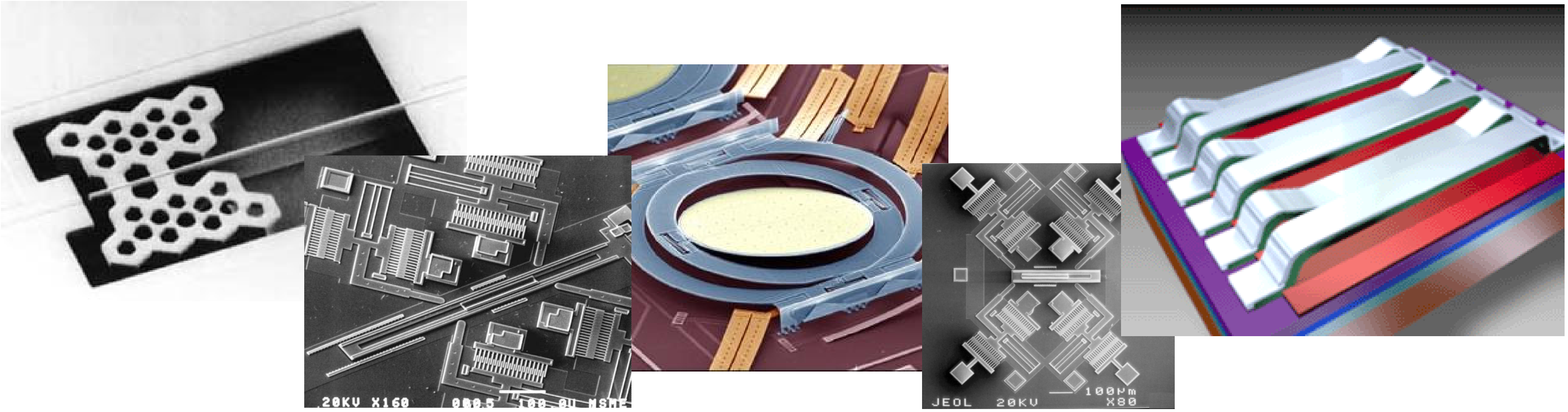
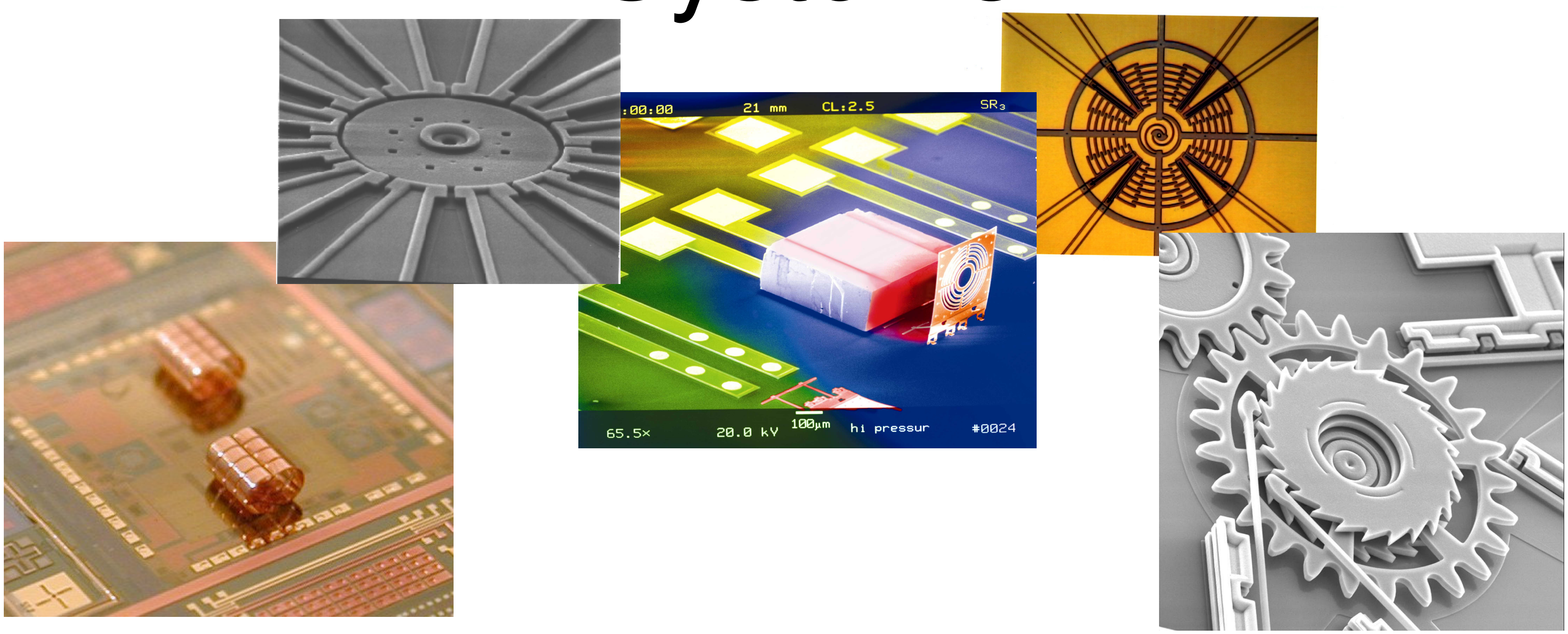


Micro-Electro-Mechanical Systems

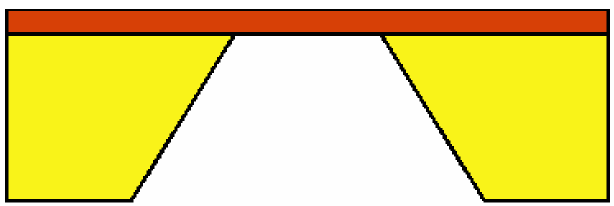


Overview

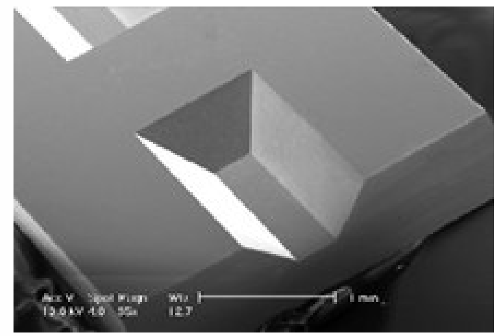
What are MEMS?

- **Micro** - Small size, microfabricated structures
- **Electro** - Electrical signal /control (In / Out)
- **Mechanical** - Mechanical functionality (In / Out)
- **Systems** - Structures, Devices, Systems
  - Control

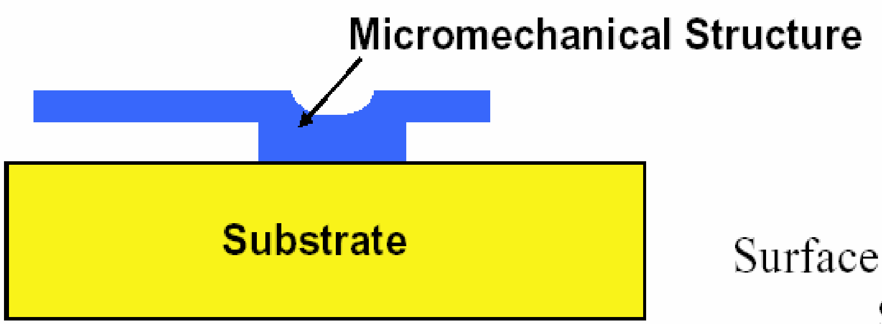
What are MEMS?



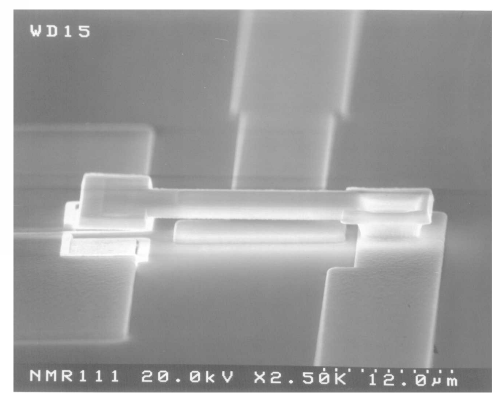
Bulk Micromachining:
Backside etch



Tronics

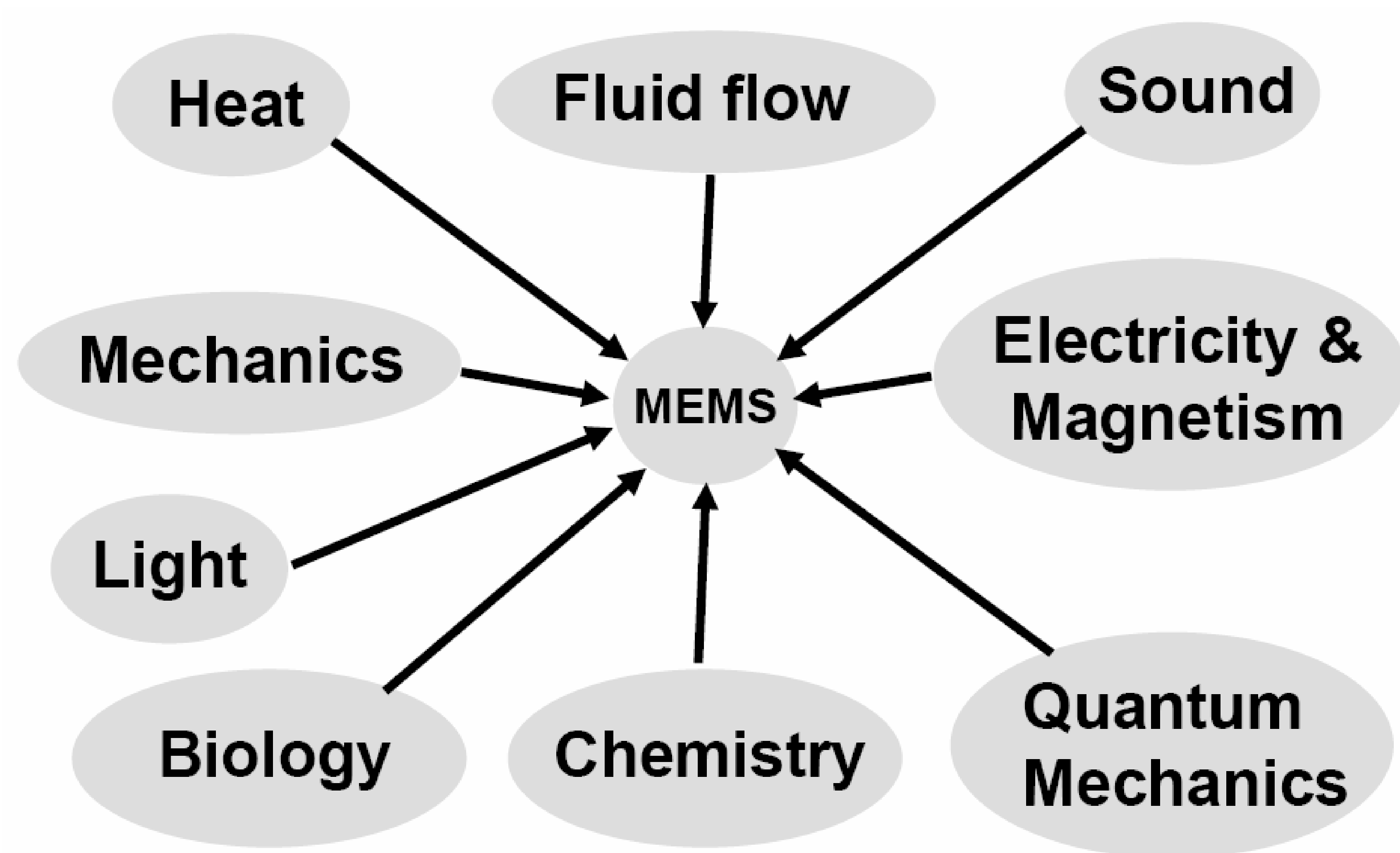


Surface Micromachined
Structure



NMRC

Multidisciplinary



Energy Domains

- **Thermal** (temperature, heat and heat flow)
- **Mechanical** (force, pressure, velocity, acceleration, position)
- **Chemical** (concentration, pH, reaction rate)
- **Magnetic** (field intensity, flux density, magnetization)
- **Radiant** (intensity, wavelength, polarization, phase)
- **Electrical** (voltage, charge, current)

History of MEMS Technology

Richard Feynman "There's Plenty of Room at the Bottom”

- Presentation given December 26,1959 at California Institute of Technology
- Tries to spur innovative miniature fabrication techniques for micromechanics
- Fails to generate a fundamentally new fabrication technique

Westinghouse creates the "Resonant Gate FET" in 1969

- Mechanical curiosity based on new microelectronics fabrication techniques

Bulk-etched silicon wafers used as pressure sensors in 1970’s

Kurt Petersen published -Silicon as a Structural Material in 1982

- Reference for material properties and etching data for silicon

Early experiments in surface-micromachined polysilicon in 1980’s

- First electrostatic comb drive actuators- micropositioning disc drive heads

Micromachining leverages microelectronics industry in late 1980’s

- Widespread experimentation and documentation increases public interest

Scaling

William Trimmer
Belle Mead Research
Robert H. Stroud
The Aerospace Corporation
Adapted from the CRC Handbook

Surface to Volume Ratio

Surface area of a sphere

$$4\pi r^2$$

Volume of a sphere

$$\frac{4}{3}\pi r^3$$

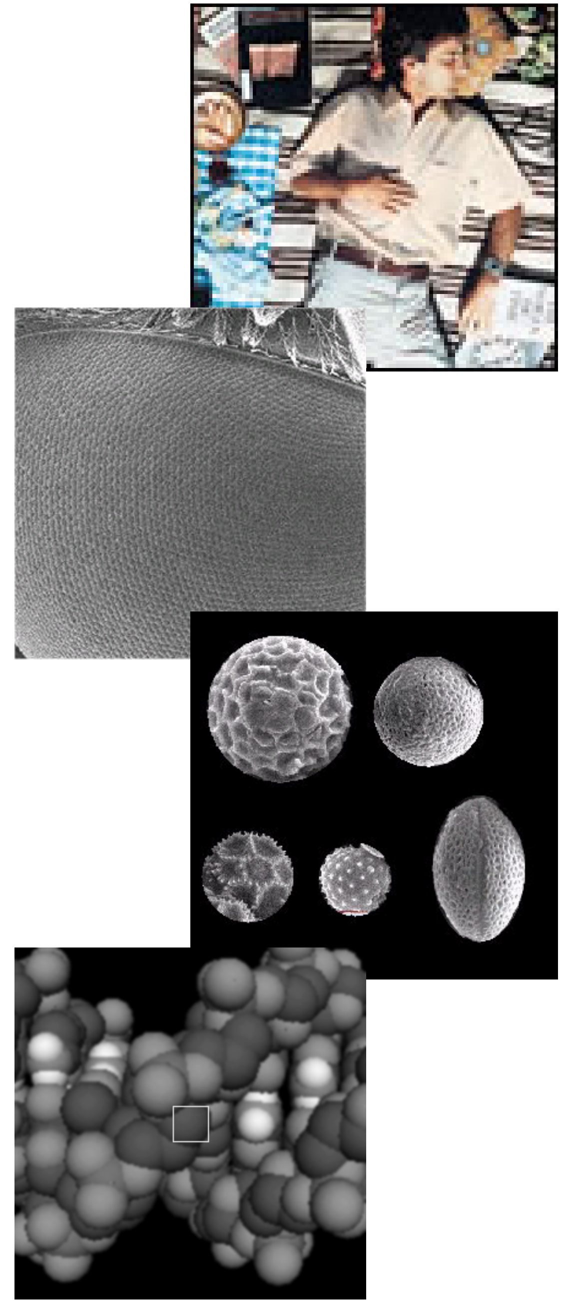
Surface to volume ratio of a sphere

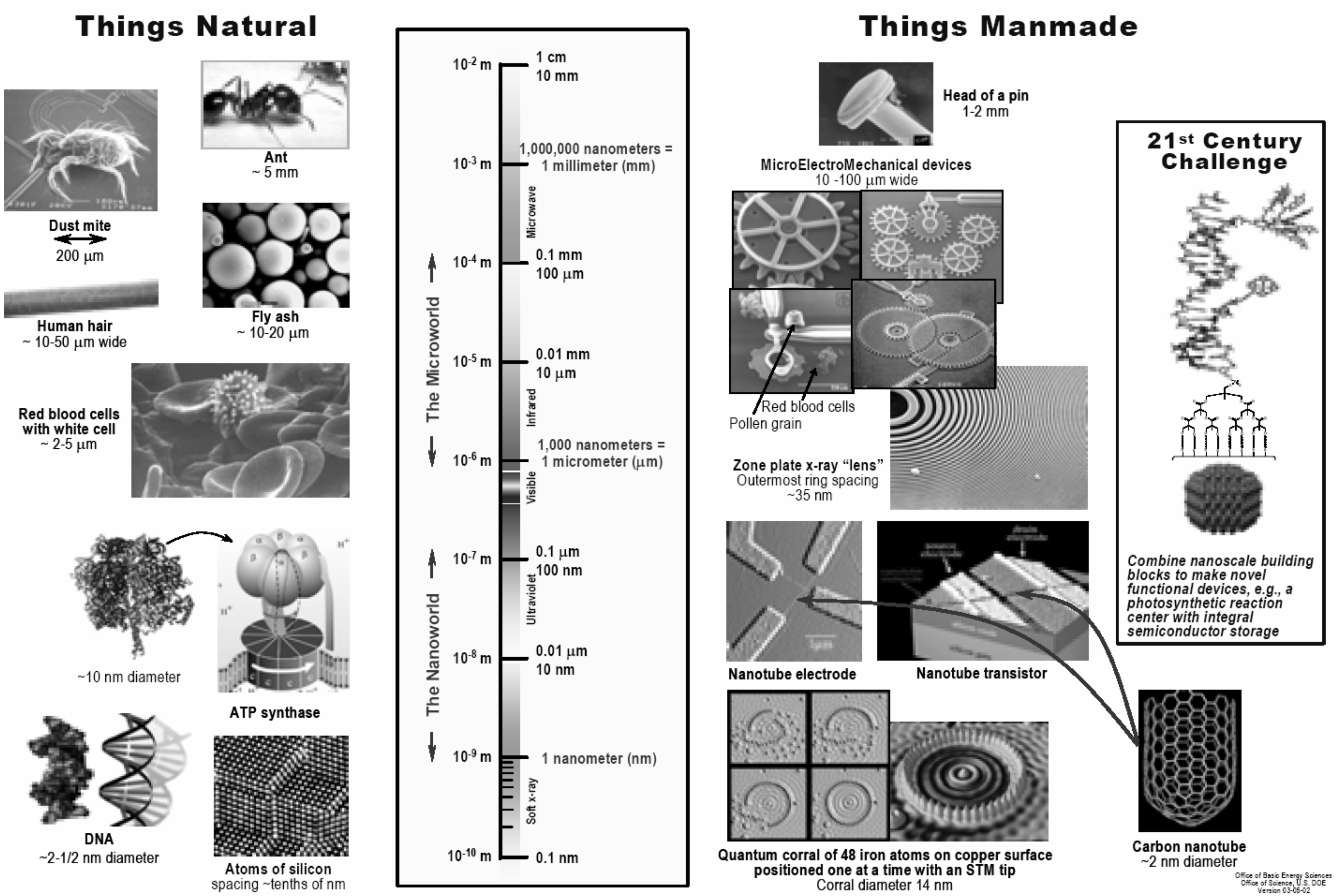
$$4\pi r^2 \Big/ \frac{4}{3}\pi r^3 = 3/r$$

Scaling

Surface to volume ratio
varies as 1/r:

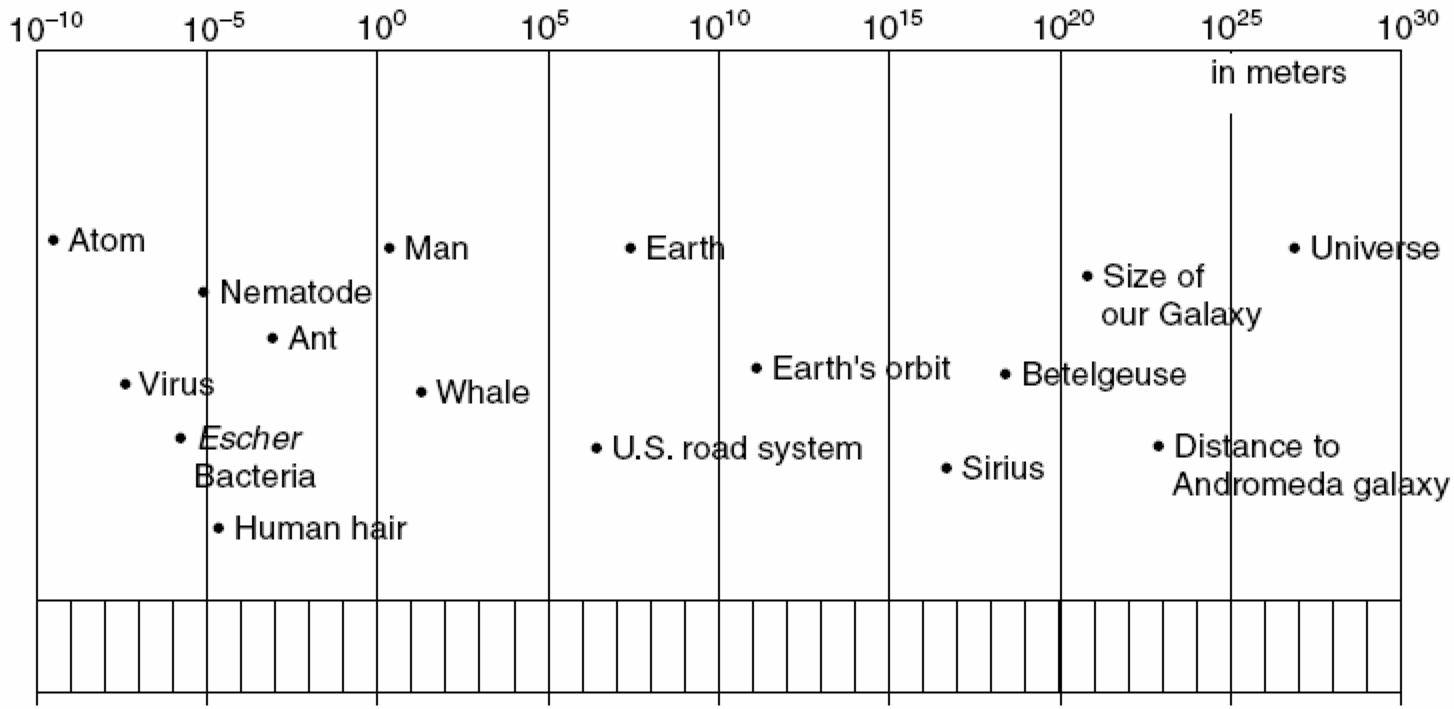
Length	*1/r (meters^{-1})*
• 1 meter	1
• 1 mm	1,000
• 1 μm	1,000,000
• 1 nm	1,000,000,000





Cheng-Hsien Liu, NTHU

Log Plot


10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}
10^{15}
10^{20}
10^{25}
10^{30}
in meters
Atom
Nematode
Ant
Virus
Escher Bacteria
Human hair
Man
Whale
Earth
U.S. road system
Earth's orbit
Sirius
Betelgeuse
Size of our Galaxy
Distance to Andromeda galaxy
Universe

Scaling of Volume

If we scale the physical dimensions by a scale factor S, then:

$L_{new} = S*L_{old}$

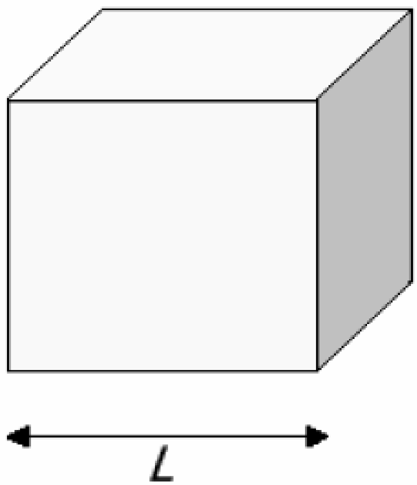
$W_{new} = S*W_{old}$

$H_{new} = S*H_{old}$

We say volume scales as S^3:

$$V = L * W * H \propto S^3$$

Scaling



- Surface area $A \propto L^2 \quad \rightarrow \quad S^2$
- Volume $V \propto L^3 \quad \rightarrow \quad S^3$
- Mass (weight) $m = \rho V \propto L^3 \quad S^3$
- Moment of inertia $I \propto mR^2 = L^5 \quad S^5$
- Torque (weight acting on a moment arm) $\tau = R \times mg \propto L^4$

S^4

Cheng-Hsien Liu, NTHU

Scaling of Forces

- The force due to surface tension scales as S^1
- The force due to electrostatics with constant field scales as S^2
- The force due to certain magnetic forces scales as S^3
- Gravitational forces scale as S^4

Water Bug

The weight of the water bug scales as the volume, or S^3, while the force used to support the bug scales as the surface tension (S^1) times the distance around the bug's foot (S^1), and the force on the bug's foot scales as $S^1 \times S^1 = S^2$

When the scale size, S, decreases, the weight decreases more rapidly than the surface tension forces. Changing from a 2-m-sized man to a 2-mm-sized bug decreases the weight by a factor of a billion, while the surface tension force decreases by only a factor of a million. Hence, the bug can walk on water.

Water Bug

Gravitational Force

$$F = G\frac{M_1 M_2}{r^2} = G\frac{(\rho_1 V_1)(\rho_2 V_2)}{r^2} \propto (G\rho_1\rho_2)\frac{S^3 S^3}{S^2} = S^4$$

Gravitational Potential Energy

Gravitational potential energy scales as S^4. If the dimensions of a system are scaled from meters (human size) to 0.1 mm (ant size), the gravitational potential energy scales as:

$$(1/10000)^4 = 1/10{,}000{,}000{,}000{,}000{,}000$$

The potential energy decreases by a factor of ten trillion. This is why an ant can walk away from a fall that is 10 times it's height, and we do not!

Gravitational Potential Energy

NASA says tiny nematode worms that were aboard the space shuttle Columbia when it exploded were recovered alive in Texas.

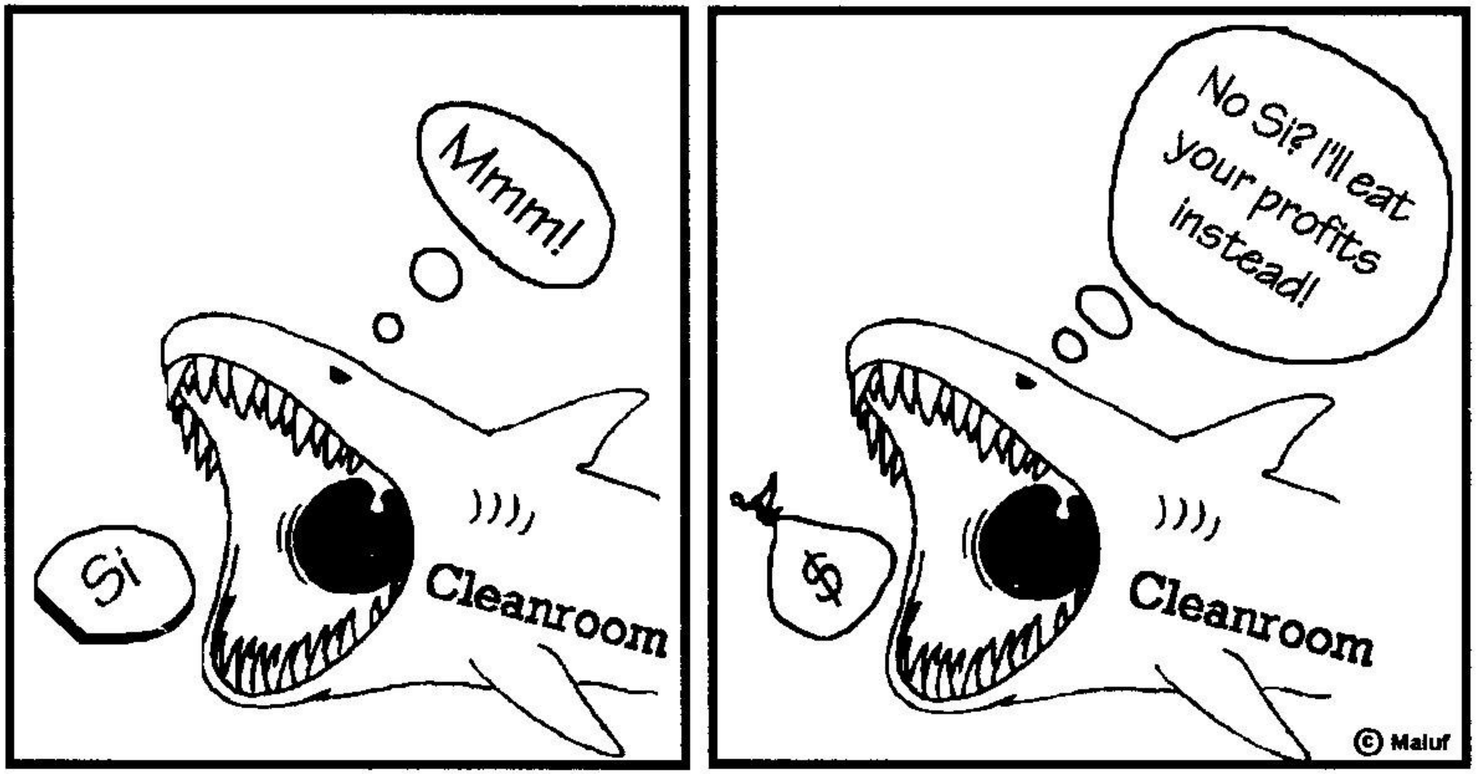
When Columbia broke up the morning of Feb. 1, 2003, the nematode canisters plunged from the orbiter at speeds up to 650 mph and hit the ground with an impact 2,295 times the force of Earth's gravity.

Why Micromachine?

Why Micromachine?

- Minimize energy and materials use in manufacturing
- Redundancy and arrays
- Integration with electronics
- Reduction of power budget
- Faster devices
- Increased selectivity and sensitivity
- Exploitation of new effects through the breakdown of continuum theory in the micro-domain
- Cost/performance advantages
- Improved reproducibility (batch fabrication)
- Improved accuracy and reliability
- Minimally invasive (e.g. pill camera)

Batch Fabrication



Volume manufacturing is essential for maintaining profitability

Nadim Maluf, An introduction to
Microelectromechanical Systems Engineering

Factors to Consider

- Establish need in light of conventional approaches (faster, smaller, cheaper)
  - Does the MEMS solution provide a significant cost reduction?
  - Does it enable a new function or level of performance that cannot be achieved otherwise?
  - Does the market justify the development of a MEMS approach? Can conventional machining or plastic molding techniques be used?
  - Does the cost analysis include package & test?
- Understand the basic physics and operating principles, including scaling laws
  - Increased surface-to-volume ratio
  - Actuation forces
  - Thermal transport
- Understand the important issues in designing macroscopic and microscopic solutions

Factors to Consider

- Survey prior working micromachined versions as well as natural (biological) analogs
  - Don’t re-invent the wheel
  - 3.5 Billion years of natural selection allows for a lot of trial and error!
- Consider the need to integrate on-chip circuitry
  - Hybrid or monolithic?
  - Fabrication tradeoffs
- Can you use an existing “standard” process?
  - If not, can you design a simple and reasonably priced fabrication process?

Factors to Consider

- Consider the issues of packaging at the outset:
  - Can existing packages be used or adapted?
  - Reliability issues (e.g. hermetically sealed)?
- Consider the issues of testing:
  - What tests are required (Telcordia, NIH)?
  - How will the testing be done?
- Estimate the final cost of the ready-to-use device
  - Difficult to get cost data out of foundry for custom process. Will depend sensitively on volume and yield. This is really difficult to access!
  - Include the cost of packaging
  - Include the cost of testing

Example: Tire Pressure Monitoring

- The U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) is proposing a new safety standard to warn the driver when a tire is significantly under-inflated
- The proposal requires manufacturers to install a four-tire Tire Pressure Monitoring System that is capable of detecting when a tire is more than 25 percent under-inflated and warning the driver
- The federal mandate is expected to cover the 16 million new vehicles sold in North America every year, each of which typically has five tires (including the spare). That means that suppliers might sell 80 million semiconductor chips and pressure sensors annually

Tire Pressure Monitoring

- Establish need in light of conventional approaches (faster, smaller, cheaper)
  - MEMS pressure sensors are known technology in the automotive sector (e.g. MAP sensor)
- Understand the basic physics and operating principles, including scaling laws
  - The basic physics and operating principals of pressure sensors are well known
  - How do you supply the power to the sensor? Battery? Inductive? Energy scavenging?
- Understand the important issues in designing macroscopic and microscopic solutions
  - Issues in designing microscopic pressure sensors well understood after 25+ years of development and manufacturing

Tire Pressure Monitoring

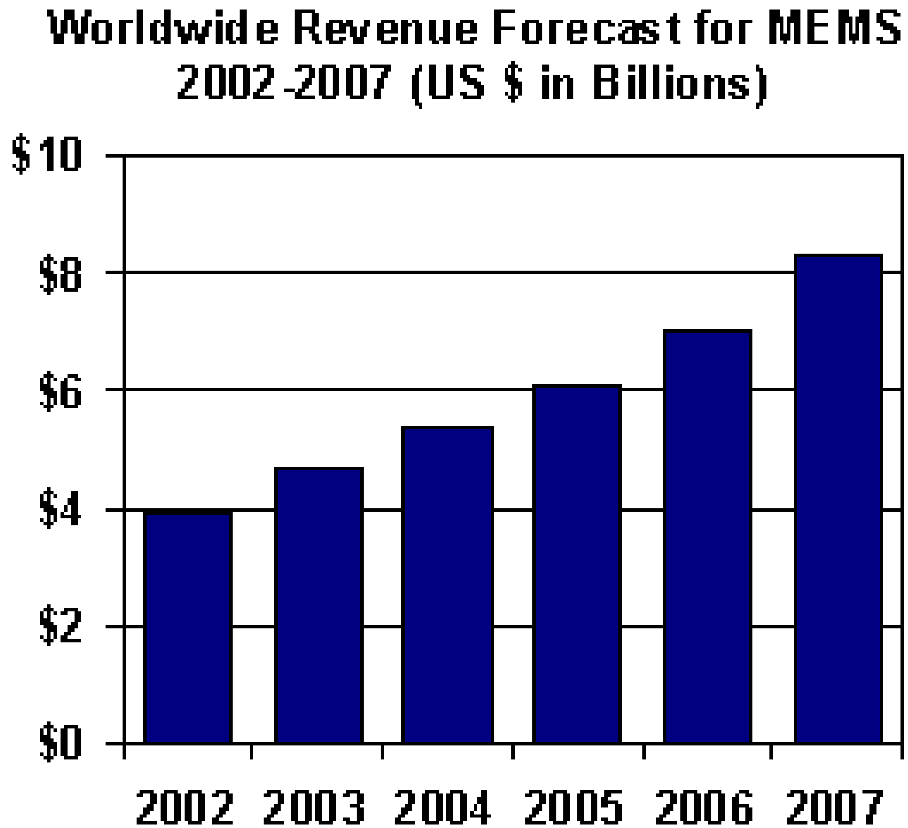
- Survey prior working micromachined versions as well as natural (biological) analogs
  - Many examples of micromachined pressure sensors to study
  - The ear is a natural pressure sensor and works by the same principal; deflection of a membrane
- Consider the need to integrate on-chip circuitry
  - Both monolithic and hybrid integration has been demonstrated
  - Likely to require integrated RF for communications
- Can you use an existing “standard” process?
  - Standard bulk and surface micromachining processes have been used to fabricate pressure sensors

Tire Pressure Monitoring

- Consider the issues of packaging at the outset:
  - Can existing packages be used or adapted? Likely
  - Reliability issues (e.g. hermetically sealed)? Where will the pressure sensor be located? On the valve stem? In the tire?
- Consider the issues of testing:
  - What tests are required by The U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA)?
  - Likely to be less burdensome than NIH testing for human applications
  - How will the testing be done?
- Estimate the final cost of the ready-to-use device
  - Use prior data for MAP sensor and include the cost of packaging and testing

MEMS Markets

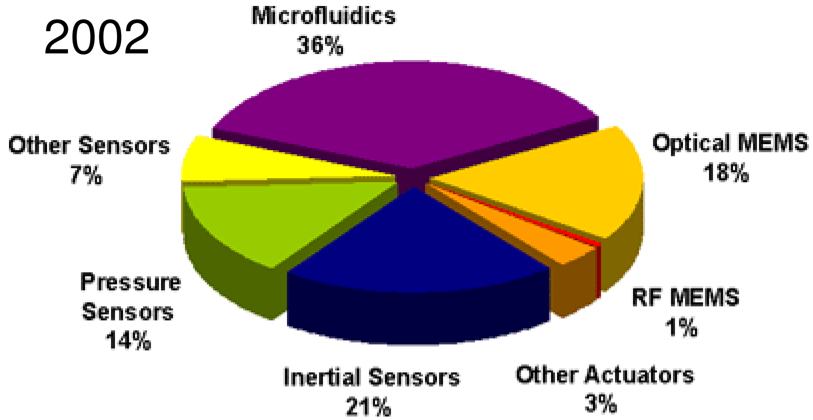
Total MEMS Revenue 2002-2007



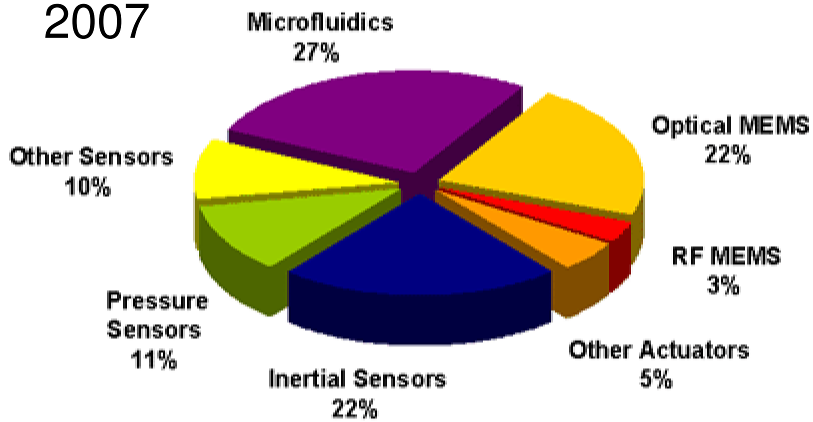
Source: In-Stat/MDR, 7/03

Share of MEMS Revenues by Device, 2002 vs. 2007

2002



2007

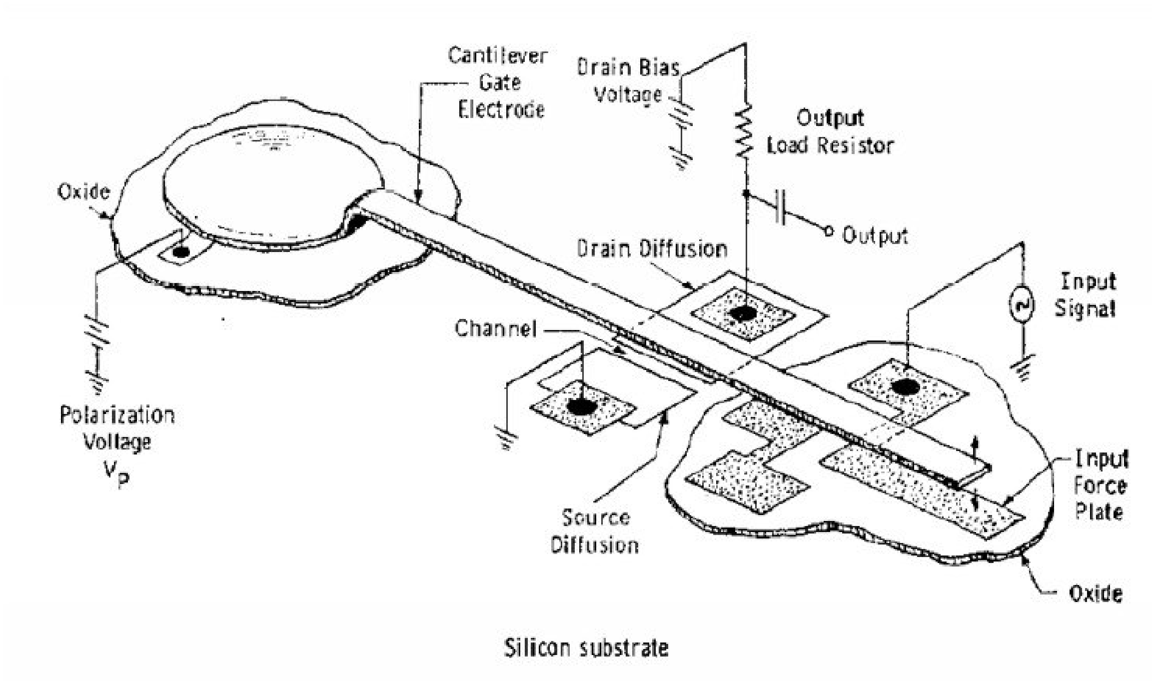


Source: In-Stat/MDR, 7/03

Overview of MEMS Applications

Historical

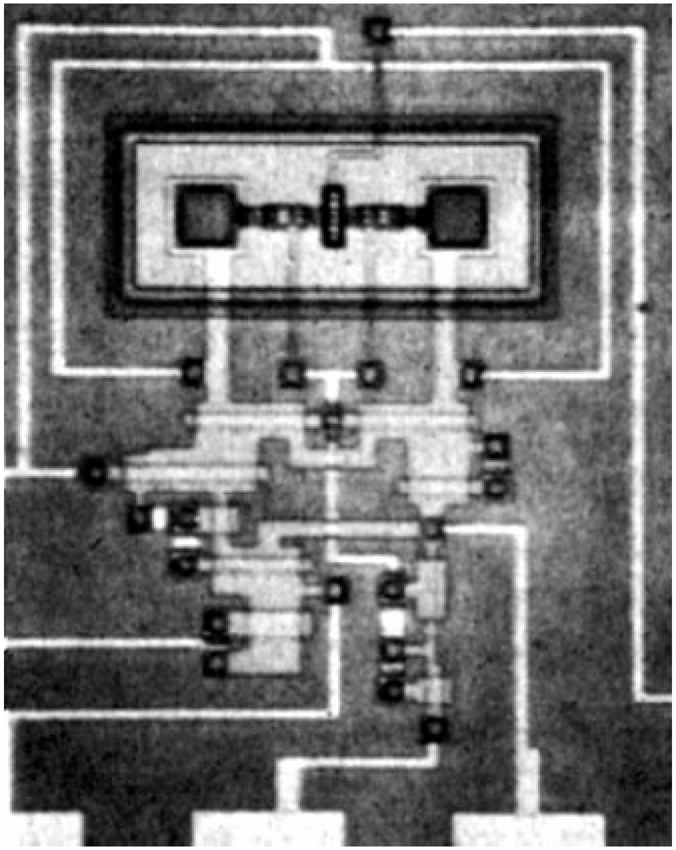
Resonant Gate Transistor



Resonant gate transistor

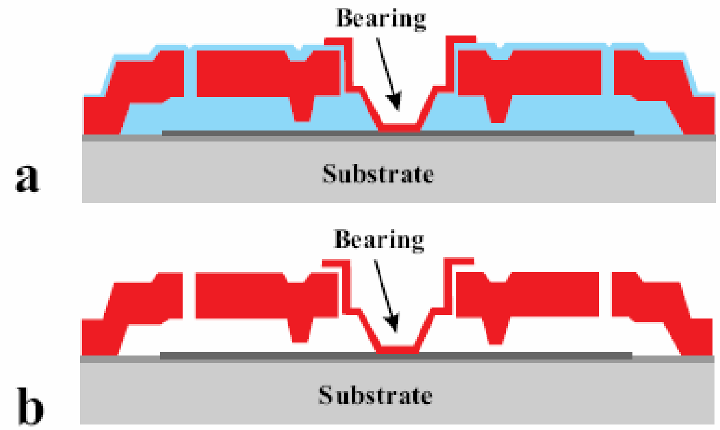
Nathanson H C, Newell W E, Wickstrom R A and Davis J R Jr 1967 The resonant gate transistor *IEEE Trans. Electron Devices* **14** 117

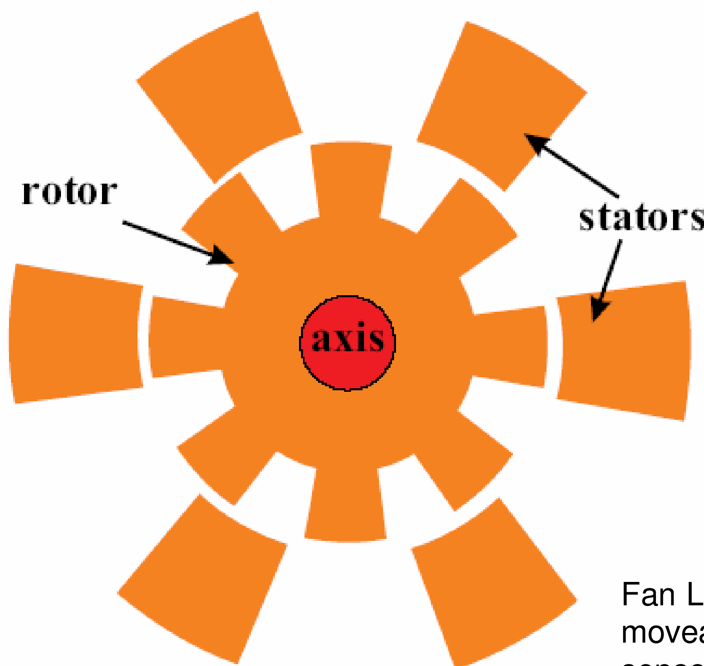
First polysilicon surface micromachined MEMS device integrated with circuits



Howe R T and Muller R S 1986 Resonant-microbridge vapor sensor *IEEE Trans. Electron Devices* **33** 499–506

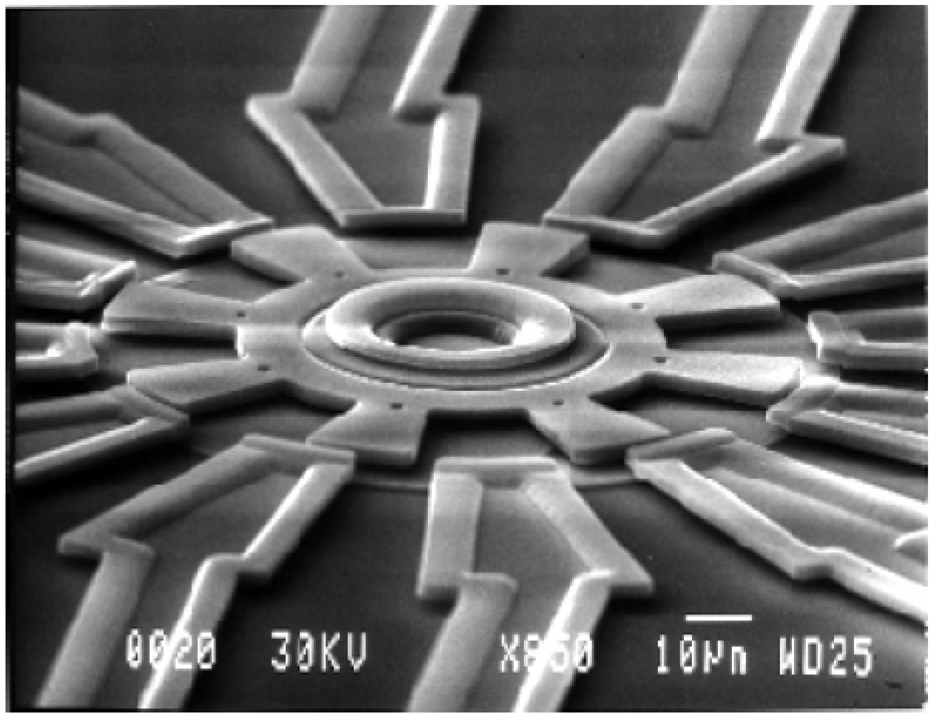
Surface Micromachined Motor





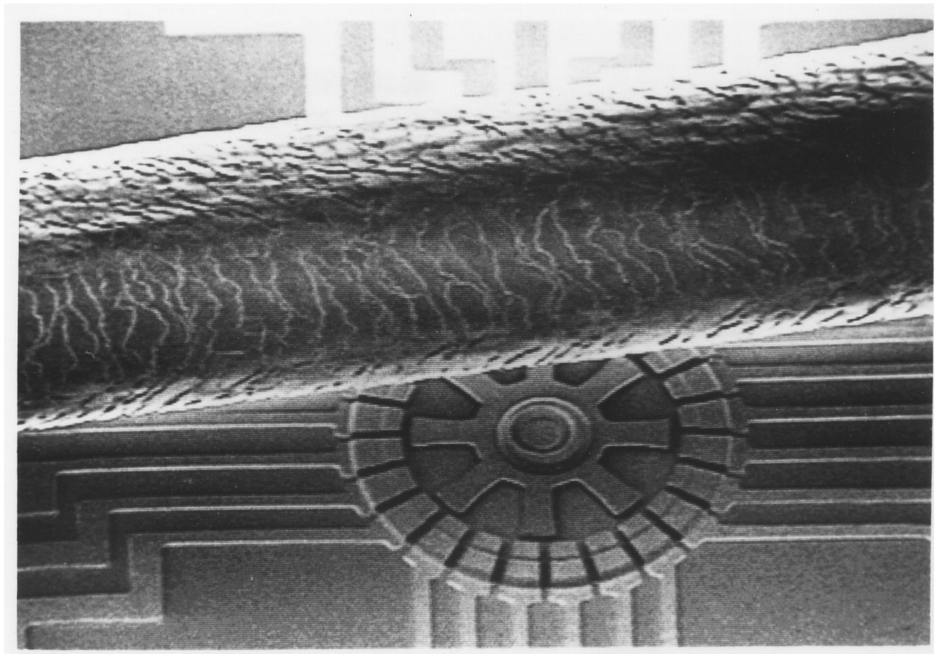
Fan L-S, Tai Y-C and Muller R S 1988 Integrated moveable micromechanical structures for sensors and actuators *IEEE Trans. Electron Devices* **ED-35** 724–30

Rotary Electrostatic Micromotor

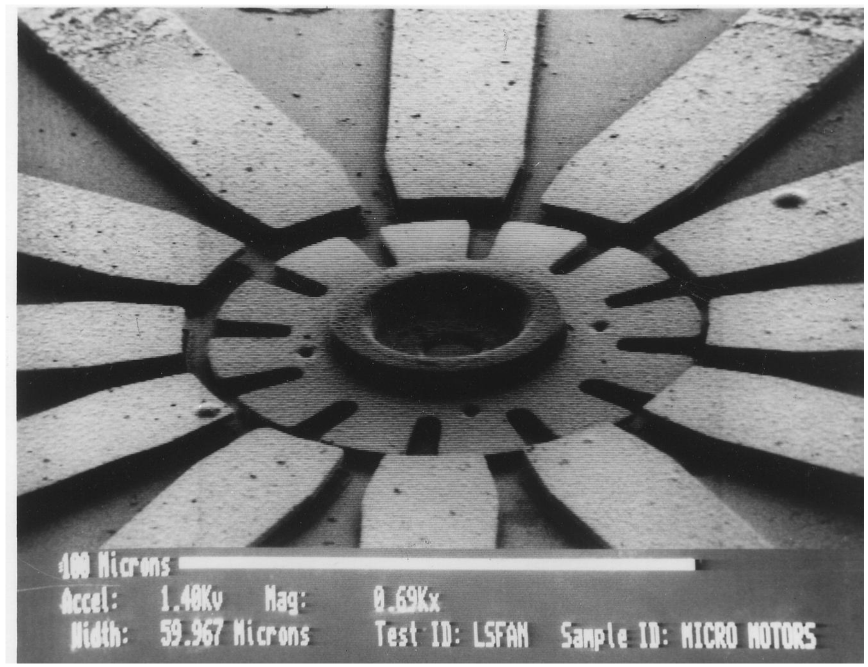


Fan Long-Shen, Tai Yu-Chong and Muller R S 1989 IC-processed electrostatic micromotors *Sensors Actuators* **20** 41–7

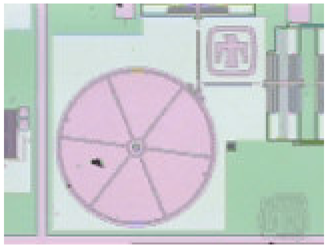
Rotary Electrostatic Micromotor

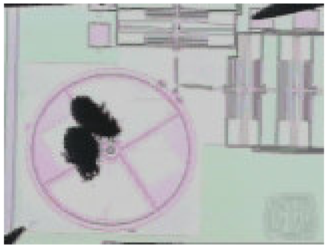


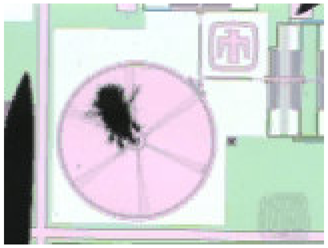
Electrostatic Wobble Micromotor

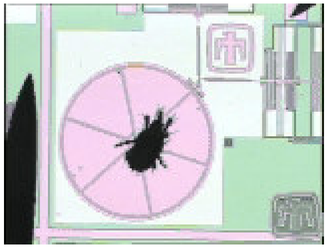


Entertainment for Dust Mites

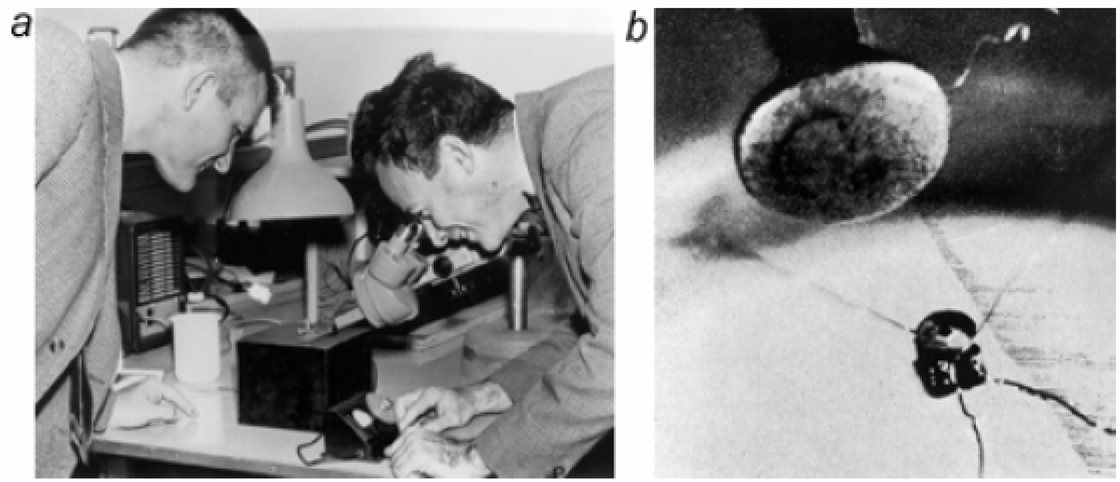








Feynman’s Challenge

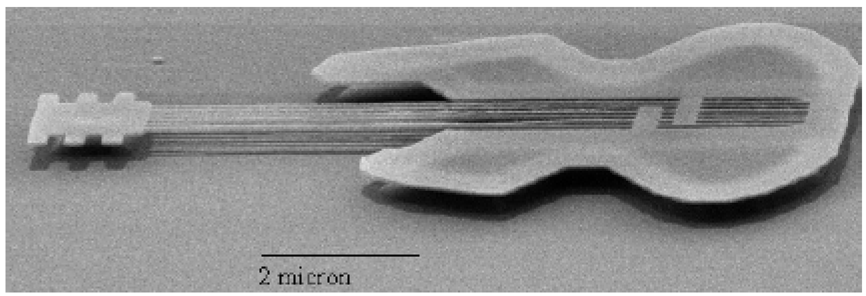


Feynman’s challenge: (a) Richard Feynman viewing the micromotor built by William McLellan (left) who won the challenge to build the first motor smaller than 1/64th of an inch. (b) a photograph of the motor, 3.81 mm wide sitting beneath the head of a pin. (Caltech).

World’s Smallest Car

World’s smallest car sitting on a coin. The car is 4.8mm long and runs on a 0.67mm electric motor.

World’s Smallest Guitar

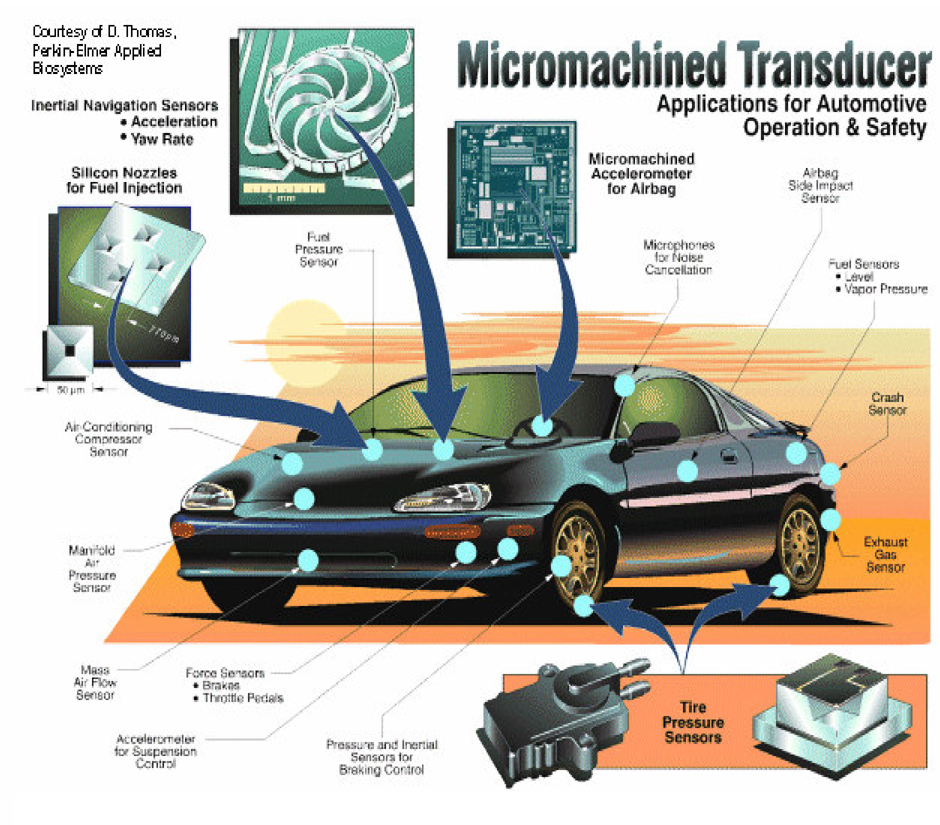


A 10 μm long Si guitar (same size as a single cell) with six strings, each ~50 nm (100 atoms) wide. (Cornell University)

Overview of MEMS Applications

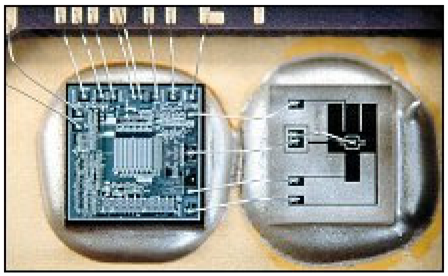
Inertial Sensors

52 Million Vehicles Means a Lot of Sensors!



- Crash Sensing for Airbag Control
- Vehicle Dynamic Control
- Rollover Detection
- Antitheft Systems
- Electronic Parking Brake Systems
- Vehicle Navigation Systems

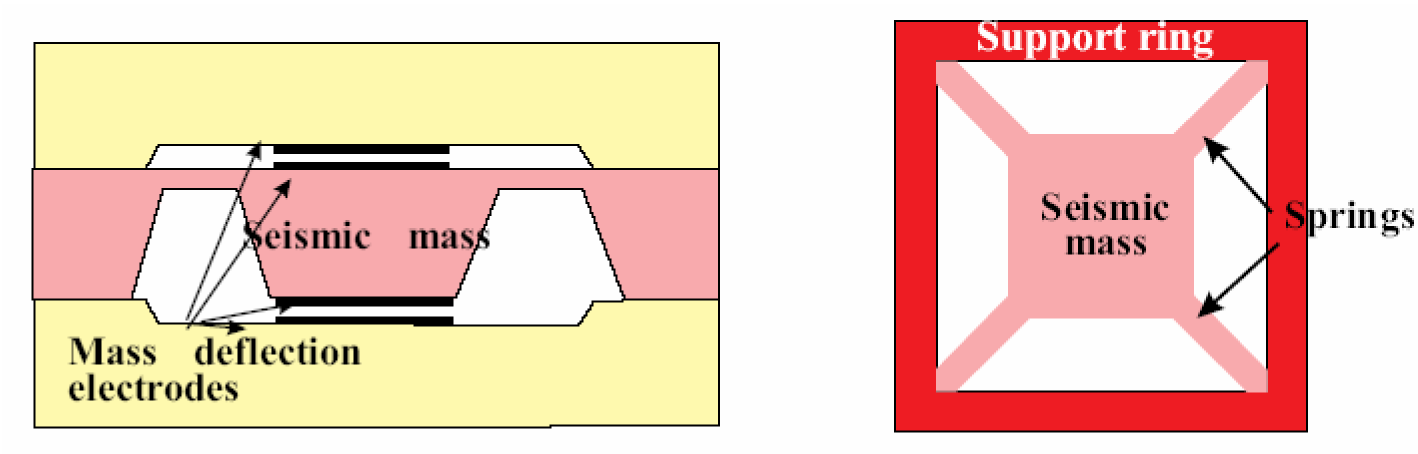
Automotive Airbag Accelerometer



Ford Microelectronics ISAAC two-chip automotive airbag accelerometer

- Sensor chip is on the right
- Signal processing and control IC is on the left
- The accelerometer structure is a bulk micromachined suspended silicon mass over a fixed metal electrode that provides a capacitive output as a function of acceleration
- The sensor is created by anodically bonding a micromachined silicon wafer to a glass wafer and etching away the bulk of the silicon, leaving only the suspended silicon mass.

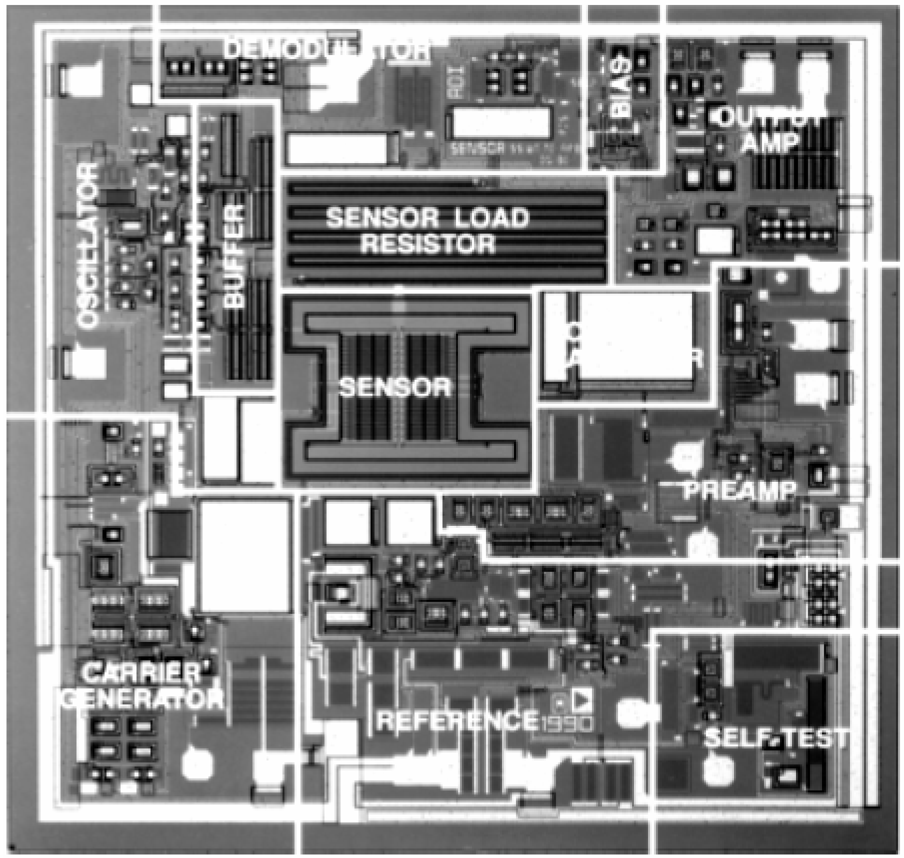
Automotive Airbag Accelerometer



Bulk micromachined proof mass suspended between mass deflection electrodes attached by wafer bonding

P J French and P M Sarroz, J. Micromech. Microeng. **8** (1998) 45–53

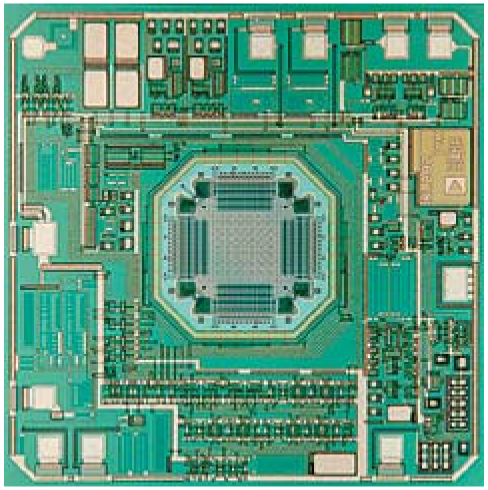
Automotive Airbag Accelerometer



Monolithic surface micromachined accelerometer with capacitive position detection. Single axis device (Analog Devices, Inc)

Core T A, Tsang W K and Sherman S J 1993 Fabrication technology for an integrated surface-micromachined sensor *Solid State Technol.* **36** 39–47

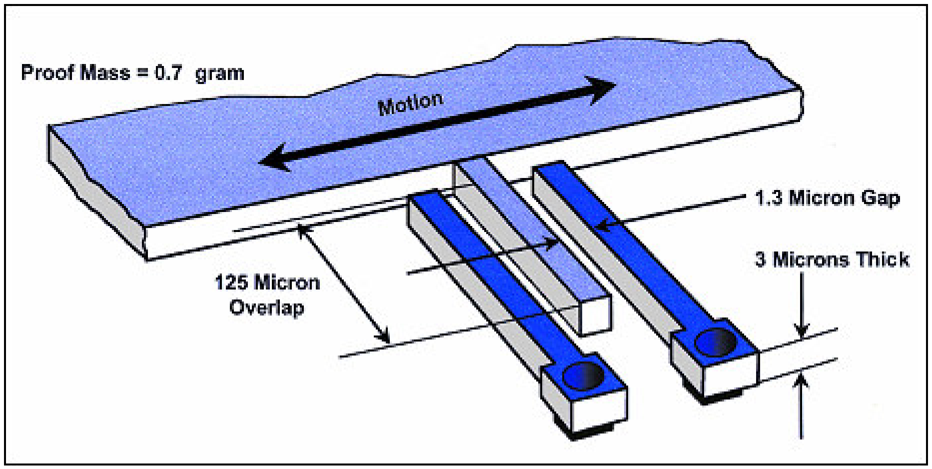
Automotive Airbag Accelerometer



In the Analog Devices ADXL 50 accelerometer

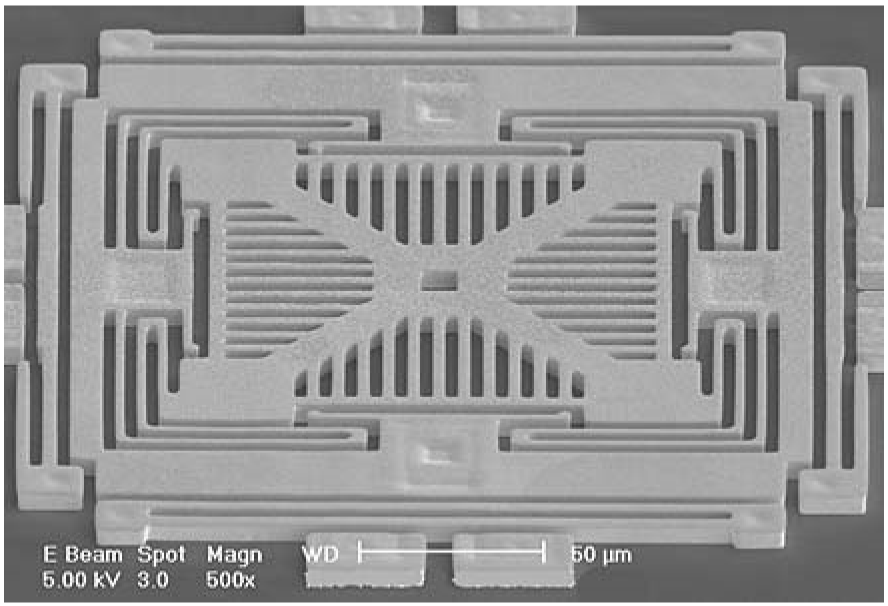
- Monolithically integrated accelerometer
- Electronics occupy the majority of the 3 mm^2 chip area
- 2-axis device

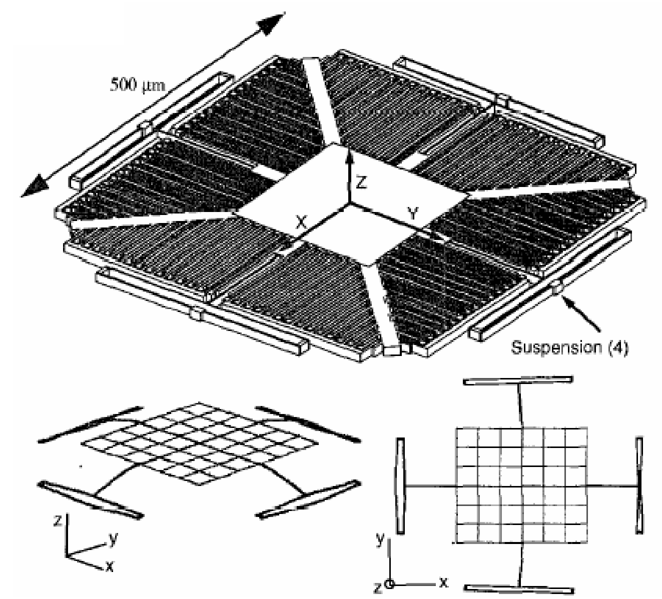
Automotive Airbag Accelerometer



ADXL202E Accelerometer

Automotive Airbag Accelerometer

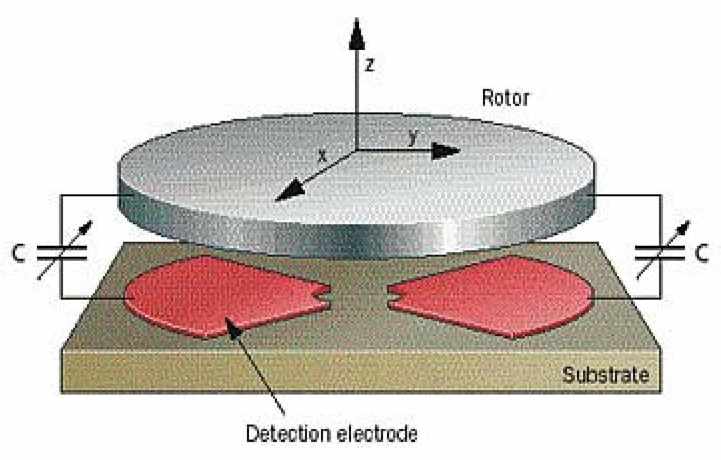


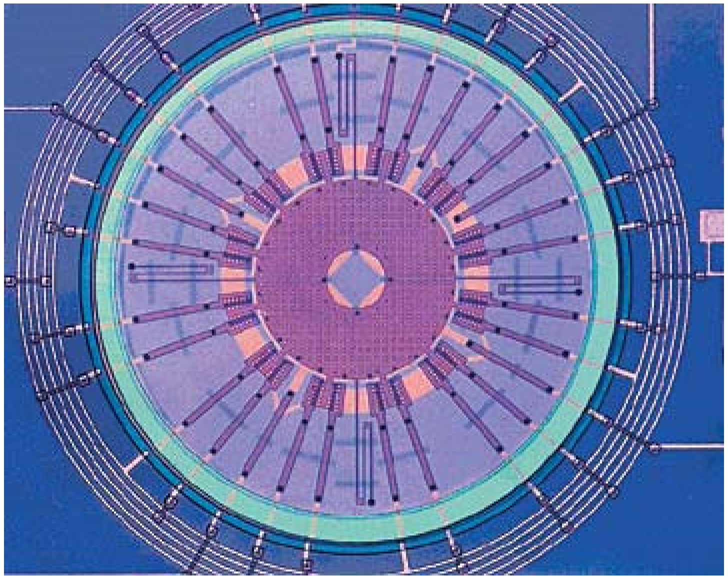


A 3-Axis Force Balanced Accelerometer Using a Single Proof-Mass

Mark A. Lemkin, Bernhard E. Boser, David Auslander*, Jim H. Smith**

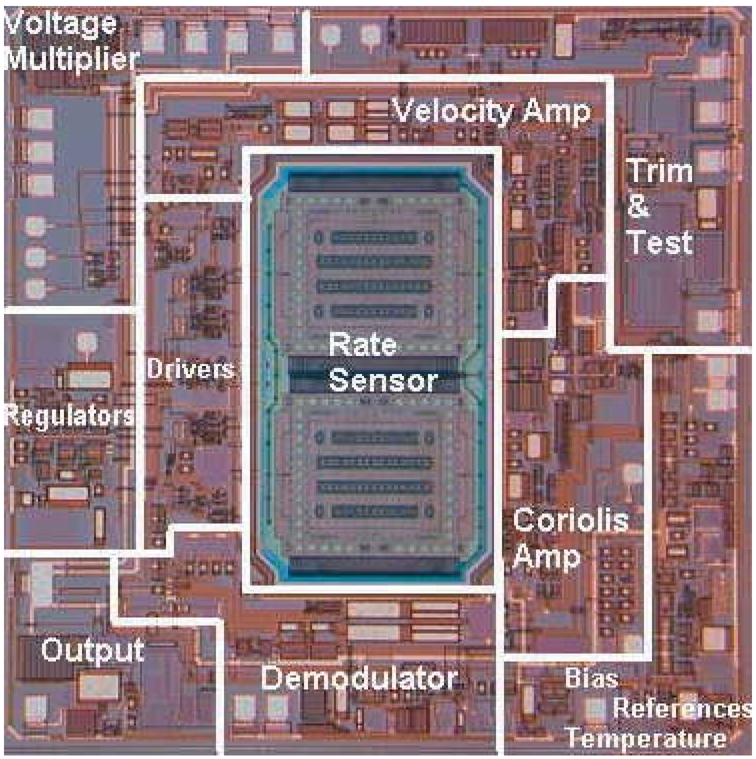
Vibrating Wheel Gyro





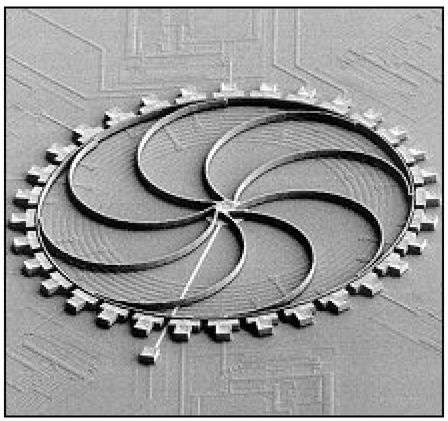
- A wheel is driven to vibrate about its axis of symmetry
- Rotation about either in-plane axis results in the wheel's tilting
- Tilting of the wheel can be detected with capacitive electrodes under the wheel

iMEMS ADXRS Angular Rate-Sensing Gyro



- Angular rate-sensing gyro integrates an angular rate sensor and signal processing electronics onto a single piece of silicon
- A proof mass is tethered to a polysilicon frame that allows it to resonate in only one direction
- Capacitive silicon sensing elements inter-digitated with stationary silicon beams attached to the substrate measure the Coriolis-induced displacement of the resonating mass and its frame

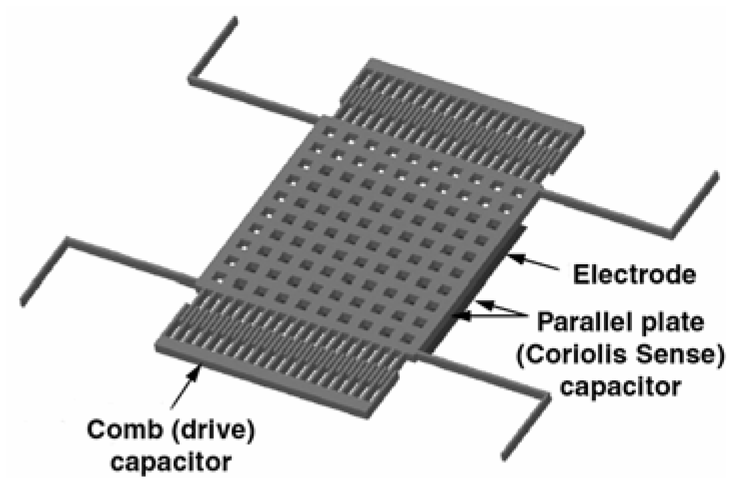
Angular Rate Sensor



Delphi-Delco CMOS integrated single-chip surface micromachined angular rate sensor

- The angular rate sensor is used for automotive steering assistance, active brake control, and rollover detection
- A micromachined ring sensor incorporates an electroformed vibrating ring structure fabricated on a silicon IC control chip
- Production sensors are vacuum sealed at the chip level using wafer-to-wafer bonding. A vacuum is required since the ring sensor has to be driven into resonance for normal operation with a Q-factor >1000.

MEMS tuning fork gyro



- Measures angular rotation rate
- A proof mass attached to springs is forced to oscillate in the horizontal plane
- A voltage is applied to a sensing electrode (sense plate) below the proof mass, creating an electrical field
- The Coriolis force imparted by angular rotation causes the proof mass to oscillate in the vertical direction, which, in turn, changes the gap between the proof mass and the sense plate
- This generates an AC current with amplitude proportional to the rotation rate

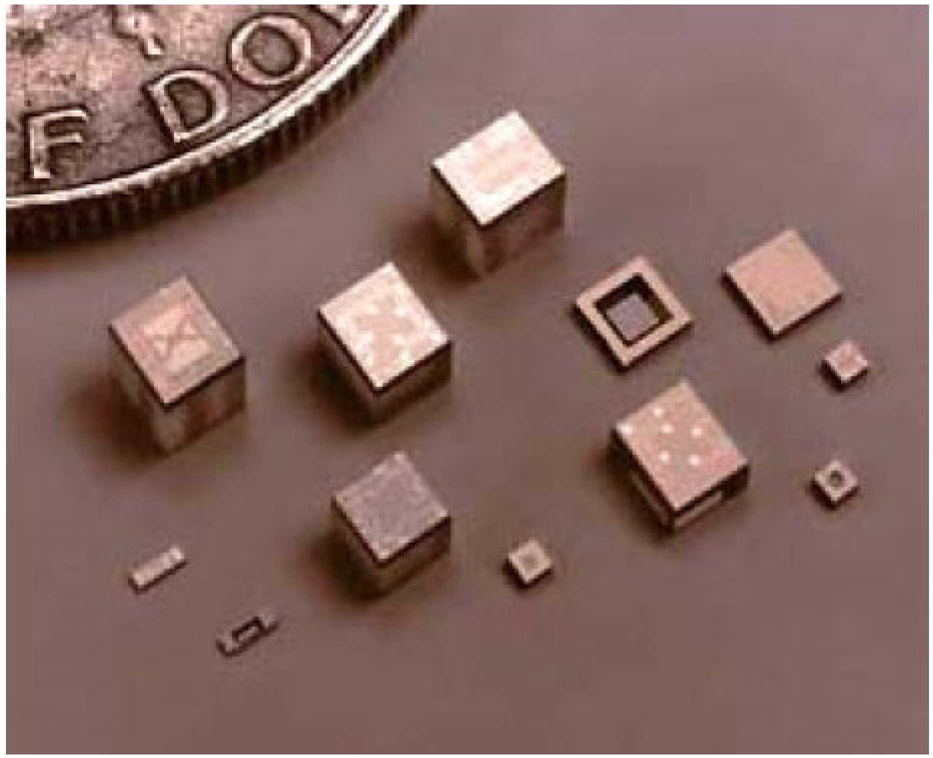
Virtual Reality (VR) Systems

- A VR systems’ utility is intimately connected to how convincingly it can recreate life
- Accelerometers and angular rate sensors) are required to achieve credibility
- Accelerometer data are converted into positional information via double integration
- Angular rate sensors determine rotational position by integrating the angular rate

Overview of MEMS Applications

Pressure Sensors

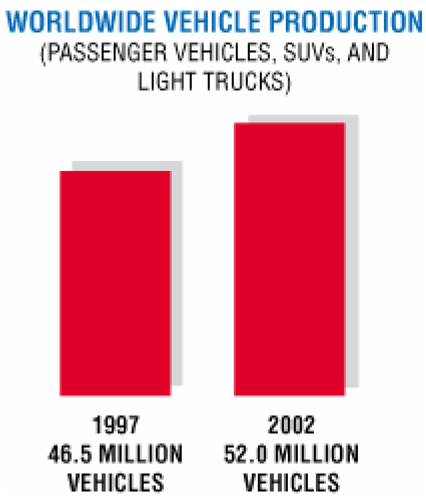
Blood Pressure Sensors

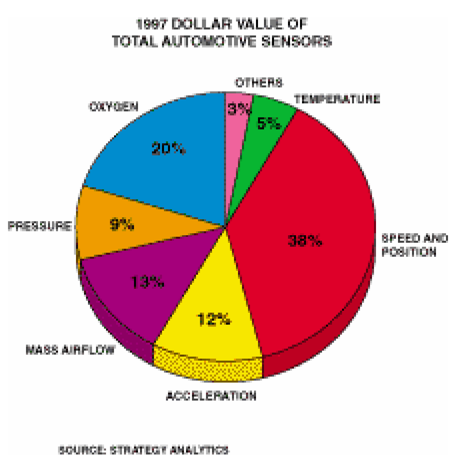


Micromachined pressure sensor dice with the smallest having dimensions $175 \times 700 \times 1000\ \mu m^3$

Data Sheet: NPC–107 Series Disposable Medical Pressure Sensor, Lucas NovaSensor, 1055 Mission Court, Fremont, CA 94539, USA, http://www.novasensor.com/

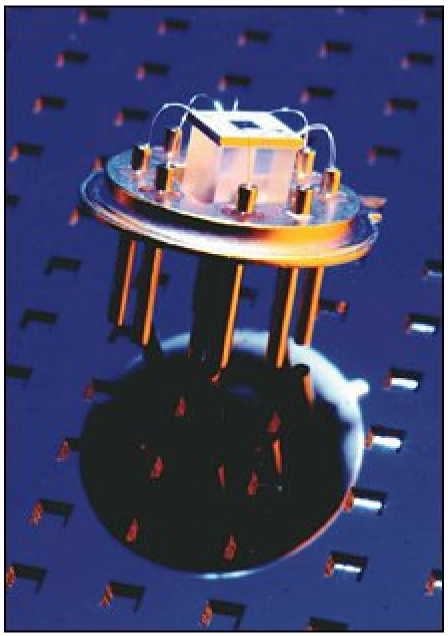
Automotive





- Federal and regional fuel efficiency, emission, and safety standards
- Manifold Absolute Pressure (MAP) sensors (1979)
- Tire Pressure Sensors

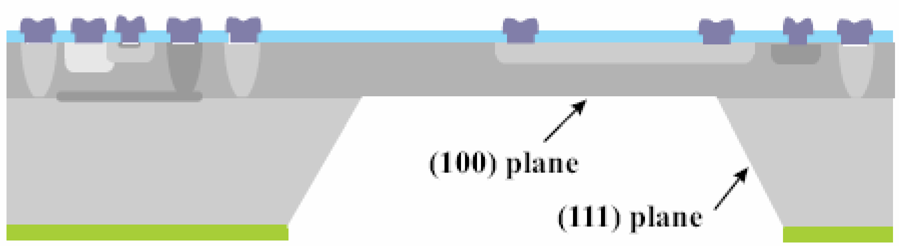
Manifold Absolute Pressure (MAP)

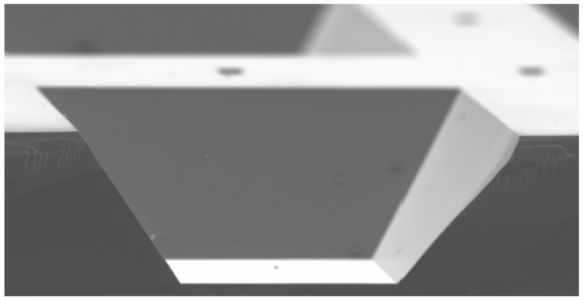


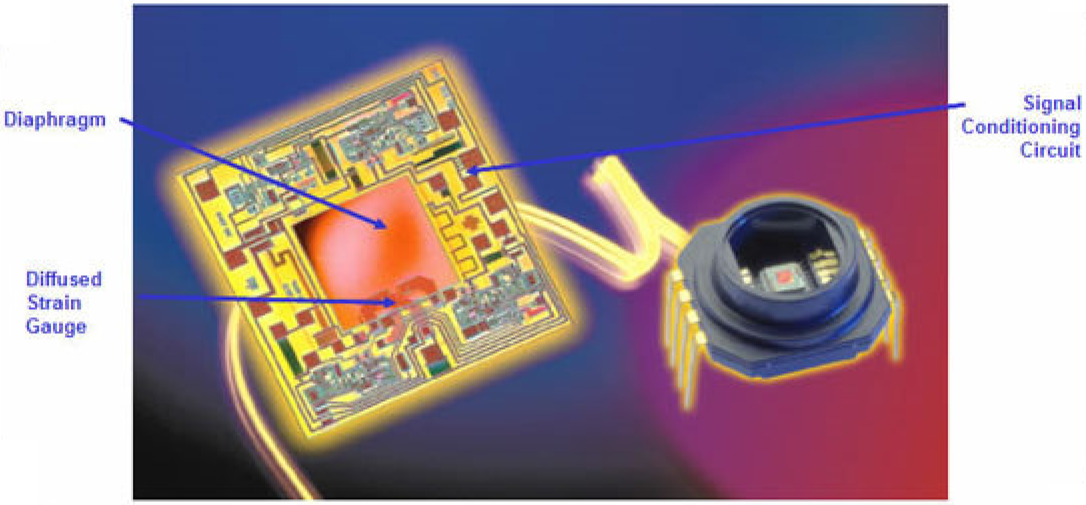
Bosch engine control manifold absolute pressure (MAP) sensor

- The manifold absolute pressure (MAP) sensor is used in automobile fuel injection systems
- By measuring the manifold pressure, the amount of fuel being injected into the engine cylinders can be calculated
- Micromachined silicon piezoresistive pressure sensors are bonded at the wafer level to a glass wafer using anodic bonding before dicing

Bulk Micromachined Pressure Sensor





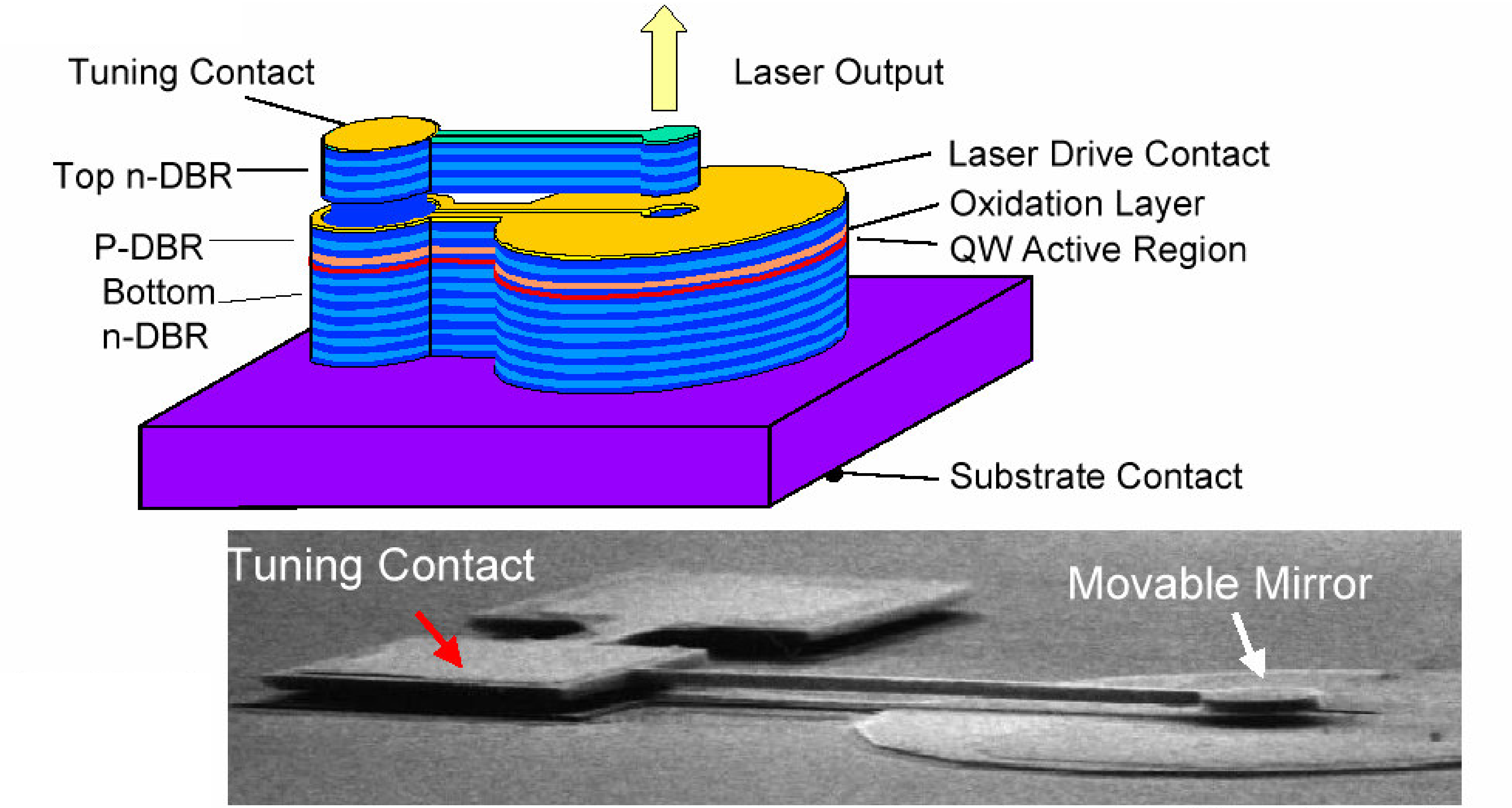


P J French and P M Sarroz, J. Micromech. Microeng. **8** (1998) 45–53

Overview of MEMS Applications

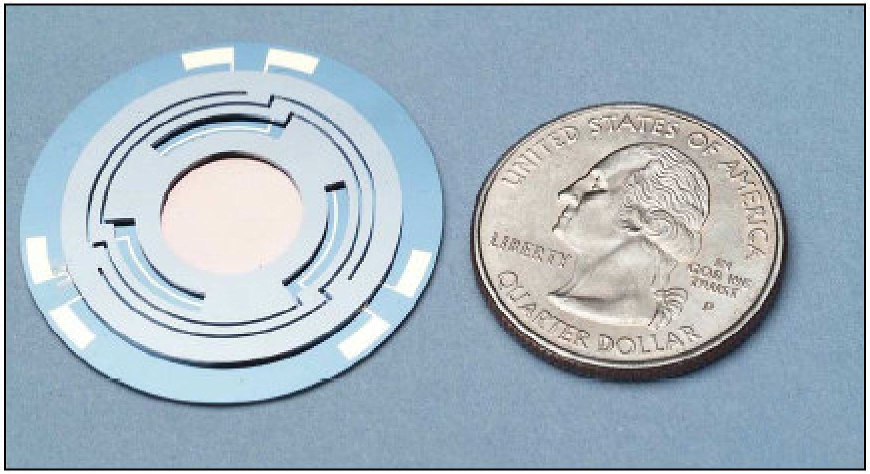
Optical MEMS

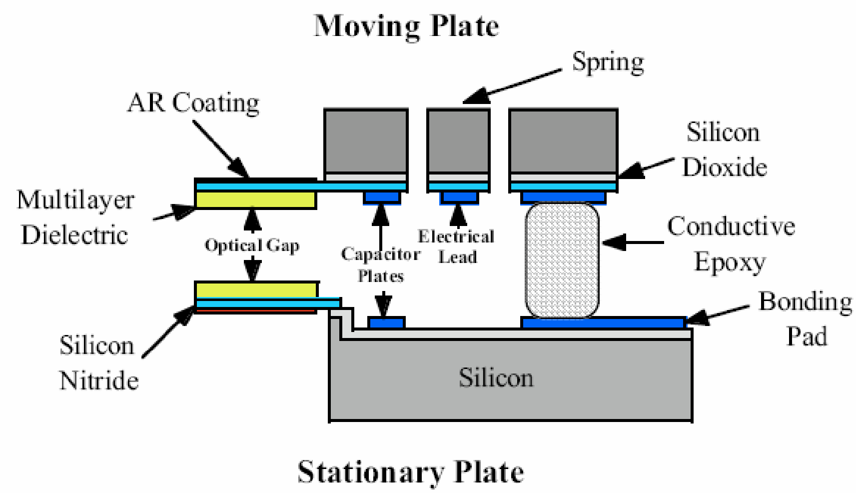
Cantilever VCSEL



Chang-Hasnain Group

Optical MEMS

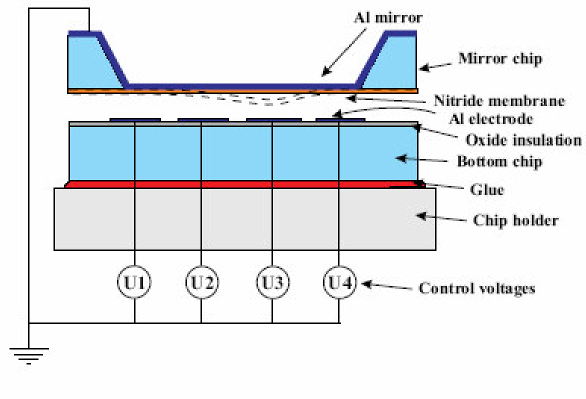


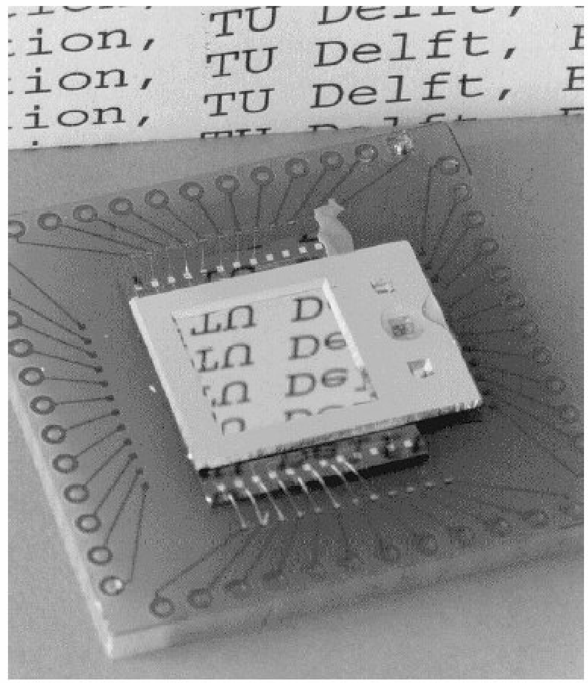


Micromachined Tunable Fabry-Perot Filters for Infrared Astronomy

NASA, Goddard Space Flight Center, Greenbelt, MD

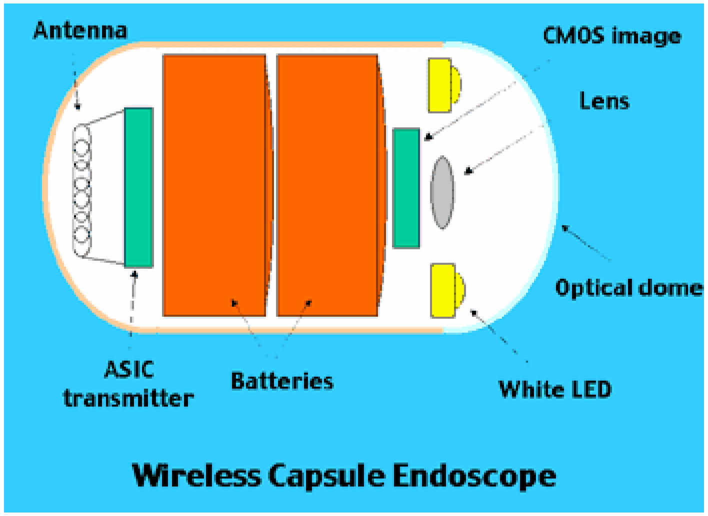
Adaptive Optics

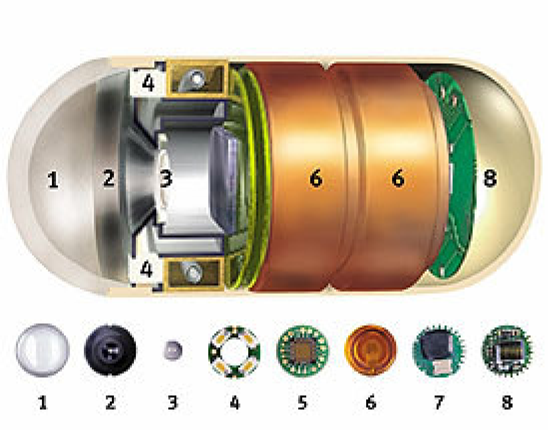




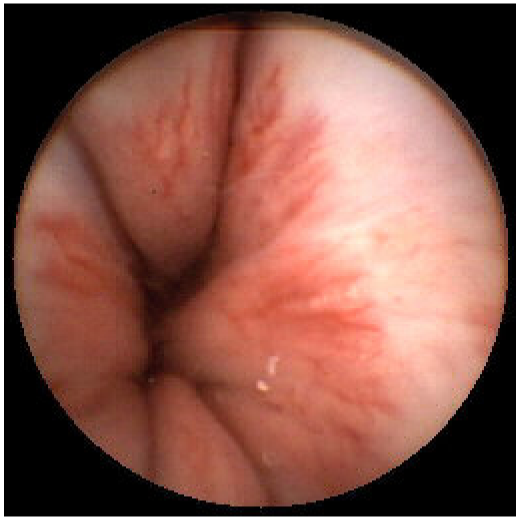
Vdovin G 1996 Adaptive mirror micromachined in silicon
PhD Thesis Delft University of Technology

Pill Camera





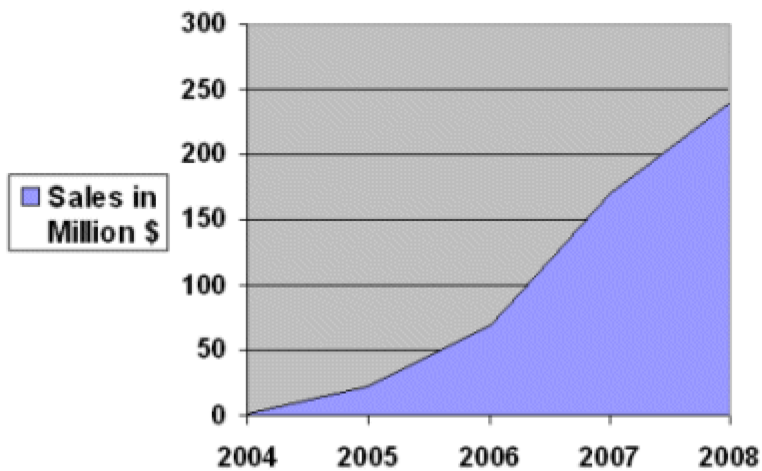
Distal esophagus with edema and erythema. Geographic ulceration suggestive of Barret's Esophagus.



Overview of MEMS Applications

RF MEMS

MEMS Market for Mobile Phones



World MEMS market
for mobile phones

MEMS4Mobile, Analysis of the applications and markets of MEMS in mobile communications, Yole Développement, February 2005

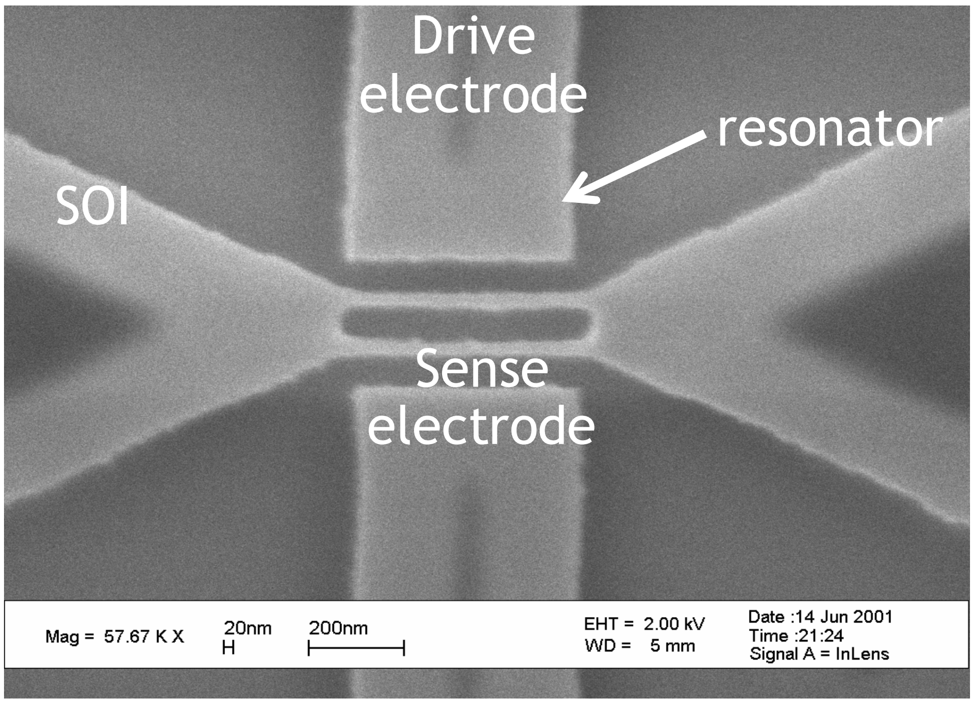
MEMS Market for Mobile Phones

Applications:

- Silicon microphone: improves the manufacturability of microphones for similar performance compared to Electret Condensor Microphone (ECD)
- 3D accelerometers: adds functions for man machine interface and silent mode activation
- RF MEMS passive and active devices: provides better integration of passive devices for RF module and faster frequency agility
- Gyroscope for camera stabilisation and GPS: enables real digital imaging, preserves the GPS signal
- Microfuel cell: provides longer lifetime for the batteries
- Chemical and Biochip: personal weather station and health care monitor

MEMS4Mobile, Analysis of the applications and markets of MEMS in mobile communications, Yole Développement, February 2005

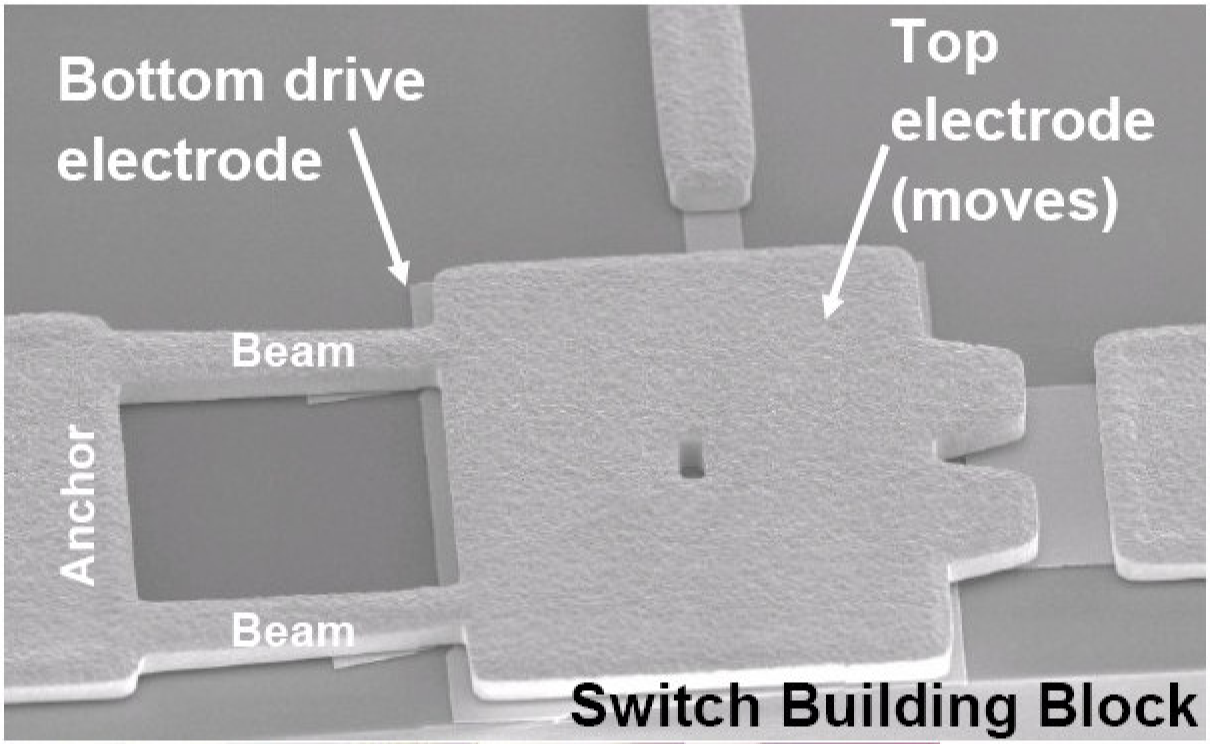
1 GHz NEMS Resonator



Si double-ended tuning fork
- tine width = 35nm
- length = 500 nm
- thickness = 50 nm

L. Chang, S. Bhave, T.-J. King, and R. T. Howe UC Berkeley (unpublished)

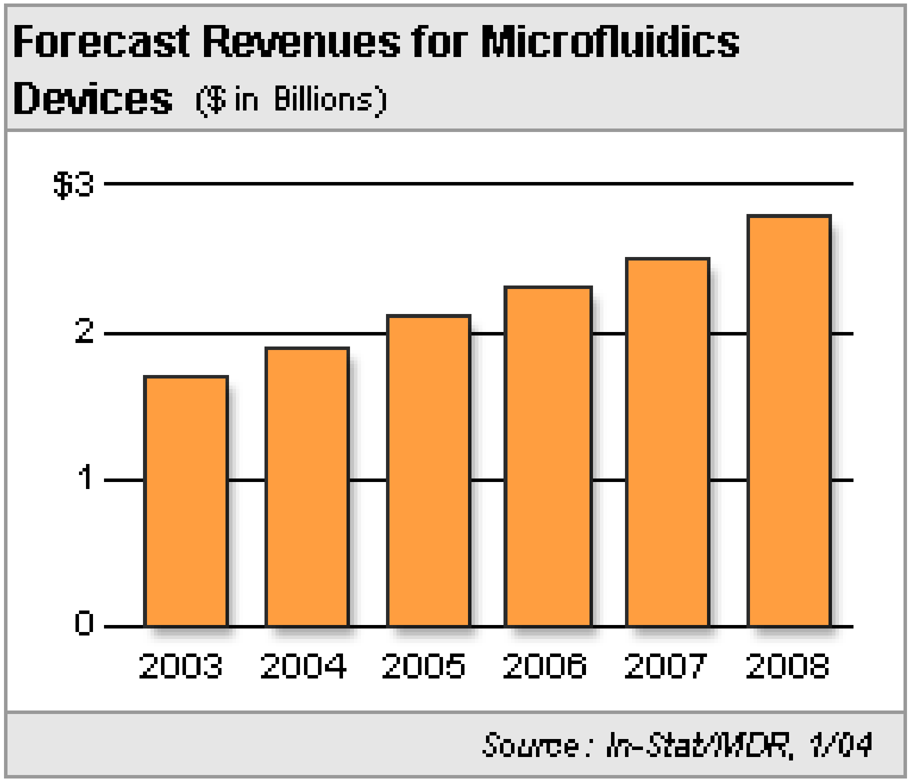
RF MEMS


Bottom drive electrode
Top electrode (moves)
Beam
Anchor
Beam
Switch Building Block

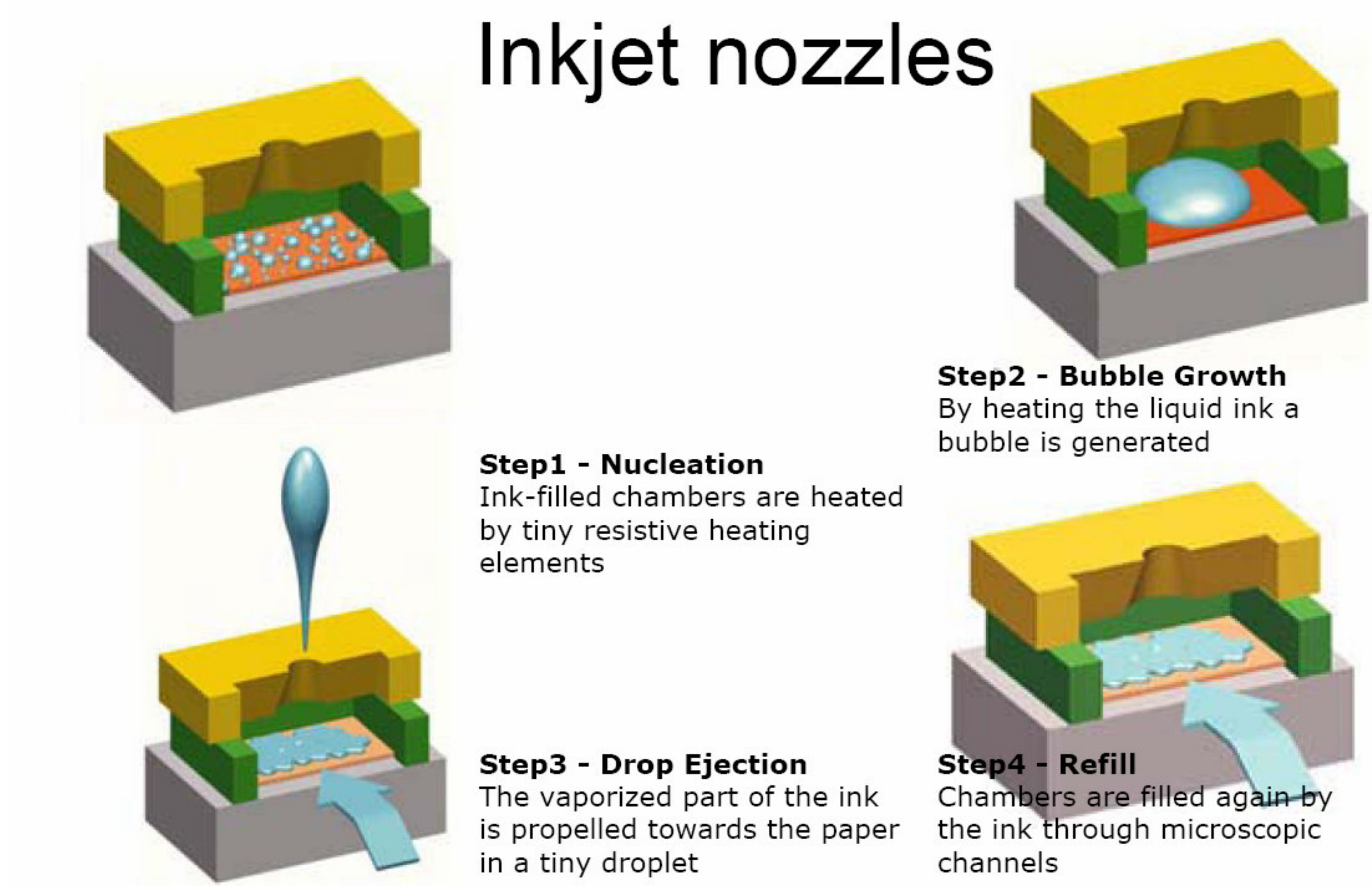
Overview of MEMS Applications

Fluidic MEMS

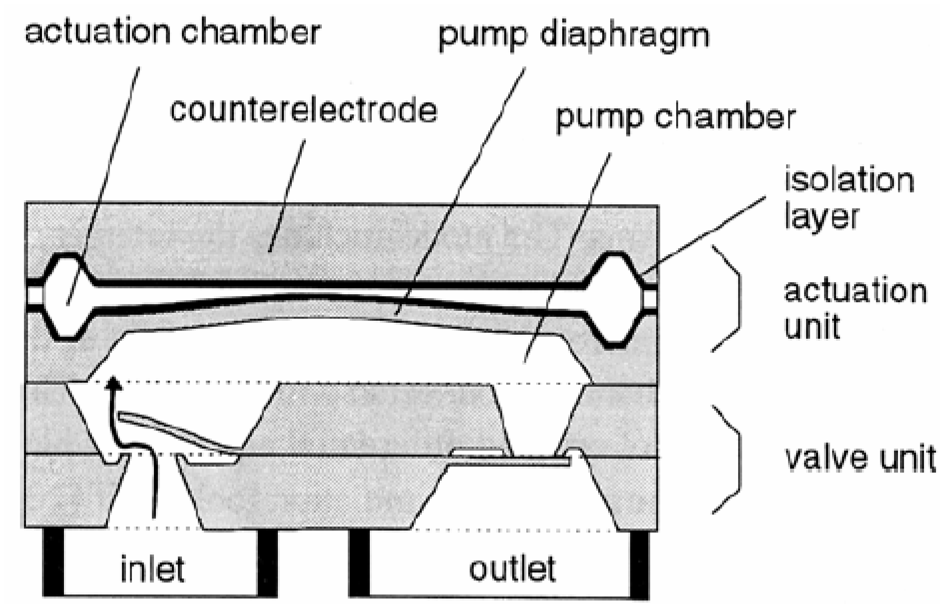
Fluidic MEMS Market



Fluidic MEMS



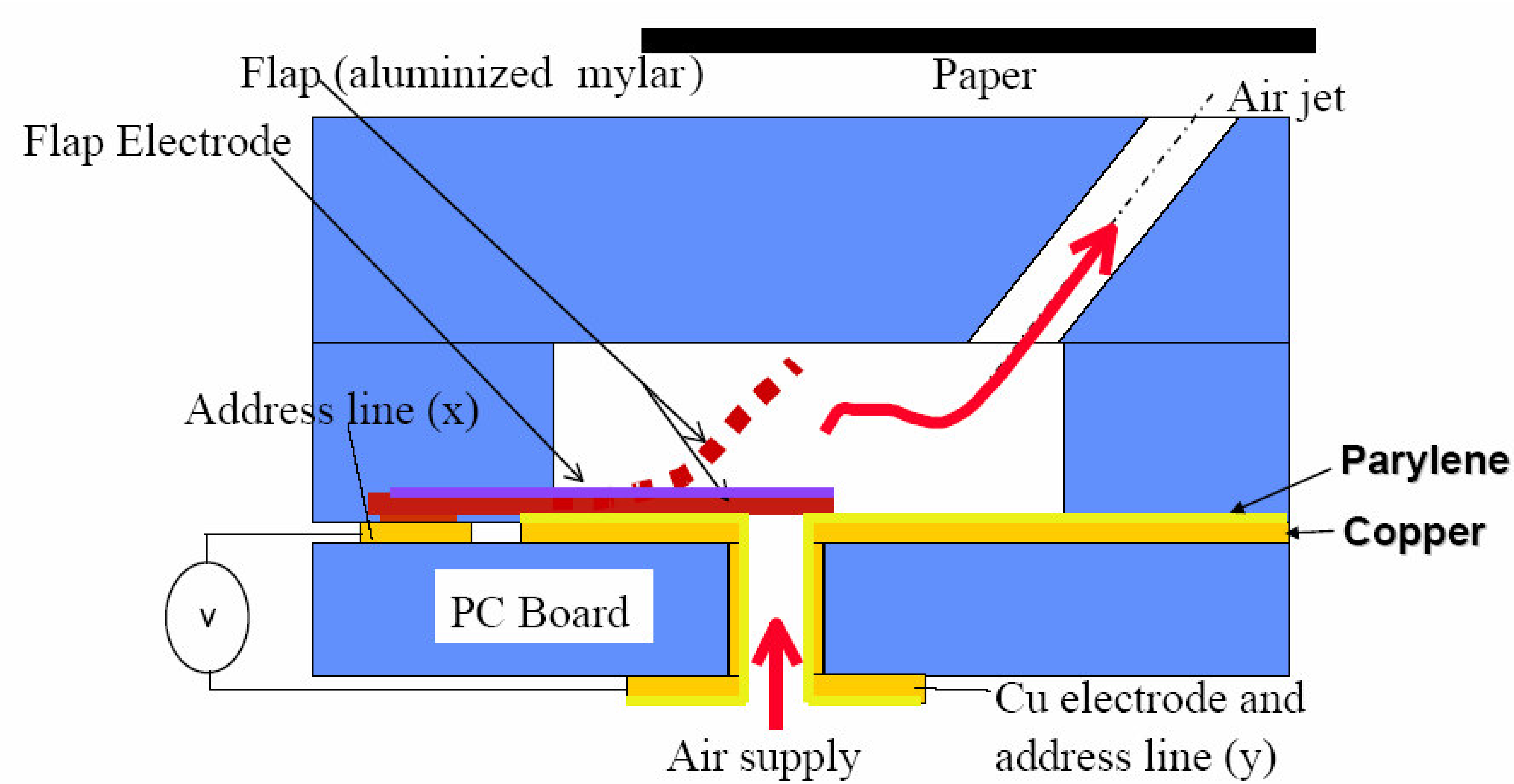
Fluidic MEMS



Electrostatic micropump with two one-way check valves

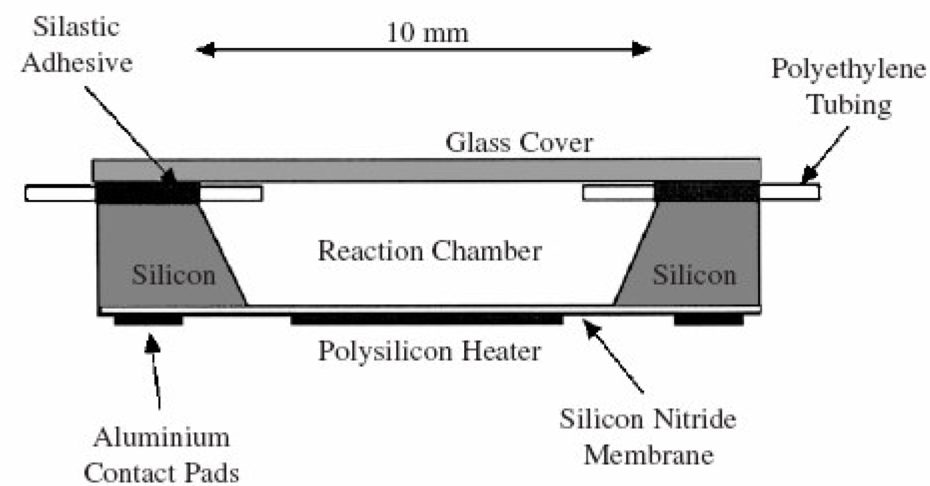
Zengerle R, Ulrich J, Kluge S, Richter M and Richter A 1995, A bi-directional silicon micropump *Sensors Actuators* A**50** 81–6

Fluidic MEMS



Dave Beigelsen and Andrew Berlin, Xerox PARC

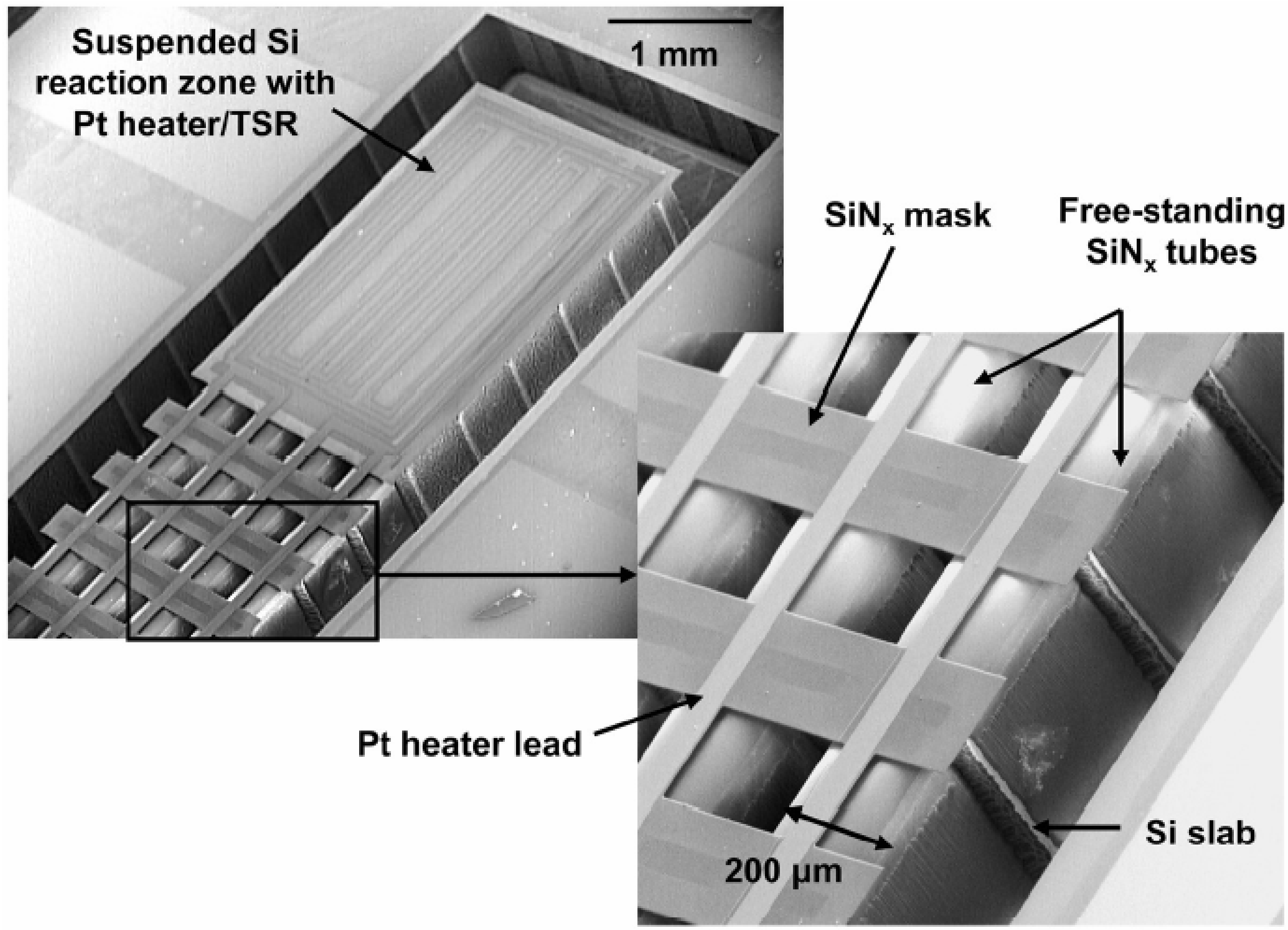
Bio MEMS



Micromachined PCR chamber

Northrup M A, Ching M T, White R M and Lawton R T 1993 DNA amplification with a microfabricated reaction chamber *Int. Conf. on Solid-State Sensors and Actuators, Transducers '93 (Yokohama, 1993)* pp 924–6

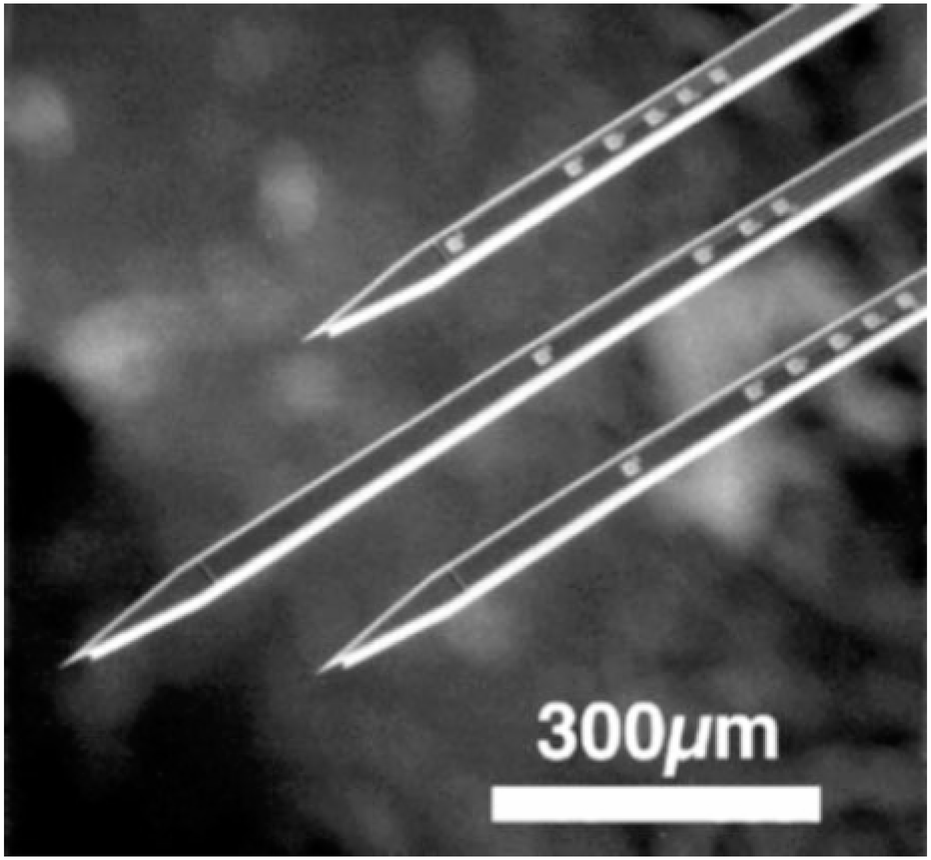
Micro Reactor



Application of micro-machining and wafer bonding to fabricate a micro reactor for reforming hydrogen from hydrocarbon fuel

Leonel. R. Arana (Ph.Dthesis) and
K.F. Jensen & M.A. Schmidt MIT

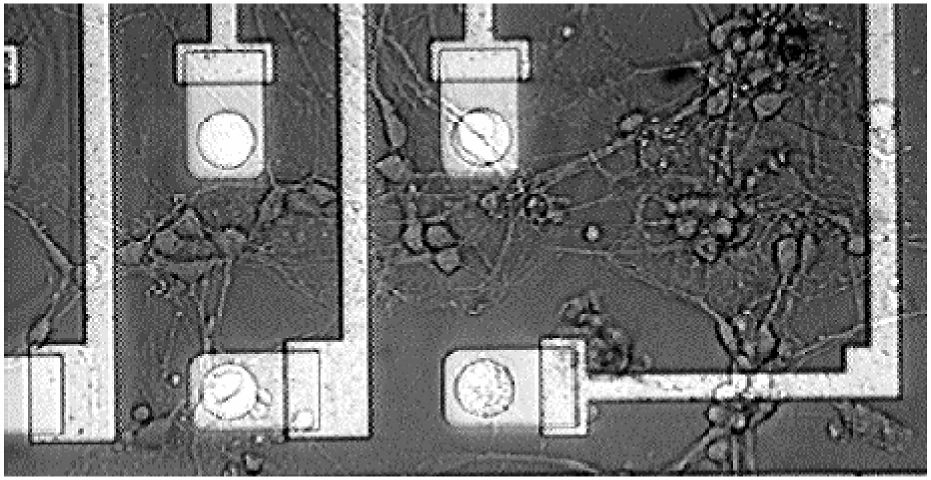
Bio MEMS



Microfabricated silicon neural probe arrays

Kewley D T, Hills M D, Borkholder D A, Opris I E, Maluf N I, Storment C W, Bower J M and Kovacs G T A, 1997 Plasma-etched neural probes *Sensors Actuators* A **58** 27–35

Bio MEMS



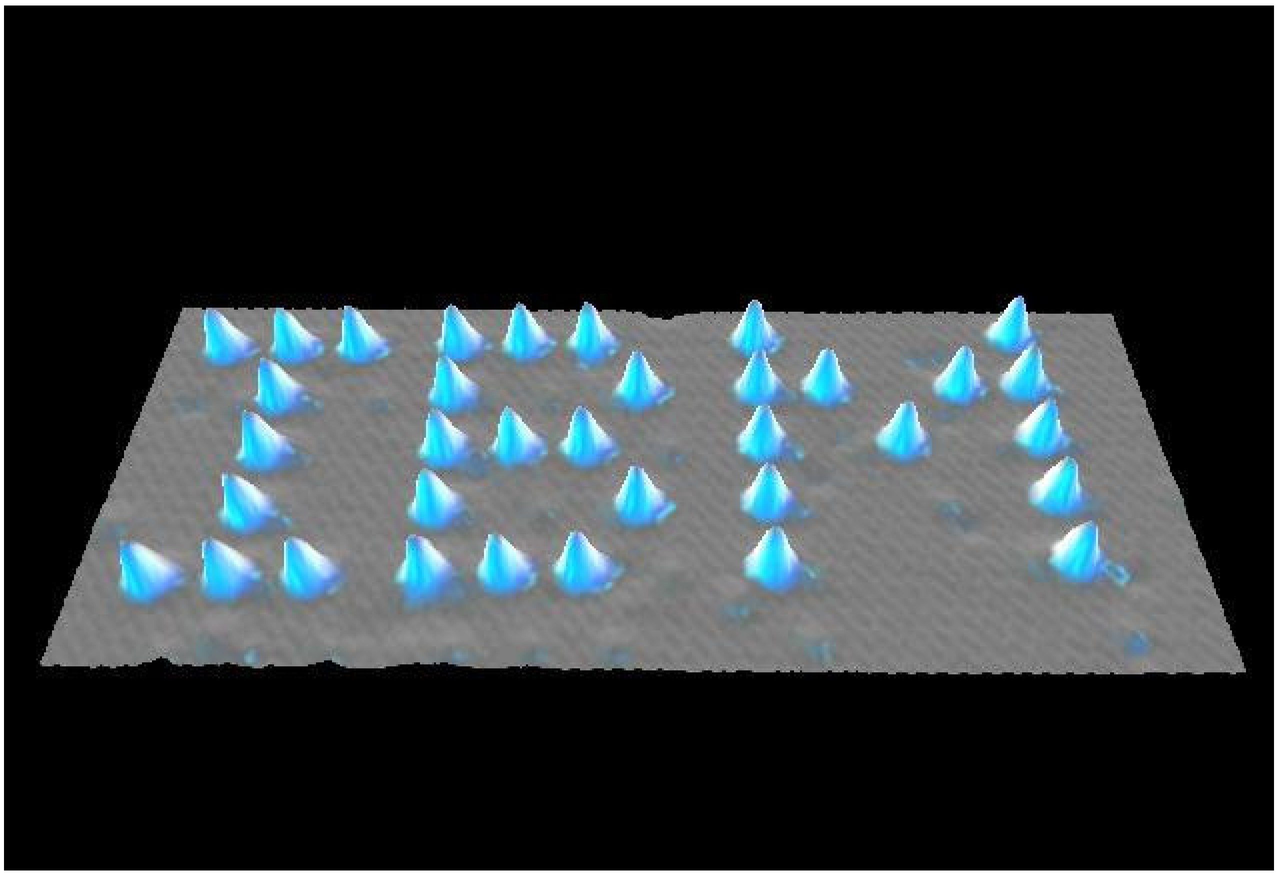
Cell-based biosensor with micro-electrode array

Borkholder D A 1998 Cell-based biosensors using microelectrodes *PhD Thesis* Electrical Engineering Department, Stanford University

Overview of MEMS Applications

Memory

Memory



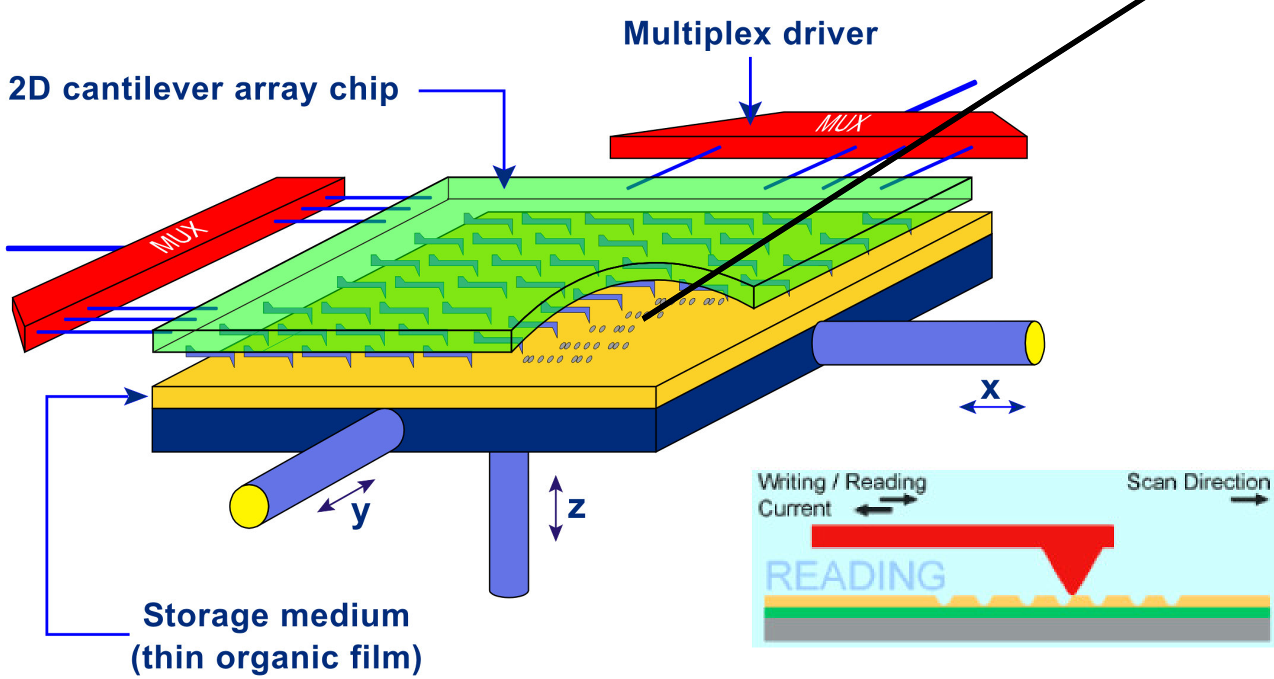
35 Xenon atoms

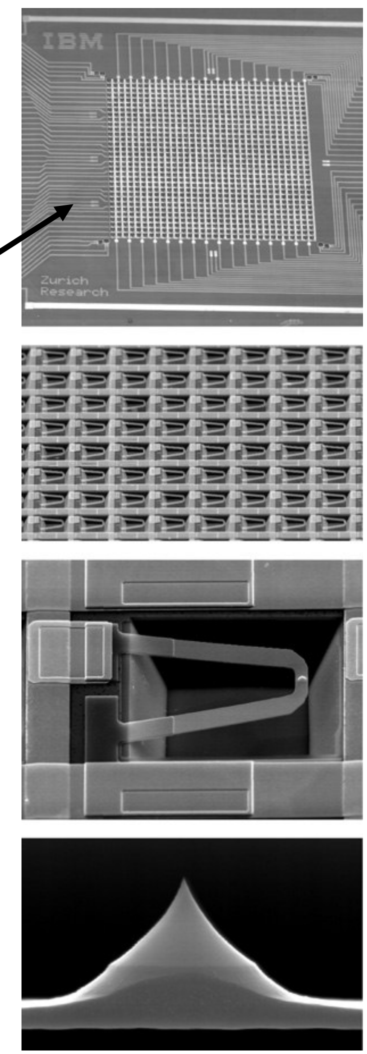
MEMS Memory: IBM's Millipede

Array of AFM tips write and read bits: potential for low and adaptive power

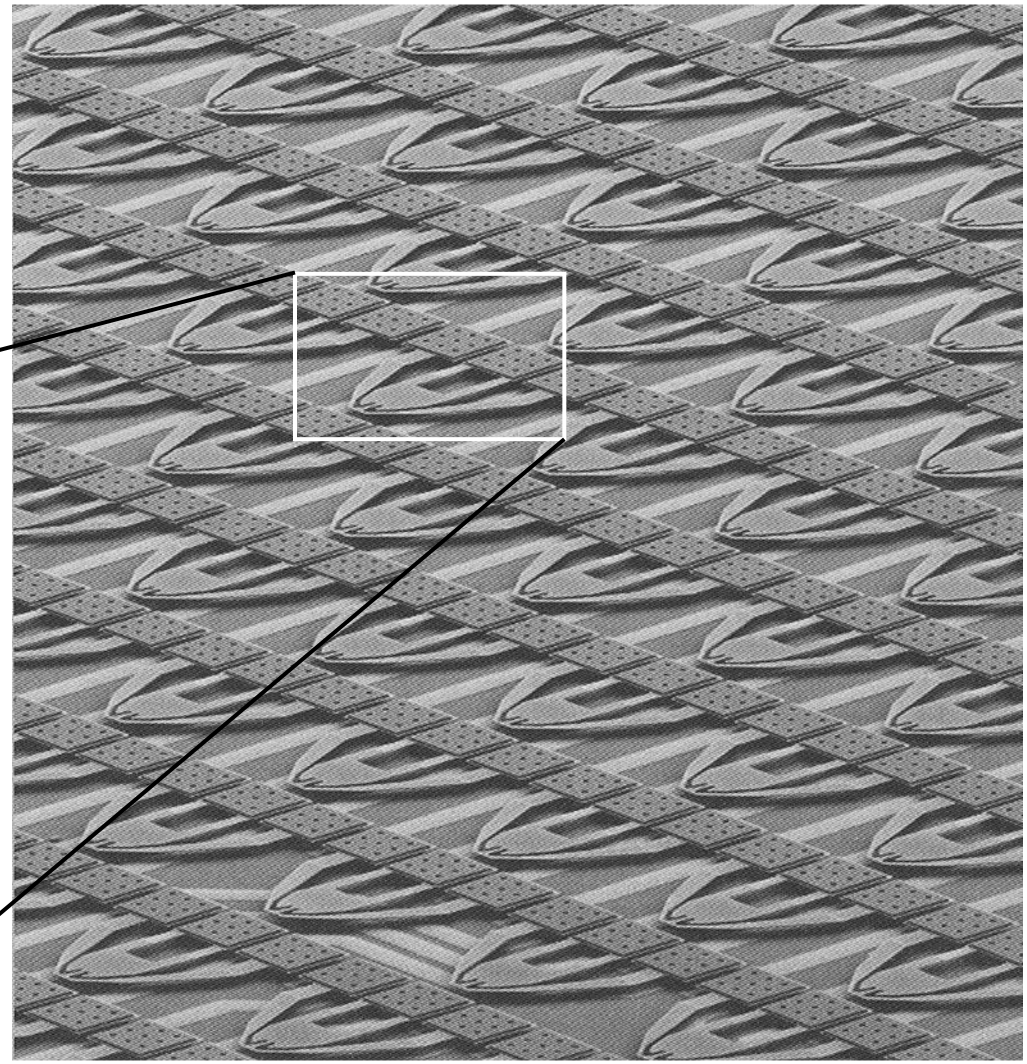
"MILLIPEDE"

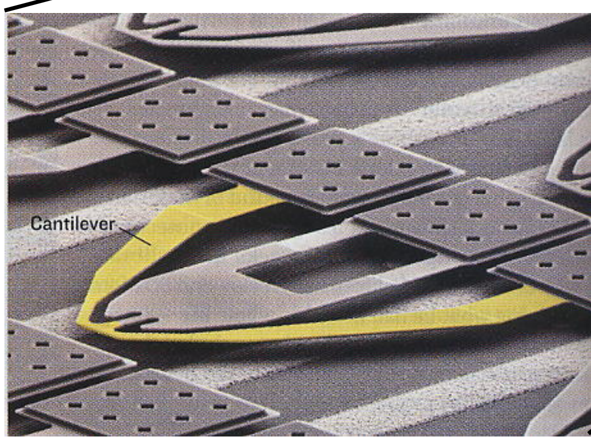
Highly parallel, very dense AFM data storage system



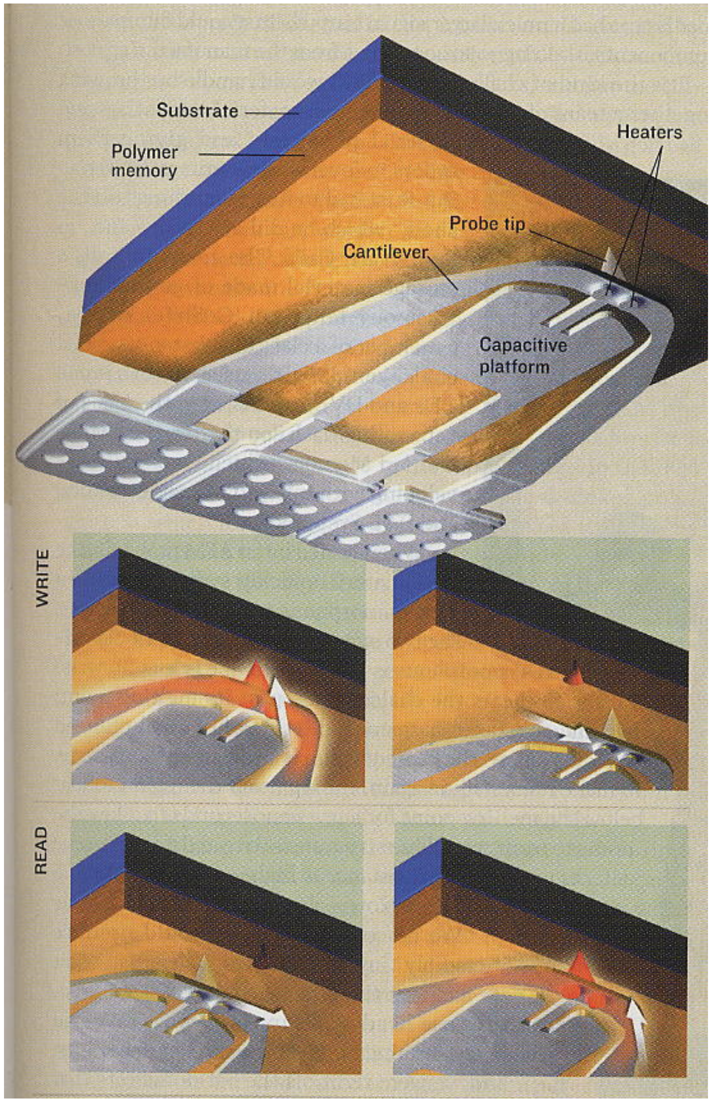


IBM Millipede





IBM Millipede



Current: 517 Gb/sq. in.

Goal: Tb/sq. in


That's All Folks!

Information Resources

Online Resources

- BSAC http://www-bsac.eecs.berkeley.edu/
- DARPA MTO http://www.darpa.mil/mto/
- IEEE Explore http://ieeexplore.ieee.org/Xplore/DynWel.jsp
- Introduction to Microengineering http://www.dbanks.demon.co.uk/ueng/
- MEMS Clearinghouse http://www.memsnet.org/
- MEMS Exchange http://www.mems-exchange.org/
- MEMS Industry Group http://www.memsindustrygroup.org/
- MOSIS http://www.mosis.org/
- MUMPS http://www.memscap.com/memsrus/crmumps.html
- Stanford Center for Integrated Systems http://www-cis.stanford.edu/
- USPTO http://www.uspto.gov/
- Trimmer http://www.trimmer.net/
- Yole Development http://www.yole.fr/pagesAn/accueil.asp

Information Resources

Journals

- Journal of Micromechanical Systems (JMEMS)
- Journal of Micromechanics and Microengineering (JMM)
- Micromachine Devices
- Micronews (Yole Development)
- MST News
- Sensors and Actuators (A, B & C)
- Sensors Magazine

Information Resources

Conferences

- International Conference on Solid-State Sensors and Actuators (Transducers), held on odd years
- International Society for Optical Engineering (SPIE)
- MicroElectroMechanical Systems Workshop (MEMS), IEEE
- Micro-Total-Analysis Systems (μTAS)
- Solid-State Sensor and Actuator Workshop (Hilton Head), held on even years