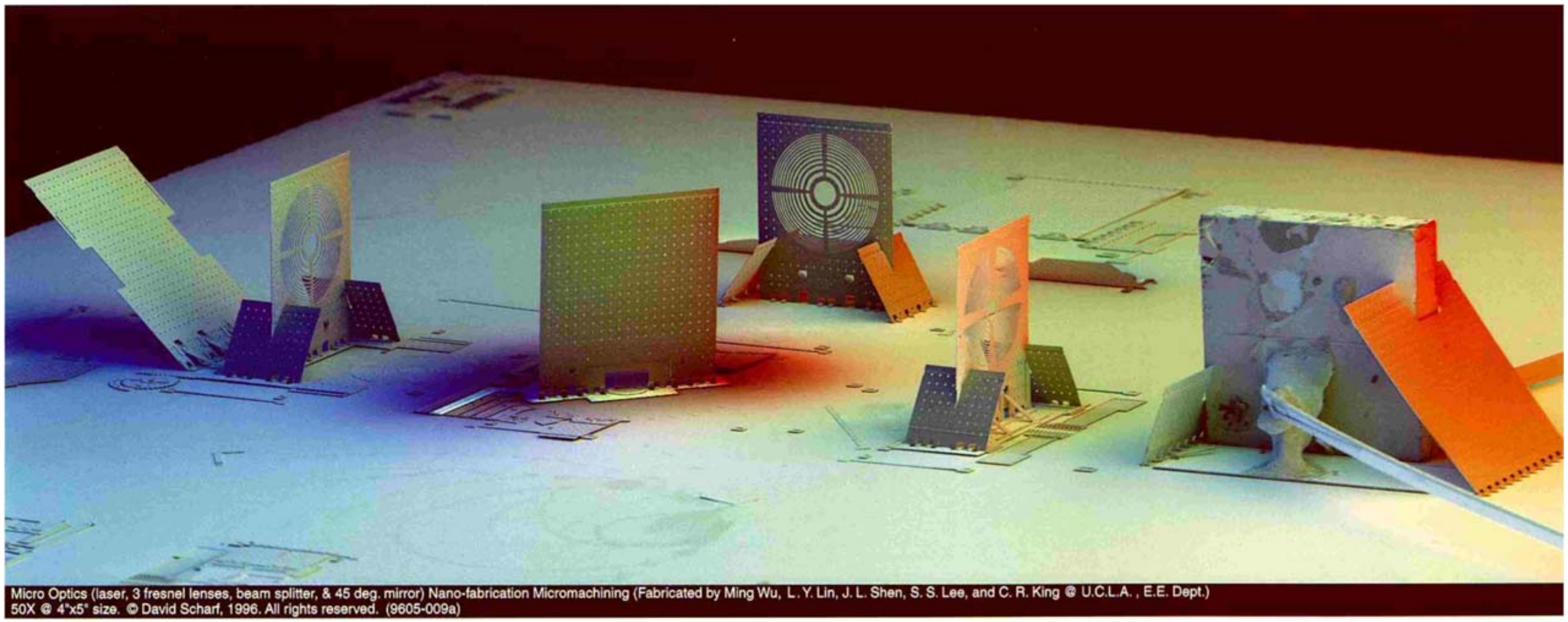


Fig. 4. $R_c - F_c$ characteristics of closing AuNi5 contacts: unstable contact at very low force, transition to lower resistance and the domain of stable contact with the measured resistance force characteristic compared to theoretical relationship according to Holm's model, from Ref. [6].

Optical Bench Example

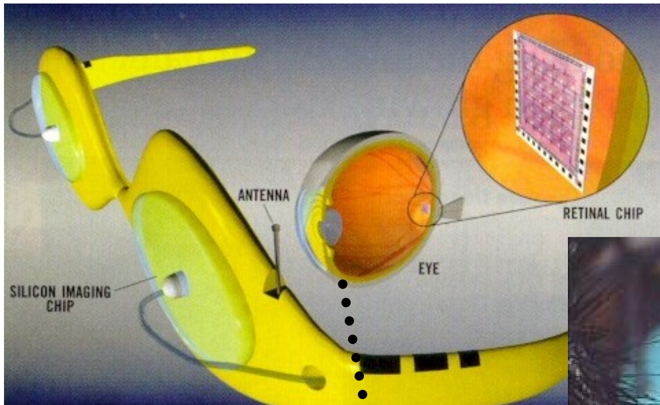


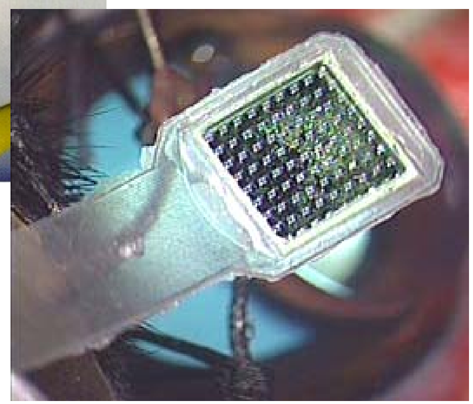
Laser, 3 Fresnel lenses, beam splitter, 45 degree mirror

Dr. Wu, U. of California, Berkley

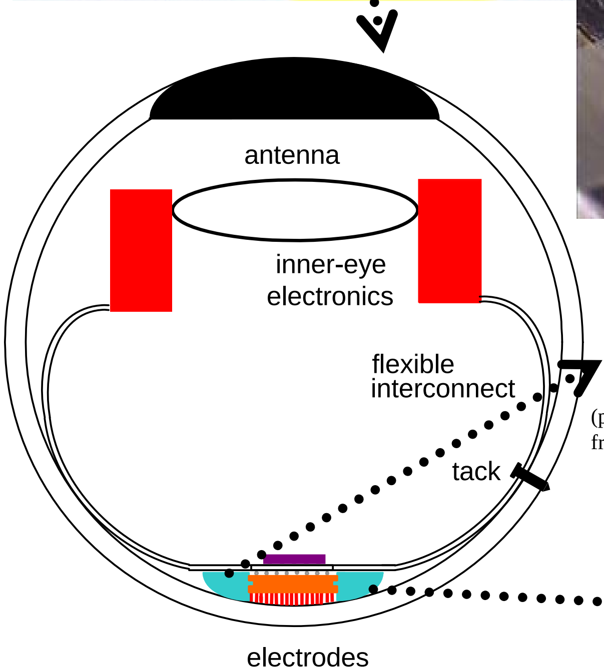
Sandia National Laboratories

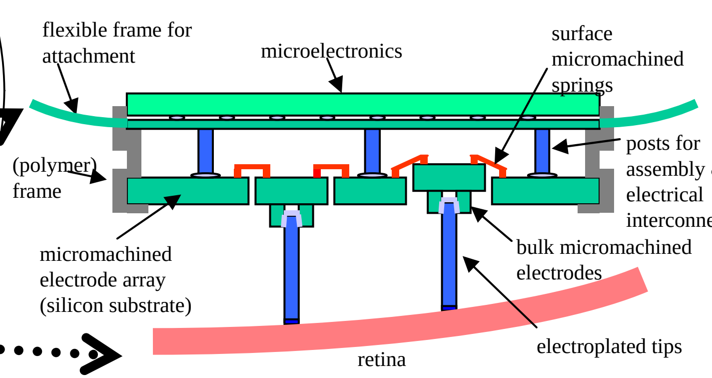
Retinal Implant

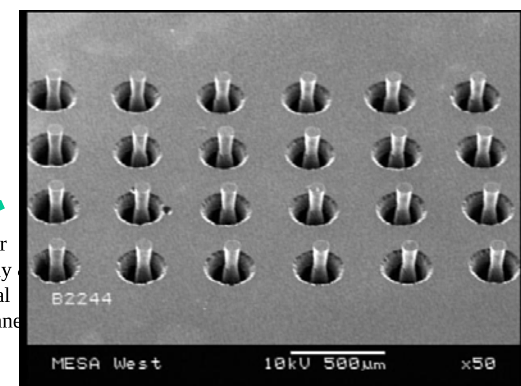




- Electrical stimulation of retinal neurons after light sensitive cells (photoreceptors) are lost.
- Micromachined conformal electrode array provides positive controlled contact with tissue (retina), accommodating overall and local curvature.
- Integrated electronics essential for high electrode count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

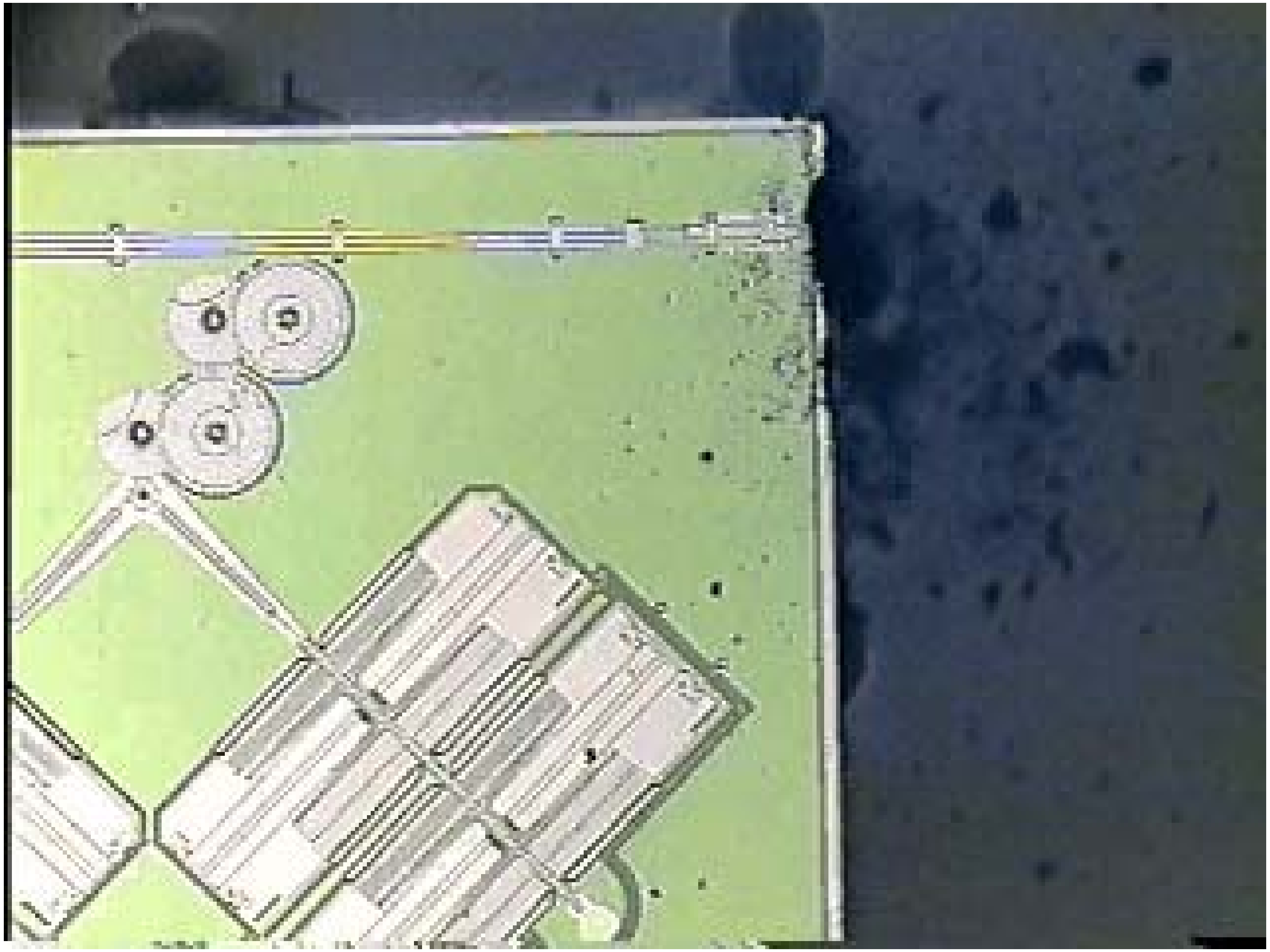




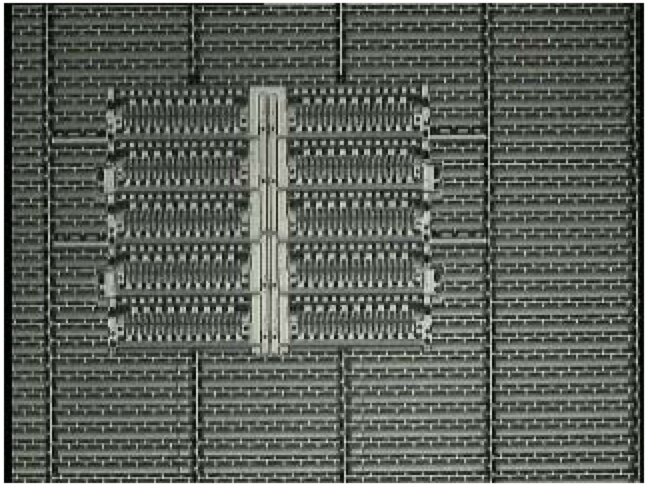


Sandia National Laboratories

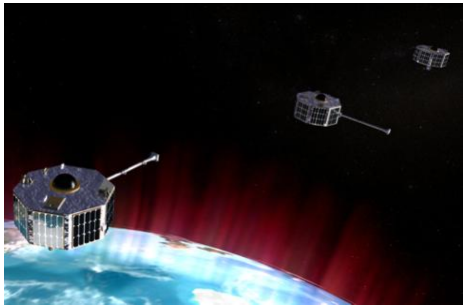
Neural Probes



MEMS Variable Emittance Louvers

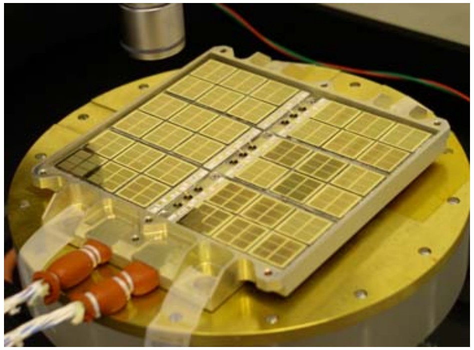


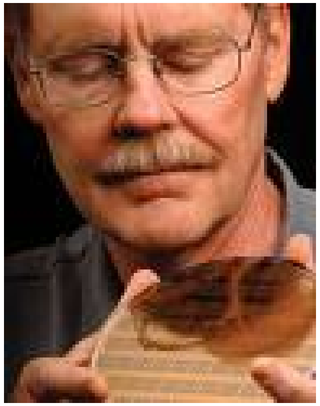
2592 SUMMiT V™ die
with Buried Interconnects



Experimental satellites
monitor space weather

4”x4” Johns Hopkins/APL
Experimental Thermal
Regulator



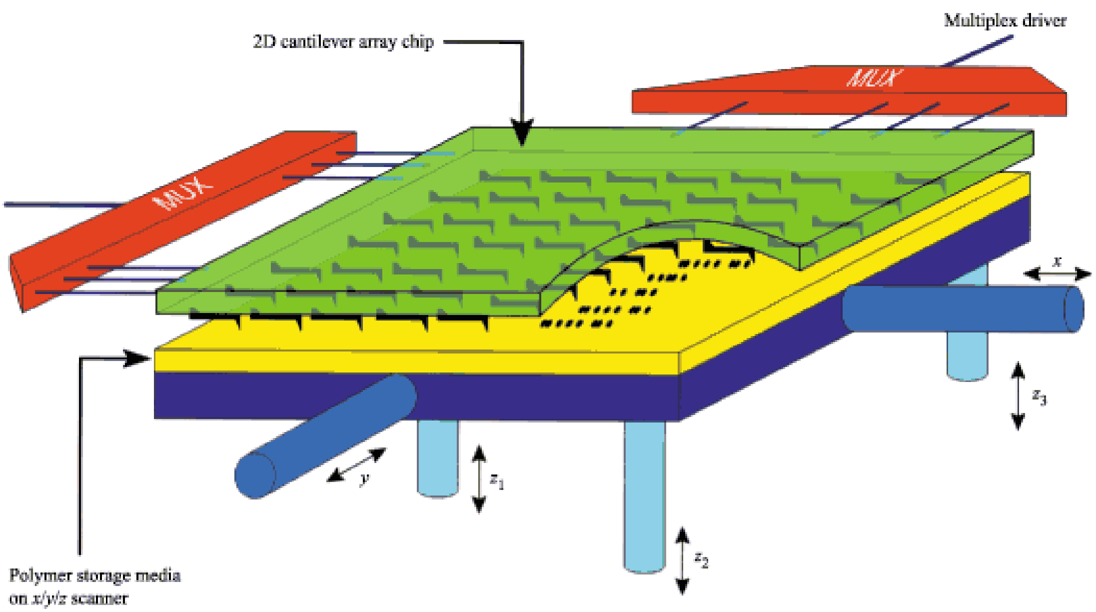


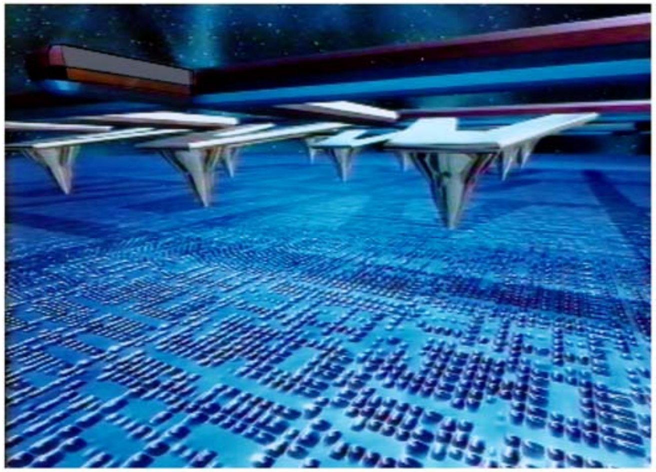
3 NASA/Goodard
ST5 Microsats
Launched 3/22/06

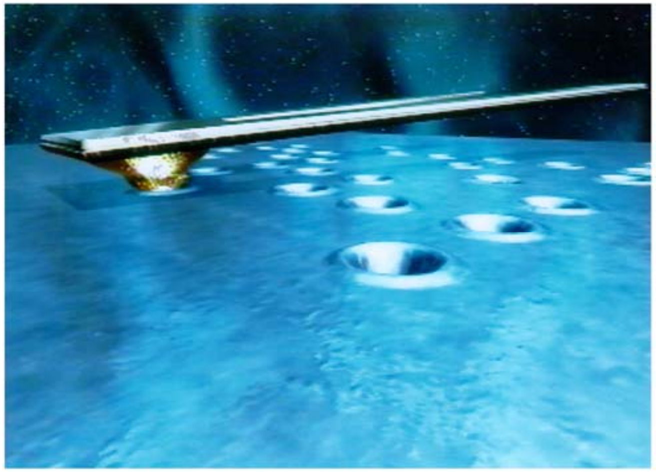
Sandia National Laboratories

IBM Millipede Storage System

- High density data storage possible(Tb/in²)
- 4x Magnetic Media
- AFM tip writes and reads data
- Bit set by melting depression into polymer medium





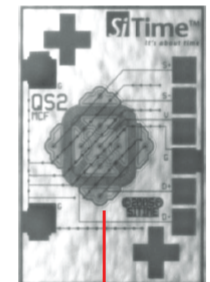


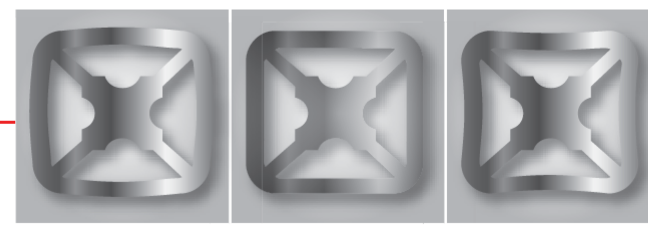
Sandia National Laboratories

SiTime Resonators

SiRes™

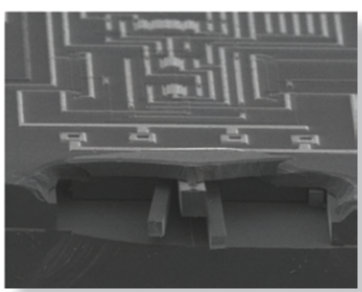
SiTime's revolutionary MEMS First™ technology allows ultra stable mechanical resonators to be integrated into standard silicon chips with performance as good as or better than traditional quartz-based systems.





SiRes™ mechanical resonator vibrating.

Single crystal Si encapsulation layer allows CMOS integration



Sandia National Laboratories

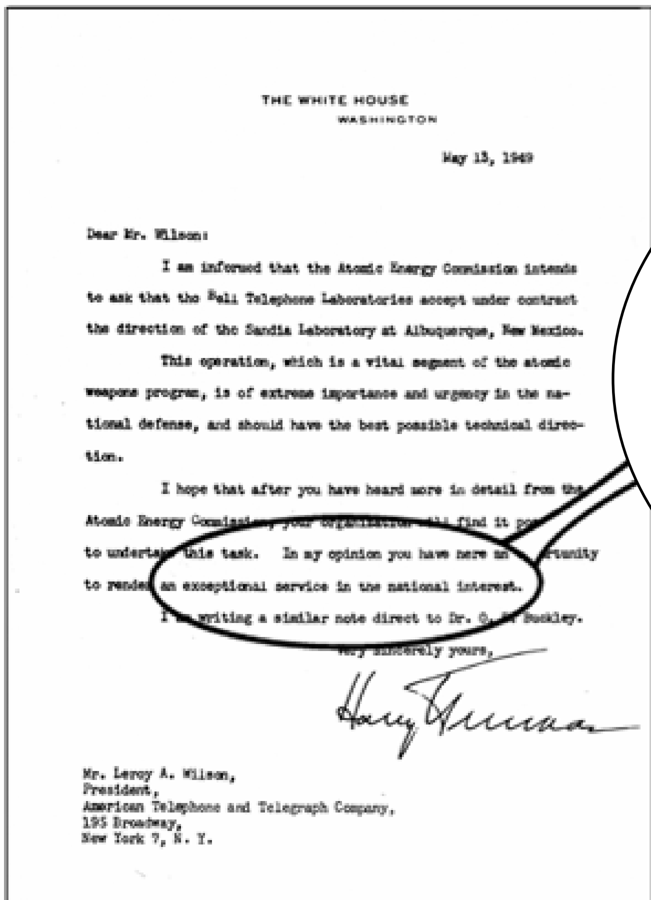
PRISM Center can greatly Impact Microsystem Development

- **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

Sandia was established in 1949 to serve the national defense needs of the nation

"Exceptional Service in the National Interest"



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

Mr. Leroy A. Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

I hope that after you have heard more

in detail from the Atomic Energy Commission,

your organization will find it possible to undertake this task.

In my opinion you have here an opportunity to

render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

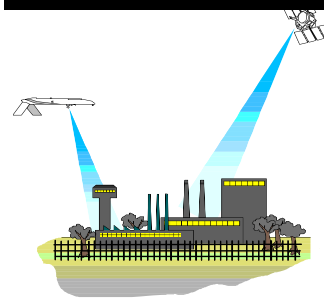
Sandia National Laboratories

Sandia is a National Security Laboratory

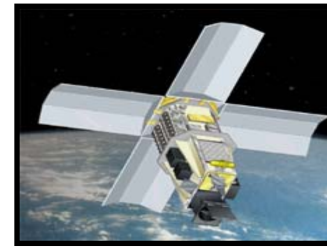
Sustain Nuclear Weapons Stockpile

Safe, Secure, Reliable Weapons

Reduce Vulnerability to Weapons of Mass Destruction



Detection



Surveillance

Advance Surety of Global Infrastructures

Energy

Information

Transportation

Enhance National Security Measures

Architectural Surety

Anti-crime and anti-terrorism technology

Smart Weapons

Sandia National Laboratories

Sandia – in round numbers

- 8,600 full-time employees
  - — ~7,700 in New Mexico
  - — ~ 900 in California
- 800 buildings, 6.1M square feet
- 1,500 Ph.D.'s, 2,700 Masters
  - — 53% engineering
  - — 20% science and mathematics
  - — 16% computing
  - — 6% other fields
- Annual budget >$2 Billion

Sandia National Laboratories