SAND2007-4730C

MEMS, Microfluidics, and BioMEMS – key concepts, examples, future directions

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Acknowledgements

- My colleagues at Sandia. Much of what I am presenting is not my own work or is only partly my work. Therefore I acknowledge colleagues too numerous to remember up front.
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Outline

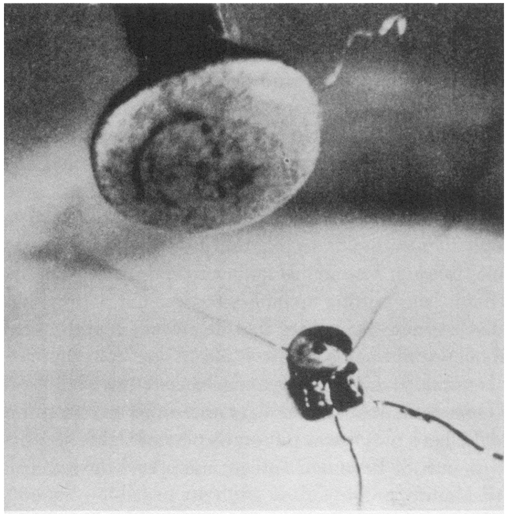
- MEMS Introduction and applications
- MEMS microfabrication (SUMMiT)
- Example MEMS microsystem - MiniME
- Microfluidics Introduction
- Microfluidics/BioMEMS applications
- Microfluidics Examples
  - Gas-Phase Micro-Chem-Lab and MEMS valve
  - Molecular Motors
- Summary and Future Directions

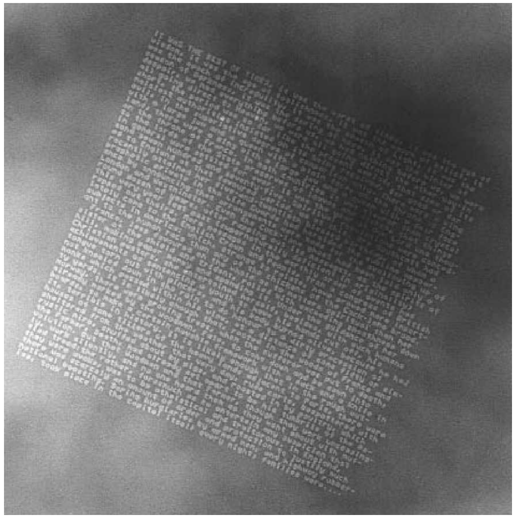
Vision of Micro-Systems

- "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

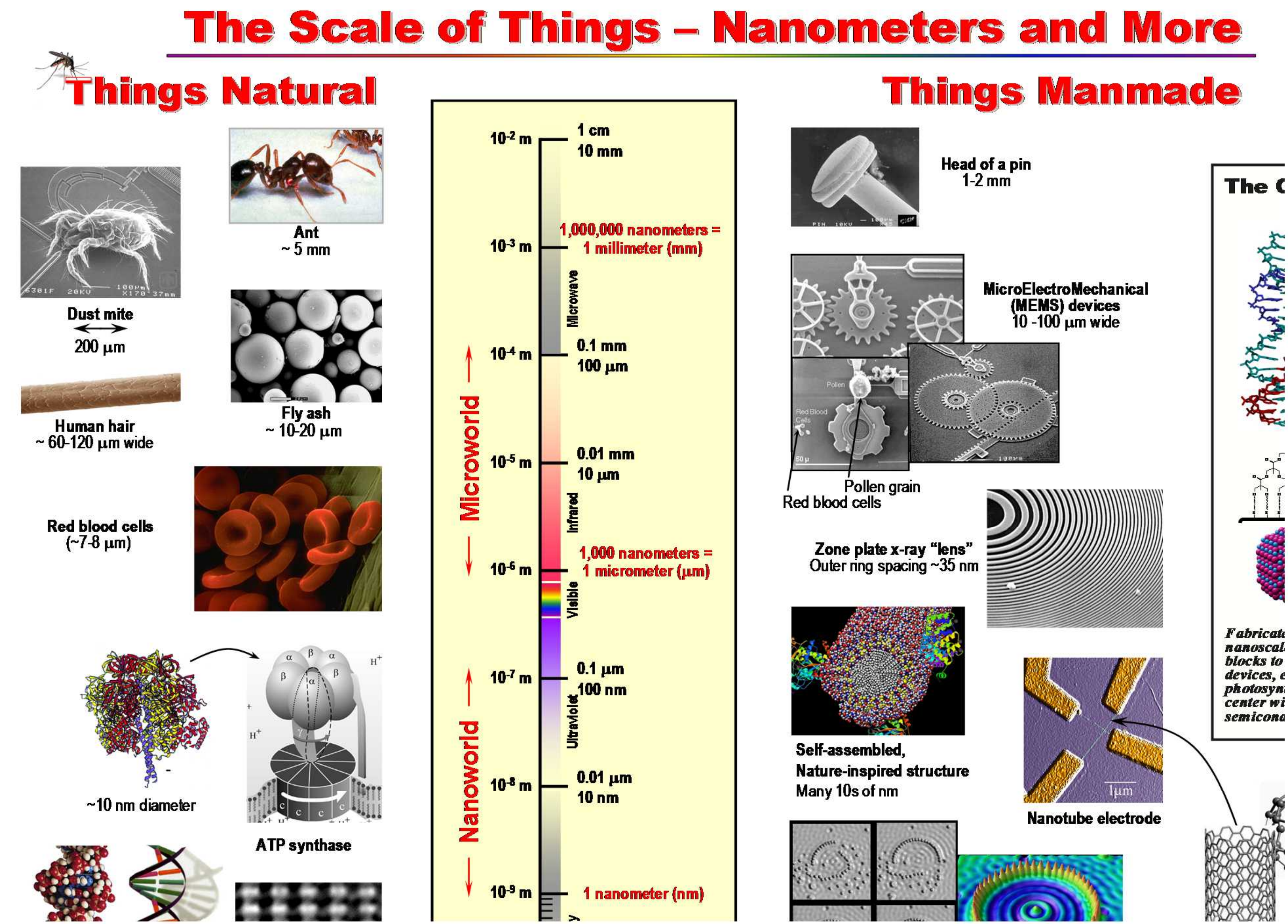
Richard P. Feynman (1918-1988)

William McLellan, 1960





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

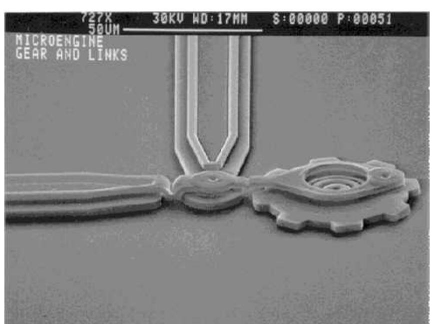


The Scale of Things – Nanometers and More
Things Natural
Things Manmade
Dust mite
200 µm
Ant
~ 5 mm
Human hair
~ 60-120 µm wide
Fly ash
~ 10-20 µm
Red blood cells
(~7-8 µm)
~10 nm diameter
ATP synthase
10-2 m
1 cm
10 mm
10-3 m
1,000,000 nanometers =
1 millimeter (mm)
Microwave
10-4 m
0.1 mm
100 µm
Microworld
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)
Head of a pin
1-2 mm
MicroElectroMechanical
(MEMS) devices
10 -100 µm wide
Pollen
Red Blood Cells
Pollen grain
Red blood cells
Zone plate x-ray "lens"
Outer ring spacing ~35 nm
Self-assembled,
Nature-inspired structure
Many 10s of nm
1µm
Nanotube electrode

Physical phenomena scale at different rates which changes their relative importance.

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

- Nano Domain
- Micro Domain
- Macro Domain



Physical Phenomena Change: The breakdown of Continuum Model

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

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

Microsystem Timeline

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 "There's plenty of room at the bottom"

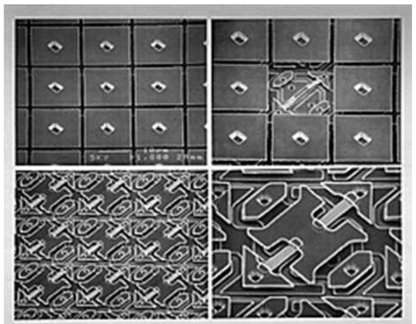
Beginnings of Microelectronic Technology → 1959 Planar Silicon Transistor; 1959 Planar fabrication process for microelectronics

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

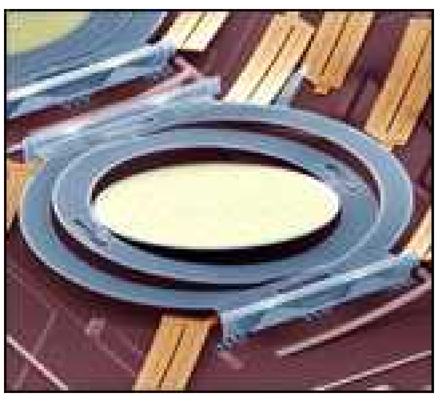
MEMS Commercial Products → 1977–1979, 1982 (Disposable blood pressure transducer), 1987, 1993–2002

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

MEMS Commercial Applications

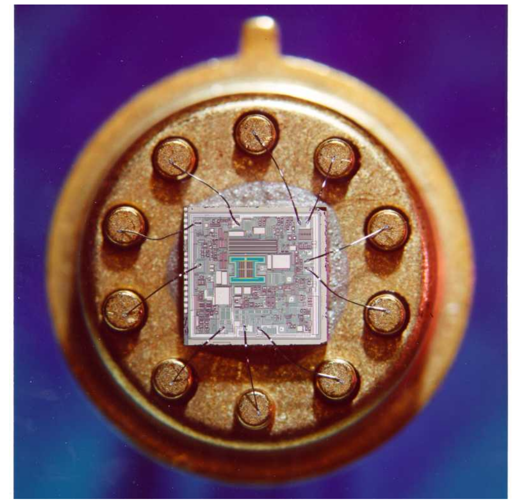


Digital Mirror Device
Texas Instruments

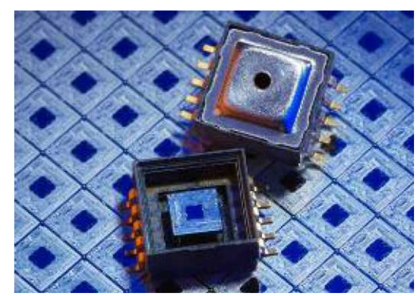


Micromirror switch
Lucent Technologies

Ink Jet Cartridge
Hewlett Packard



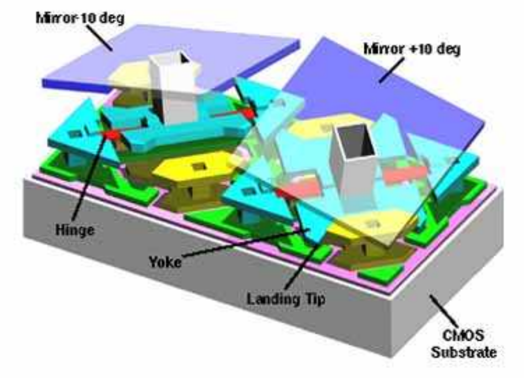
Accelerometer
Analog Devices



Pressure Sensor
Bosch MEMS

TI DMD Light Switch

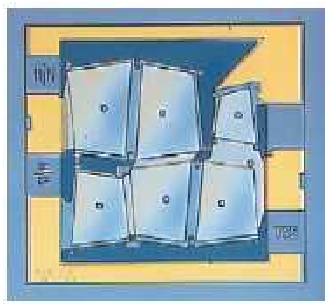
- Each light switch has an aluminum mirror (16 μm square) that can reflect light in two directions
- Rotation of the mirror occurs from an electrostatic attraction between the mirror and underlying memory cell
- System occupies 90% of projected image – mirrors separated by only 1 μm



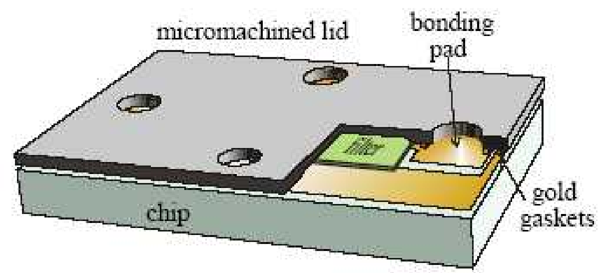
Agilent Technologies RF MEMS

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



MEMS Microfabrication – focus on SUMMiT

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}

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

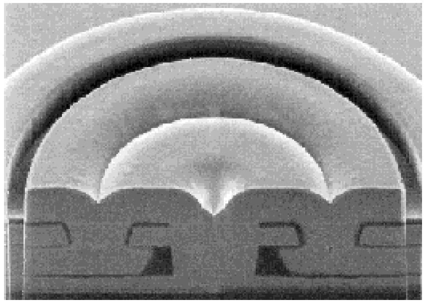
Precision Machining

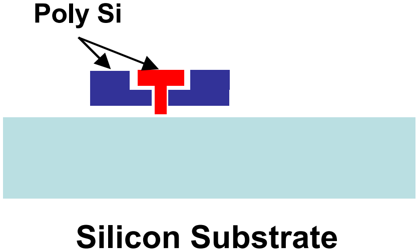
- Materials: Most metals, alloys, and superalloys & most polymers and ceramics
- Processing: One piece at a time
- Assembly: Assembly required
- Geometry: Full three-dimensionality

Three Dominant MEMS Fabrication Technologies

Surface Micromachining

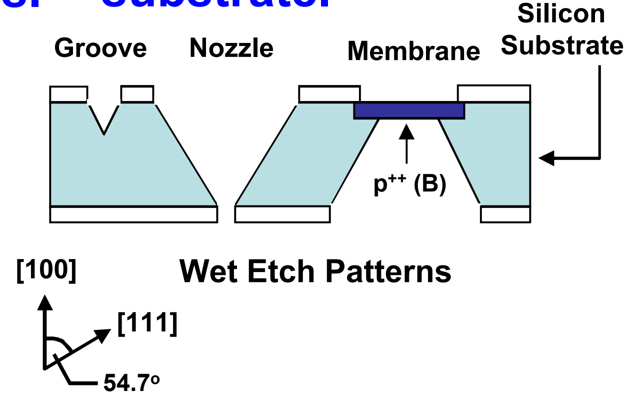
structures formed by deposition and etching of sacrificial and structural thin films.

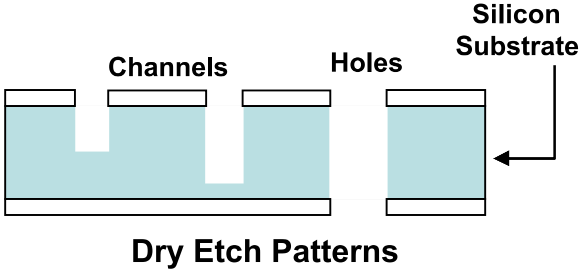




Bulk Micromachining

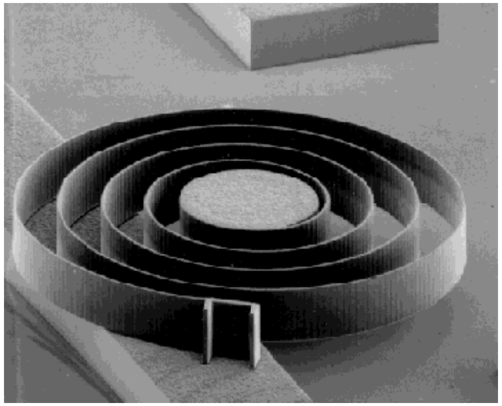
3D structures formed by wet and/or dry etching of silicon substrate.

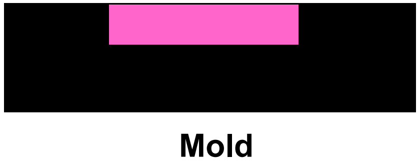




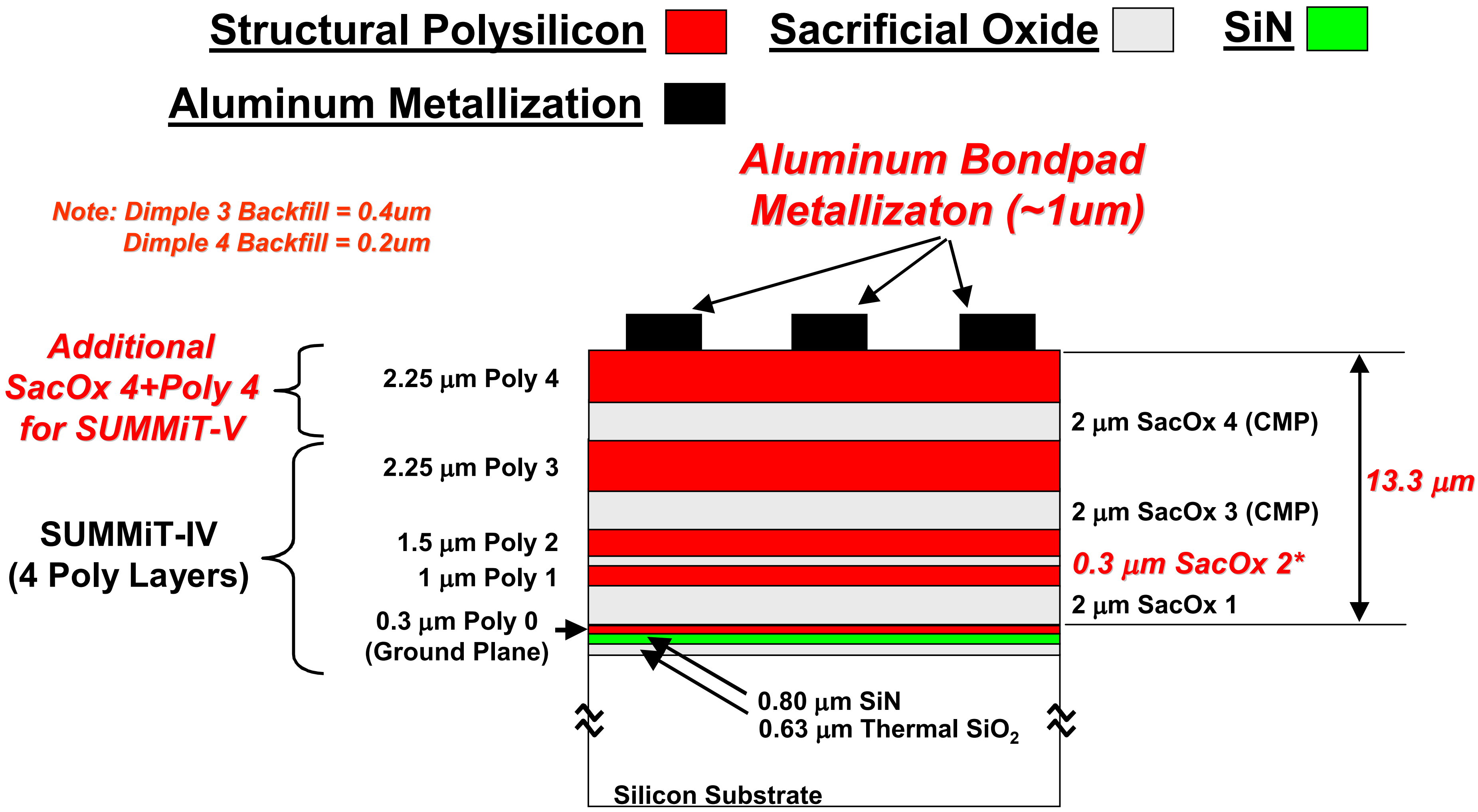
LIGA

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





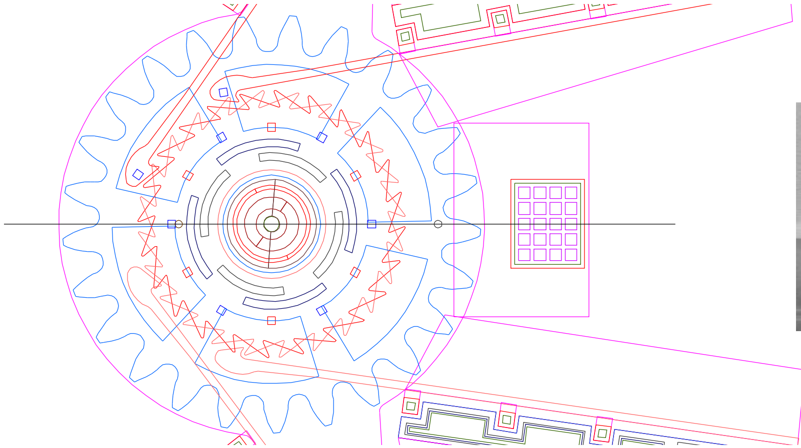
Baseline SUMMiT-V Technology

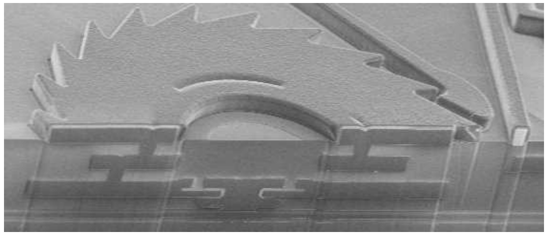


*Note: In SUMMiT-IV Sacox2 = 0.5 um

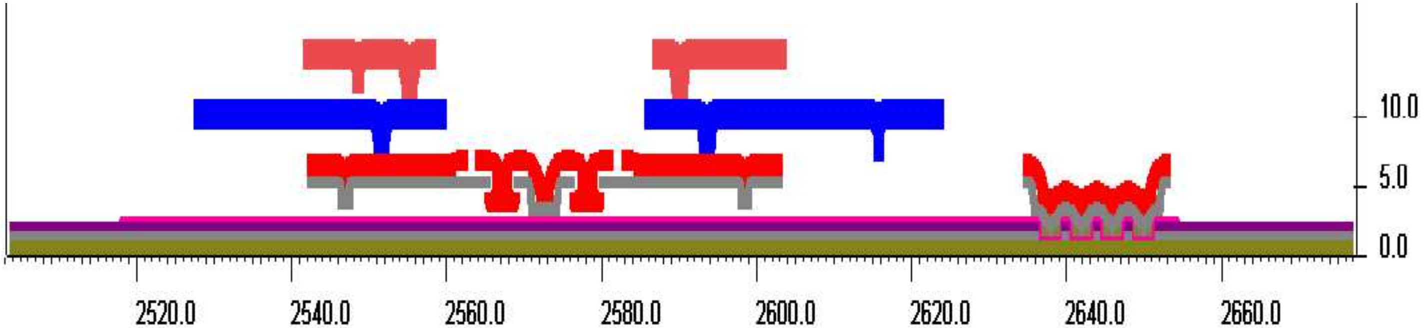
SUMMiTV Cross-Sections: Released Structure

SEM perspective view of fabricated device





FIB Cross-section of fabricated device



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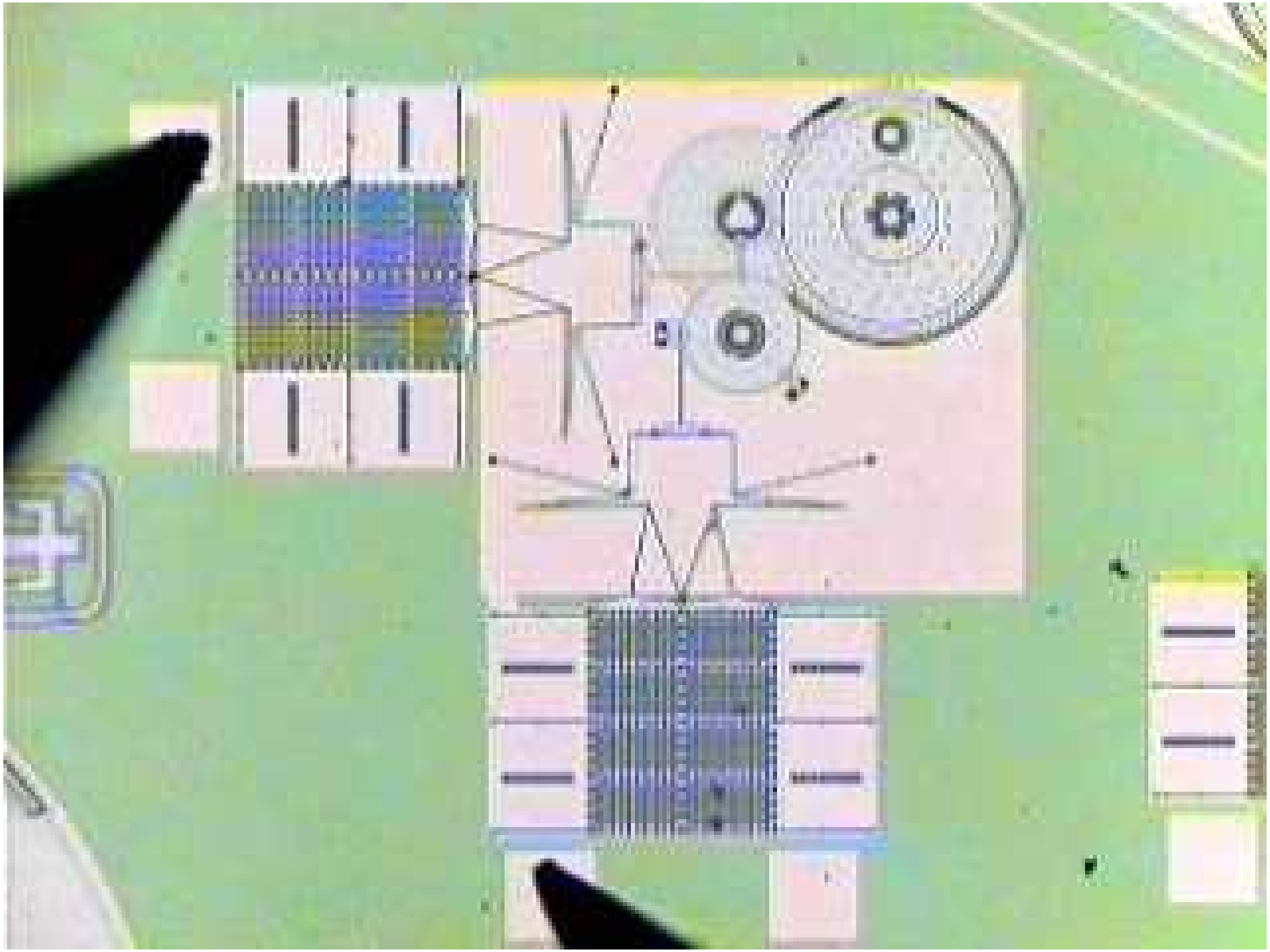
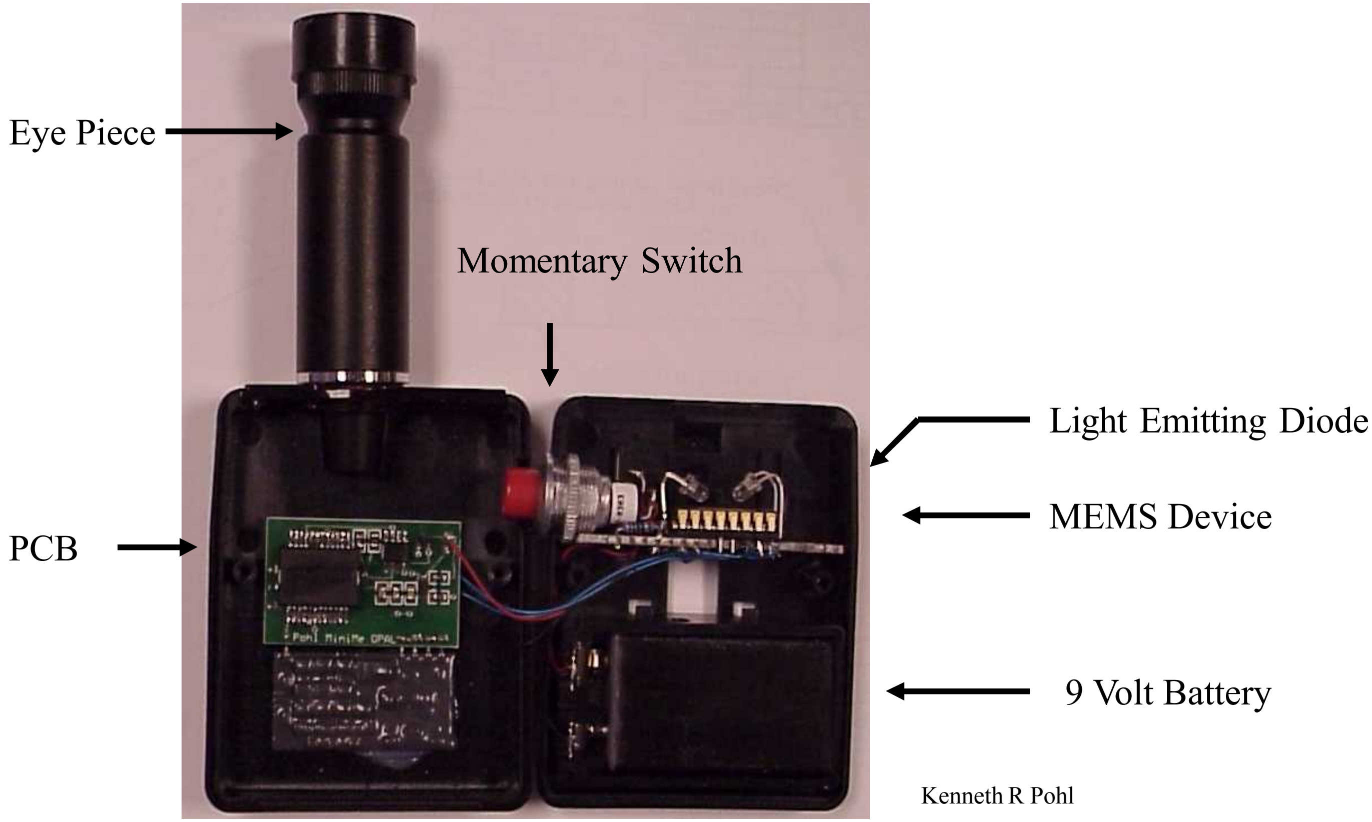


An Example MEMS Microsystem

Hand-held microsystem (MiniME)

MinIME
(Miniature Integrated MEMS/Electronics)

Inside of MiniME
MinI ME Component Placement

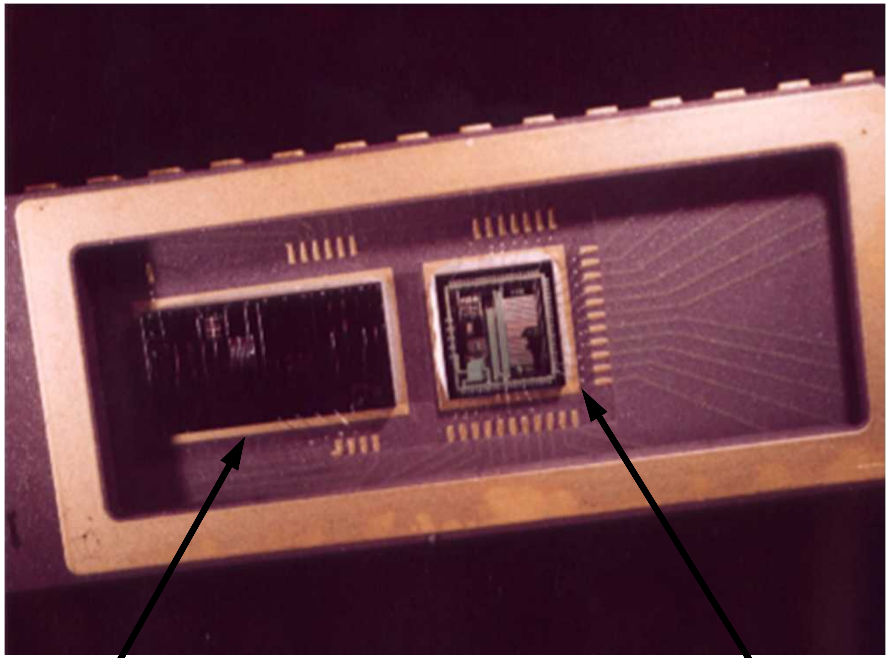


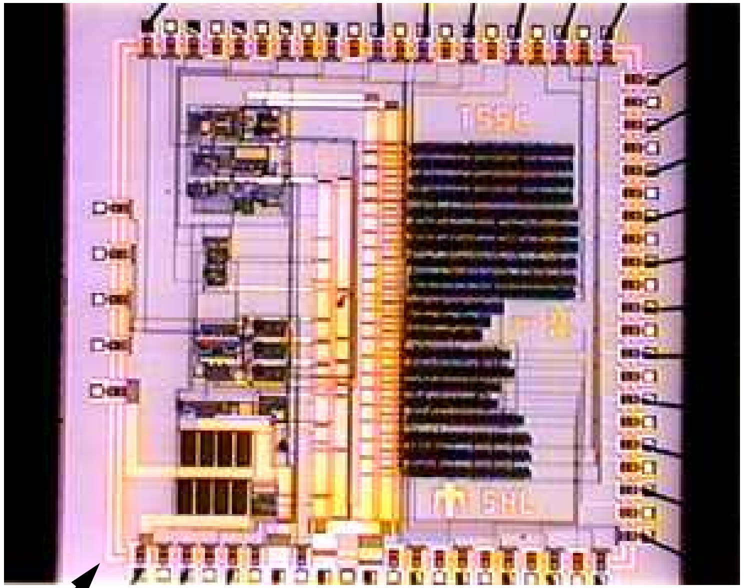
Kenneth R Pohl

TRA Driven Mirror Array

From Ken Pohl, SNL

Power and Mechanics in one DIP (Dual Inline Package)





MEMS part

ASIC - built in standard 1.2 micron CMOS, 5 V in and 90 V out to power MEMS

From Mark Poloski, Sandia National Laboratories

Microfluidics Introduction

Microfluidics Scales

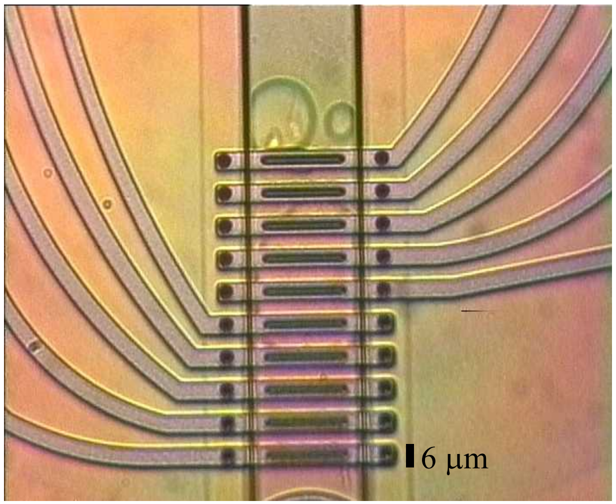
- Meso-scale fluidics – pneumatic and hydraulic control, fluid handling robots, pipetting. Channels on the order of 10 mm to 10ths of mms. Reynolds numbers 1 to 100's. Volumes on the order of ml's to μl's.

- Microfluidics - μTAS (Micro-Total (chemical) Analysis Systems) or Chem-lab-on-a-chip, laminar flow, diffusion dominated transport, electrophoresis/electrosmosis. Channels on the order of 100's of microns to a few microns. Volumes on the order of μl's to pl's and Reynolds numbers from <<1 to 100 (unsteady). A very small drop is on the order of a μl.

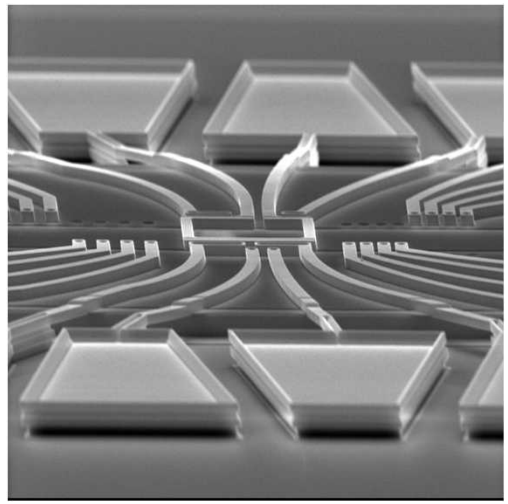
- Nano-scale fluidics – macromolecular machines, biological processes. Channels on the order of a μm or less, volumes on the order of femtoliters, and Rey<<1.

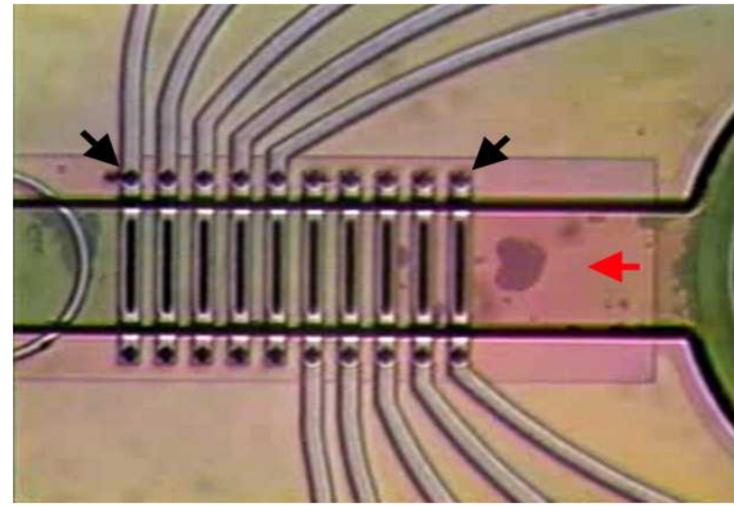
- To interact with the nano-scale you must typically go through the meso and micro scales.

Electrochemistry/photochemistry – particle manipulation in microfluidic channels



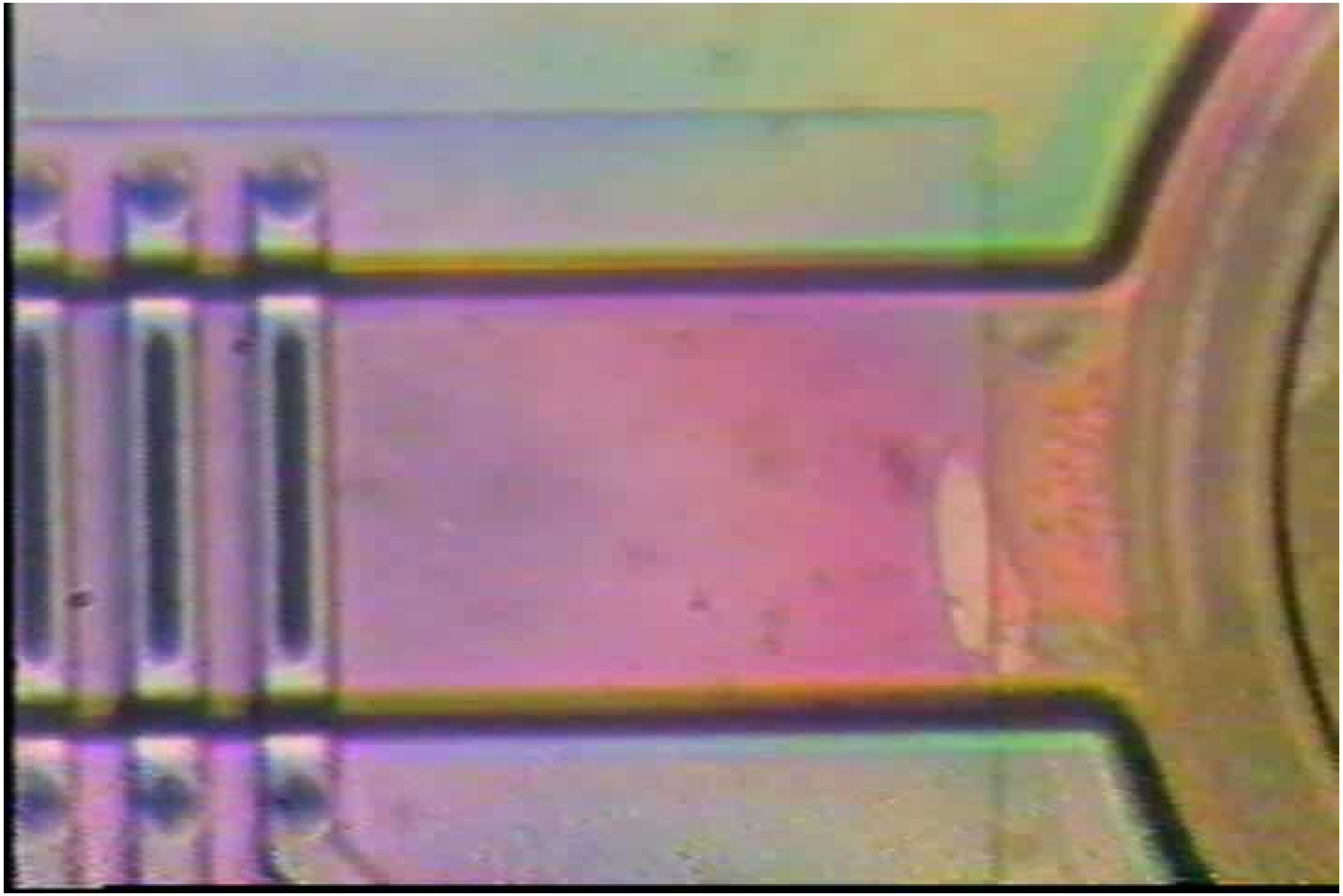
electrolysis bubbles inside the channel





Trapping of beads by application of AC waveform (measurement by Conrad James, 1769)

- Some of the very interesting aspects of micro-nanoscale reactions become observable/feasible at the scale of these devices.
- Reactions can be controlled by the applied field, light, temperature and flow conditions.
- Particles/streams inside the channel can be controlled by various means (dielectrophoretic trapping, magnetic fields, etc.)

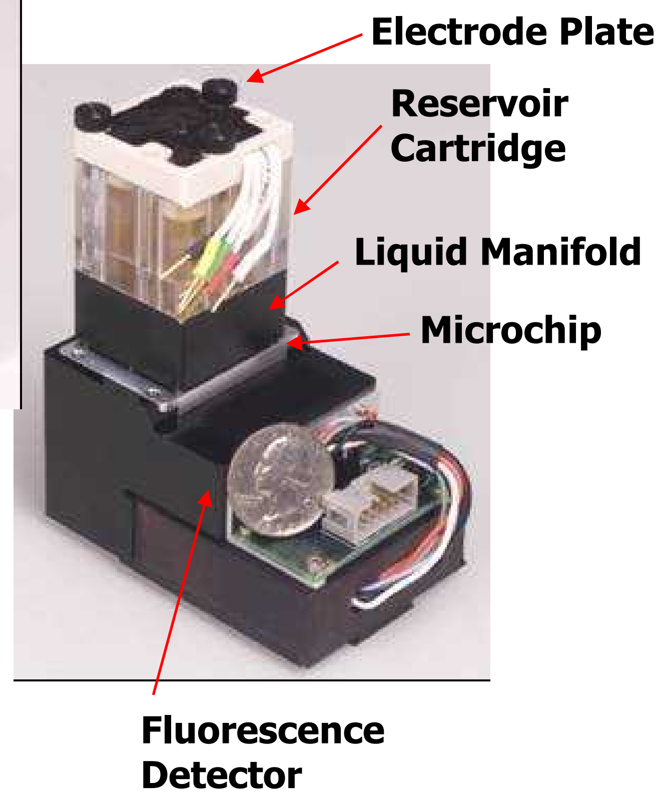


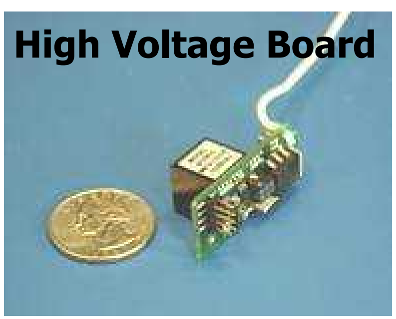
μChemLab microfluidics technology incorporated into complete microsystem

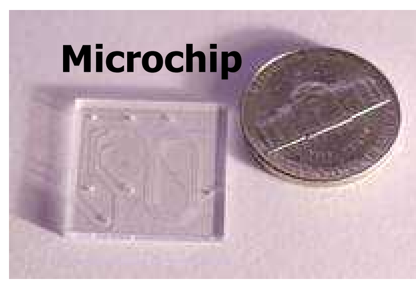
- Hand portable
- Battery operated
- On-board data analysis

A flexible, reliable platform for routine laboratory R&D

- Modular packaging
- Two analysis modules

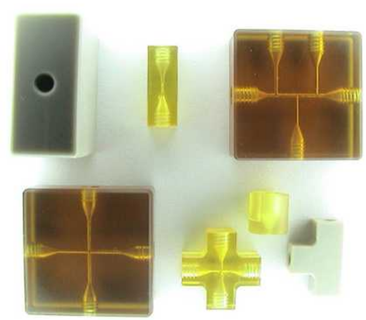




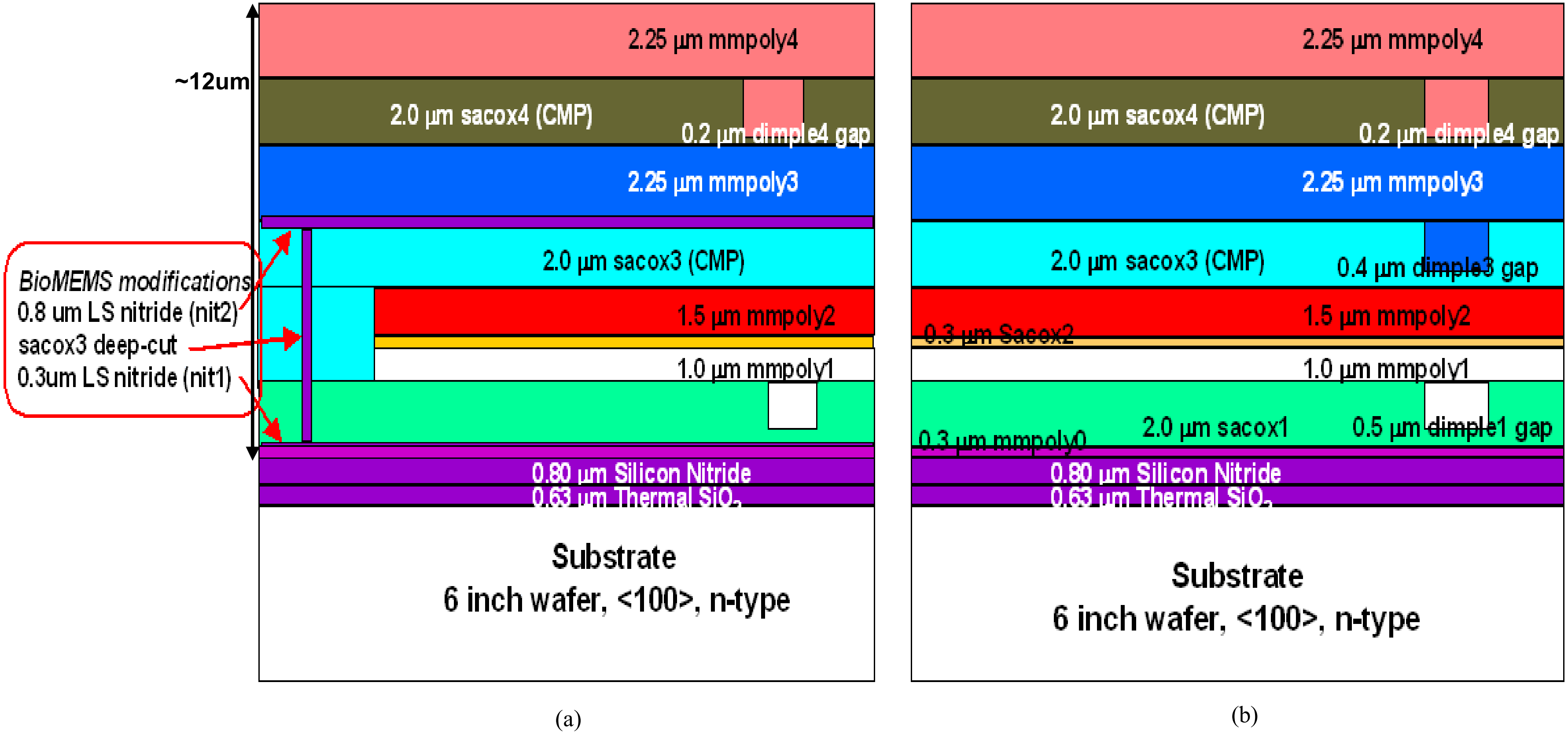


Microfluidic Technologies

- Capillary Chip Electrophoresis
  - CGE, CZE, IEF
  - Laser-Induced Fluorescence detection
- Electrokinetic Pumping
  - EK-High Performance Liquid Chromatography (HPLC),
  - Infusion pumps
- Insulator-based Dielectrophoresis(iDEP)
  - Particle concentration
  - Sorting
- Gas Chromatography
  - SPE, GC, SAW detection
- High Pressure CapTite Capillary Fittings
  - Sub-miniature
  - Reusable



SwIFT™ and SUMMiT™

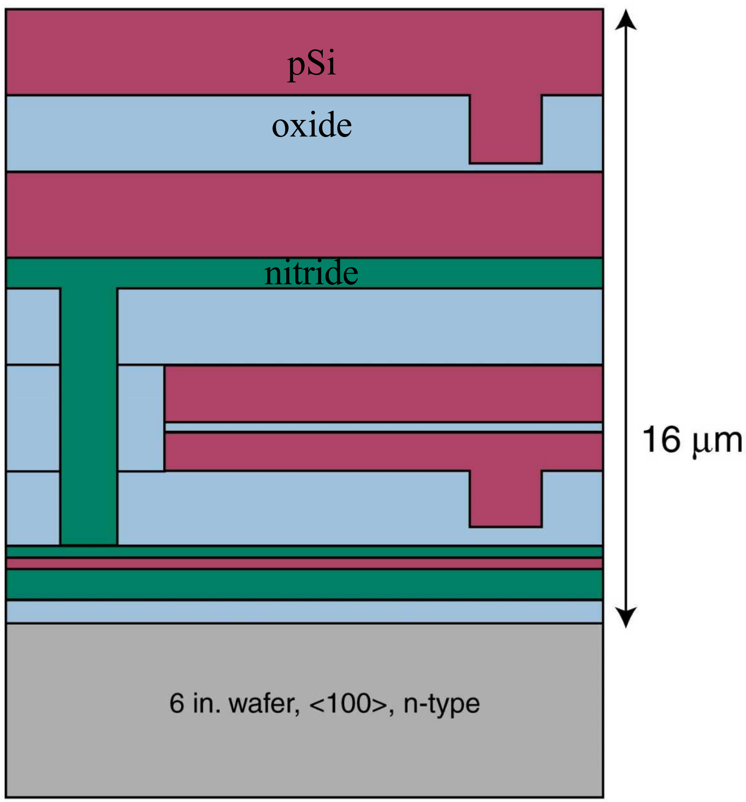


(a) SwIFT™ and (b) SUMMiT™ layers. The incorporation of the low stress silicon nitride layers allows the creation of complex microfluidic structures and enclosed cavities with optical access and provides the ability to create arbitrary fields inside these structures.

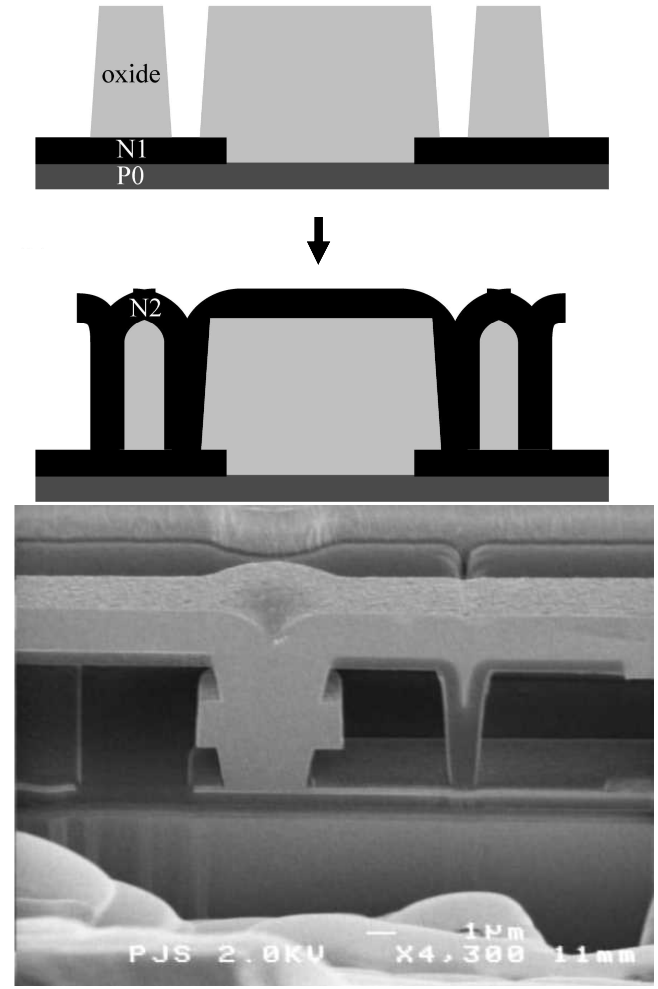
SWIFT

SwIFT ™ (<u>S</u>urface Micromachining <u>w</u>ith <u>I</u>ntegrated micro<u>F</u>luidic <u>T</u>echnology)

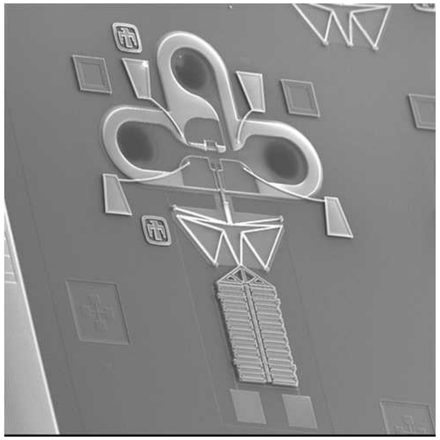
sacrificial layers of SiO_2, five layers of doped pSi, ~ 200 nm resolution, three layers of Si_xN_y

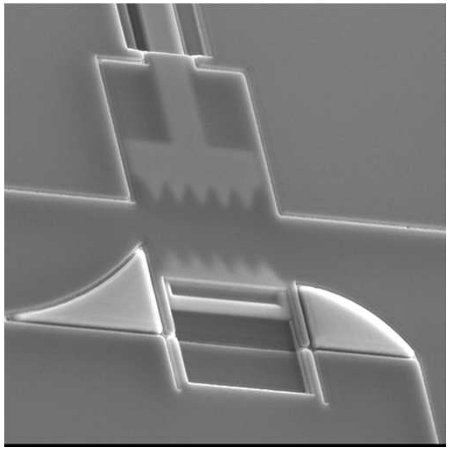


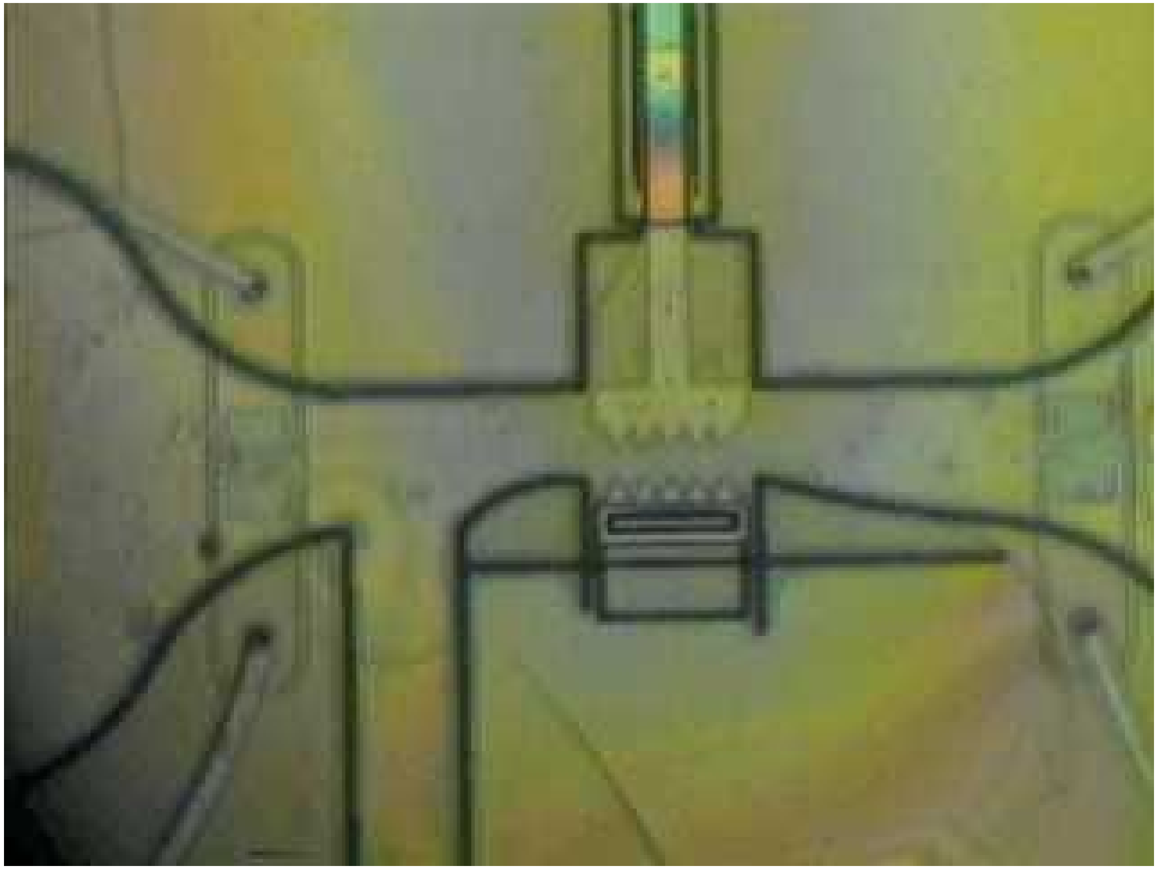
Fluidic channel fabrication:



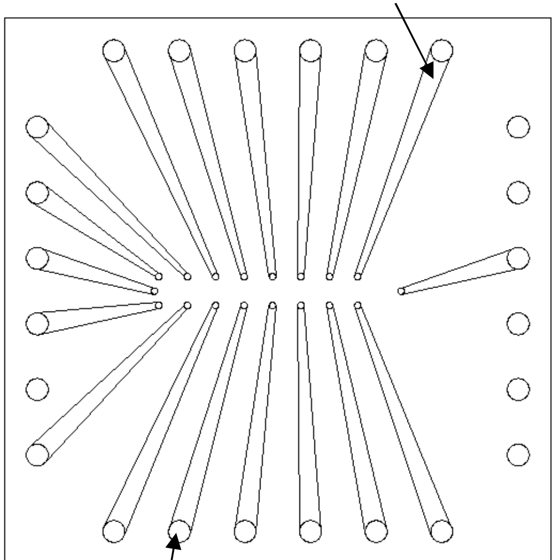
Mechanical Cell Lysis Device - Example

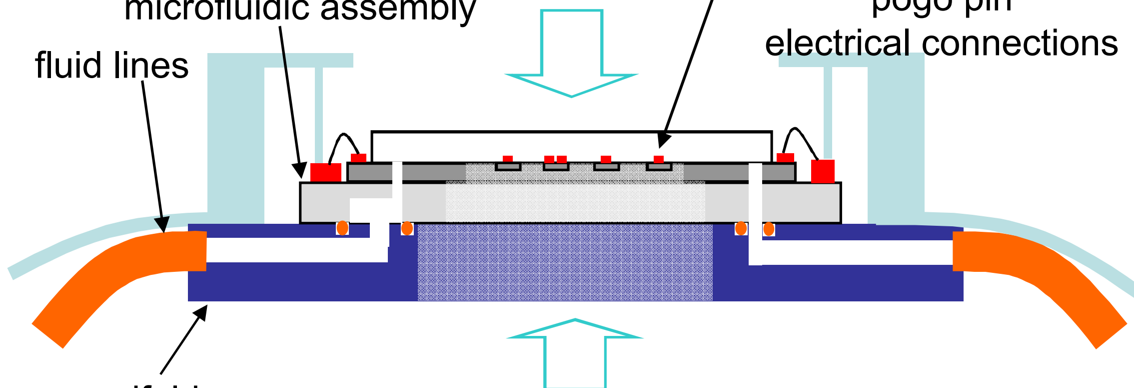




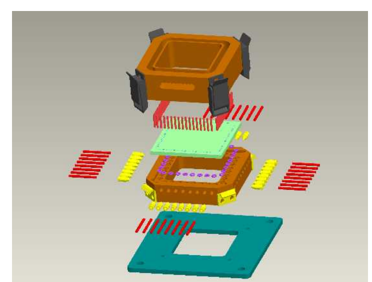


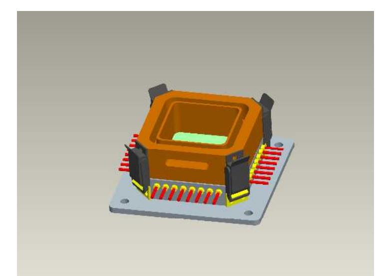
Microfluidic Platform – fanout and manifold connections





The cover and fan out glass must be anodically bonded to the Microfluidic Synthesis DP.





Integration package

- 64 pogo-pin connections utilizing one common interface connector
- 32 fluidic connections
- 1.5 inch square top/bottom access

- O-ring seals to 500 psi
- Dowel pin alignment
- 4-place draw-latch compression

- Circuit board connections soldered directly to pogo-pins
- MDM connector for reliable
- assembly and disassembly

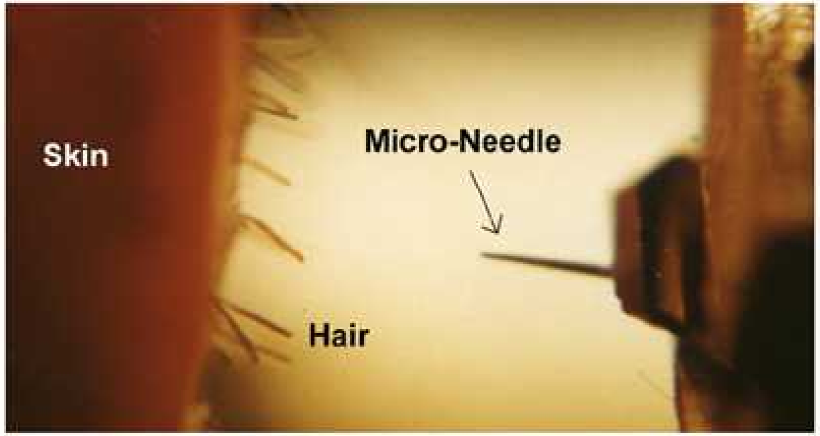
Microfluidics/BioMEMS applications

Drug Delivery

MiniMed

Implantable insulin pump

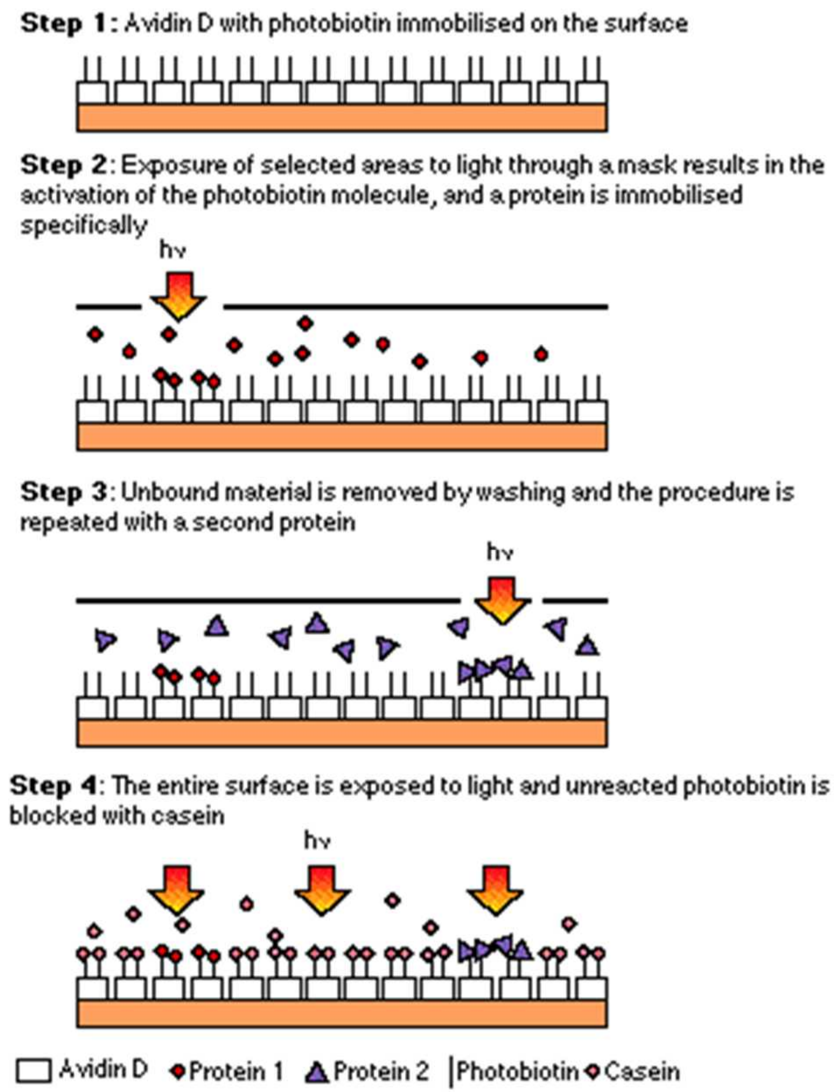
Painless blood-analyte monitoring



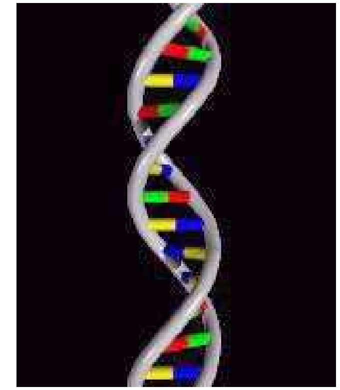
Kumetrix

Sensors

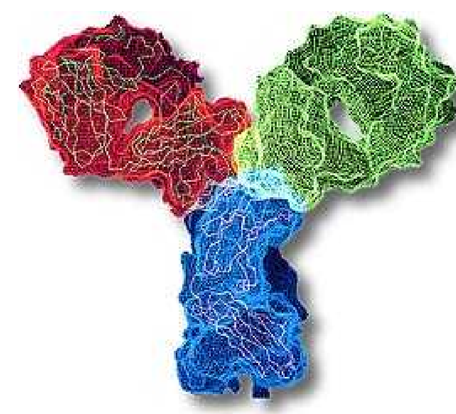
Using photolithography to produce multi-functional surfaces affords multiplexing capabilities to various assay/diagnostic applications



Farmanet

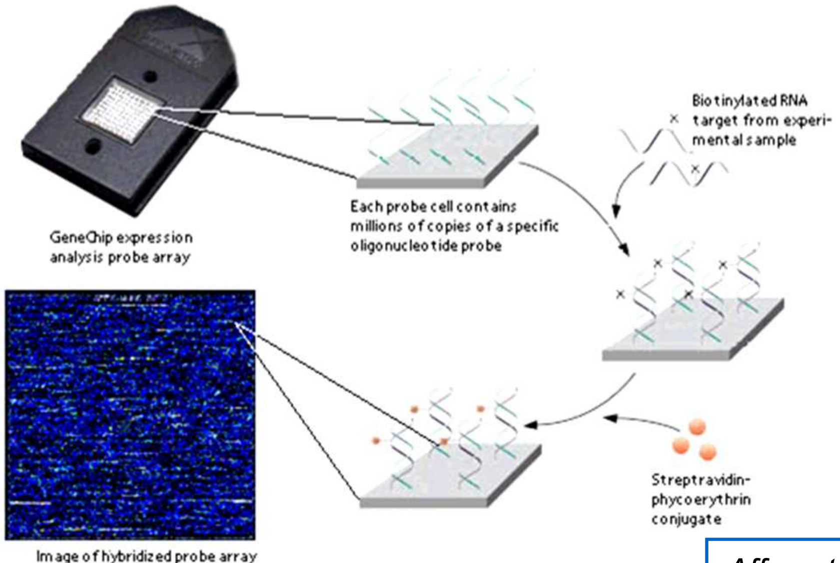


Nucleic acids

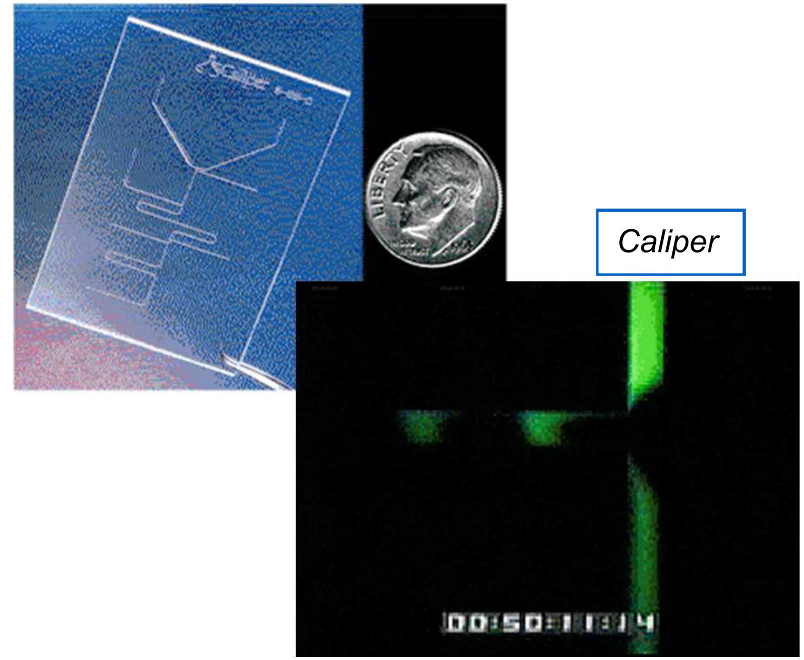


Antibodies

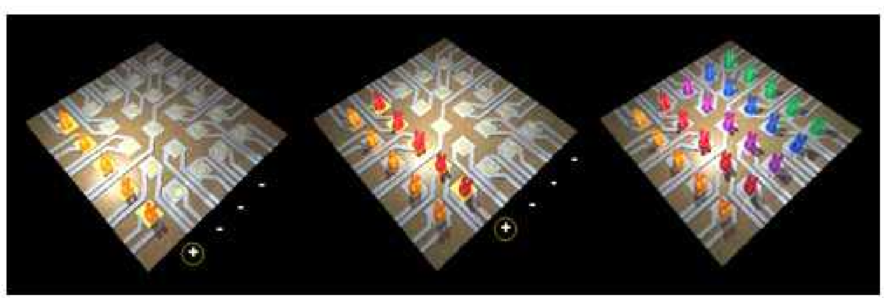
Drug Discovery / Research Tools

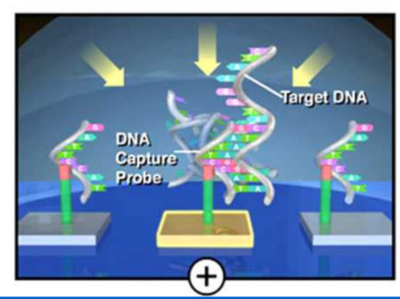


Affymetrix



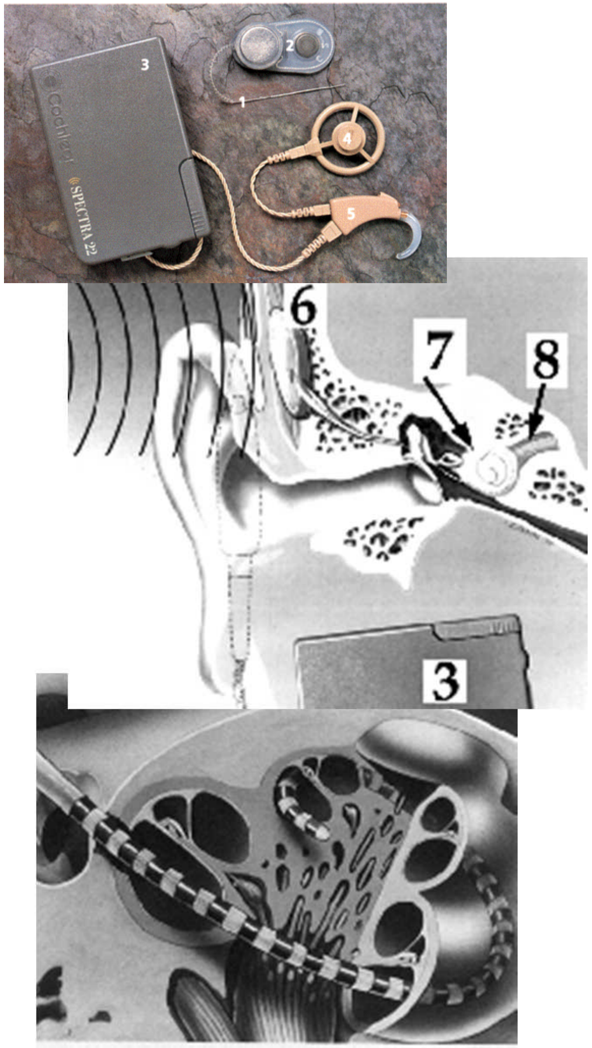
Caliper



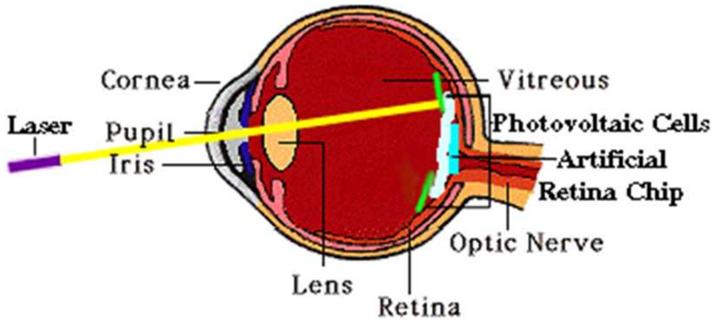


Nanogen

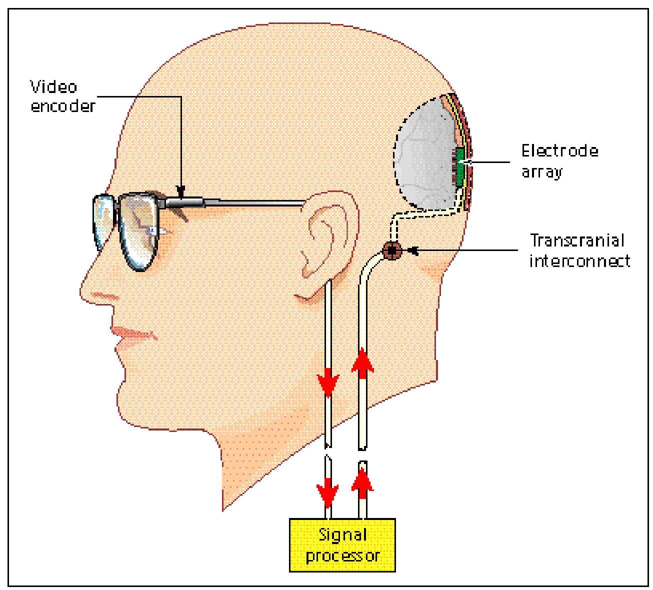
Prosthetic Devices



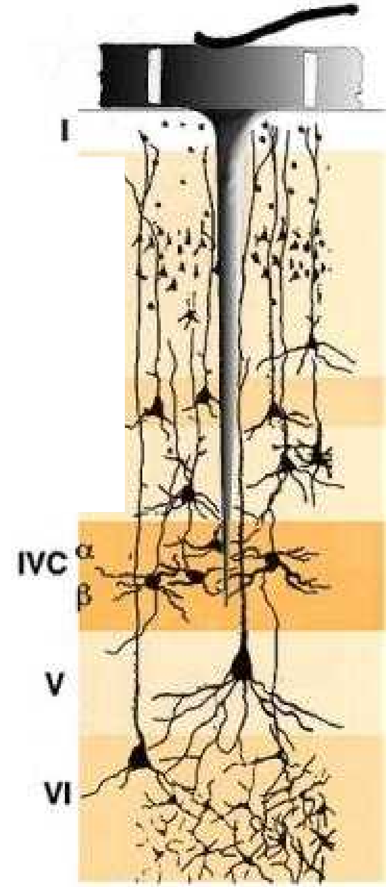
Spectra

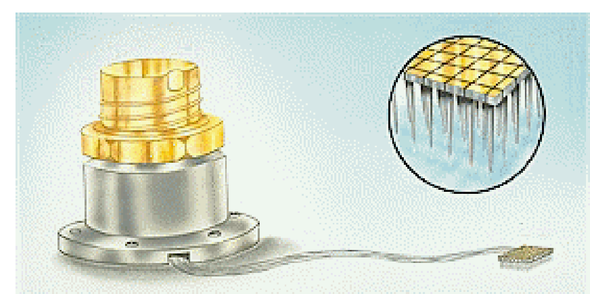


Johns-Hopkins



IEEE



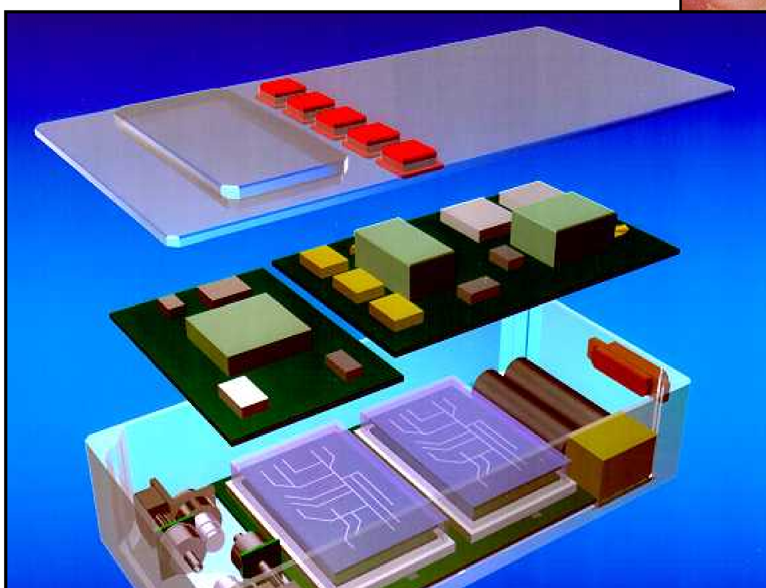


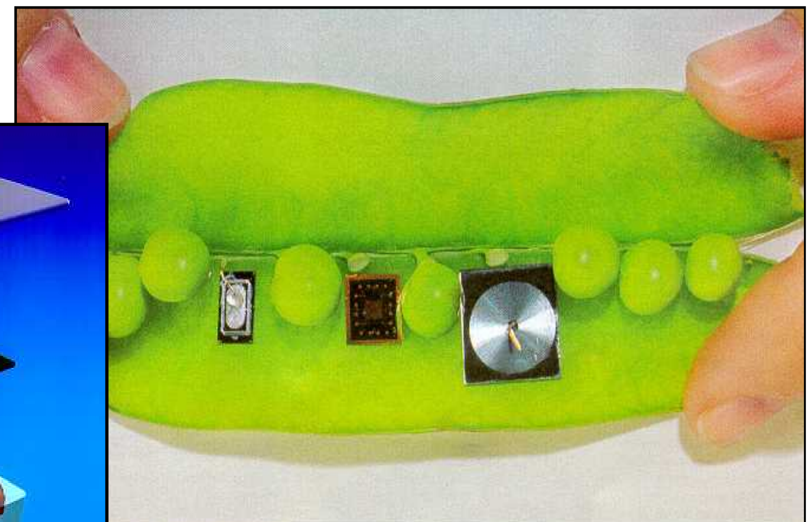
Bionic tech.

Gas-Phase Chem Lab

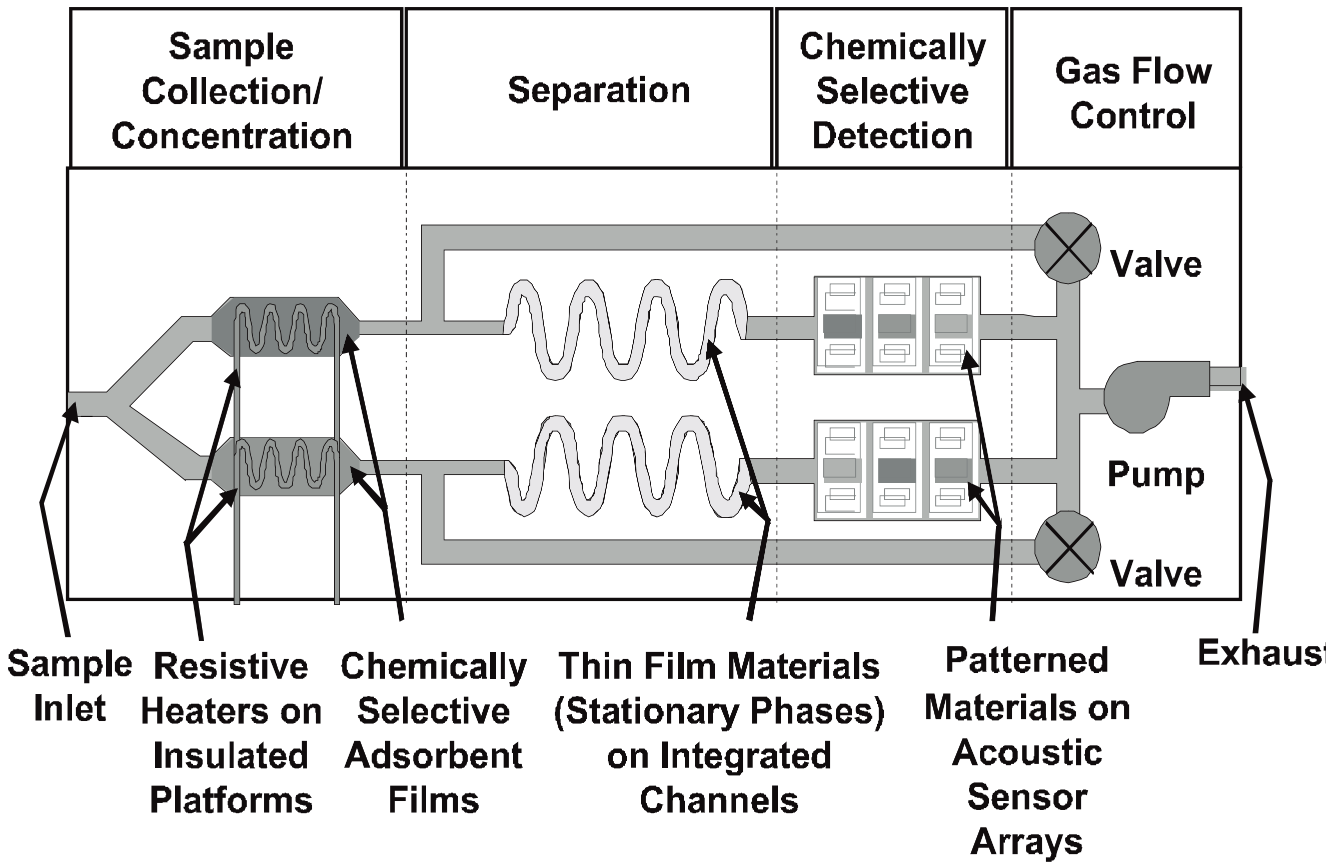
μ-Chem-Lab-on-a-Chip

- A portable device to detect chemical warfare agents in air samples.
- Integrated microfluidics, electronics, and chemistry

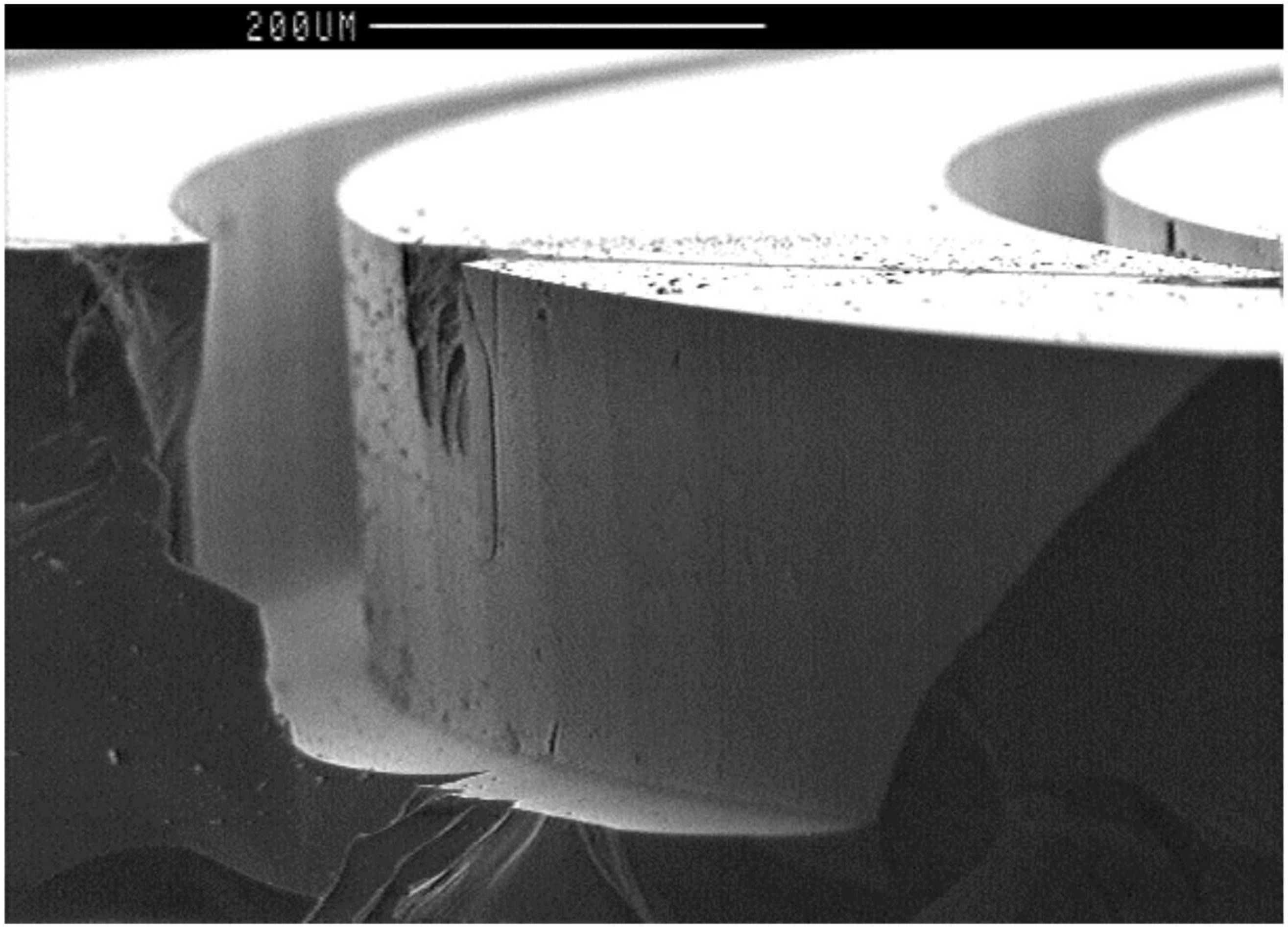




Chem-Lab - Integration of components



Chem-Lab - GC column fabrication

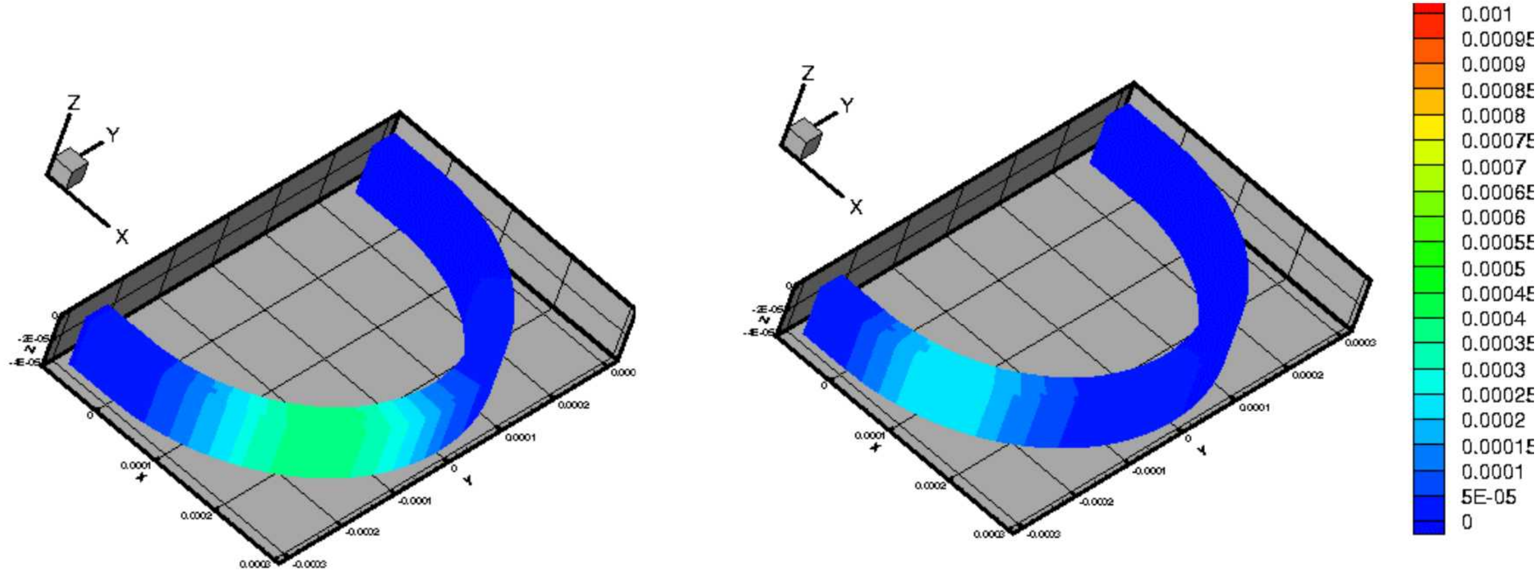


Species Transport and separation

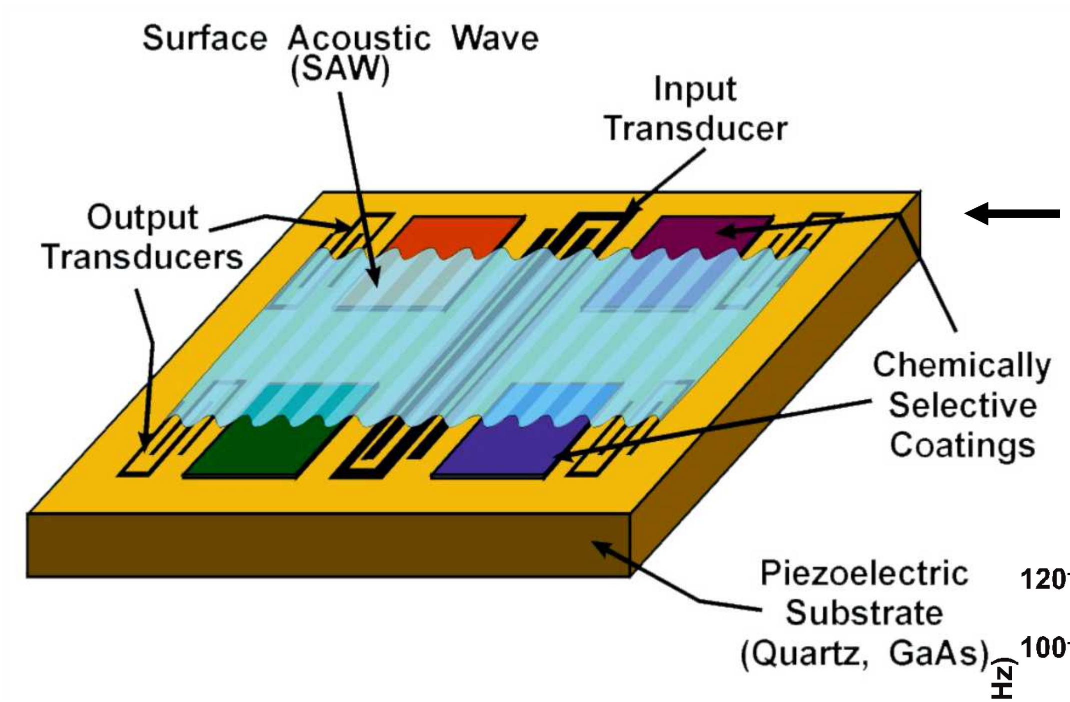
MPSalsa simulations of species transport and separation in GC columns:

3D xyz channels: d=40 microns, h=40 microns, l=1 mm, R=270 microns, DP=126 Pa

Air-DMMP-Benzene

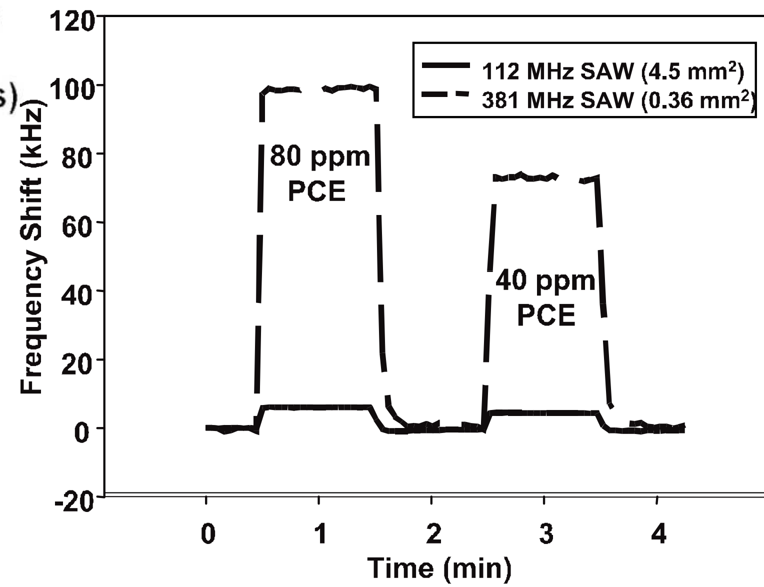


SAW (surface acoustic wave) detector



← SAW sensor components

SAW sensor output →



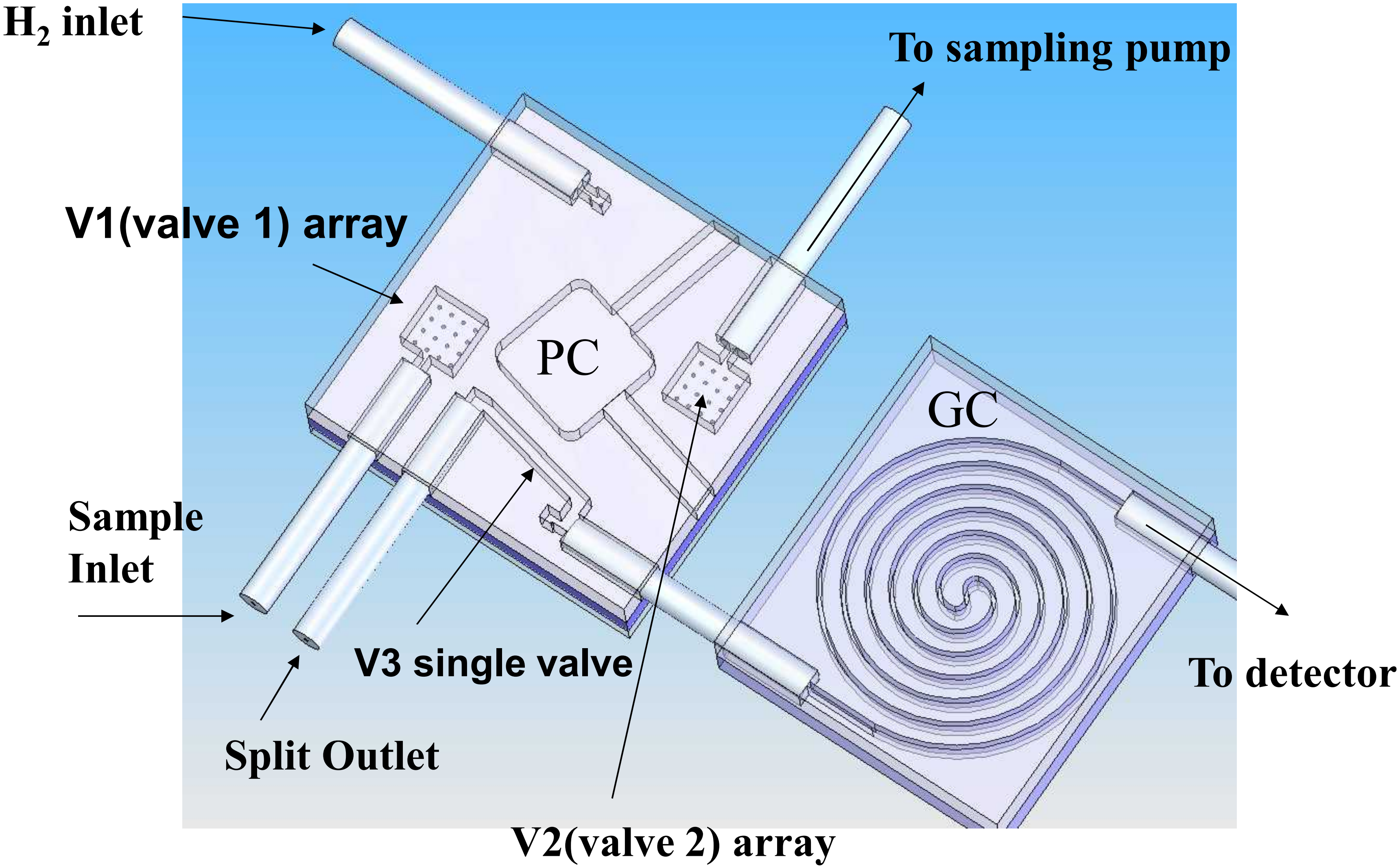
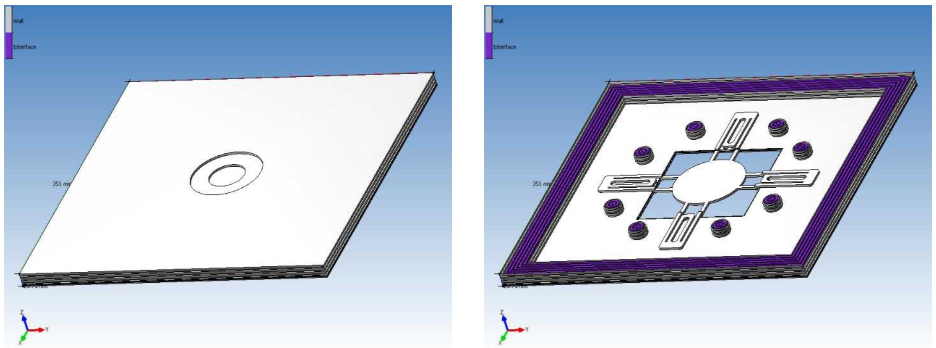


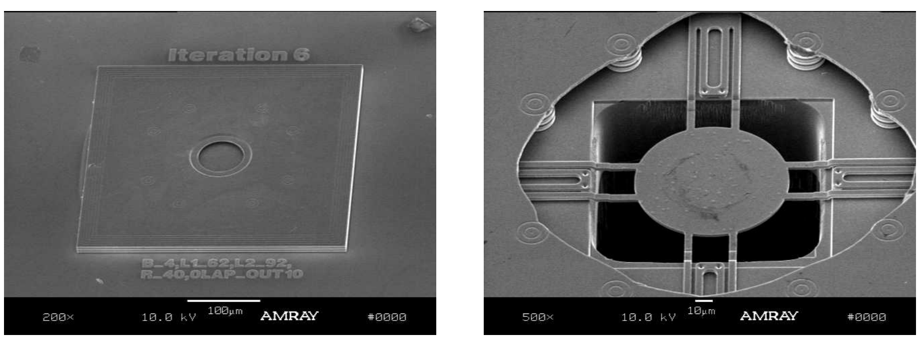
Figure 1. Integrated MEMS valve array/pre-concentrator (PC) chip reduces gas chromatograph (GC) inlet sample volume allowing fast, high resolution separations. Very small dead volume capillary tubes connect PC to GC and other components.

Passive MEMS Check Valve

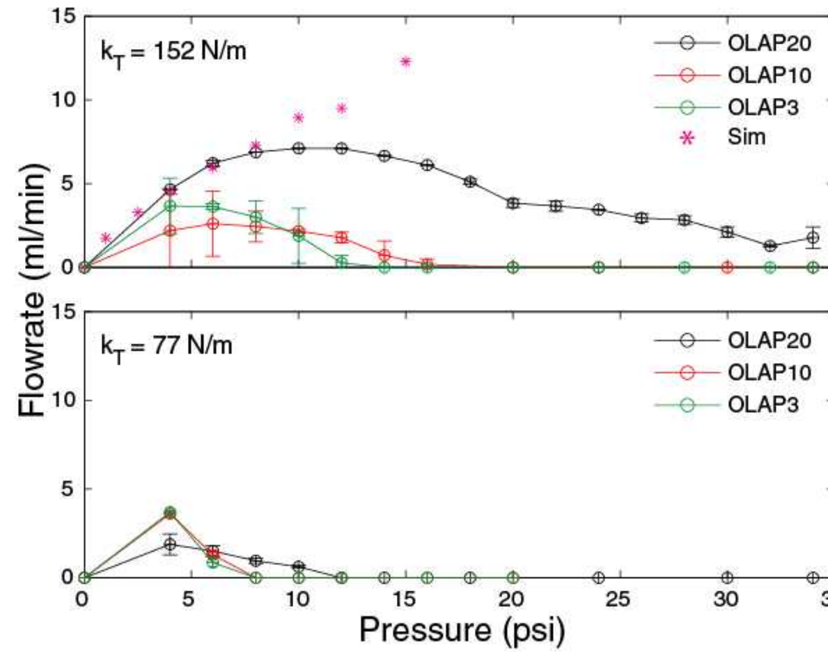
Designed a set of passive MEMS check valves for an internal customer. The SUMMIT V ™ valve remains fully open when pressurized below 5 psi, and fully closes when pressurized above a certain psi (varies for different designs). The flap seals against a surface micromachined lid on the front of the wafer. The footprint for a single valve is 0.35 mm x0.35 mm, and the maximum flowrate through one valve is ~4.5 ml/min at 5 psi.



Schematic design of a passive MEMS valve. On the right, the lid is removed to display the valve flap and springs. The inlet (through the wafer) is 125 μm wide and the outlet (through the front-side lid) is 40 μm wide.



SEM images of two valves. One valve lid is partially removed. The designed spring constant = 152 N/m. The valve is pressurized from the backside of the wafer, and the flap seals against the surface-micromachined lid.

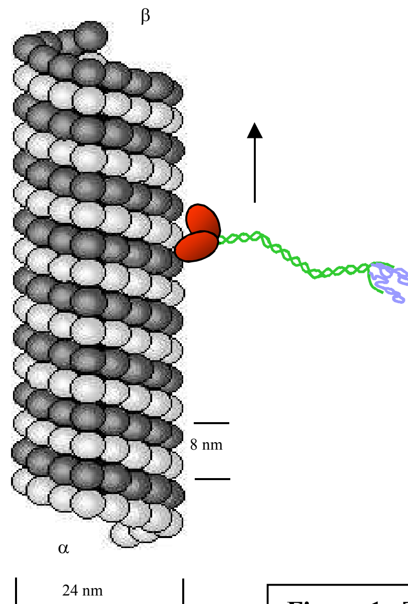


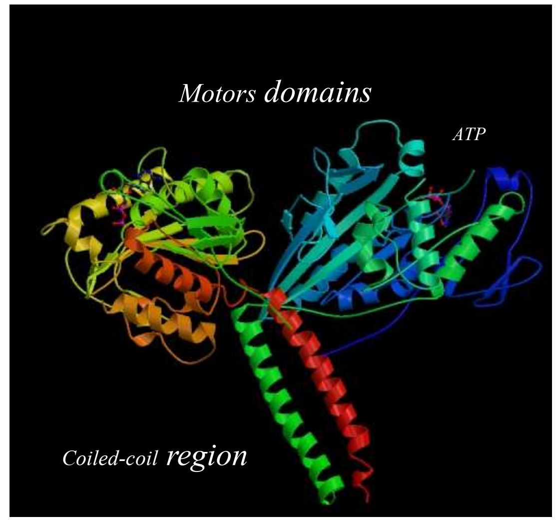
Flowrate through two valve designs (spring constant, k_T = 152 and 77 N/m) as a function of pressure. OLAP3: 3 μm radial overlap between the lid and flap, producing a 74 μm diameter outlet; OLAP10: 10 μm overlap, 60 μm outlet; OLAP20: 20 μm overlap, 40 μm outlet.

Paul Galambos, Conrad James, Jaime McClain (01769)

Molecular Motors

Nanofluidics – molecular machines (I)





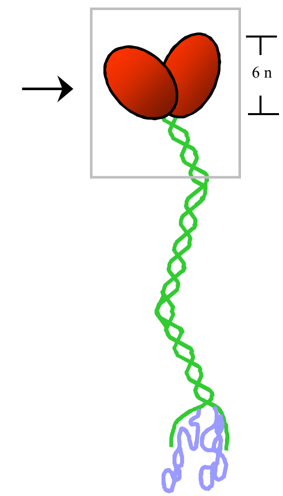
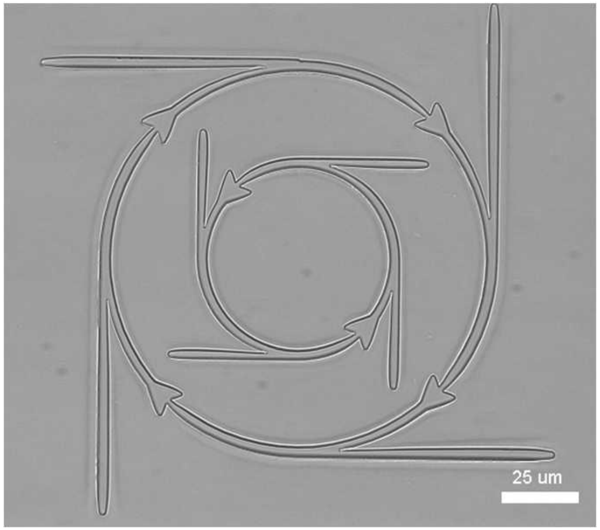


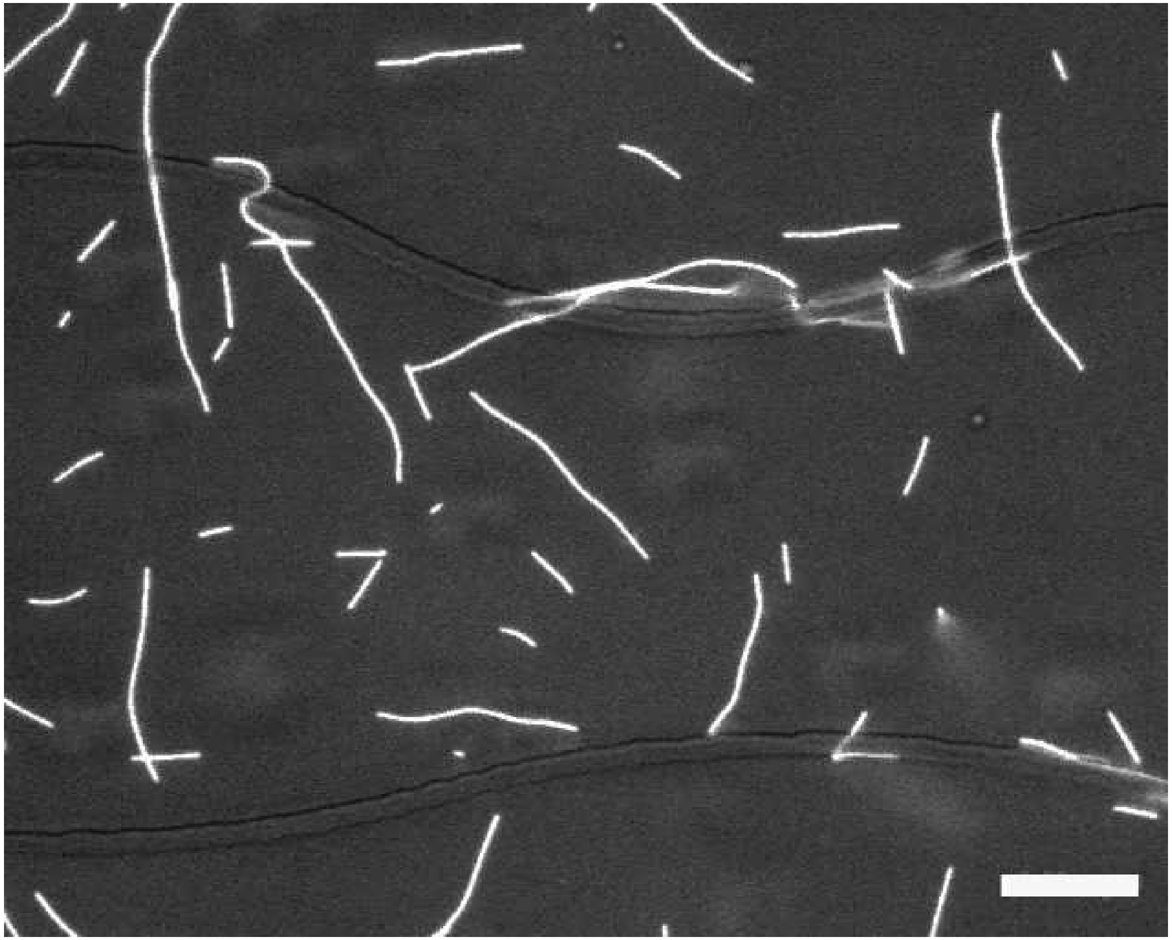
Figure 1. The machinery of the subcellular railroad. The microtubule railroad tracks are actually nanotubules, hollow tubes 24 nm in diameter, formed by the self-assembly of tubulin subunits. MTs have a lattice structure with an 8 nm periodicity corresponding to the dimensions of the subunits and are structurally polar due to the asymmetry of the subunits. The kinesin motor proteins consist of two protein chains entwined into an elongated molecule about 80 nm in length. The force generating motor domain of kinesin is a pear-shaped globular domain with dimensions of only 4 x 7 nm (shown in red). We believe this system can be integrated into microdevices to achieve levels of device sophistication that are not now possible.

From Dr. Russell Stewart – University of Utah

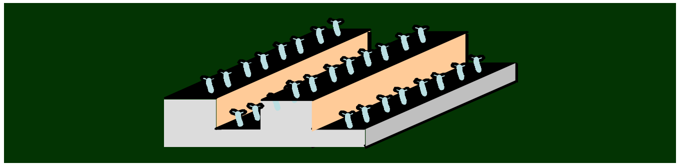
Topography guided microtubule transport

From George Bachand, Sandia National Laboratories





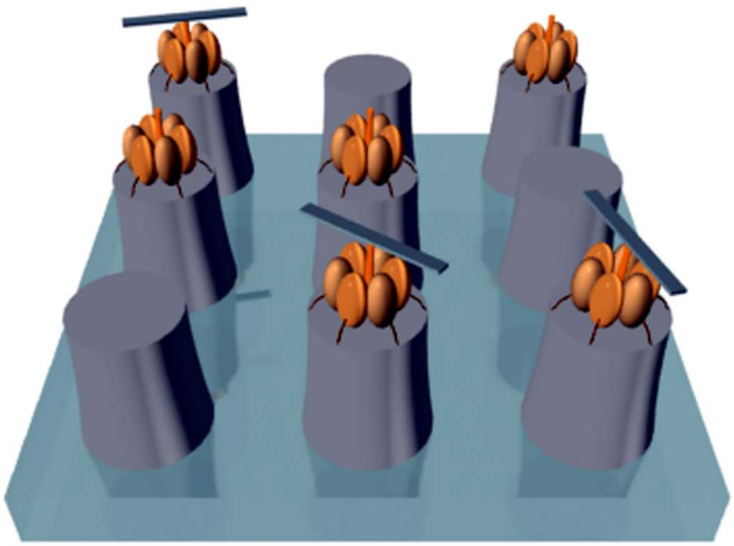
Collaboration with V. Vogel (Univ. of Wash.)

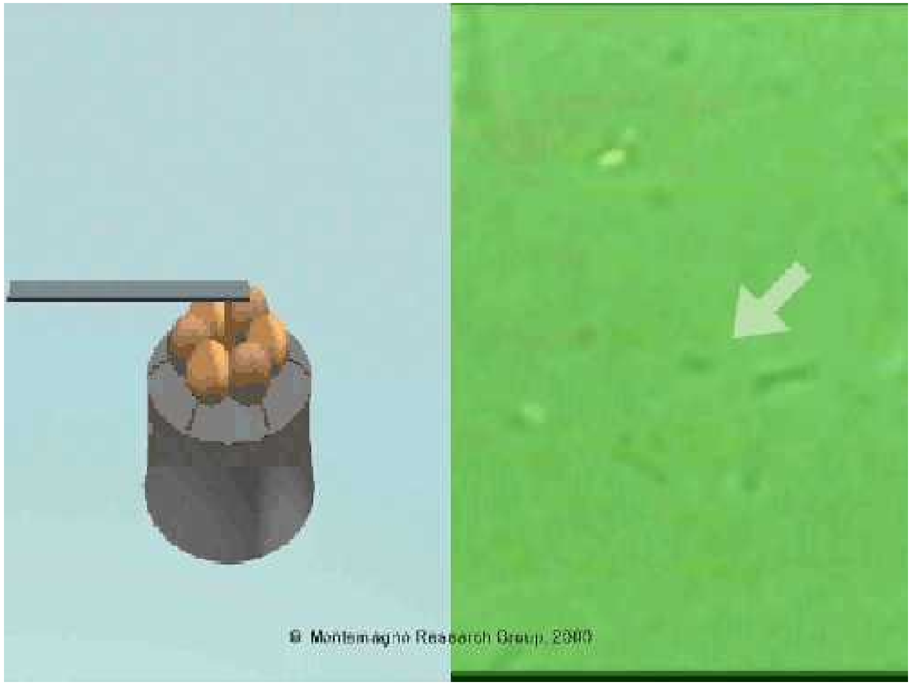


Fabricated by Carolyn Matzke (1763)

ATP Synthase – Powered Nanodevices

1. **Nickel capped posts (80 nm x 200 nm)**
2. **F_1-ATPase motors**
3. **Nickel propellers (150 nm x 750-1500 nm)**





- **Rotational velocity: 1.5 – 8.5 rps**
- **Rotation Torque: 40 pN•nm per step**
- **Efficiency: 50%**
- **Duration: >2 hrs**

Soong, R.K., Bachand, G.D., et al. (2000) Science 290: 1555
Montemagno Research Group, Cornell University

From George Bachand, Sandia National Laboratories

Summary

- MEMS (started ~1960) is now part of our everyday life with products ranging from airbag accelerometers to digital TV's. New applications and research are on-going.

- Microfluidics (started ~1980) associated with analytical instruments, ink-jet printing and solution based fabrication is now a full fledged technology. New applications and research are on-going.

- BioMEMS – integration of machines and biology (including people) is in a similar state of development to microfluidics. New applications and research are on-going.

- NEMS (started ~1990) is still in the laboratory, but first applications are probably not far away (e.g. quantum dots and nanoparticles). New applications and research are on-going.

See JMEMS (Journal of Micro-Electromechanical Systems), Journal of Micromechanics and Microengineering, Sensors and Actuators, Nanotechnology, Microfluidics and Nanofluidics, Small Times, Sandia MEMS Short Course

Future Directions

- MEMS sensors
  - Physical – accelerometers, gyros, force, pressure
  - Chemical – flourescence, antibody based, beads
- RF MEMS
- MOEMS – Micro-Opto-Electro-Mechanical Systems
- MEMS actuators
  - Higher force actuators (e.g. thermal)
  - MESO scale actuation
- Microfluidics
  - surface tension based pumping, EKP, surface control (hydrophobic/hydrophilic), PDMS and beyond.
- Nano-cantilvers, Molecular machines, Nano-particles (e.g. Quantum dots), Nano-optics.