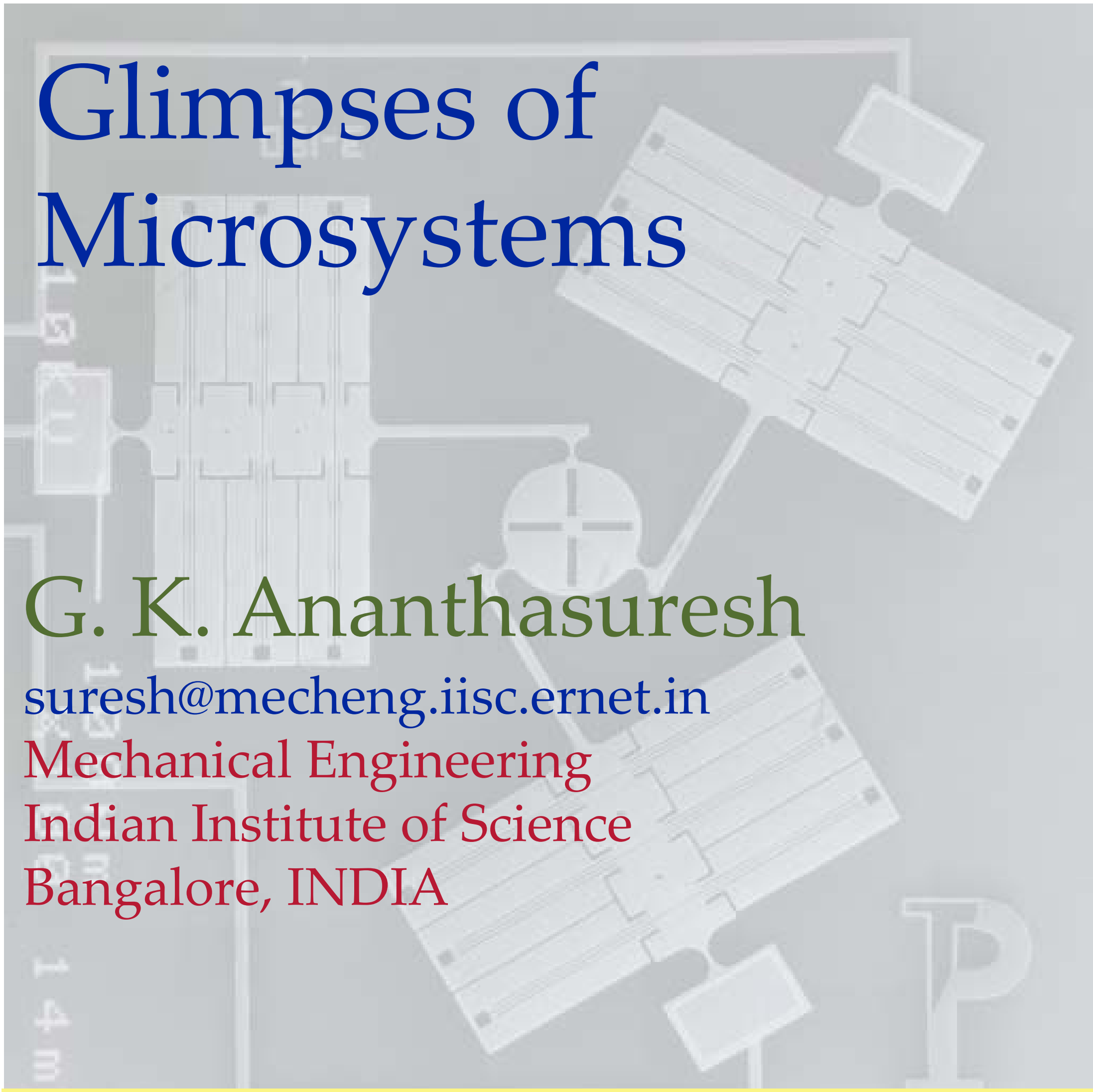

Glimpses of Microsystems

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August, 2014;   for ME 237/NE 211, IISc

MEMS craze began in early 1990s.

It was thought sometime ago that MEMS will be pervasive in all disciplines long after MEMS ceases to be a fad.

But that day arrived in just 20 years.

Microsystems are here to stay!

That is why, we are discussing MEMS now.

And we are not talking about nanotechnology.

Let us begin with some questions.

Microsystems or MEMS

- ✓ What are they?
- ✓ How small are they?
- ✓ How are they useful?
- ✓ How do they work?

More important questions…

- ✓ What to call them?
- ✓ Why miniaturize?

What’s in a name?

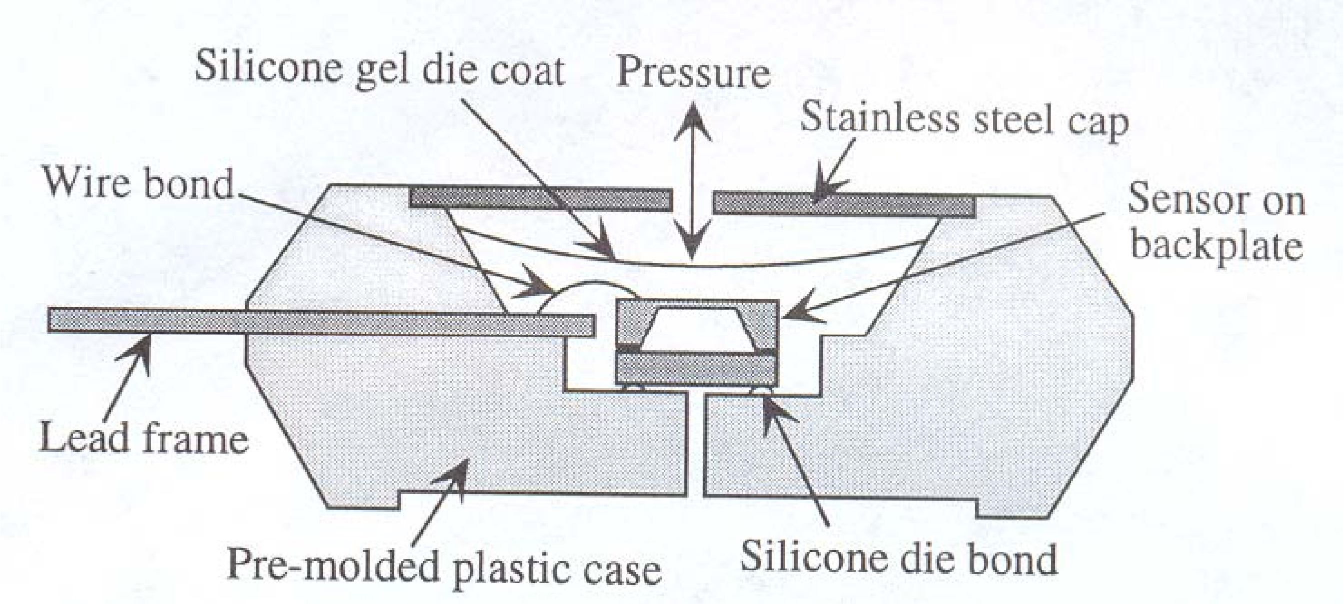
- Micro-Electro-Mechanical Systems (MEMS)
  Widely used in Americas.
- MicroSystems Technology (MST)
  Popular in Europe. Eevn now.
- Micromachines
  Was in use in Japan.
- Microscience
  Some people prefer to call it this way as they begin to explore scientific aspects of MEMS.
- NEMS and nanotechnology
  When a feature becomes less than a micron and is respectably measured in nanometers.

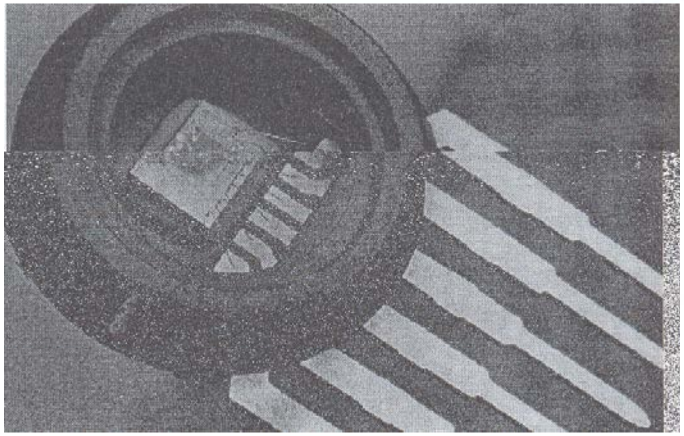
Why miniaturize? Reason 1

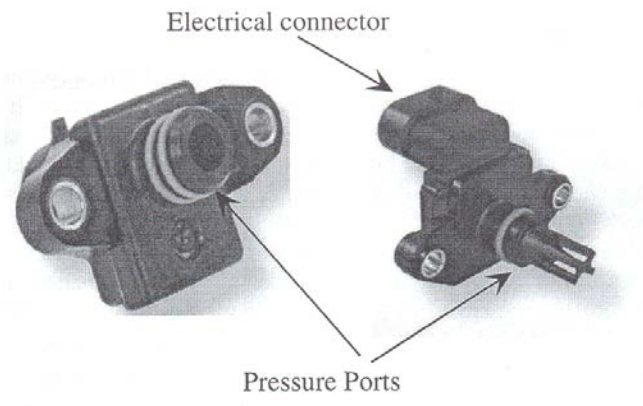
- Economy associated with scaling, especially large-volume, batch-production as in IC-chips

A packaged pressure sensor

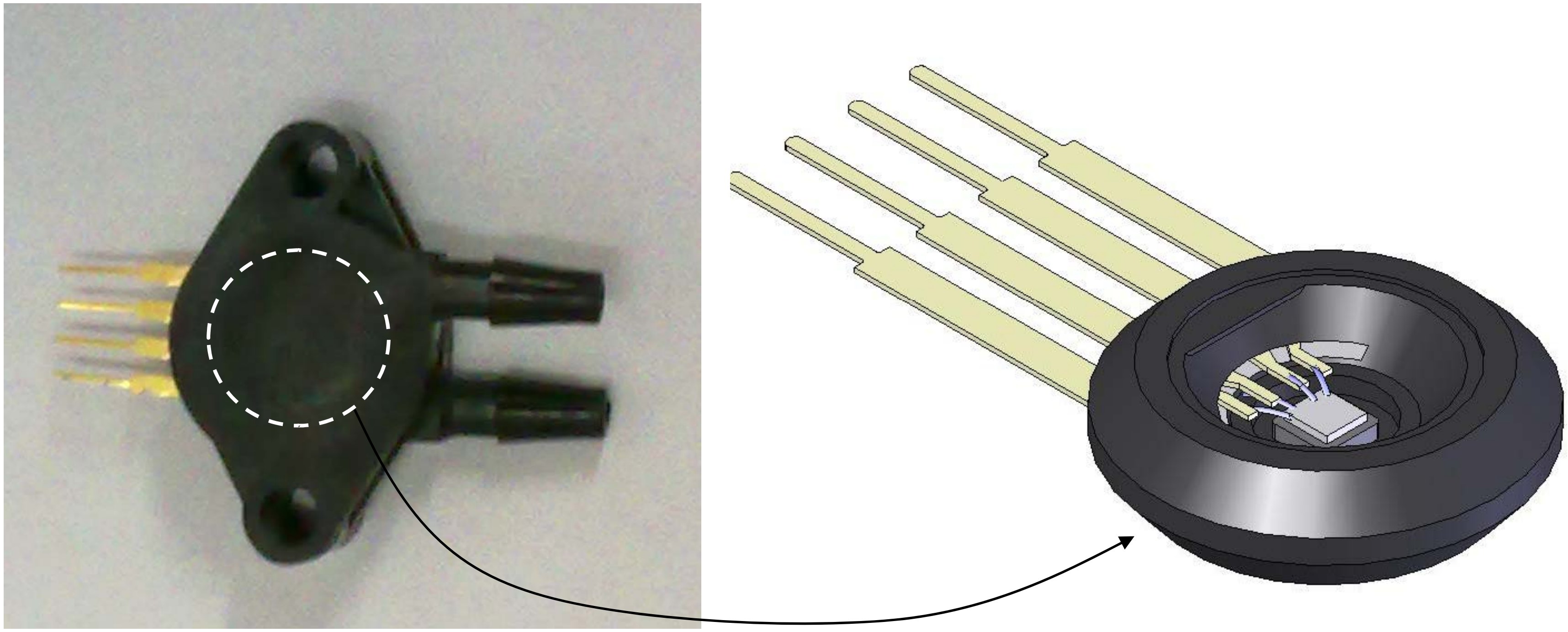
Motorola's Manifold Pressure Sensor







Motorola's micromachined pressure sensor

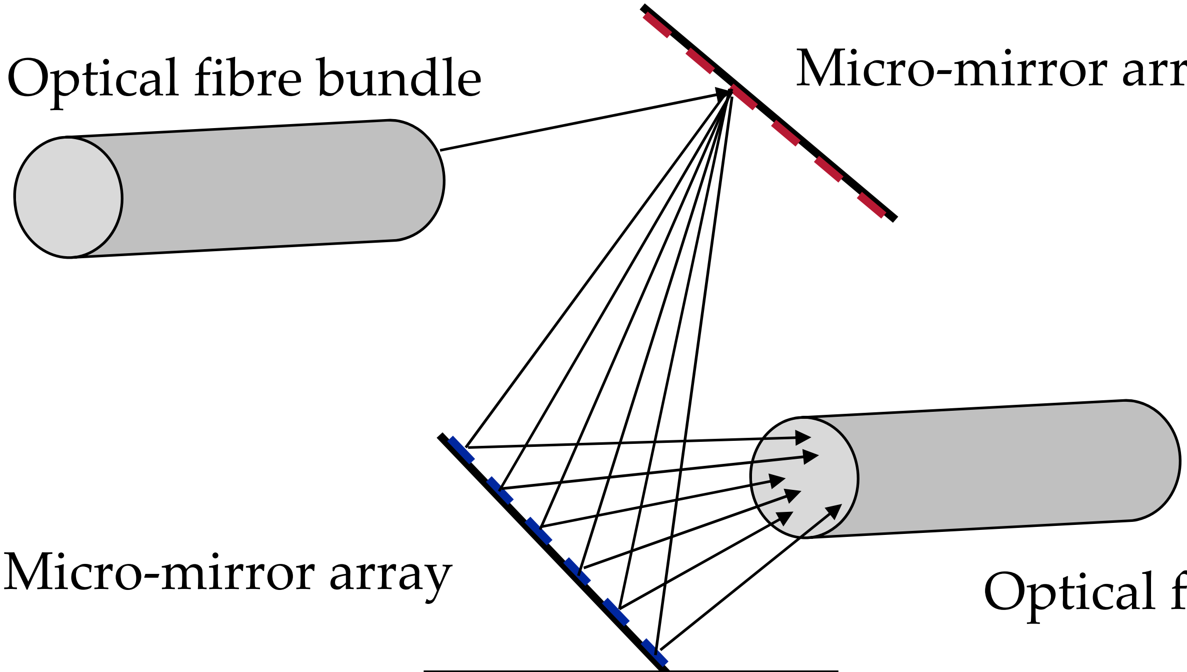


Why miniaturize? Reason 2

- Economy associated with scaling, especially large-volume, batch-production as in IC-chips
- Some micro devices would not work if they are made any bigger (although most would).

Lucent’s optical cross-connect

Routing of wave-length multiplexed optical signals



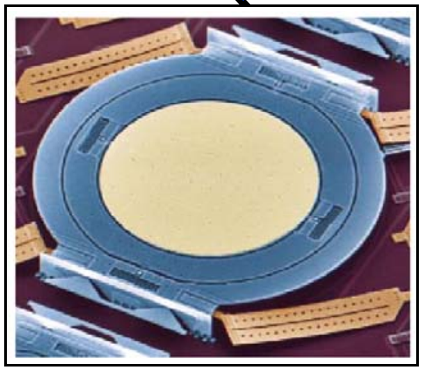
Optical fibre bundle

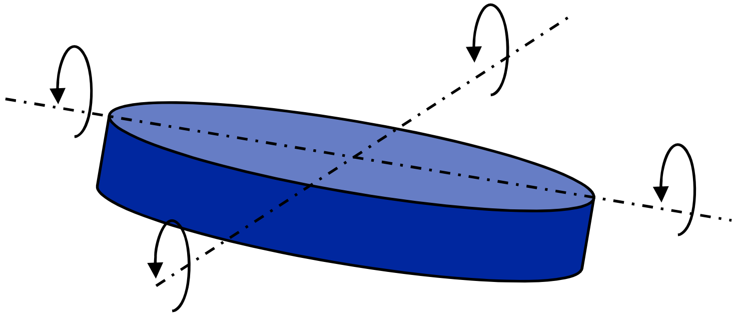
Micro-mirror array

Micro-mirror array

Optical fibre bundle

Two-axis micro-
mirror





DLP-based LCD projection (InFocus, *hp*)

Consists of an individually addressable array of micro mirrors that tilt about an axis.

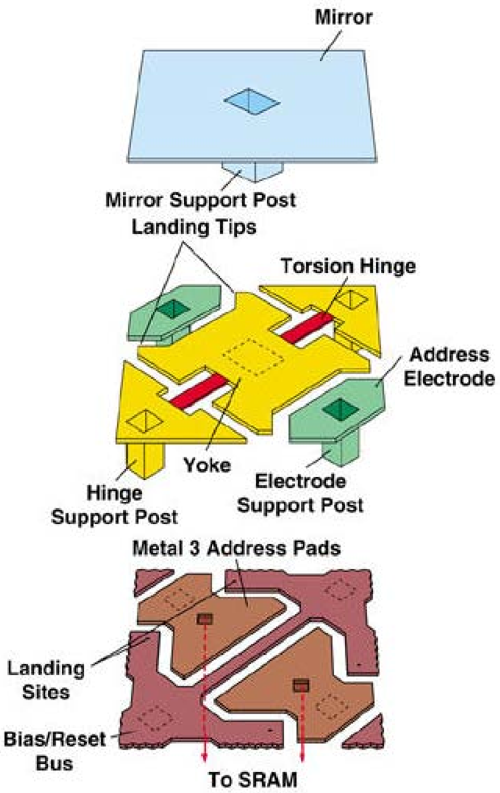
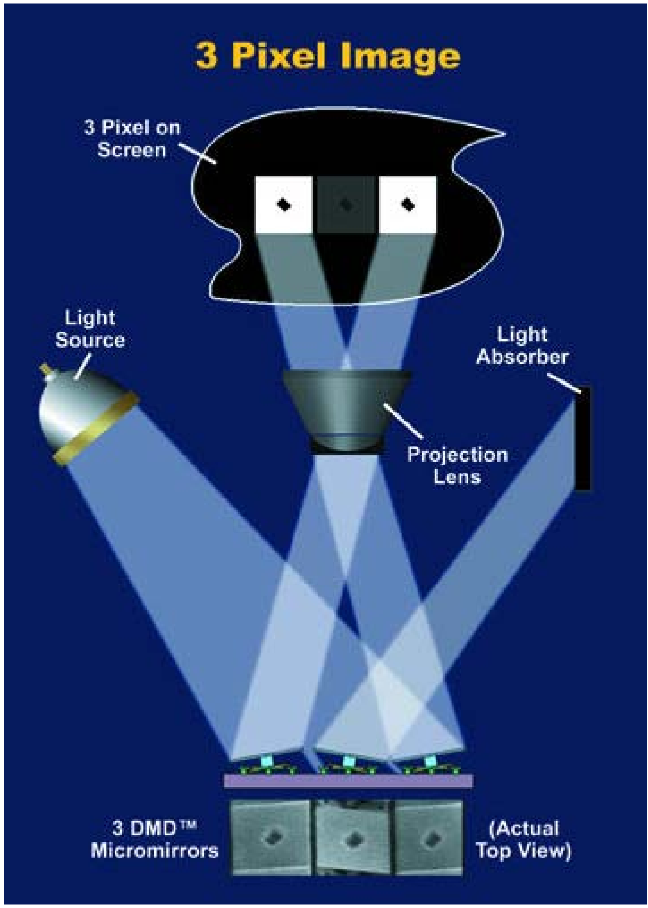
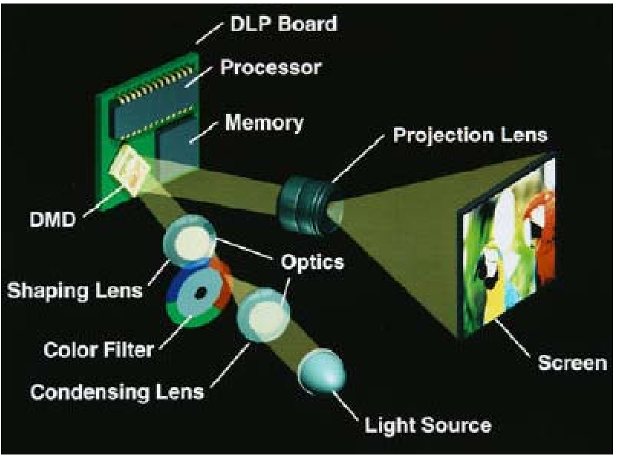


Photo courtesy Texas Instruments

Exploded view of an individual mirror on a DMD



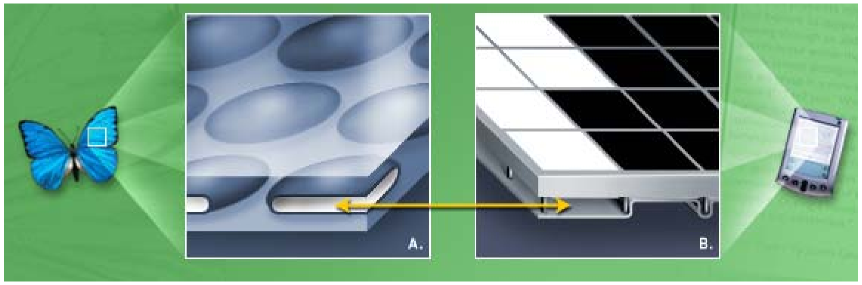


Why miniaturize? Reason 3

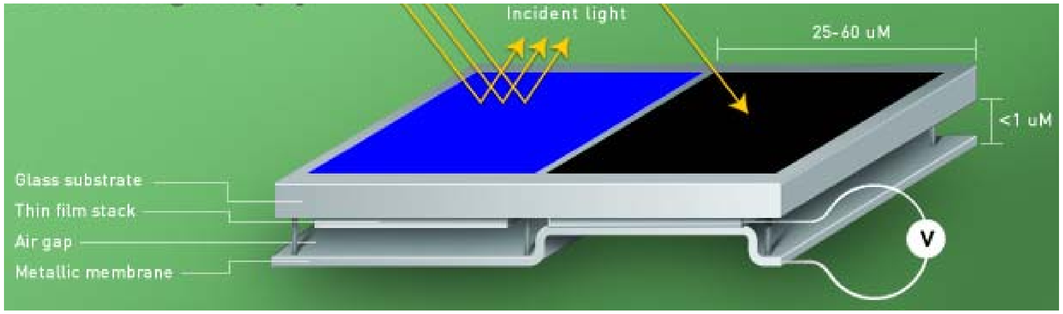
- Economy associated with scaling, especially large-volume, batch-production as in IC-chips
- Some micro devices would not work if they are made any bigger (although most would).
- Scaling down favors some micro devices.

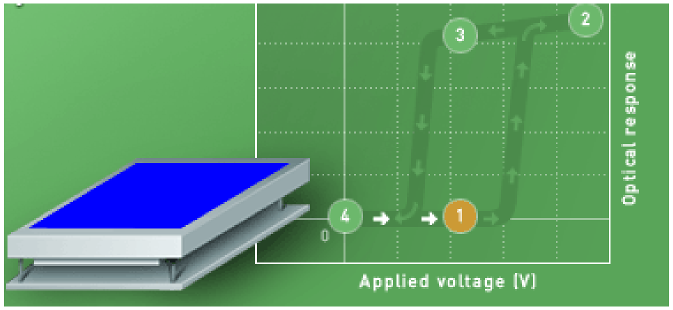
One more way to play with light

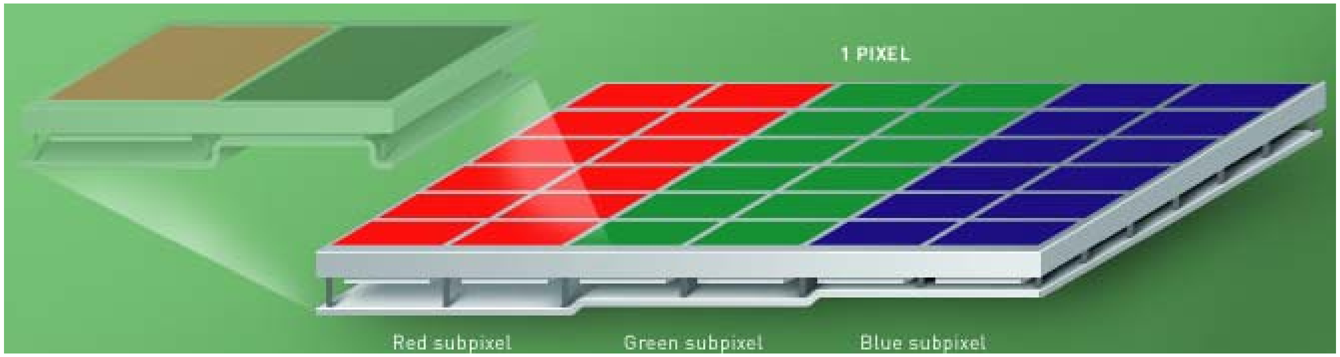
www.iridigm.com (a QualComm acquisition)



Interference-modulation by electrostatic actuation of vertically moving membranes.



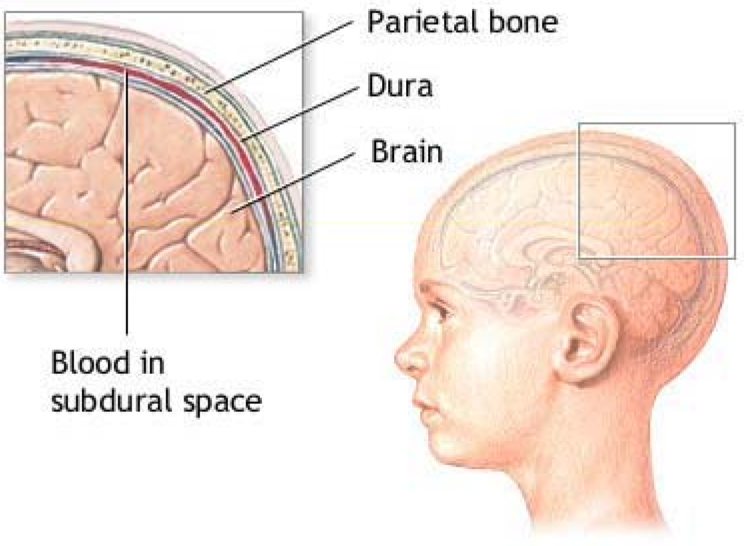




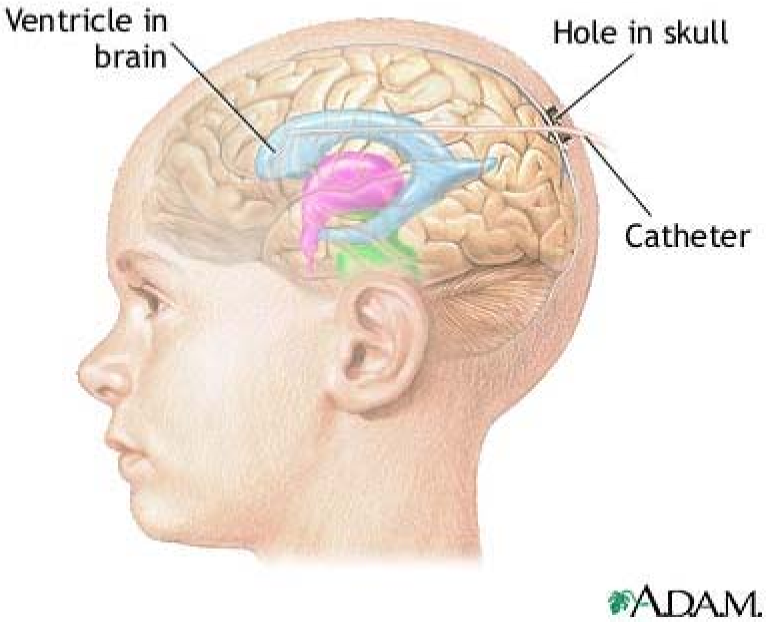
Why miniaturize? Reason 4

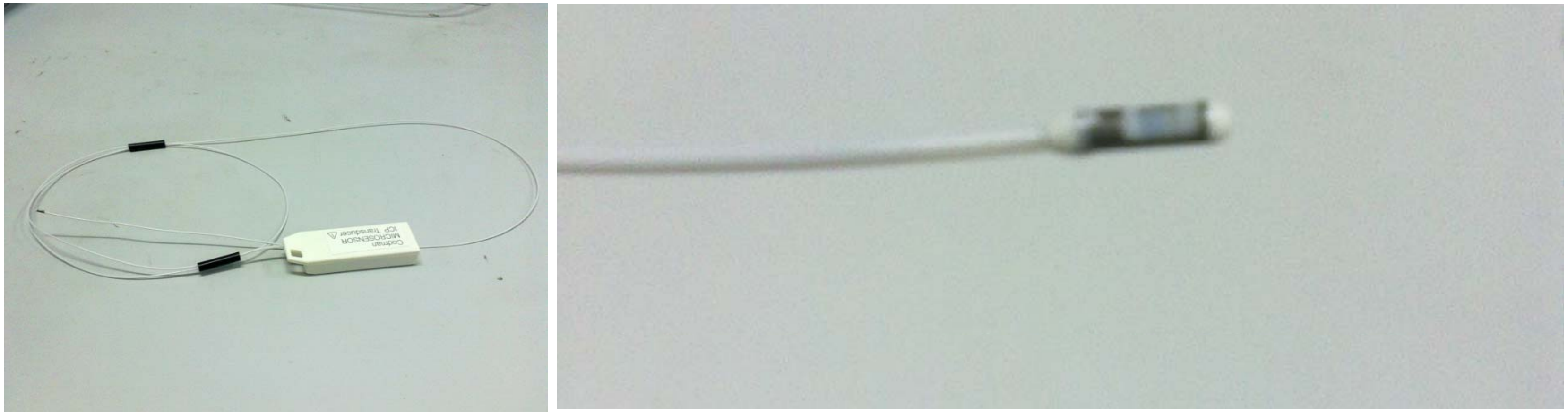
- Economy associated with scaling, especially large-volume, batch-production as in IC-chips
- Some micro devices would not work if they are made any bigger (although most would).
- Scaling down favors some micro devices.
- Reduction in size, weight, power consumed may be important in some applications.

Need for miniaturization

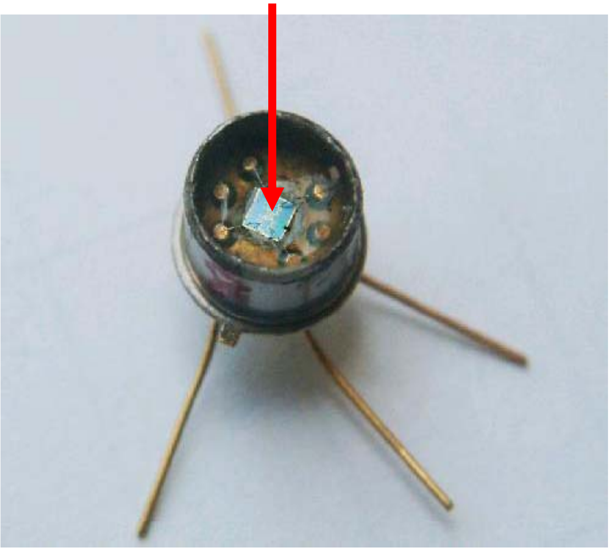


Source: www.nlm.nih.gov

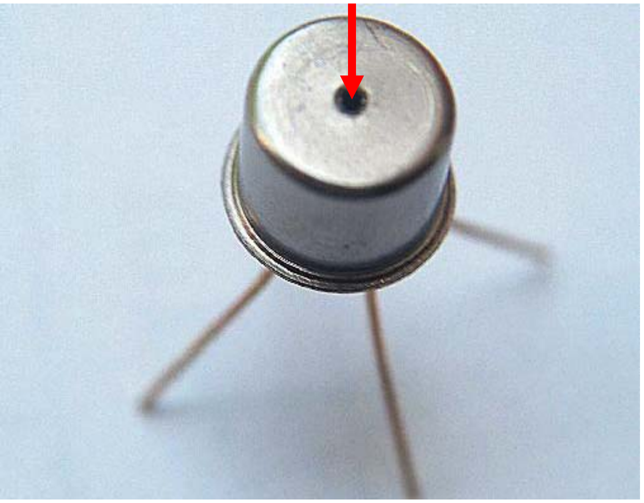




Micromachined pressure sensor (made in India)



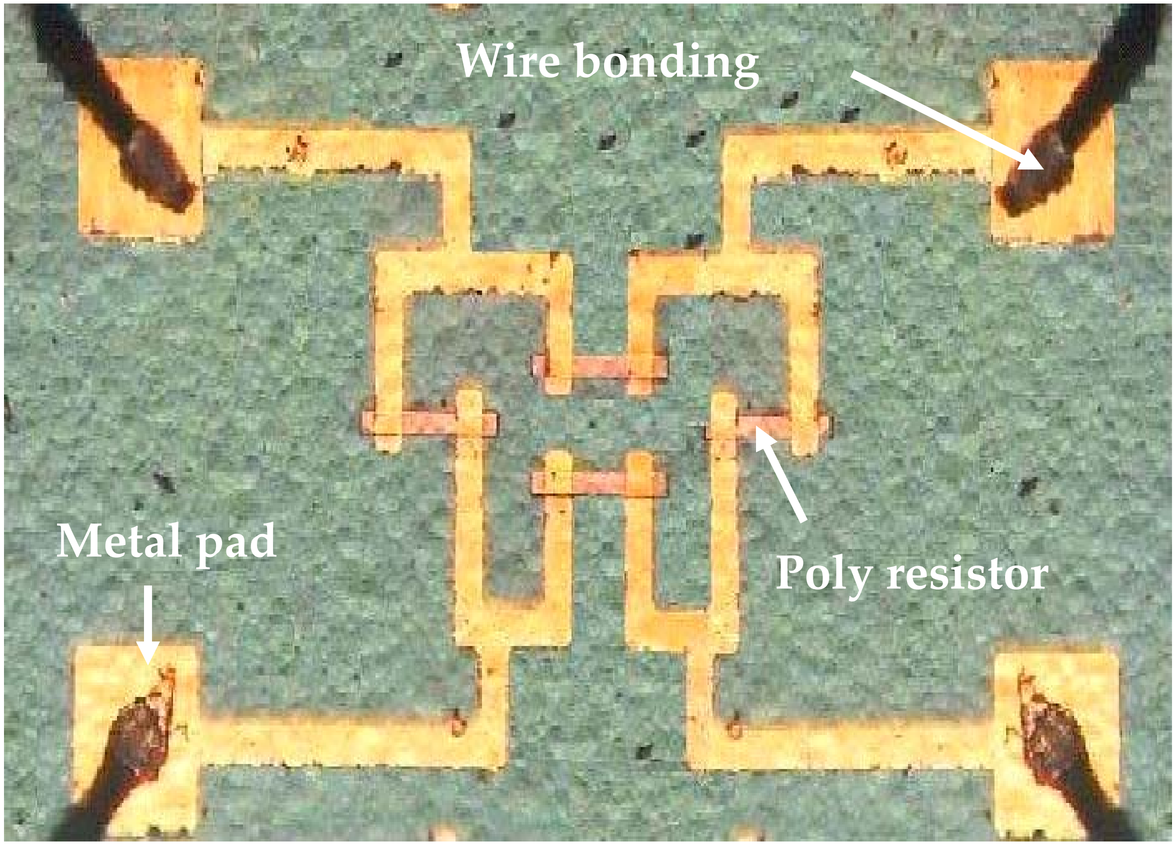
Diced Pressure sensor



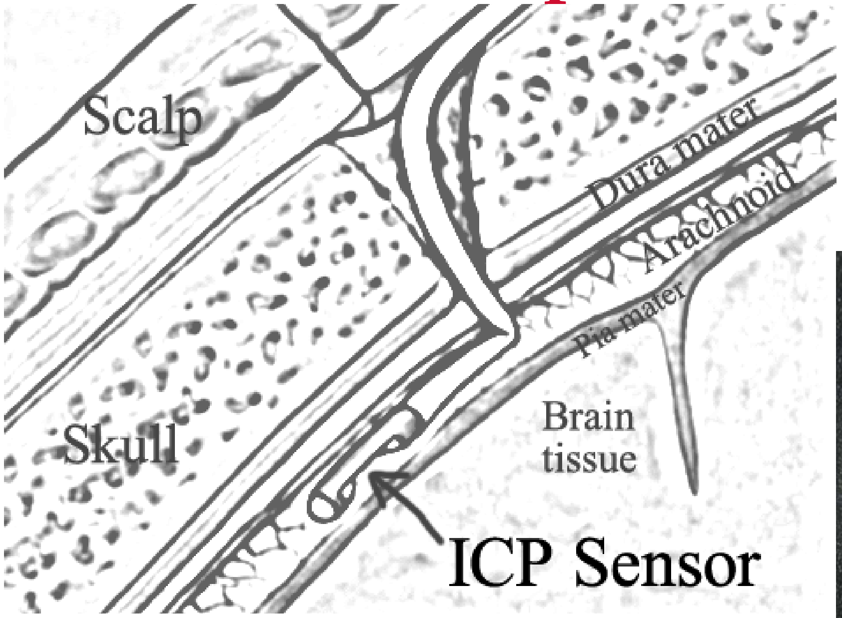
Pressure port

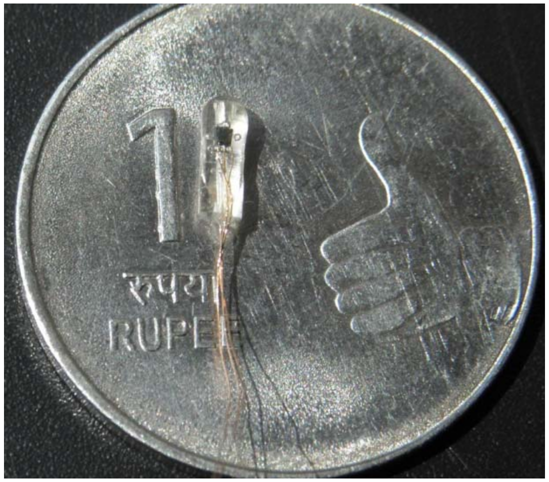
IIT-M and BEL pressure sensor

Courtesy: Prof. K.N. Bhat



Intracranial pressure sensor made in IISc





- Sensor design, process flow, microfabrication in IISc.
- Packaging
- Electronics
- System integration
    - The box is ready!

- Measures ICP with the required accuracy and range.
- Compensates for temperature
- Can measure temperature too.

Why miniaturize? Reason 5

- Economy associated with scaling, especially large-volume, batch-production as in IC-chips
- Some micro devices would not work if they are made any bigger (although most would).
- Scaling down favors some micro devices.
- Reduction in size, weight, power consumed may be important in some applications.
- Most importantly, "distributed arrays" are possible with miniature systems.
  - The VLSI analogy
  - and "an army of ants lugging a big insect" analogy

DLP (digital light processor)

Texas Instruments DLP

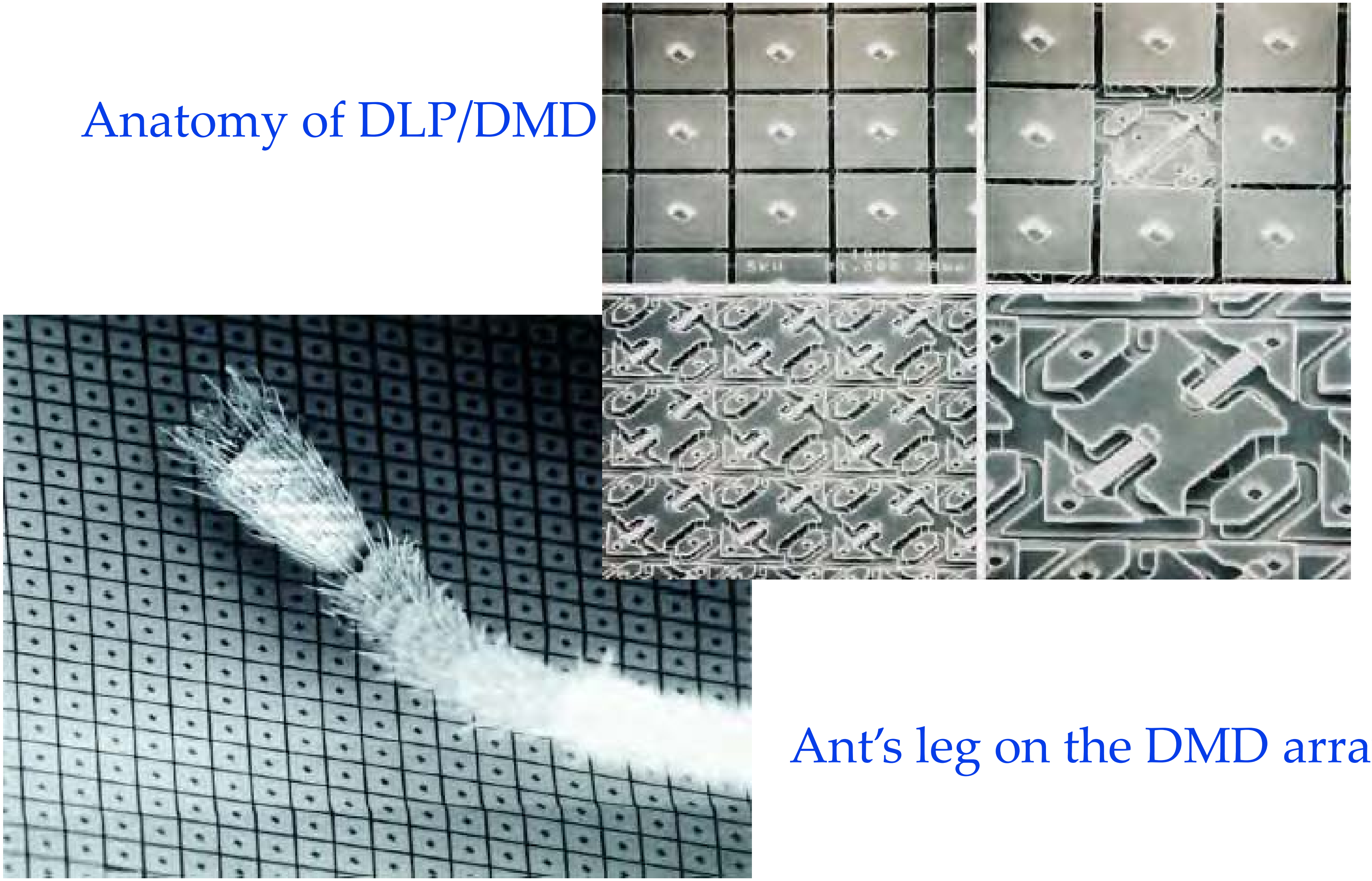
A TEXAS INSTRUMENTS TECHNOLOGY

InFocus digital projectors

What lies beneath

TI's digital light processor (DLP) and deformable mirror display (DMD)

Anatomy of DLP/DMD



Ant's leg on the DMD array

Summary: Rationale for miniaturization

- Economy associated with scaling, especially large-volume, batch-production as in IC-chips
- Some micro devices would not work if they are made any bigger (although most would)
- Scaling down favors some micro devices
- Reduction in size, weight, power consumed may be important in some applications
- Most importantly, “distributed arrays” are possible with miniature systems
    - The VLSI analogy
    - and “an army of ants lugging a big insect” analogy

Why are they small? Here is the *real* reason.

“Micro” size is *almost* incidental.

- They are small because of the technologies used to make them.

Why MEMS? The main reason

Because… M€M$

There is money to be made through commercialization of MEMS technology.

- It is economical to make them small – when made in large volumes as in microelectronics.

What are they?

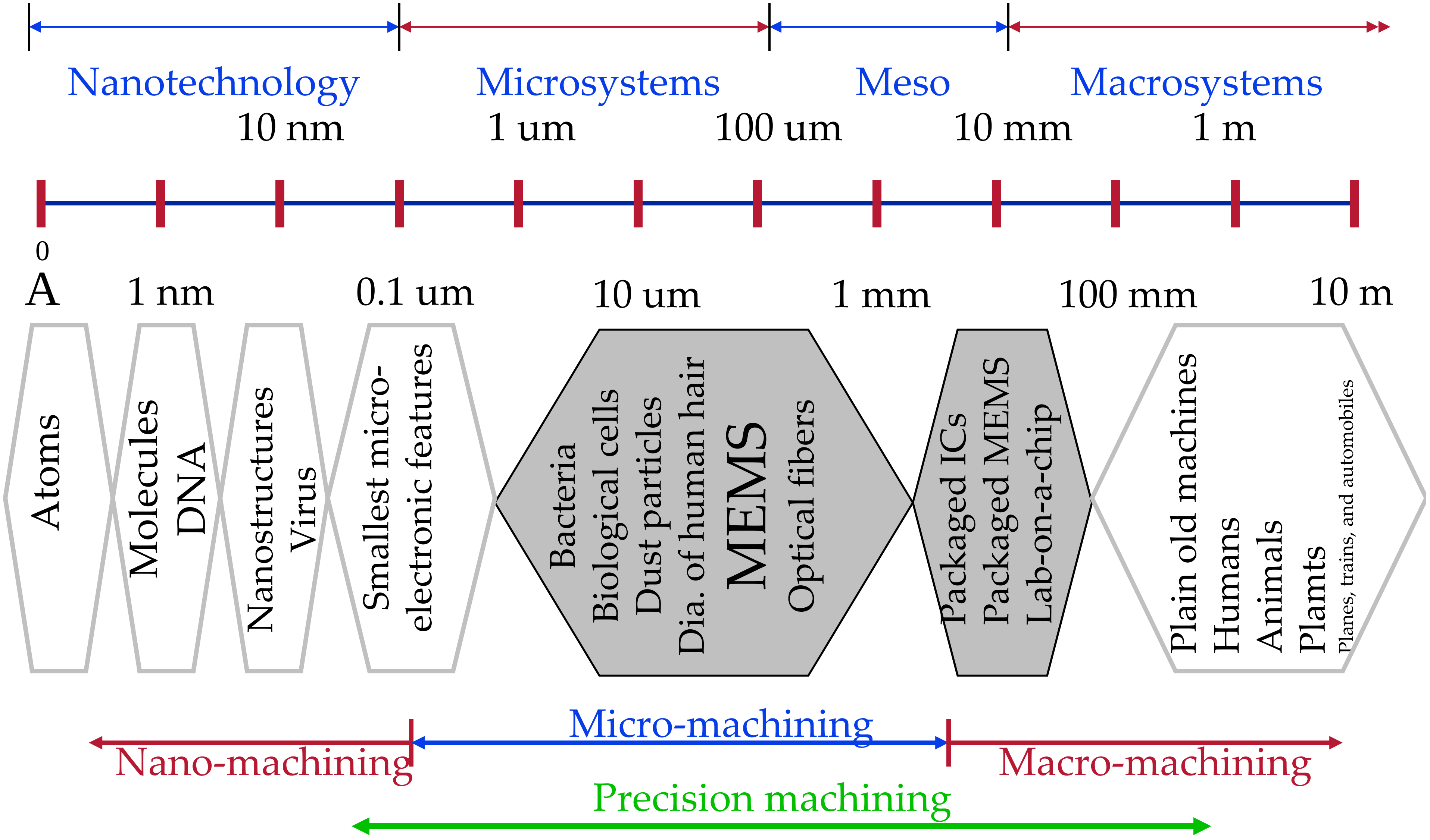
- **MEMS are systems that integrate…**
  - sensing
  - actuation
  - computation
  - control
  - communication
  - power

They are…
smaller
more functional
faster
less power-consuming
and cheaper!

MEMS = micro sensors + micro-actuators + etc.

- Most of the successful MEMS are simply sensors.
- Some are actuators
    - Which actuate themselves or act against small loads.
- There are very few systems
    - When MEMS are in a system, the actual cost of the MEMS component is not the major cost-component.

How small are they?



Nanotechnology | Microsystems | Meso | Macrosystems

10 nm | 1 um | 100 um | 10 mm | 1 m

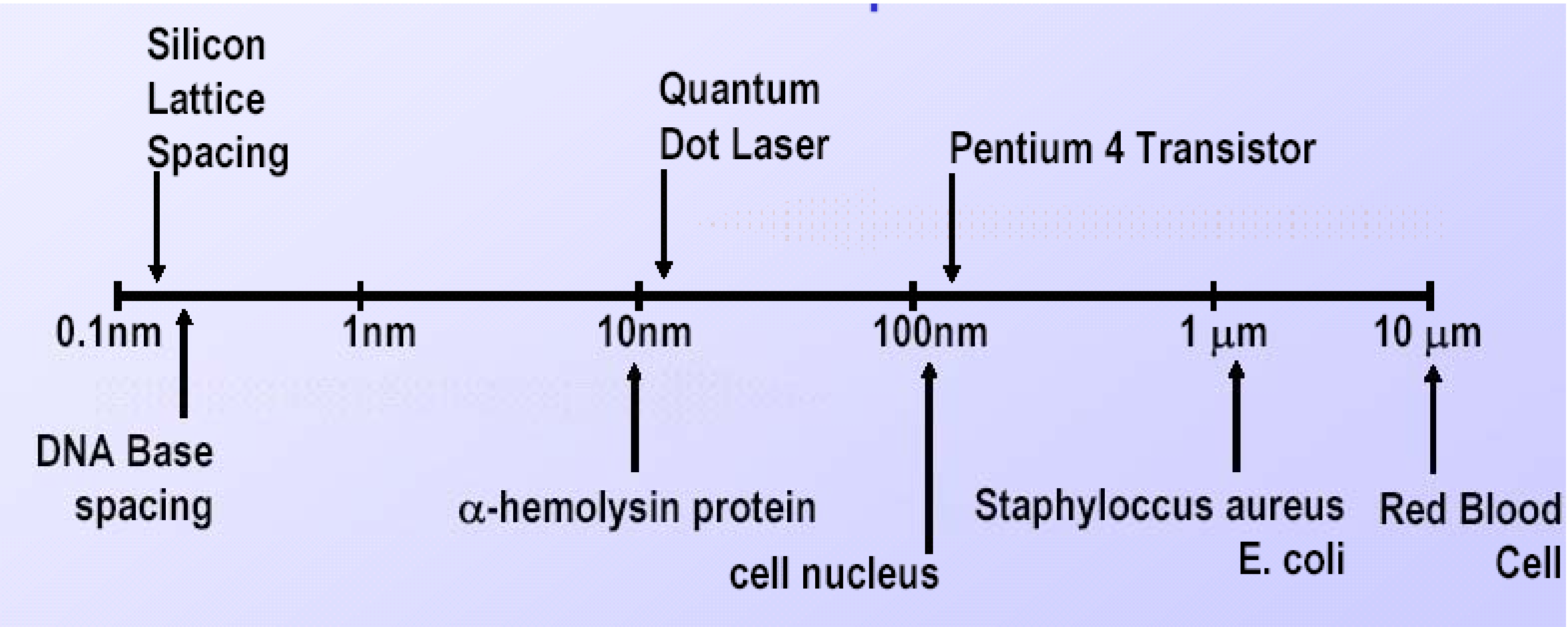
0
A | 1 nm | 0.1 um | 10 um | 1 mm | 100 mm | 10 m

- Atoms
- Molecules
  DNA
- Nanostructures
  Virus
- Smallest micro-
  electronic features
- Bacteria
  Biological cells
  Dust particles
  Dia. of human hair
  MEMS
  Optical fibers
- Packaged ICs
  Packaged MEMS
  Lab-on-a-chip
- Plain old machines
  Humans
  Animals
  Plamts
  Planes, trains, and automobiles

Nano-machining | Micro-machining | Macro-machining

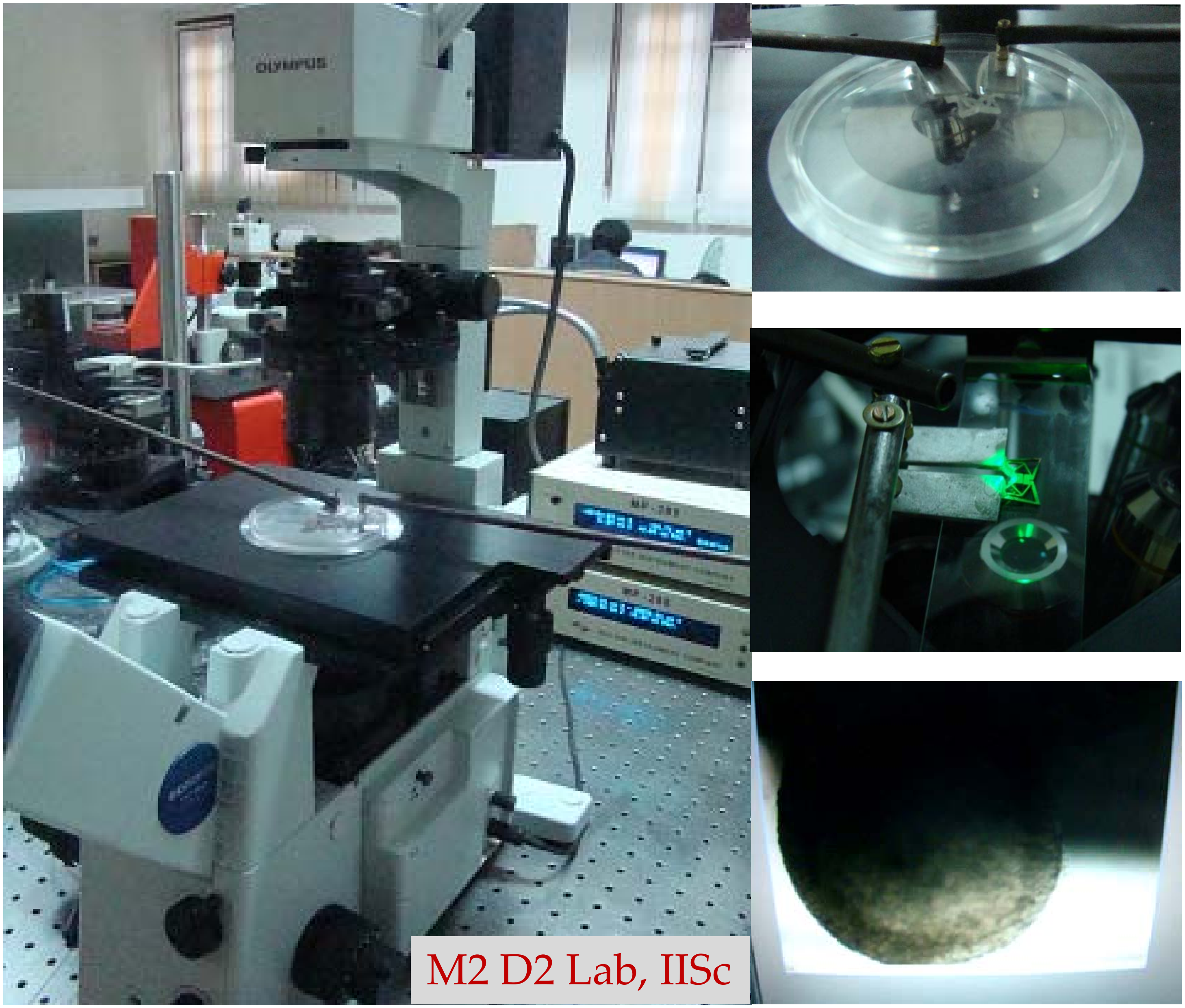
Precision machining

Why are they exciting? Reason 1



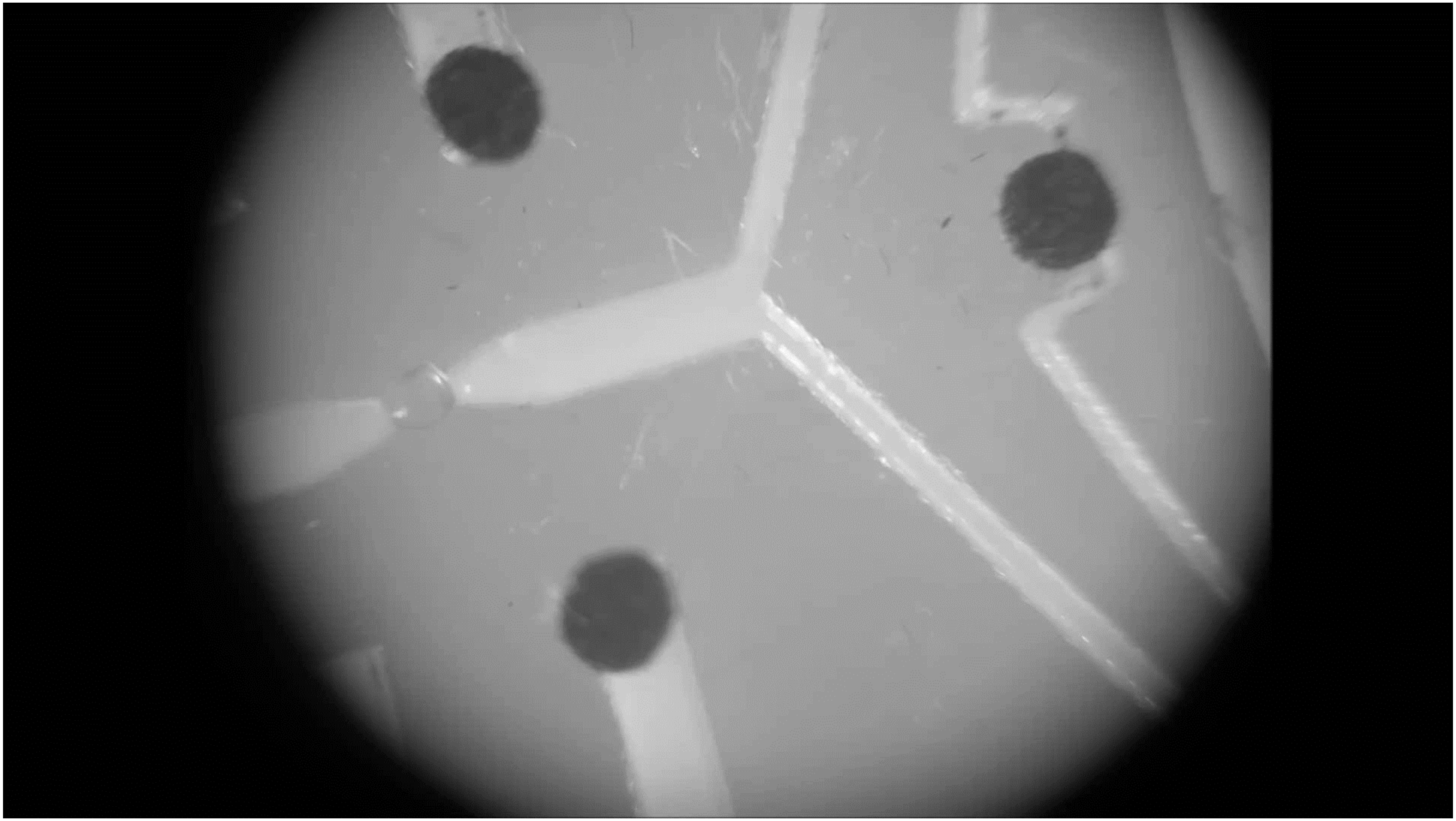
Micro-technology brings engineering to the size scale of the "workshops" of the biological world.

Micromanipulators for biological cells



M2 D2 Lab, IISc

Grasping a biological call

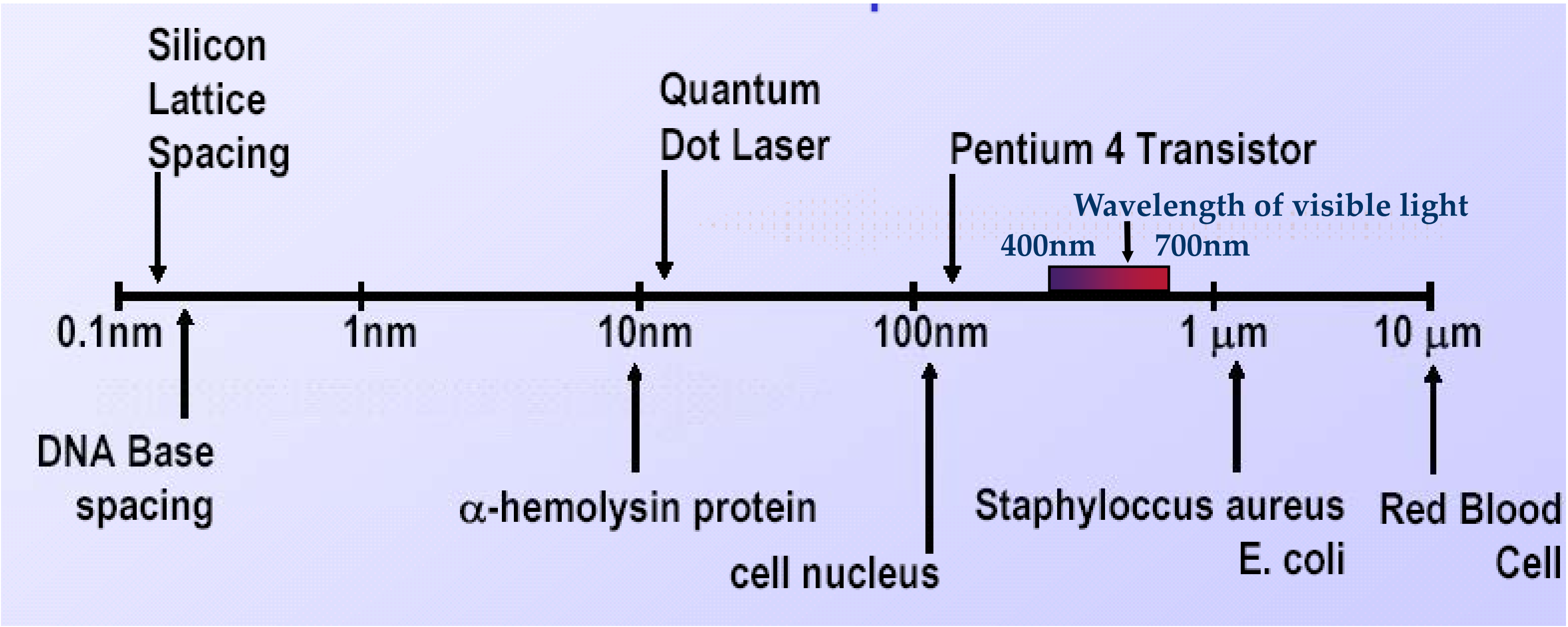


Dr. Santosh Bhargav, M2D2 lab, IISc

Rolling and squeezing a biological cell

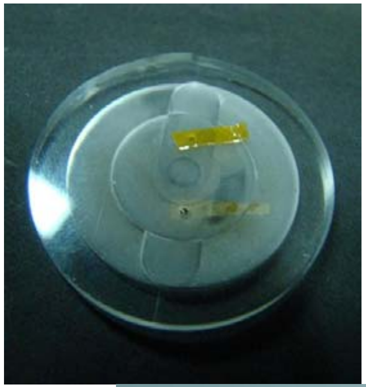
Dr. Santosh Bhargav, M2D2 lab, IISc

Why are MEMS exciting? Reason 2



The motions of micro-mechanical devices overlap with the wavelength of the visible light and thus allowing us to “play with light” in interesting and useful ways.

Is this MEMS?
Wrist-watch sized, packaged pump

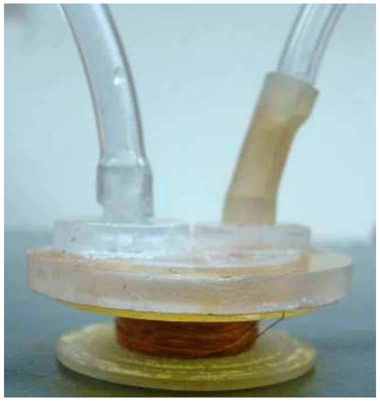


Passive flap-valves
with Kapton

Fluidic fittings

Placement of
magnet

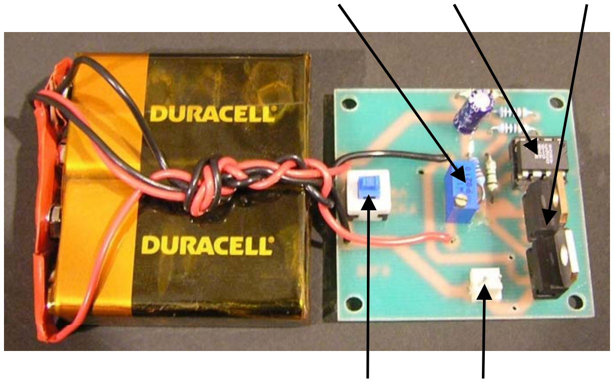
Wound coils
and assembly



Final unit

Balaji, G., Singh, A. and Ananthasuresh, G. K., *Journal of Physics*, Institute of Physics Publishing, 34 (2006), pp. 258-263.

Driver circuit



Prefixes to sizes…
but meso has no particular size.

- Milli 10^{-3}
- Micro 10^{-6}
- Nano 10^{-9}
- Pico 10^{-12}
- Femto 10^{-15}
- Atto 10^{-18}
- Zypto 10^{-21}

Meso = hundreds of microns to cm size

A bit of history…

- *"There is plenty of room at the bottom"*
  - A 1959 lecture by Richard Feynman
- Pioneered by Professor James Angell at Stanford University, researchers at Westinghouse in late 1960s into 1970s
- *"Infinitesimal Machinery"*
  - A 1983 lecture by Richard Feynman
- Formal identity ("MEMS") to the field came in late 1980s.

MEMS devices in 1970s

Ink-jet printer head

Bassous E., Taub H.H., Kuhn L. "**Ink jet printing nozzle** arrays etched in silicon" Appl. Phys. Lett. 31, 135 (**1977**)

Micro mirrors for steering light

Petersen K.E. "Micromechanical **light modulator** array fabricated on silicon" Appl. Phys. Lett. 31, 521-523 (**1977**)

Petersen K.E. "Silicon **torsional scanning mirror**" IBM J. Res. Dev. 24, 631-637 (**1980**)

Accelerometer

Roylance L.M., Angell J.B. "A batch fabricated silicon **accelerometer**" IEEE Trans. on Electron Devices 26, 1911-1917 (**1979**)

Optical fiber connector

Schroeder C.M. "Accurate silicon spacer chips for an **optical fiber cable connector**" Bell. Syst. Tech. J. 57, 91-97 (**1977**)

Microfluidic device

Terry S.C., Jerman J.H., Angell J.B. "A **gas chromatograph** air analyzer fabricated on a silicon wafer" IEEE Trans on Electron Devices 26, 1880-1886 (**1979**)

MEMS devices in late 1970s and early 1980s

Pressure sensors

Clark S.K., Wise K.D. “Pressure sensitivity in anisotropically etched thin diaphragm **pressure sensors**” IEEE Trans. on Electron Devices TED-26, 1887-1896 (**1979**)

Ko W.-H., Hynecek J., Boettcher S.F. “Development of a miniature **pressure transducer** for biomedical applications” IEEE Trans. on Electron Devices T-ED26, 896-1905 (**1979**)

Other types of sensors

Kimura K. “**Microheater** and **microbolometer** using microbridge of SiO2 film on silicon” Elect. Lett. 17, 80-82 (**1981**)

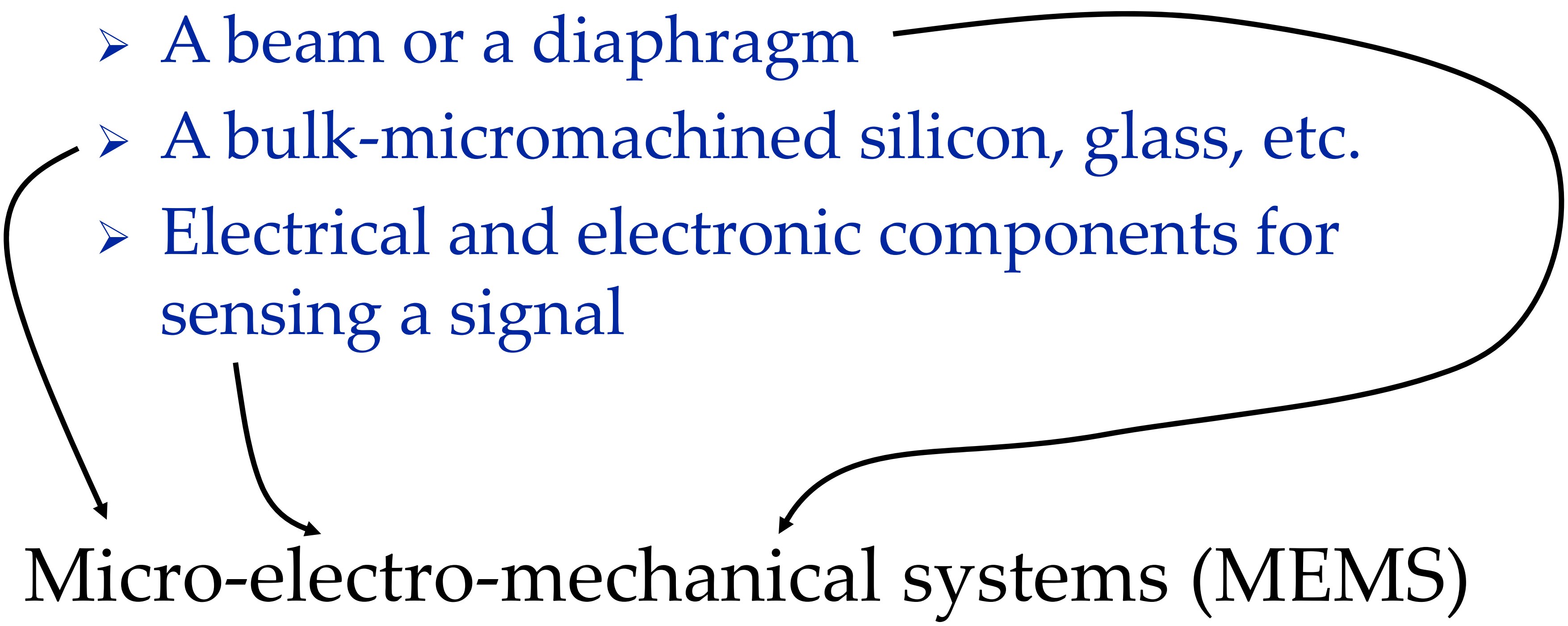
Najafi K., Wise K.D., Mochizuki T. “A high-yield IC-compatible **multichannel recording array**” IEEE Trans on Electron Devices 32, 1206-1211 (**1985**)

Stemme G. “A monolithic **gas flow sensor** with polyimide as thermal insulator” IEEE Trans. on Electron Devices TED-33, 1470-1464 (**1986**)

Optical switching and multiplexing

Gustafsson K., Hök B. “**Fiberoptic switching** and multiplexing with a micromechanical scanning mirror” Proc. 4th Int. Conf. on Solid-State Sensors and Actuators, Tokyo, June 3-5, P 212 (**1987**)

What is common to all of them?



- A beam or a diaphragm
- A bulk-micromachined silicon, glass, etc.
- Electrical and electronic components for sensing a signal

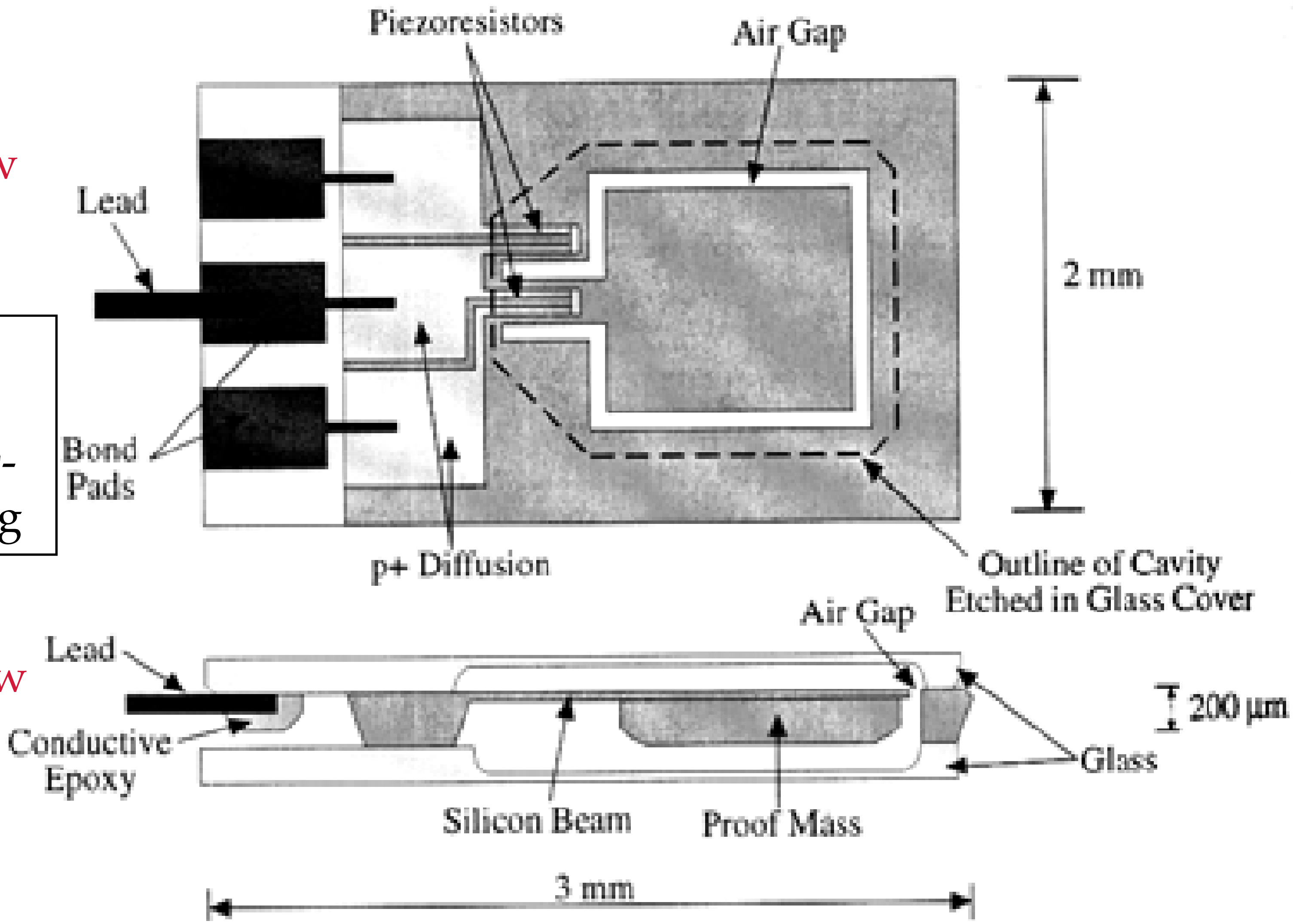
Micro-electro-mechanical systems (MEMS)

A 1979 micro-accelorometer

Top view

Side view

Bulk micro machined; Piezoresistor-based sensing



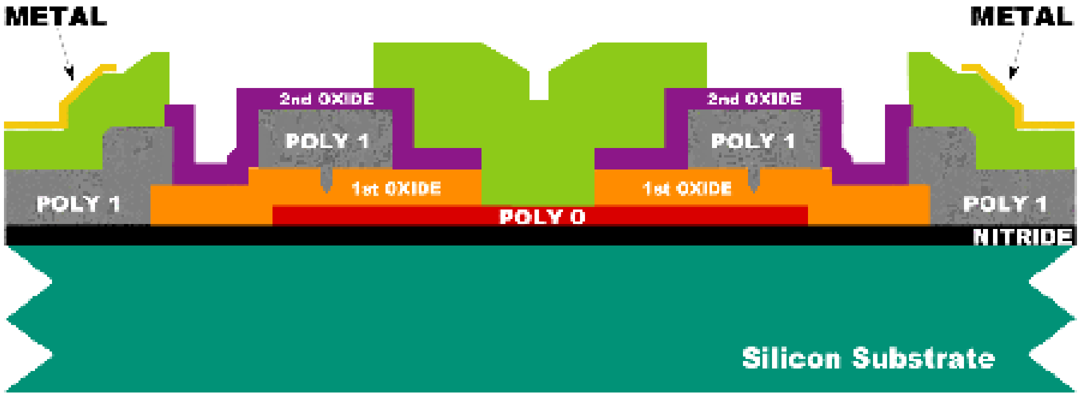
Roylance L.M., Angell J.B. "A batch fabricated silicon accelerometer" IEEE Trans. on Electron Devices 26, 1911-1917 (1979)

Widespread attention came with a micromotor.

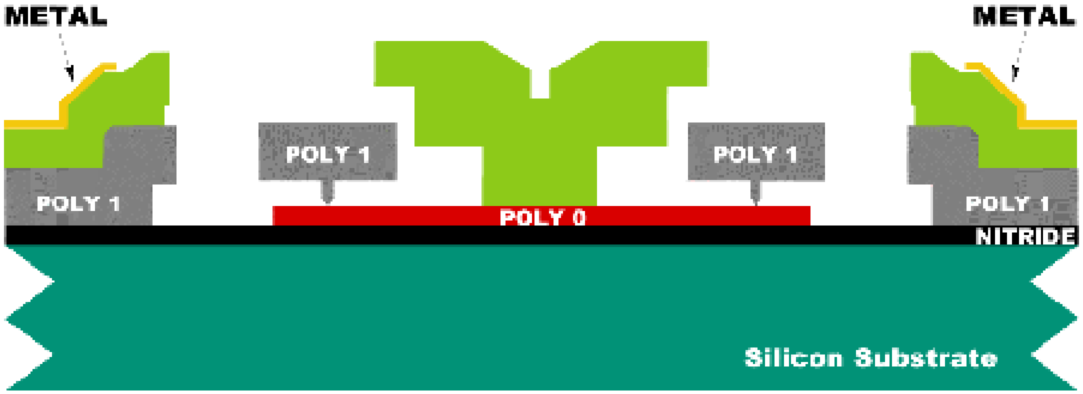
- The excitement began only after a rotary motor, revolute (pin) joints, and prismatic (sliding) joints were demonstrated.
  - At U. C. Berkeley, MIT, and Bell Labs
  - The reason for the excitement was batch-fabrication of “assembled” micro-mechanisms without assembly.
  - <u>Crucial development</u>: sacrificial layer process using polysilicon as the structural layer.

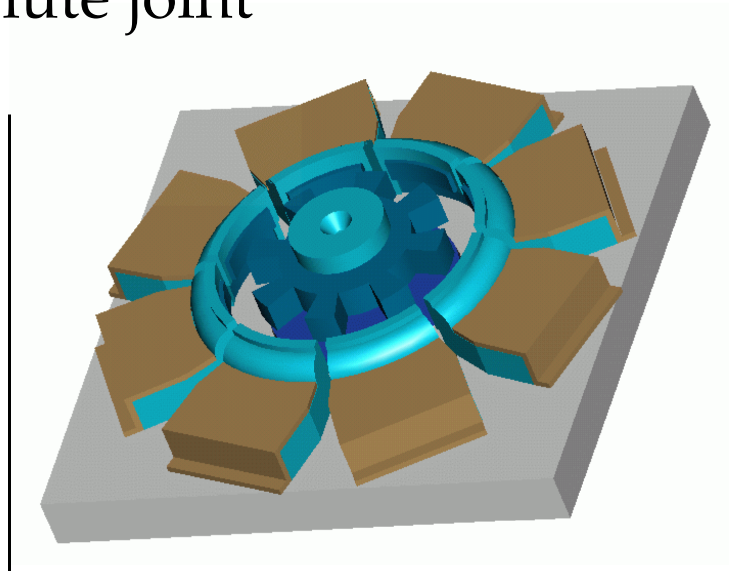
Electrostatic micromotor

Sacrificial layer process to make a revolute joint

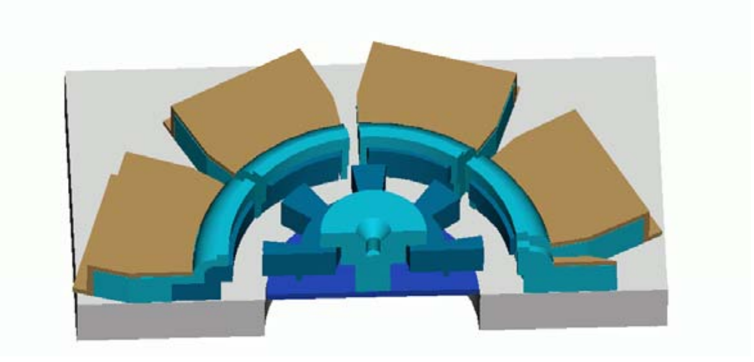


MUMPs process (MCNC)





Ravi Jain, undergraduate at Penn.



Early references on micromotors

Gears

M. Mehregany, K.J. Gabriel, and W.S.N. Trimmer, "Micro Gears and Turbines Etched from Silicon," *Sensors and Actuators,* vol. 12, pp. 341-348, Nov./Dec. 1987

Revolute joints and linkages

L.S. Fan, Y.C. Tai, R.S. Muller, "Integrated Movable Micromechanical Structures for Sensors and Actuators," *IEEE Trans. on Electron Devices,* Vol. ED-35, No. 6, pp. 724-730, June 1988.

M. Mehregany, K.J. Gabriel, and W.S.N. Trimmer, "Fabrication of Integrated Polysilicon Mechanisms," IEEE Trans. Electron Devices, vol. ED-35, no. 6, pp. 719-723, June 1988.

Micro rotary motors

Y.C. Tai and R.S. Muller, "IC-processed Electrostatic Synchronous Motor," *Sensors and Actuators,* Vol. 20, No. 1&2, pp. 49-56, Nov. 15, 1989.

M. Mehregany, S.F. Bart, L.S. Tavrow, J.H. Lang, S.D. Senturia, and M.F. Schlecht, "A Study of Three Microfabricated Variable-Capacitance Motors," *Sensors and Actuators,* vol. A21–A23, pp. 173-179, 1990.

What (more) are they?

Early on…

Solid state transducers → MEMS sensors actuators

And later…

Integrated systems

- are batch fabricated
- are economical
- have more functionality
- involve physical, chemical, biochemical phenomena at small scales
- act upon macro scale too

Take leverage of the enormously successful VLSI technology

How are they useful?

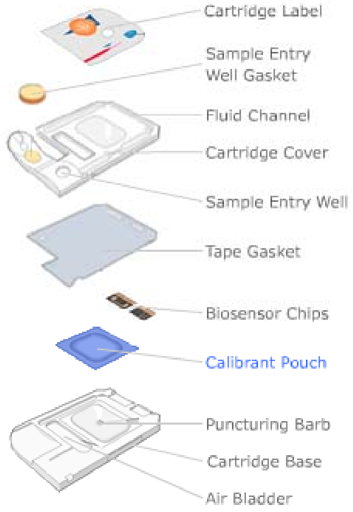
Commercial successes

- Pressure sensors (Motorola and several others)
- Accelerometers (Analog Devices, Delphi, Motorola)
- Ink-jet printer heads (HP)
- Projection display with micro mirror array (TI)
- Portable clinical analyzers (Abbott)
- etc.

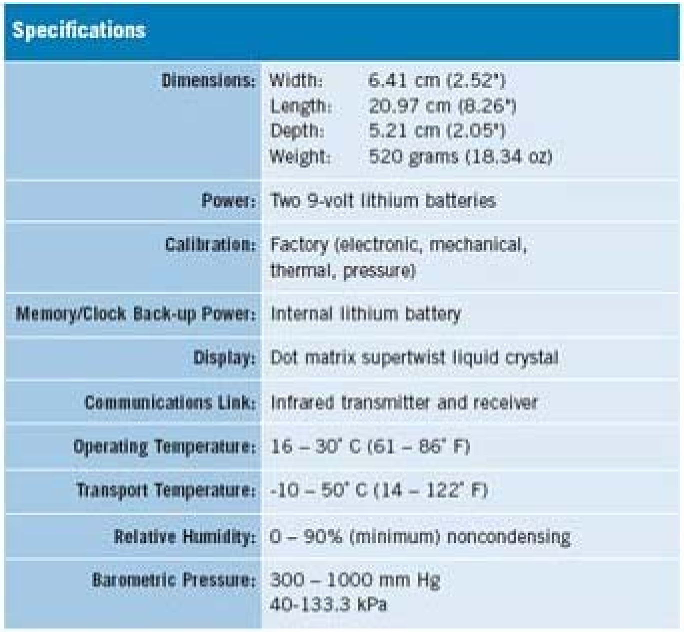
Movable solids and flowing fluids at microscale made possible lots and lots of sensors and actuators.

Hand-held blood analyzer

Abbott Point of Care
http://www.istat.com/



With a few drops of blood, under a minute it gives blood analysis: gases, chemistry, cardiac markers, etc.

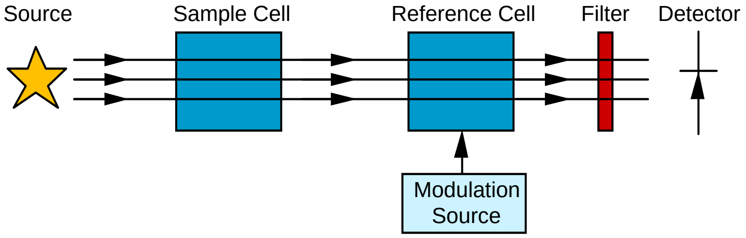


Specifications

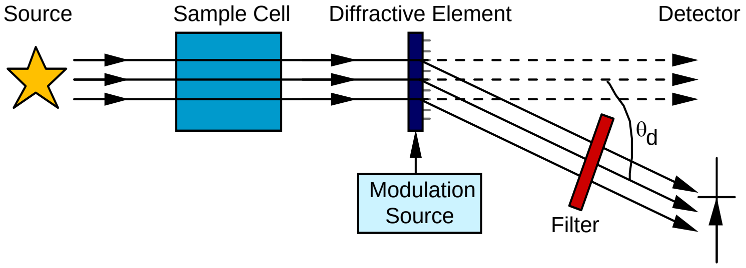
Dimensions:	Width: 6.41 cm (2.52") Length: 20.97 cm (8.26") Depth: 5.21 cm (2.05") Weight: 520 grams (18.34 oz)
Power:	Two 9-volt lithium batteries
Calibration:	Factory (electronic, mechanical, thermal, pressure)
Memory/Clock Back-up Power:	Internal lithium battery
Display:	Dot matrix supertwist liquid crystal
Communications Link:	Infrared transmitter and receiver
Operating Temperature:	16 – 30˚ C (61 – 86˚ F)
Transport Temperature:	-10 – 50˚ C (14 – 122˚ F)
Relative Humidity:	0 – 90% (minimum) noncondensing
Barometric Pressure:	300 – 1000 mm Hg 40-133.3 kPa

Opto

A remote gas sensor (a MOEMS device)



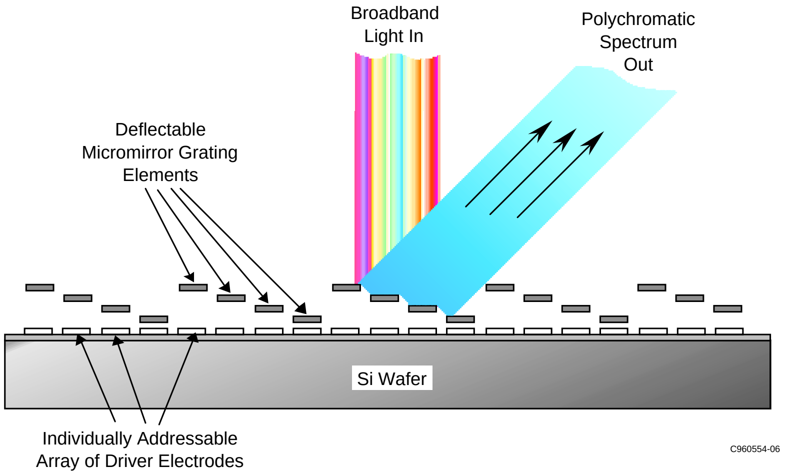
Traditional Correlation Spectroscopy Approach

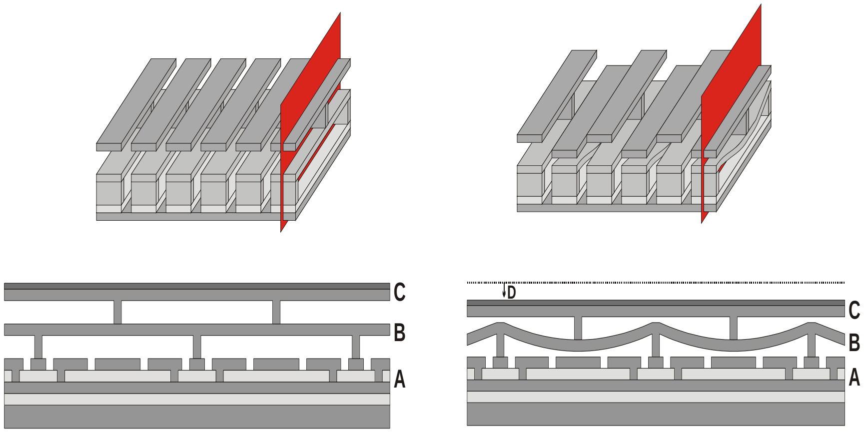


Holographic Correlation Spectrometer

Polychromator:

Honeywell-MIT-Sandia project

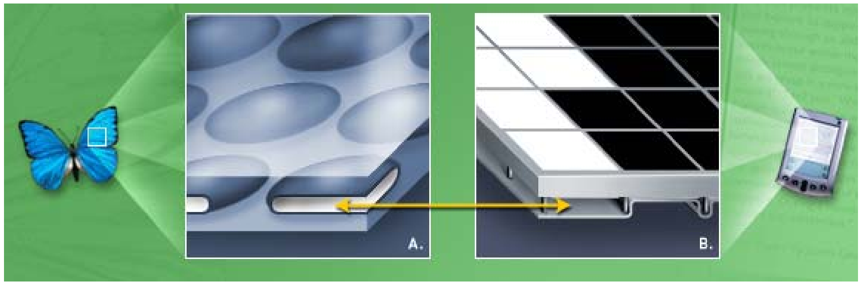




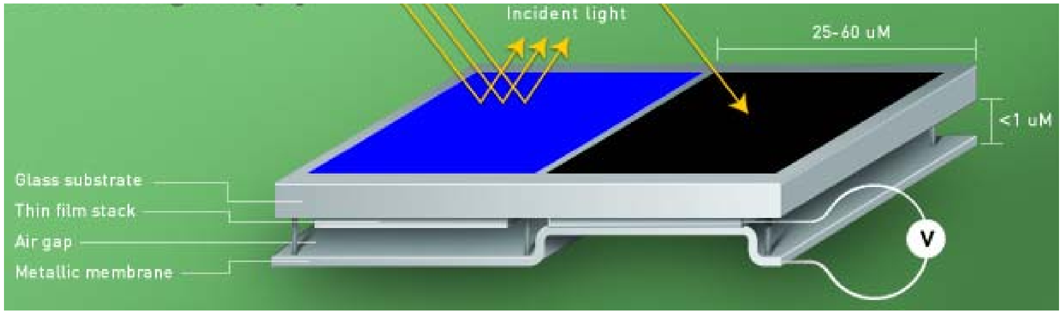
(Source for figures: Honeywell and S. D. Senturia)

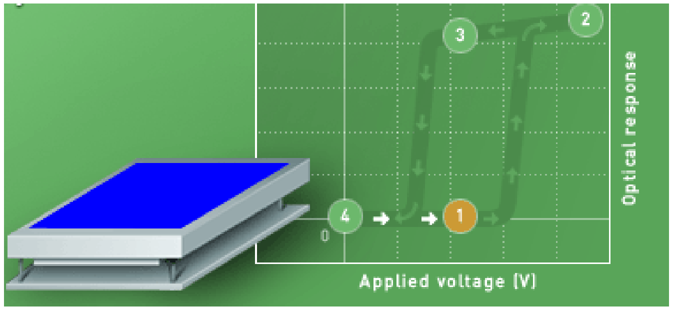
One more way to play with light

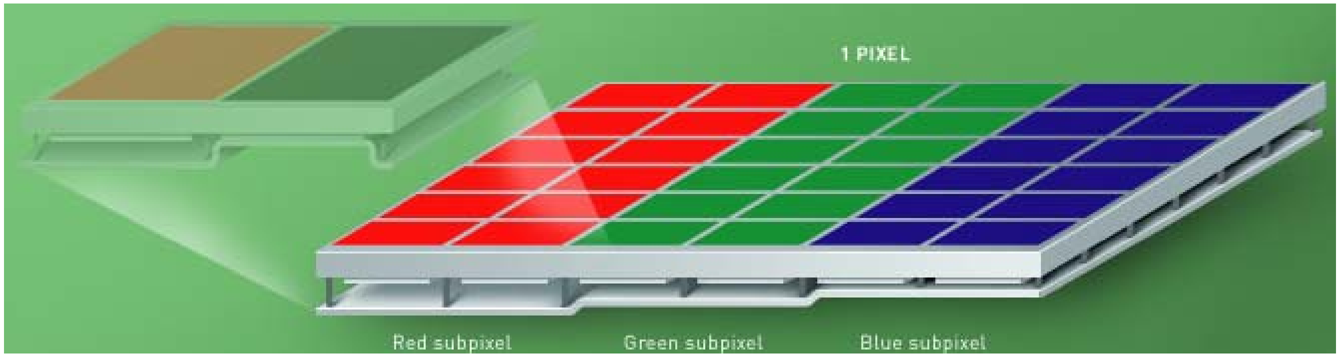
IRIDIGM™ www.iridigm.com (a QualComm acquisition)



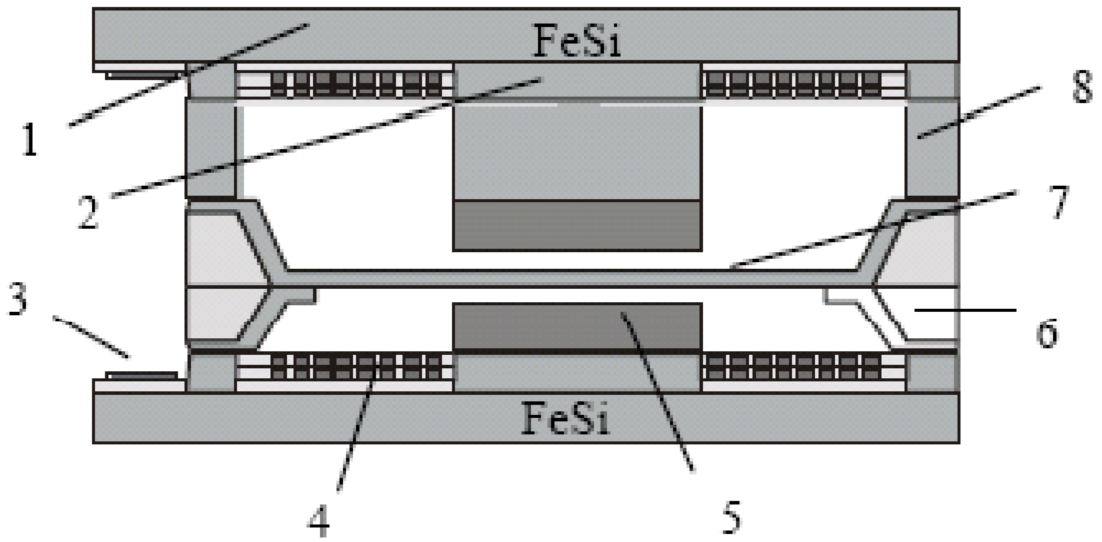
Interference-modulation by electrostatic actuation of vertically moving membranes.







Micro loudspeakers for hearing-impaired.



Rehder et al., 1999

Magnetic actuation
5x5x2 mm^3

Better frequency range.

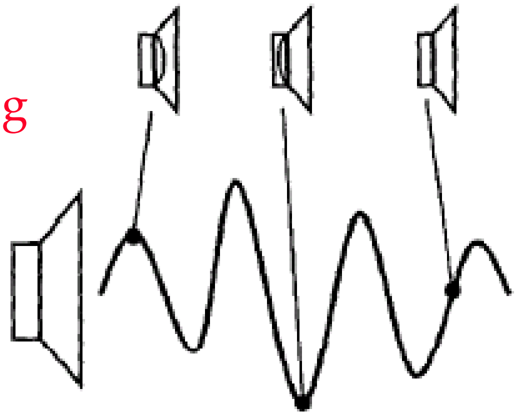
Easy manufacture and low cost.

Could be used in an array more easily.

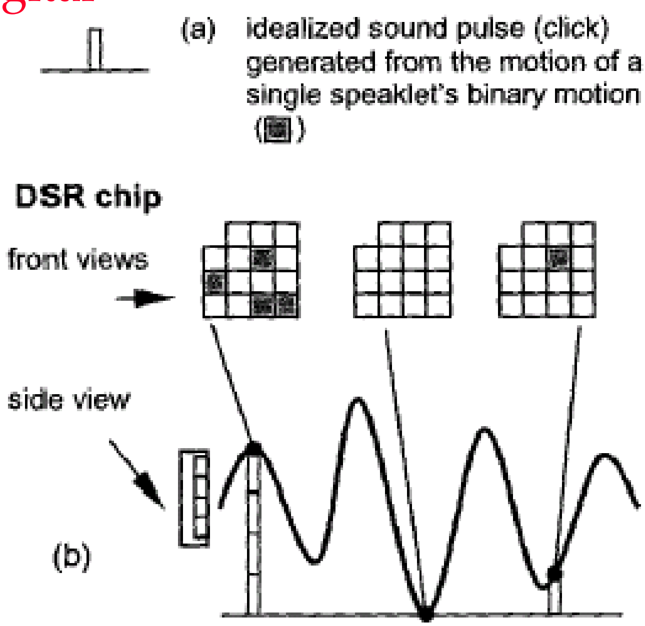
Could be integrated with on-chip circuitry.

Truly digital sound using MEMS

Analog



Digital



Advantages of DRS:

Large dynamic range is not necessary.

Nonlinearity can be controlled ➔ distortion is minimized.

Fault tolerance.

Intensity control.

Speaklets are combined to produce the sound effect.

With low-pass filters, the sound is smoothened.

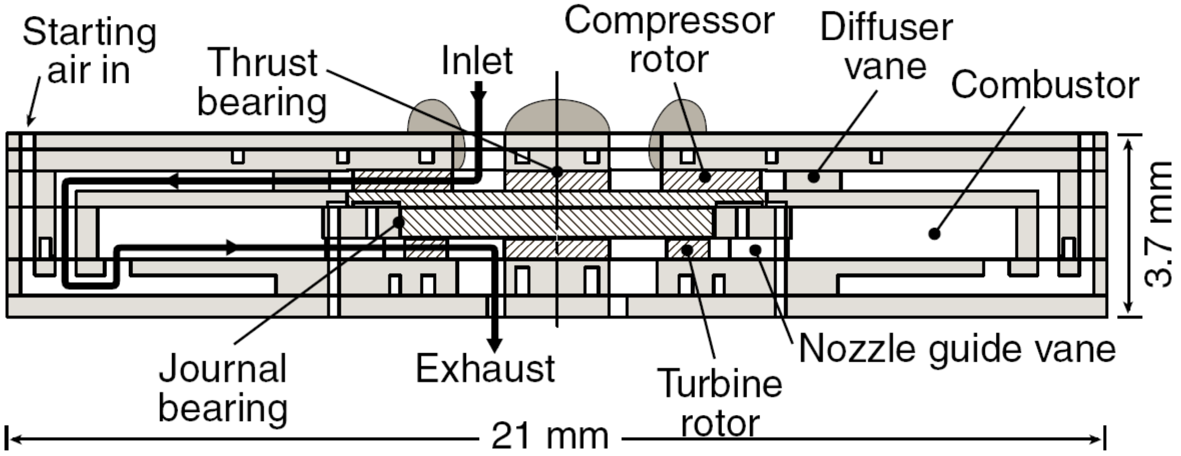
Diamond et al., 2003

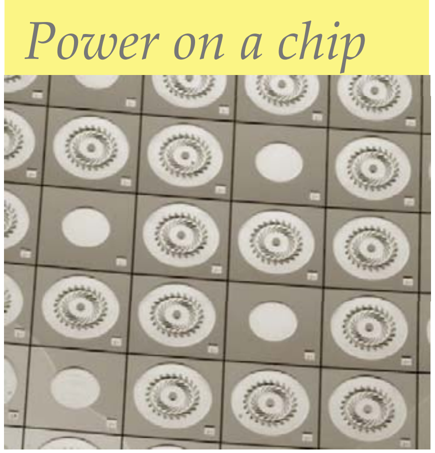
More applications

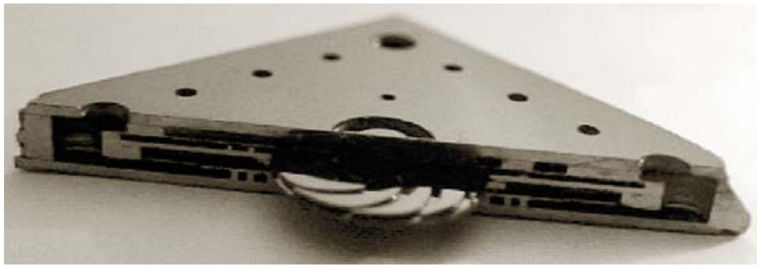
- Inertial measurement devices
  - Accelerometers, gyroscopes
- Mass data storage
- Opto-mechanical devices
  - Projection displays, photonics, optics-on-a-chip
- Flow control
- Bio-chemical sensors/actuators
  - “lab-on-a-chip”, drug delivery, bio-sensors
- Communication hardware
  - Mechanical filters, RF-switches and relays, wireless MEMS
- Chemical microreactors (“plant-on-a-chip”)
- Power MEMS
  - Micro engines, generators

Micro-engine: Power on a chip

MIT Microengine (Source: Epstein, 2003)

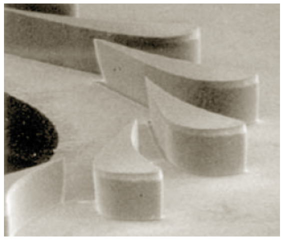






Demo engine with H_2 fuel

Turbine-compressor test



Detail of the DRIE-etched blades

Consumer electronic products

Accelerometers:
In laptops, PDAs, camcorders, CD, DVD, and MP3 players

Microphones, filters, switches, etc.:
Cell phones

Revenues in 2001: $124.3 M
Projected revenues in 2006: $613.5 M

www.instat.com (Marlene Bourne)

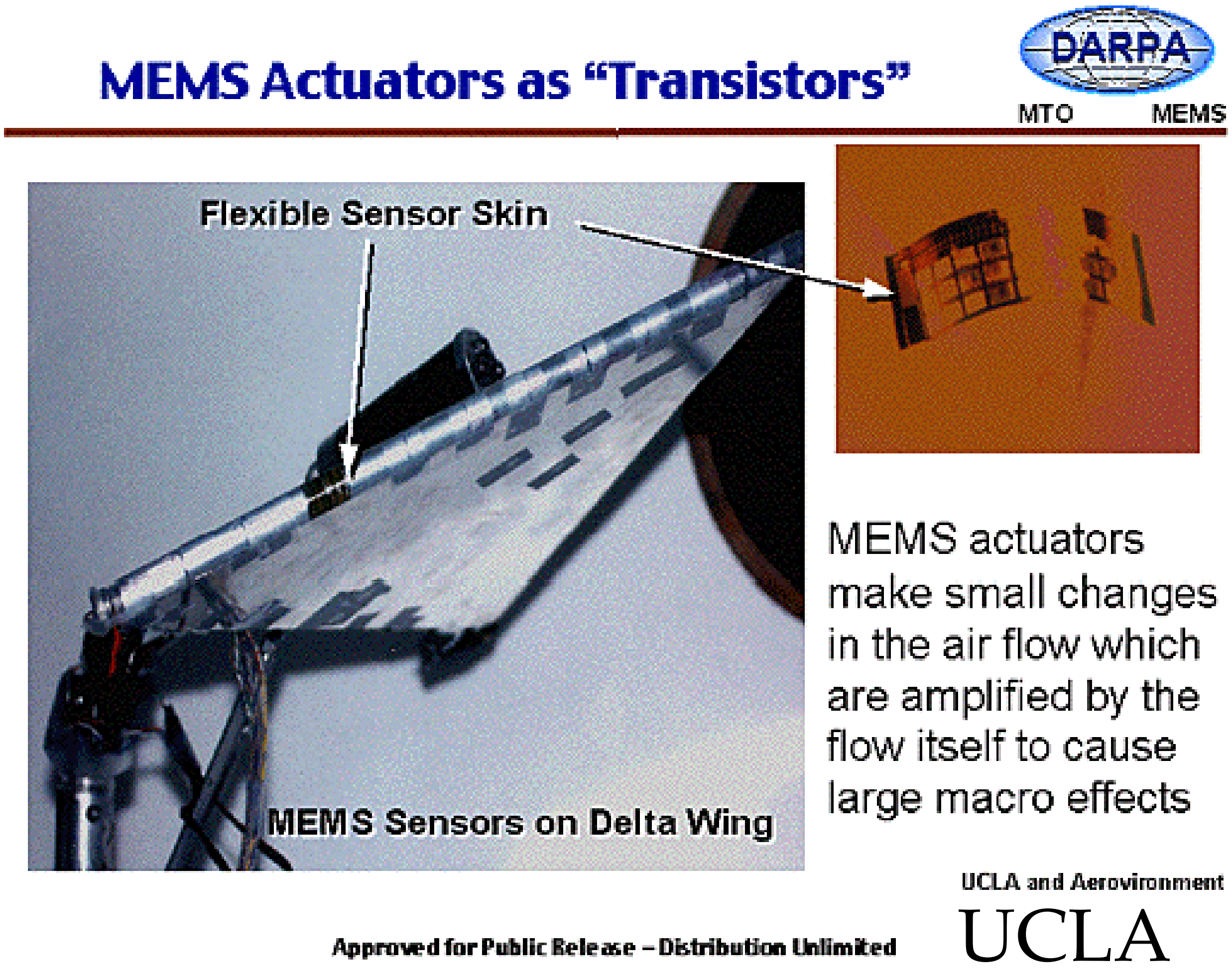
Toys!

- Teaching a new dog some new tricks…

SONY AIBO dogs reportedly use micro-accelerometers.

Source: SmallTimes 9/10,2003

MEMS affecting the macro world



MEMS Actuators as “Transistors”

MEMS actuators make small changes in the air flow which are amplified by the flow itself to cause large macro effects

UCLA and Aerovironment

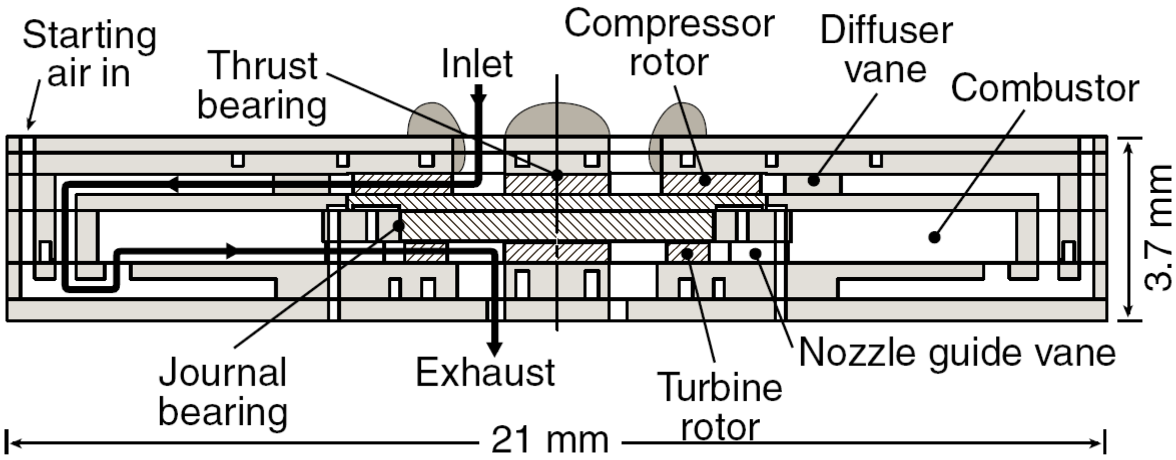
UCLA

Approved for Public Release – Distribution Unlimited

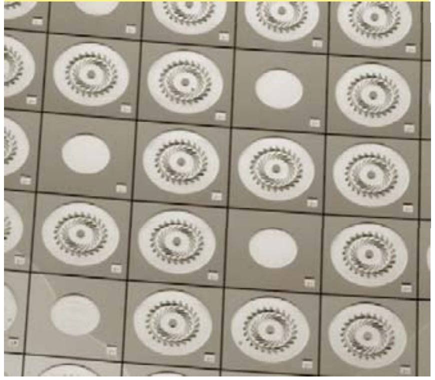
MEMS creating large effects – an example

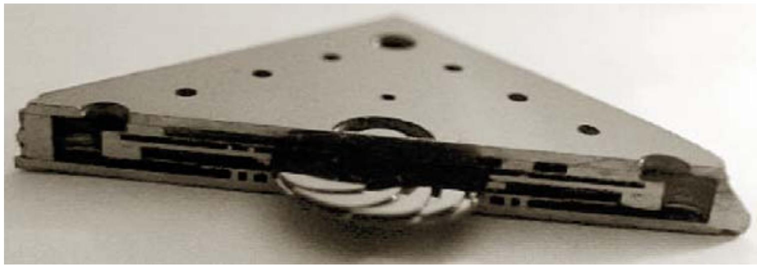
MEMS to power the macro world?

MIT Microengine (Source: Epstein, 2003)



Power on a chip





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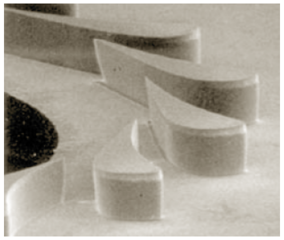
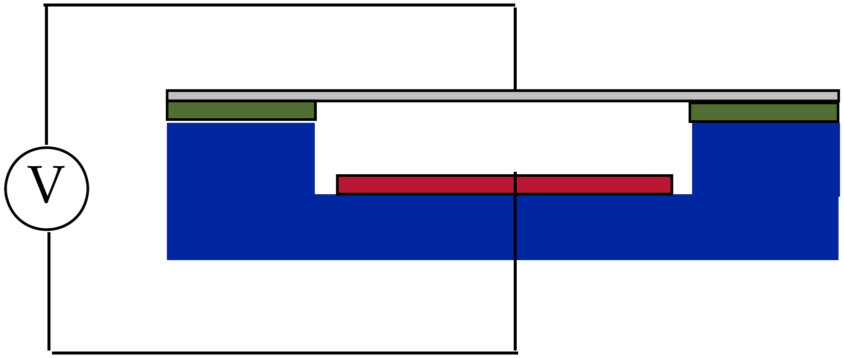


Detail of the DRIE-etched blades

Outline

- ✓ What are they?
- ✓ How small are they?
- ✓ How are they useful
- ➢ **How do they work?**

Pressure sensor



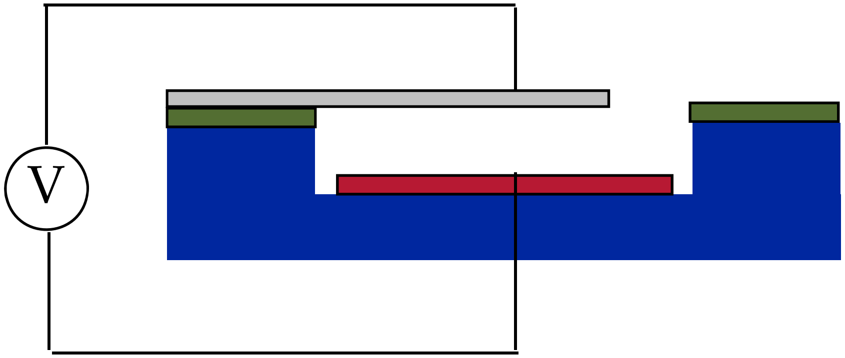
Capacitive sensing

Piezoresistive sensing

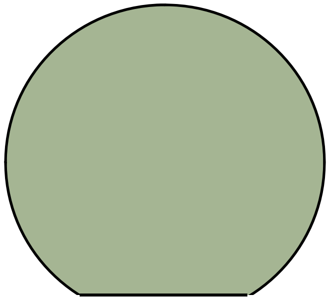
How do they work?

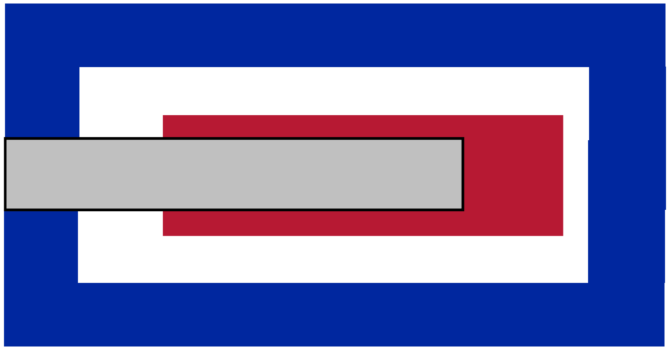
Accelerometer

Side view

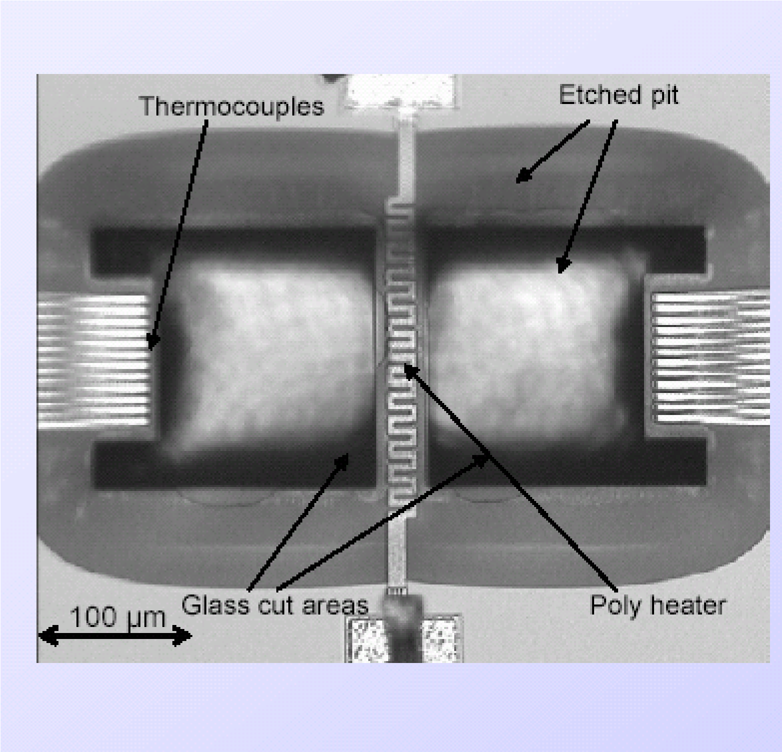


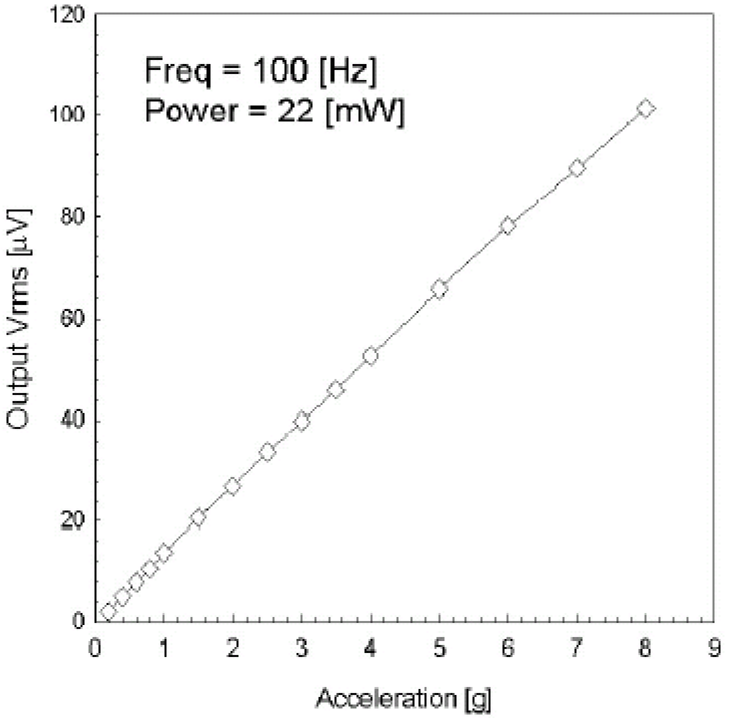
Top view





Many ways to do one thing.





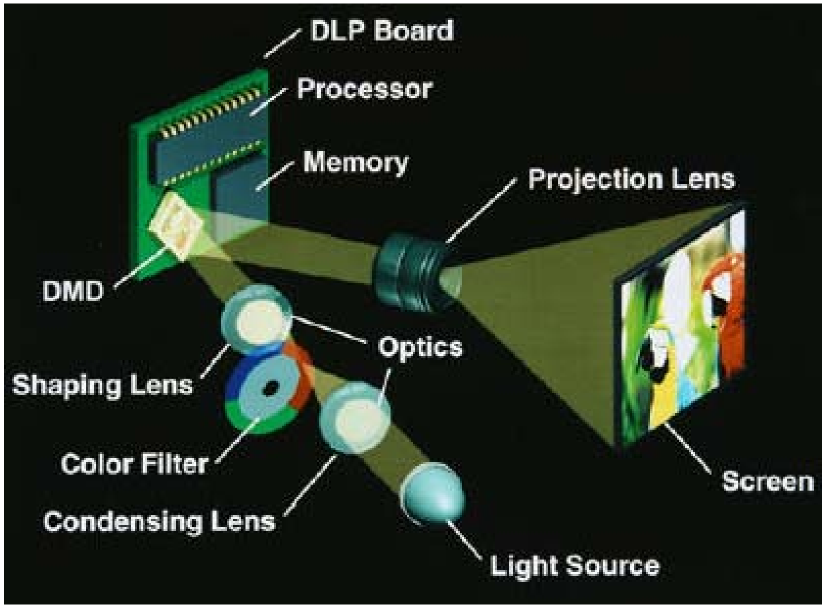
Convective accelerometer

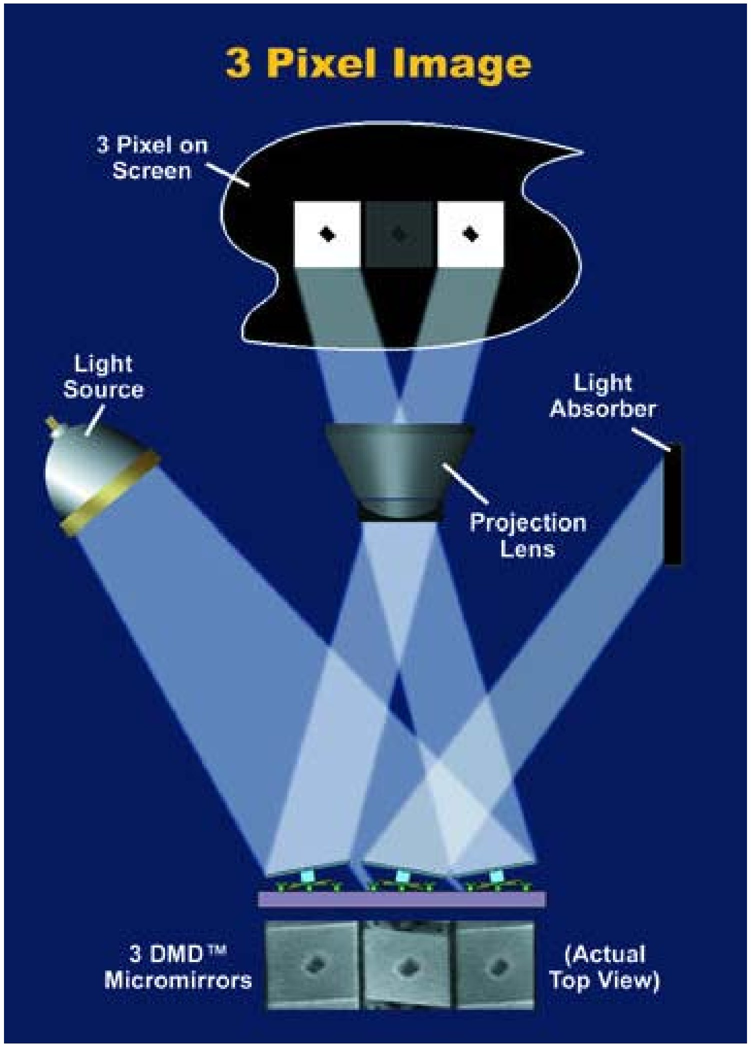
No moving parts!

Dao et al., 1996; Leung et al., 1997.

Accessories of DLP-based LCD projector

Processor
Memory
Color wheel
Optics
Light source





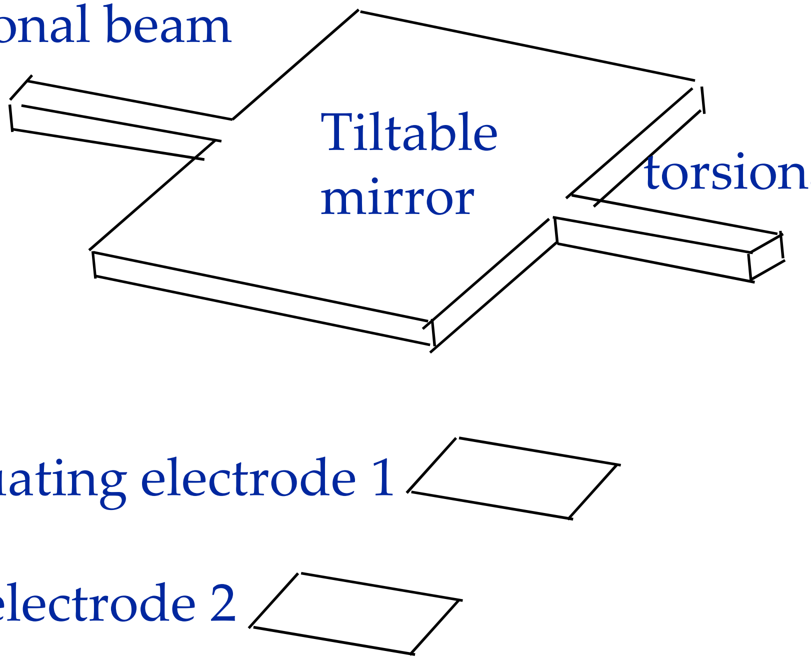
How do they work?

Texas Instrument's digital light processor

InFocus digital projectors

How do they work?

TI's digital light processor (DLP)



torsional beam

Tiltable mirror

torsional beam

actuating electrode 1

actuating electrode 2

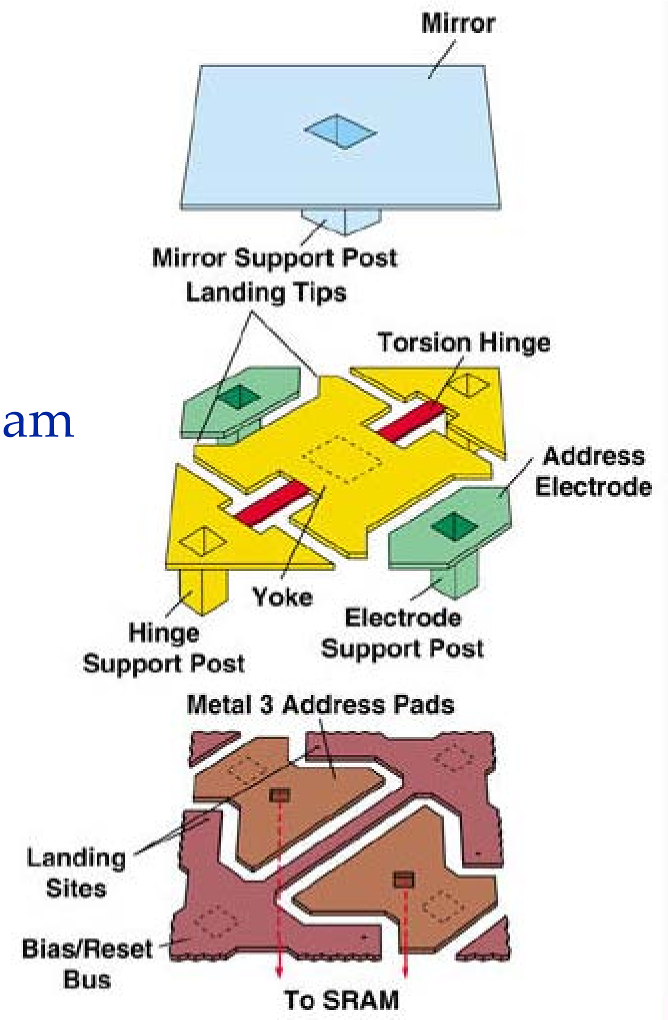


Photo courtesy Texas Instruments

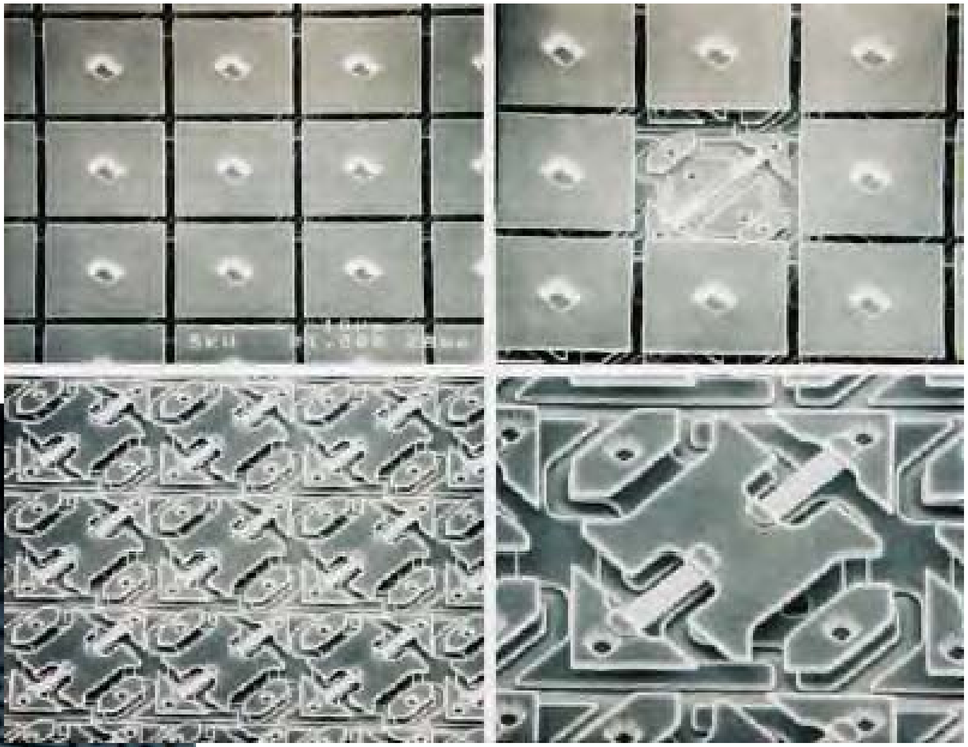
Exploded view of an individual mirror on a DMD

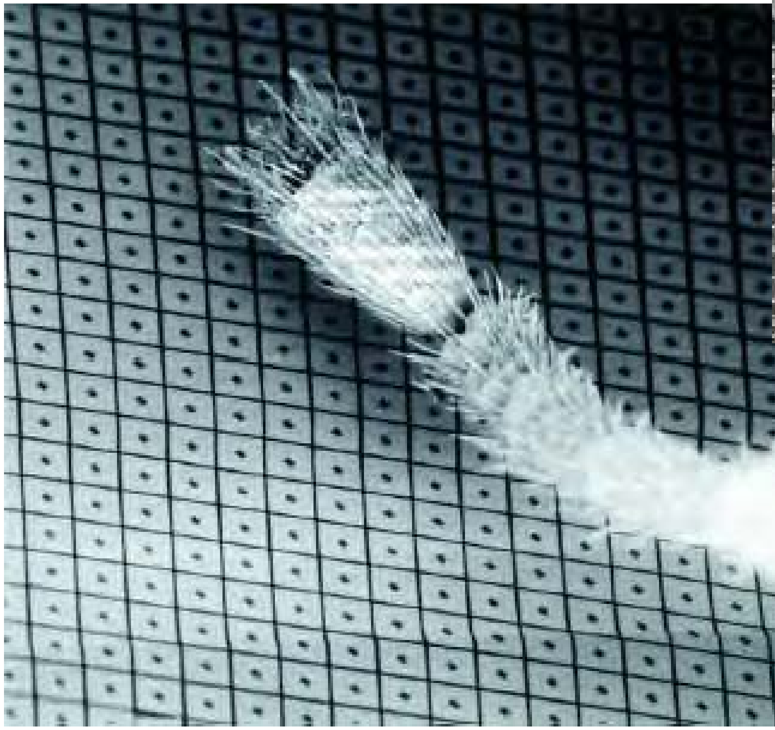
(Source: www.howstuffworks.com)

What lies beneath

TI's digital light processor (DLP) and deformable mirror display (DMD)

Anatomy of DLP/DMD

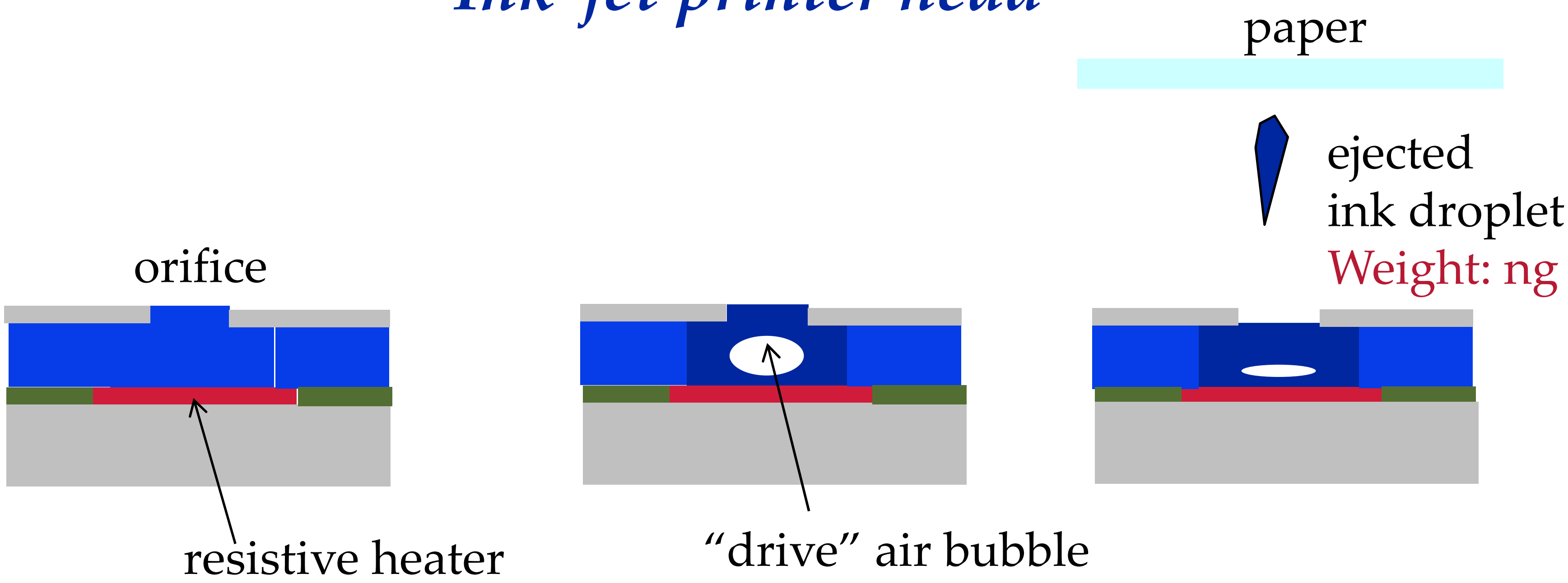




Ant's leg on the DMD array

How do they work?

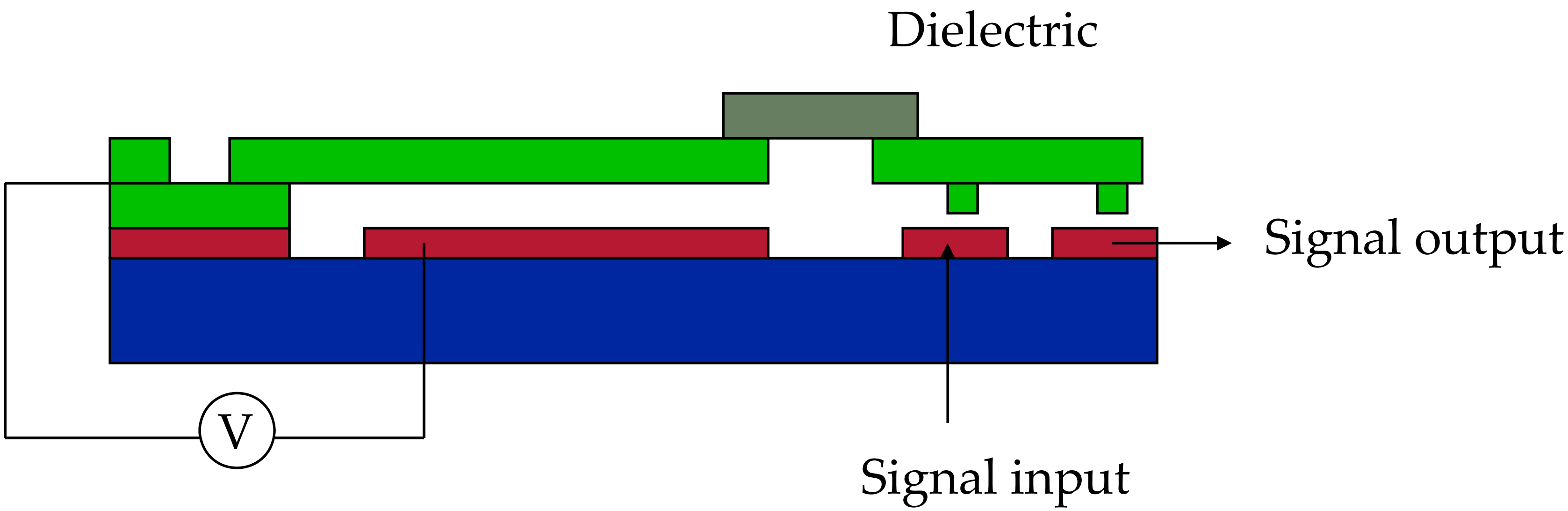
Ink-jet printer head



- Electronics are integrated to trigger the drive bubble

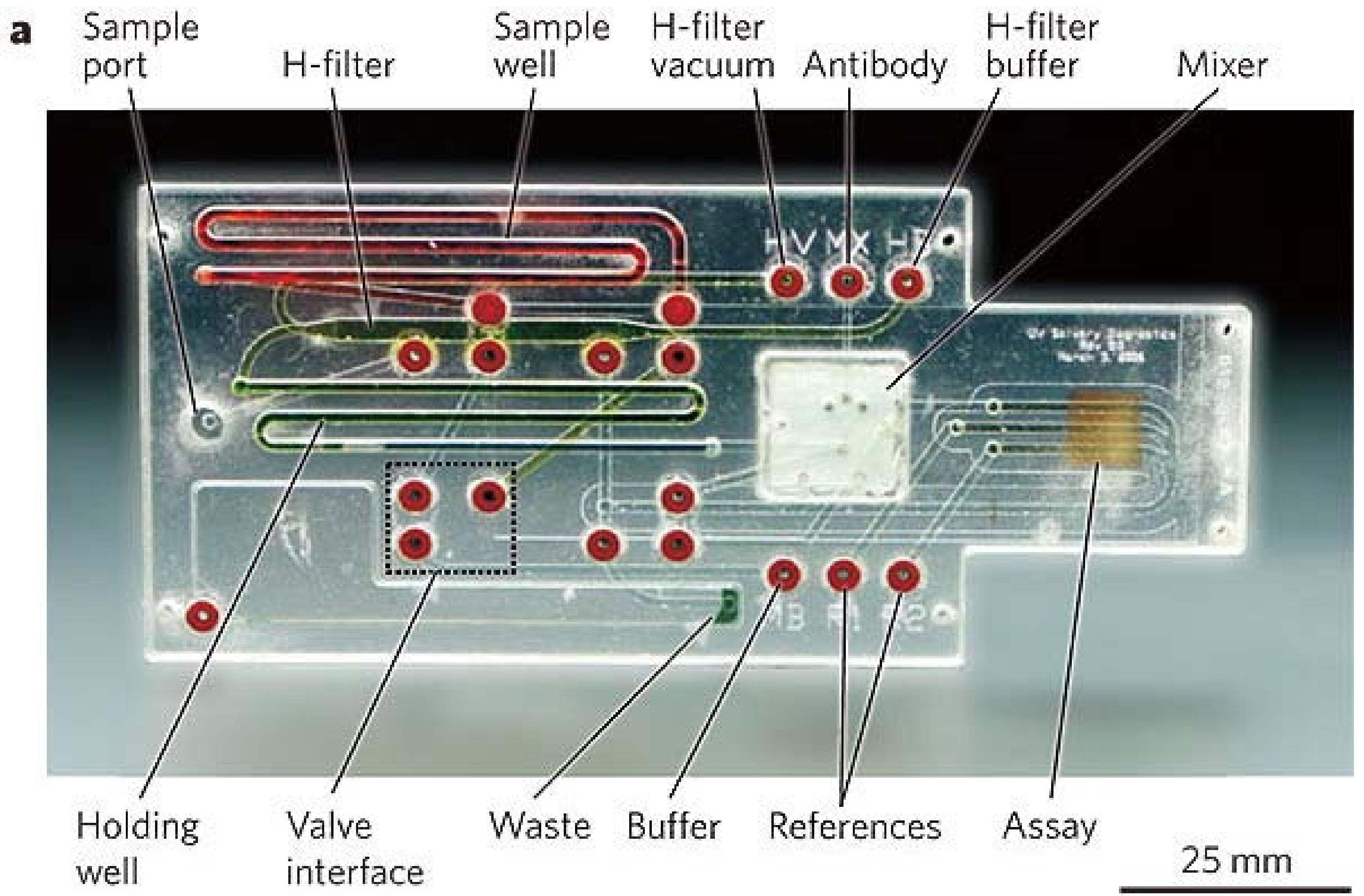
How do they work?

A mechanical relay



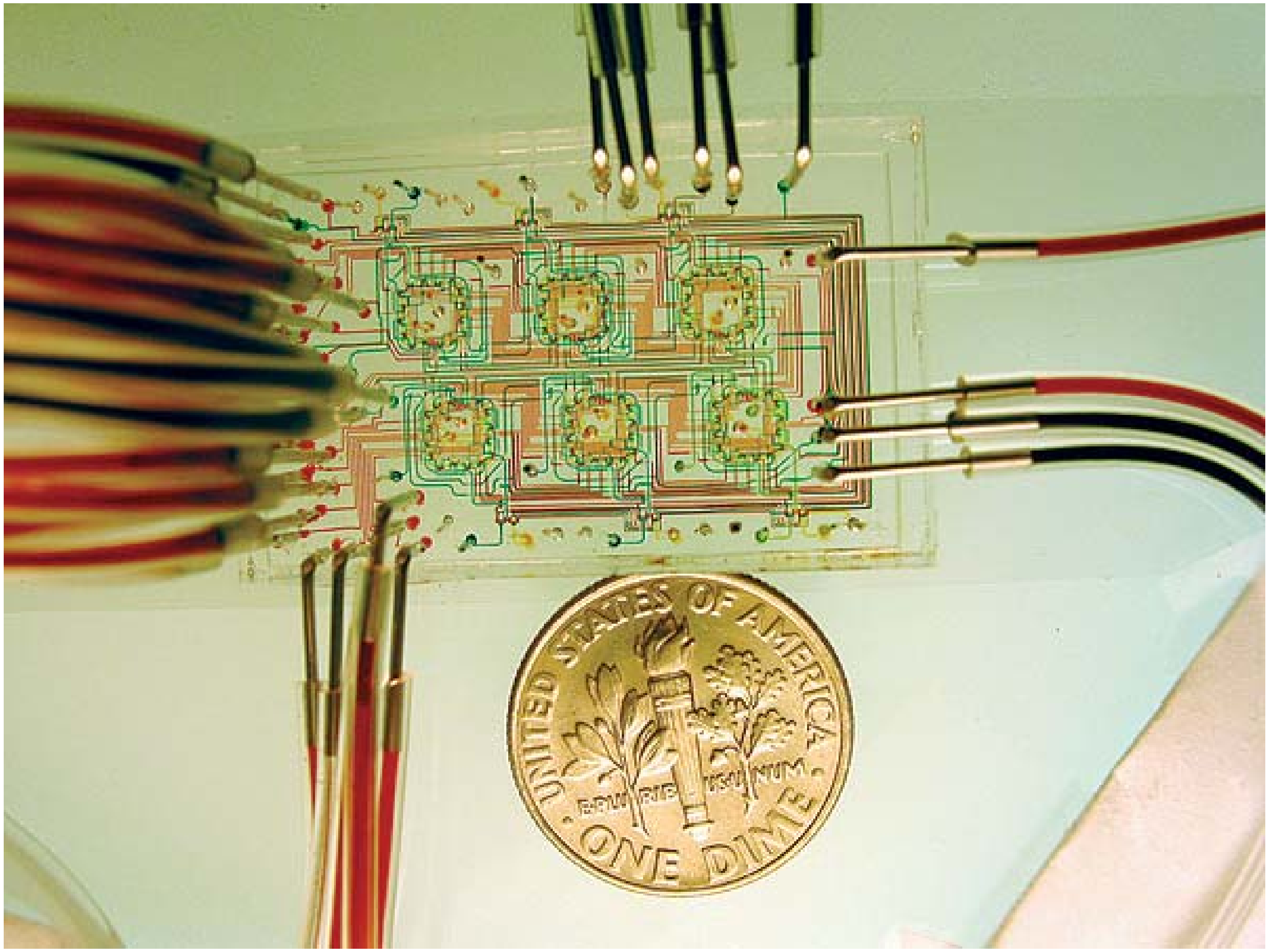
How do they work? Lab-on-a-chip

A slide given by Prof. Srikar Vengallatore, McGill University



How do they work? Microfluidic systems

A slide given by Prof. Srikar Vengallatore, McGill University

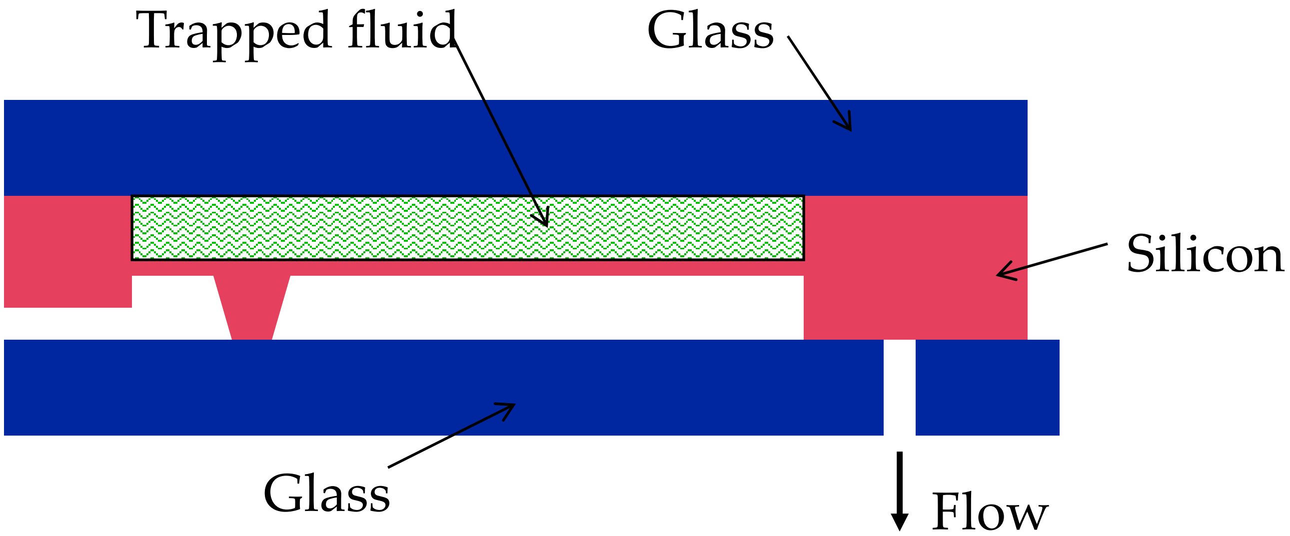


Classic Example: Microfluidic Devices

(G. Whitesides)

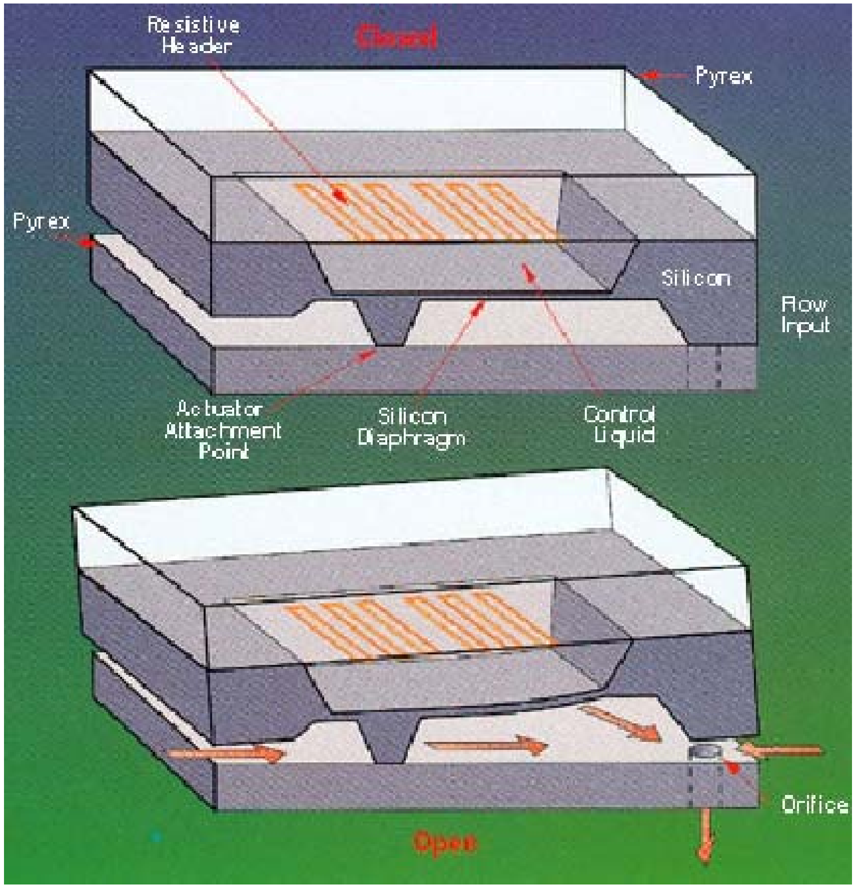
How do they work?

A normally closed fluidic valve

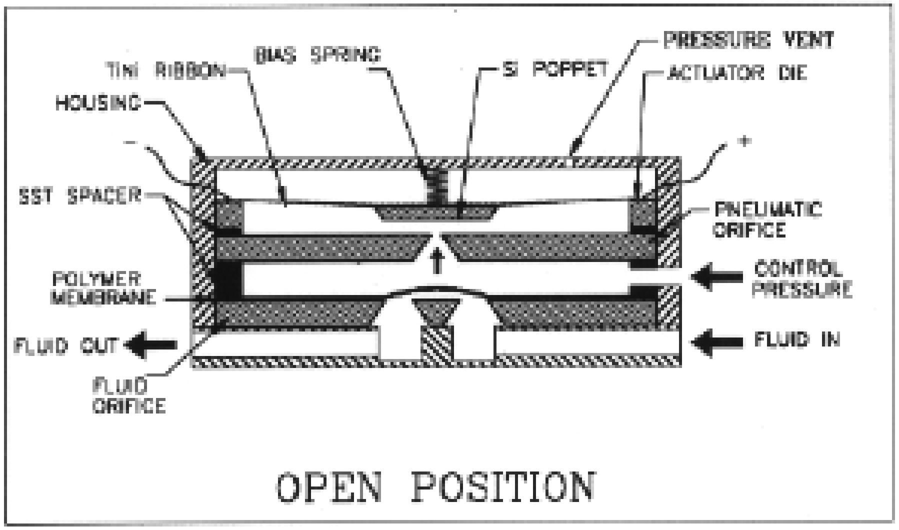


(Redwood Microsystems)

Two commercial micro-valves



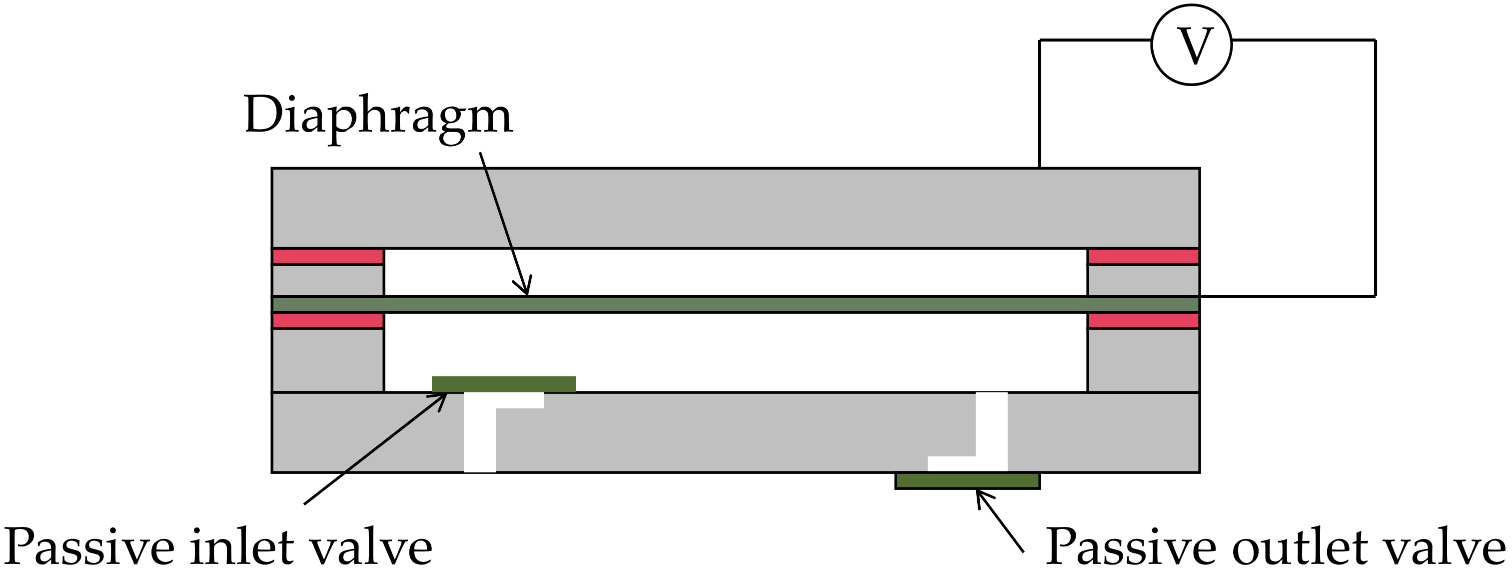
Redwood Microsystems's thermo-pneumatic normally closed valve



A normally open valve; www.smavalves.com

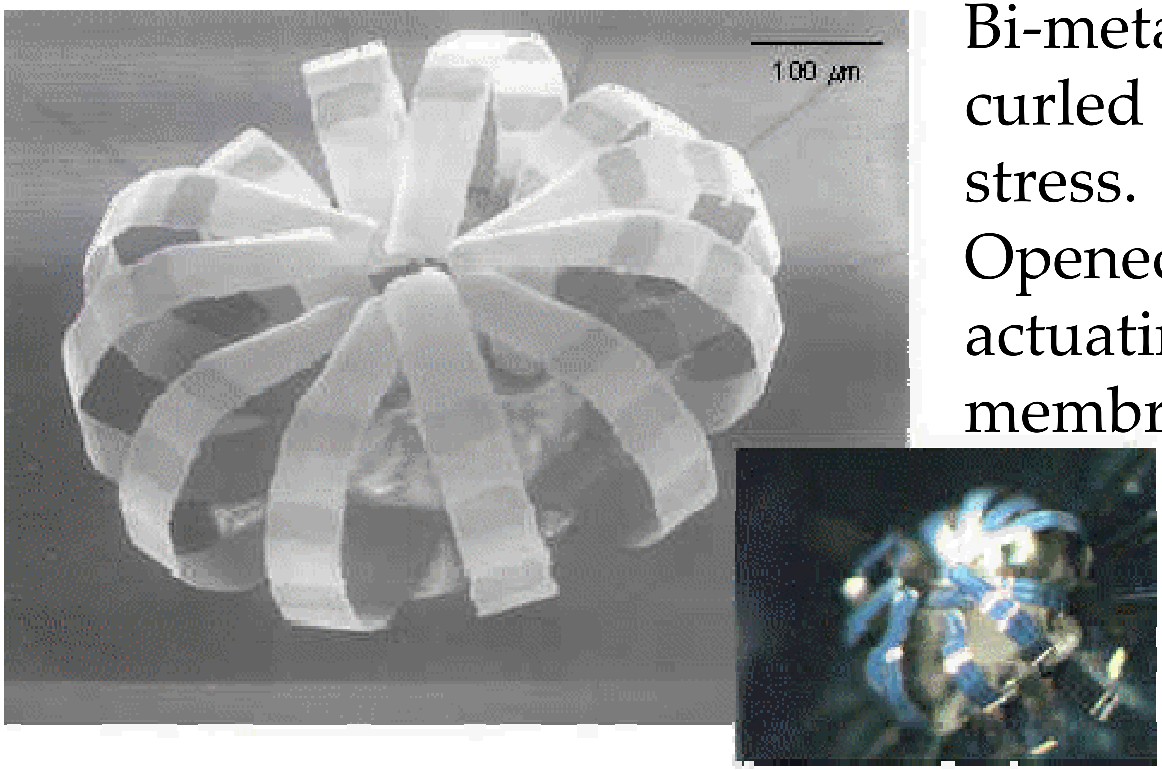
How do they work?

A diaphragm pump



Micro-cage with cantilevers

C. J. Kim, UCLA



Bi-metal cantilevers curled due to residual stress.

Opened with actuating the bottom membrane

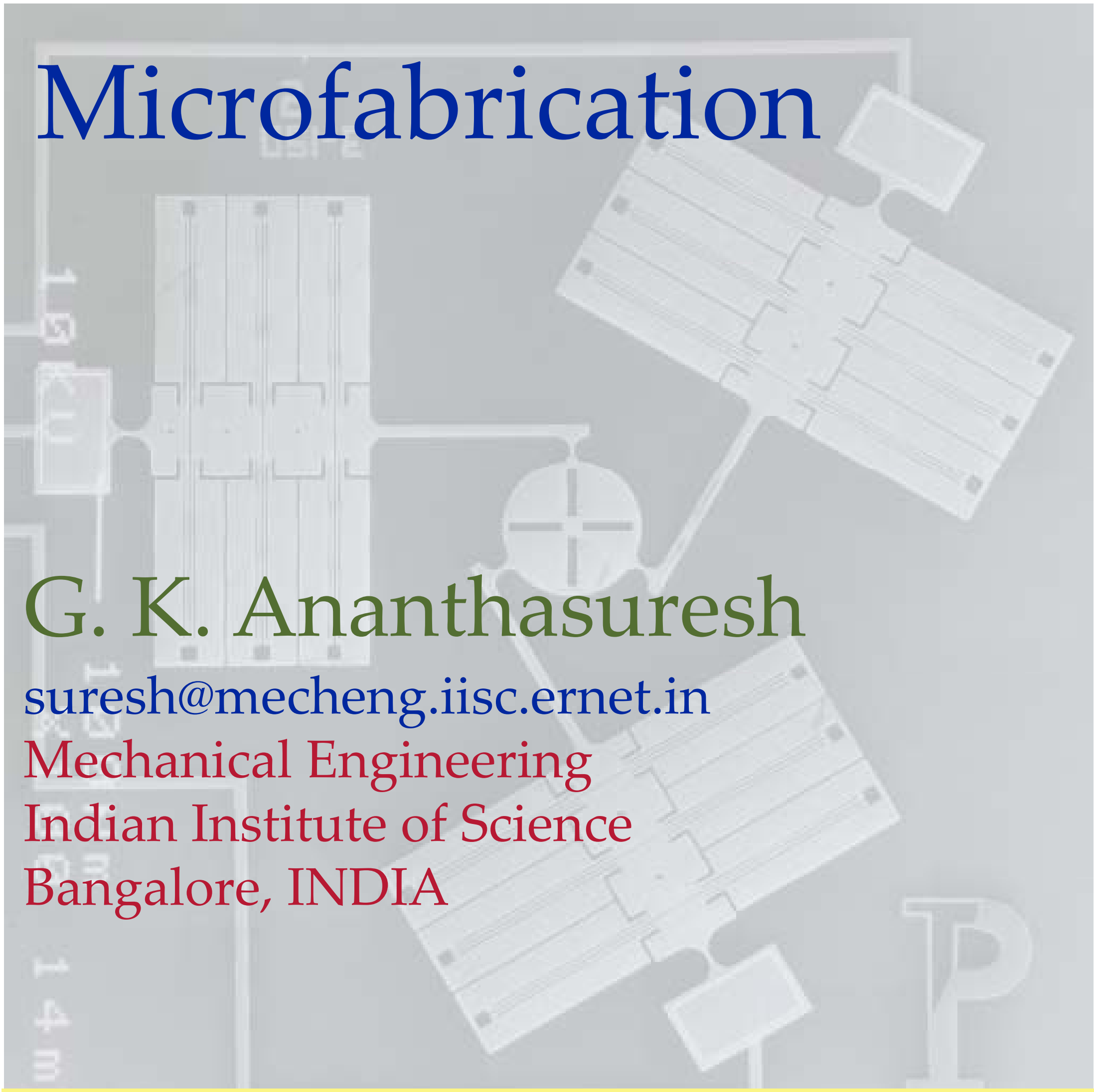
Outline

- ✓ What are they?
- ✓ How small are they?
- ✓ How are they useful
- ✓ How do they work?

Lecture 1

- ➢ What are they made of?
- ➢ How are they made?

Lecture 2



Microfabrication

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Indian Institute of Science
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August 2014; for ME 237/NE 211, IISc

Outline

- ✓ What are they?
- ✓ How small are they?
- ✓ How are they useful
- ✓ How do they work?

- ➢ What are they made of?
- ➢ How are they made?

What are they made of?

Phase 1: Old materials and *old* processes

Silicon, its oxide, nitride, and some metals
IC-chip processing technology

Lithography
Thin film deposition (e.g., chemical vapor deposition – CVD)
Etching
Doping

Phase 2: Old materials and *new* processes

Silicon, its oxide, nitride, glass, polysilicon, and some metals
IC-chip processing techniques enhanced as “micromachining” techniques

Sacrificial layer process   Dissolved wafer process   Wafer bonding
LIGA   Hexil   Deep reactive ion etching   Etc.

What are they made of (contd.)

Phase 3: New materials and *old* processes

Polymers
More metals
Ceramics
Silicon carbide
Piezoelectric films
Ferroelectric films
Shape-memory materials, etc.

e.g., PDMS, SU-8, PMMA

Phase 4: New materials and *new* processes

Processes unconventional to the microelectronic field

Processes that re-define the size of MEMS – micro to meso or nano

Deposition and etching for the new materials

How are they made?

- Surface micromachining
    - Deposition of thin films (mainly polysilicon)
    - Etching using masks
    - Layered construction
- Bulk-micromachining
    - Carving features into “bulk” wafers by etching
- Wafer bonding
    - Patterning individual wafers
    - Wafer-to-wafer bonding
- LIGA, HEXIL, and other HARM processes
- DRIE
- Others: laser, micro EDM, etc.

Micromachining is not precision machining!

Precision machining ➔ Relative tolerance (feature to part size) is better than 10^{-4}.

For micromachining, it is 10^{-2} to 10^{-3}.
Roughly what we have for building houses.

With micromachining,
You can make it small, but not precisely.

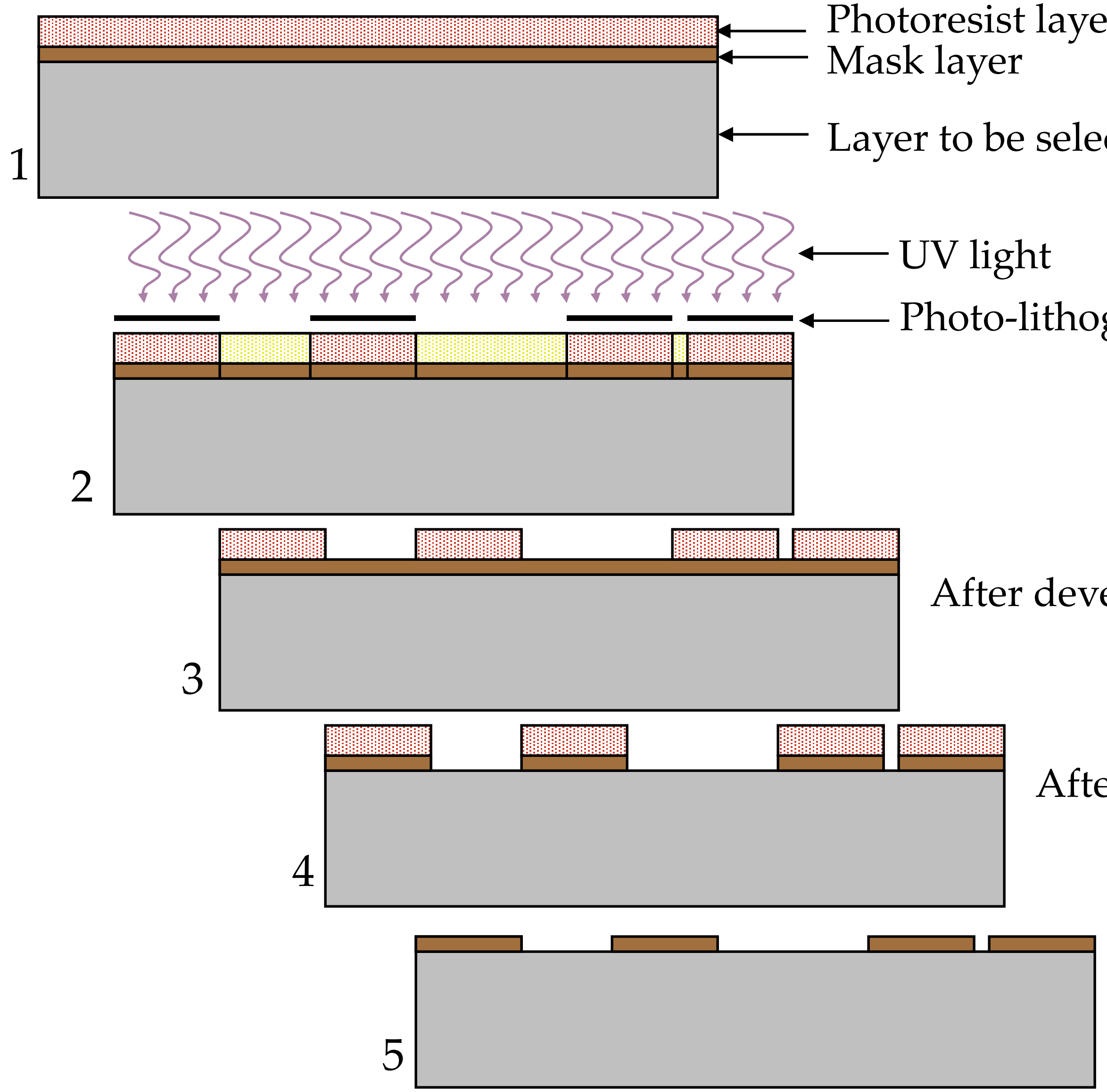
Basic materials used in microfabrication

- **Silicon and its compounds**
  - Single-crystal silicon (SCS)
  - Polycrystalline silicon (poly)
  - Silicon dioxide (oxide)
  - Silicon nitride (nitride)
  - Silicon carbide
- **Metals**
  - Aluminium, gold, copper, silver, nickel, etc.
- **Glass**
  - Pyrex, sapphire, quartz, etc.
- **Ceramics**
  - Mostly used in packaging in multi-chip modules
- **Polymers**
  - Mostly in bioMEMS applications

Basic process steps

- Photolithography
- Oxidation
- Thin-film deposition
- Selective etching through a mask
- Wafer bonding
- Doping
- Epitaxial growth
- Thick-film deposition
- Dicing, die-bonding, and wire-bonding

Photolithography for patterning a mask layer



Photoresist layer (spincast and baked))

Mask layer

Layer to be selectively etched

UV light

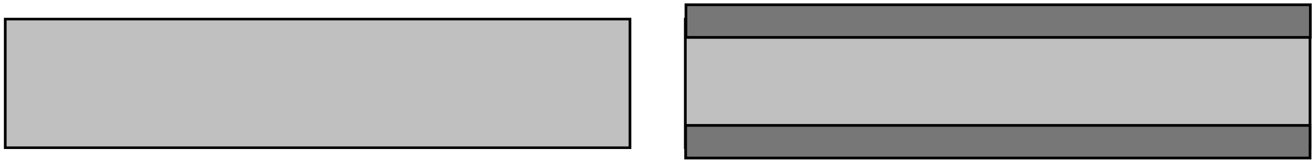
Photo-lithography mask

After developing the photoresist

After etching the mask layer

After stripping off the photoresist

Oxidation



If the oxide layer's thickness is t_{ox},

Net increase in wafer thickness is $0.54t_{ox}$.

$$Si + 2H_2O \rightarrow SiO_2 + H_2$$ Wet

$$Si + O_2 \rightarrow SiO_2$$ Dry

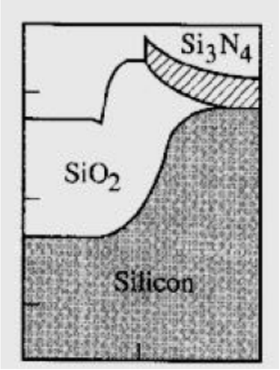
B.E. Deal and A.S. Grove, "General Relationship for the Thermal Oxidation of Silicon", J. Appl. Phys. 36, 12, 3770 (1965)

$$x_{ox}(t) = \frac{A}{2}\left[\left\{1 + \frac{(t+\tau)}{A^2}4B\right\}^{1/2} - 1\right]$$ Deal and Grove model

$$A = 2D\left(\frac{1}{k_s} + \frac{1}{h}\right); \quad B = 2DC^* / N; \quad \tau = \frac{(x_0^2 + Ax_0)}{B}$$

Local Oxidation of Silicon (LOCOS)

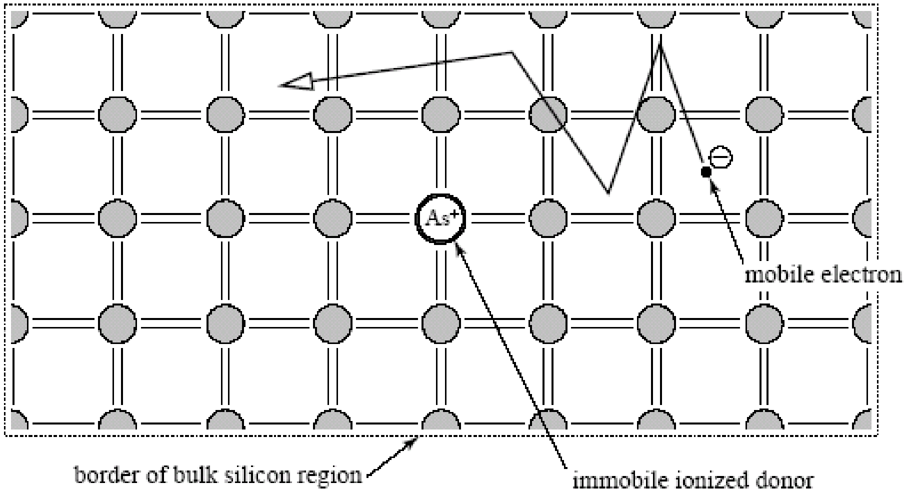
LOCOS in recessed silicon



Thin-film deposition techniques

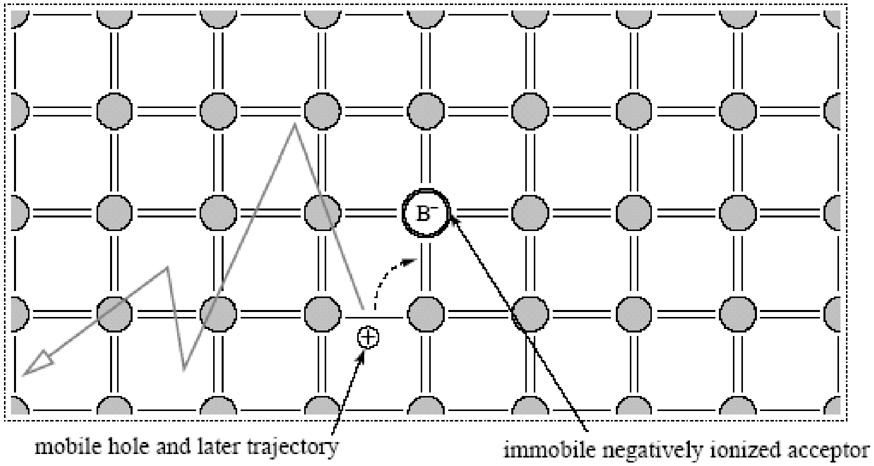
- **Chemical vapour deposition (CVD)**
  - LPCVD
  - PECVD
- **Physical vapour deposition (PVD)**
  - Vacuum evaporation
- **Sputtering**
- **Epitaxy**
  - VPE, LPE, MPE
- **Electroplating**
- **Electroless plating**
- **Spincasting**

Doping with donors and acceptors



V-group (Phosphorous, Arsenic, etc.) have five valence electrons. They donate one electron and permanently become positive ions. This electron roams around and helps increase conductivity.

III-group (Boron, Gallium, etc.) have three valence electrons. They accept one electron and permanently become negative ions. This leads to a mobile hole.



Source: unknown

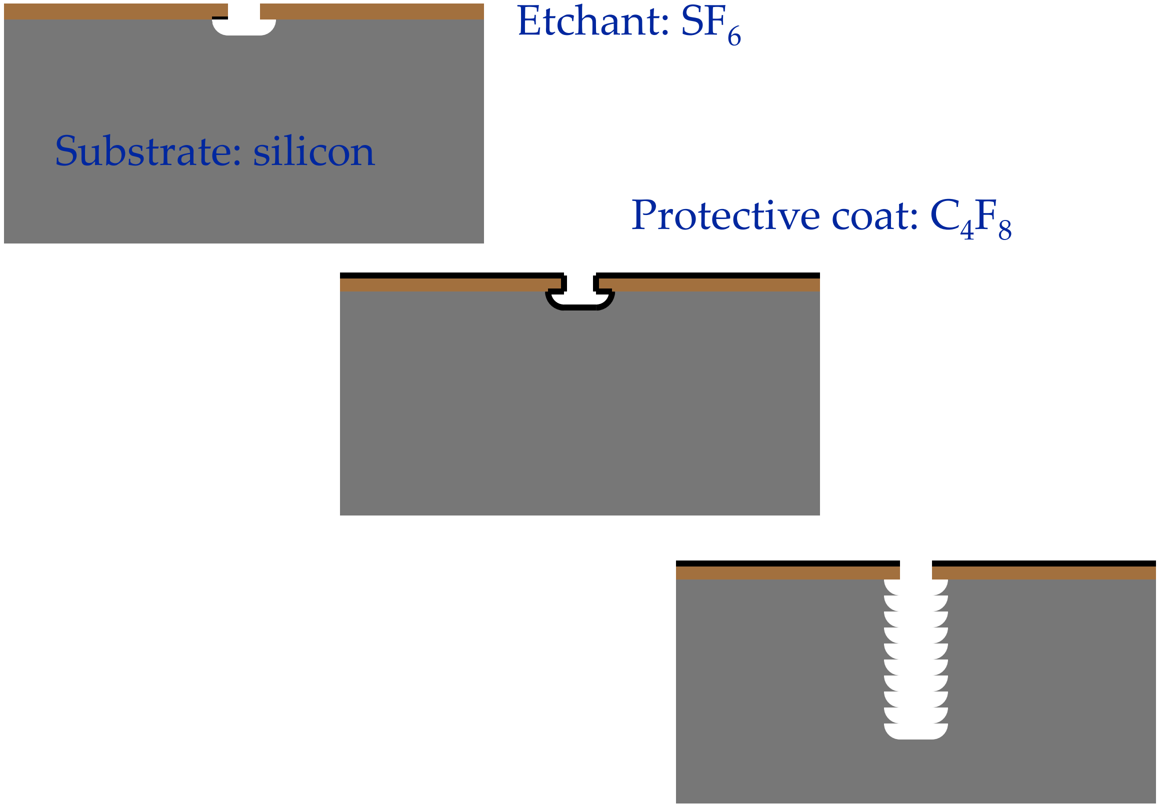
Etching

- **Wet**
  - Isotropic
  - Anisotropic
  - Electrochemical
  - Lift-off patterning
- **Dry**
  - Plasma etching: Reactive ion etching (RIE)
  - Deep RIE (DRIE)
  - Vapour phase dry etching
  - Lift-off deposition

DRIE

Developed and patented by Bosch (Germany).

It is time-multiplexed deep etching (TMDE).

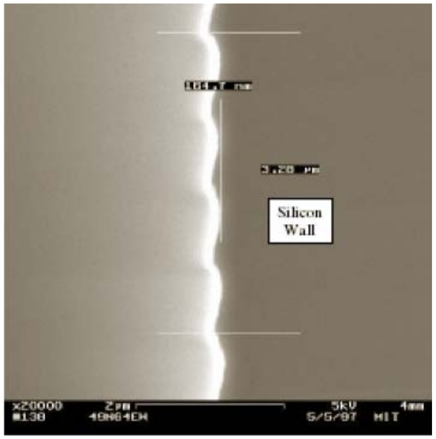


Mask: oxide

Substrate: silicon

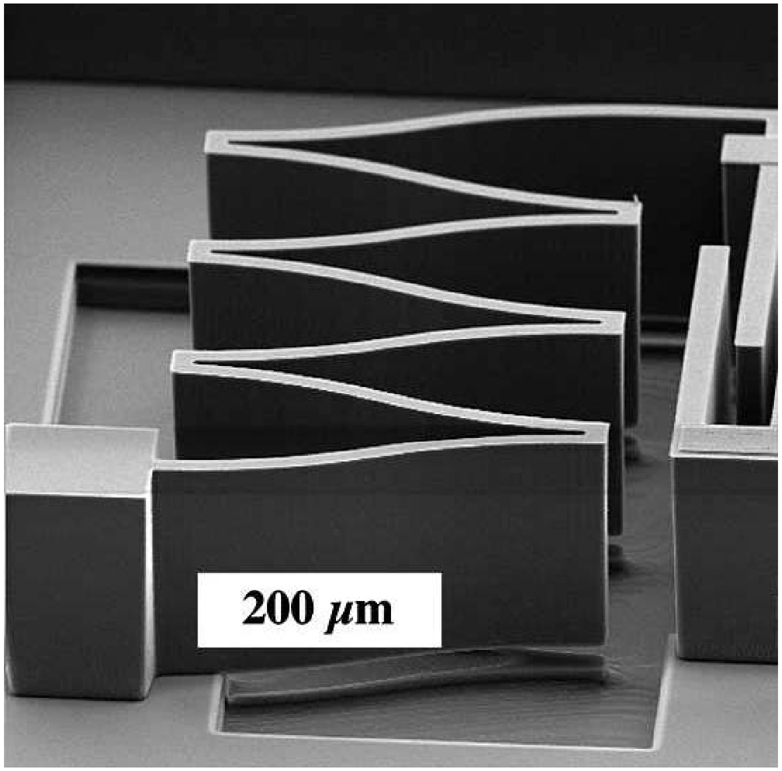
Etchant: SF_6

Protective coat: C_4F_8



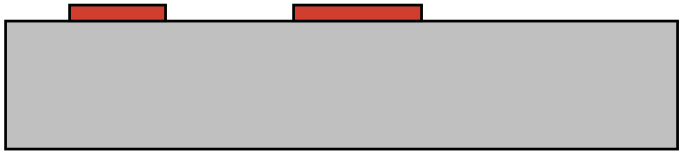
Scalloping effect

DRIE-spring



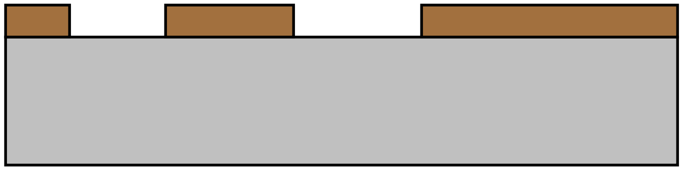
Klaassen, E. H., et al. "Silicon Fusion Bonding and Deep Reactive Ion Etching; A New Technology for Microstructures," Digest of Technical Papers from Transducers '95/Eurosensors IX, Vol. 1, June 25 - 29, 1995, Stockholm, Sweden, pp. 556 - 559.

Lift-off deposition/patterning

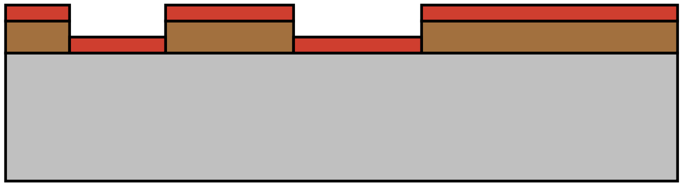


Desired patterning of the layer to be deposited

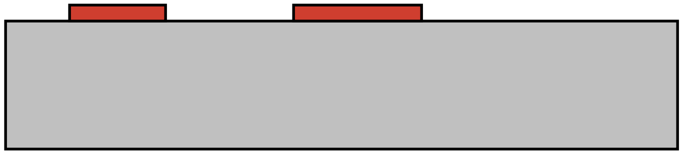
It is like using a stencil (or screen printing)



Spincast and pattern photoresist



Evaporate (deposit) the layer



Lift-off unwanted deposition along with the photoresist

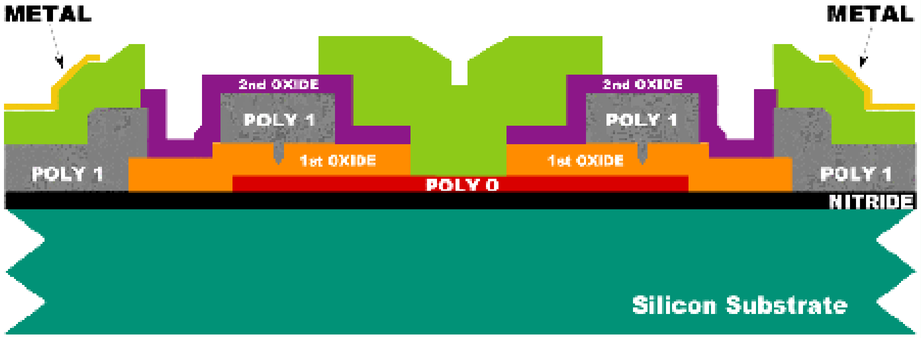
Wafer bonding

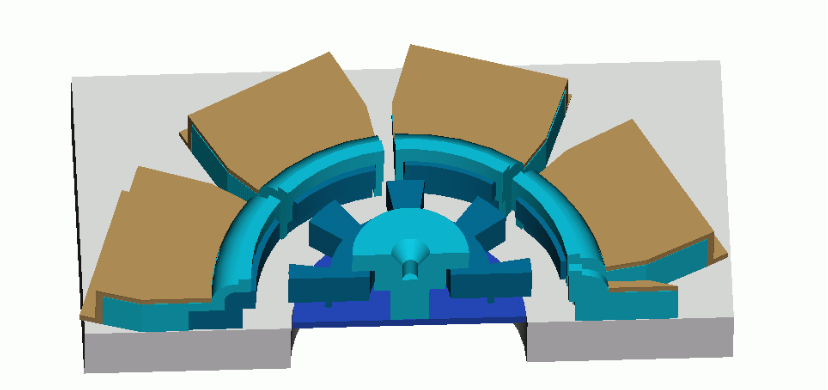
- **Wafer-to-wafer bonding**
    - Anodic
    - Fusion
    - Adhesive
    - Eutectic

Planarization

Why do we need planarization?

MUMPs process with three structural layers



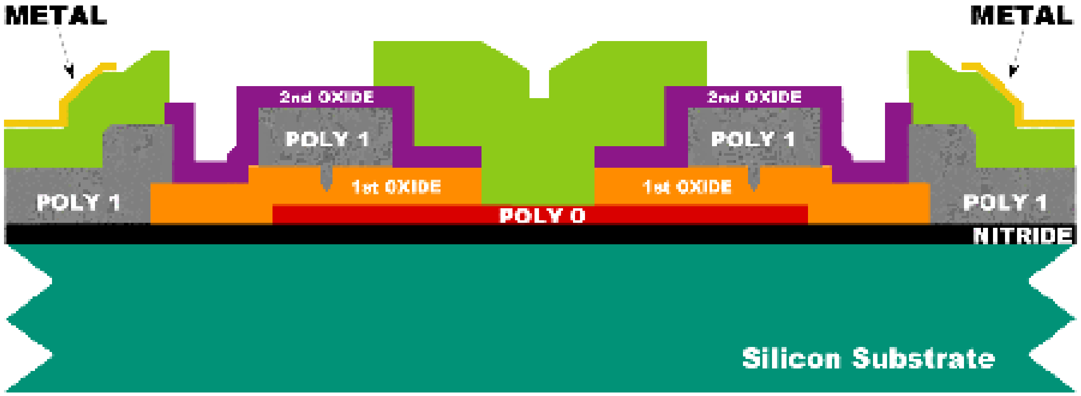


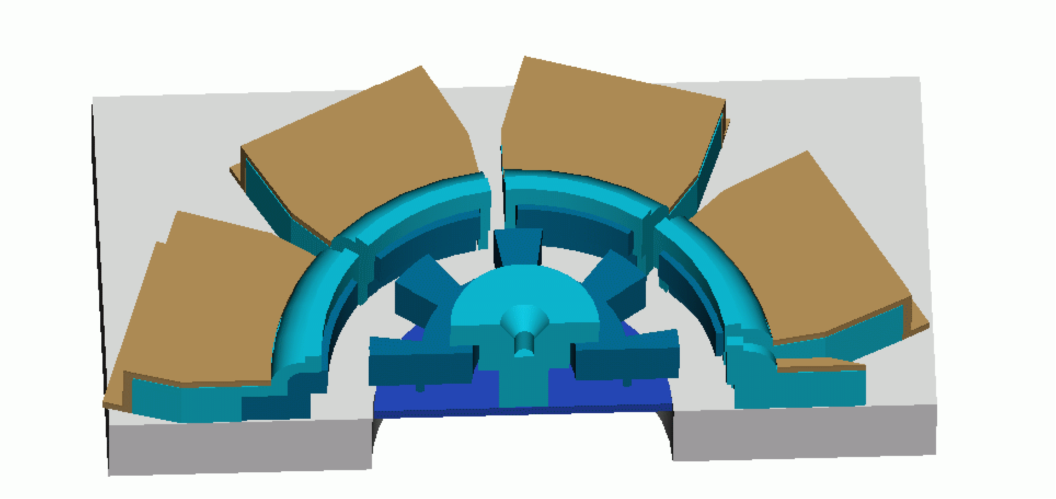
The geometry and topography of the latter layers get increasingly more complicated. Leads to the problem of stringers (loose pieces upon release) too.

- Planarization
  - Chemical mechanical polishing
  - Resist-etchback
  - Polymer-filling

The need for planarization step in MEMS

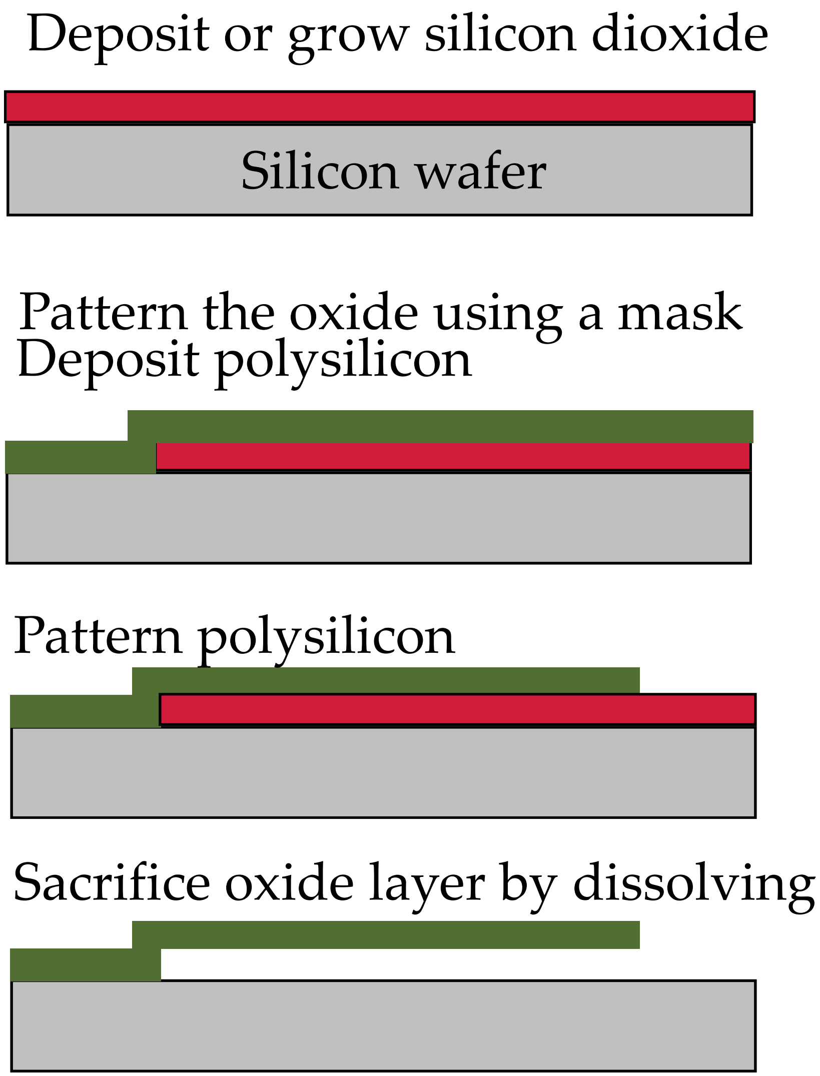
MUMPs process with three structural layers





The geometry and topography of the latter layers get increasingly more complicated. Leads to the problem of stringers (loose pieces upon release) too.

Surface micromachining



Deposit or grow silicon dioxide

Pattern the oxide using a mask
Deposit polysilicon

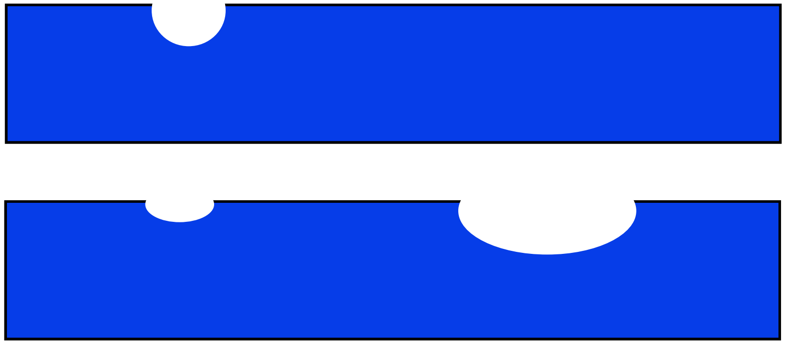
Pattern polysilicon

Sacrifice oxide layer by dissolving

The sacrificial layer process to make released structures (Berkeley)

Types of etching

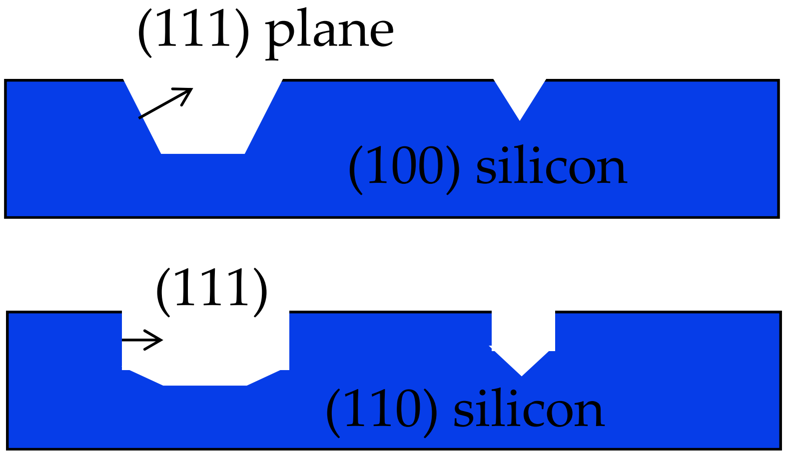
Isotropic etching



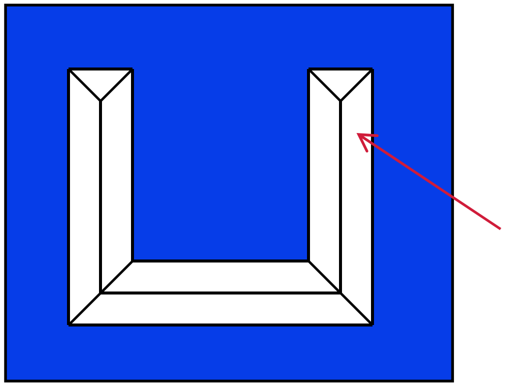
With agitation

Without agitation

Anisotropic etching



Top view



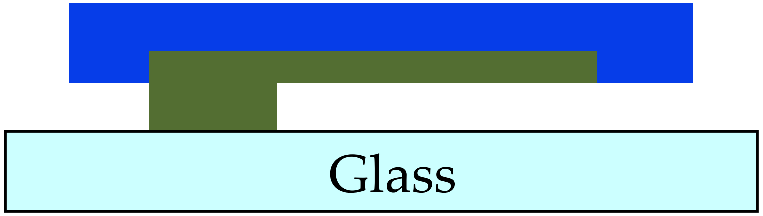
Slanted
surfaces

Bulk micromachining

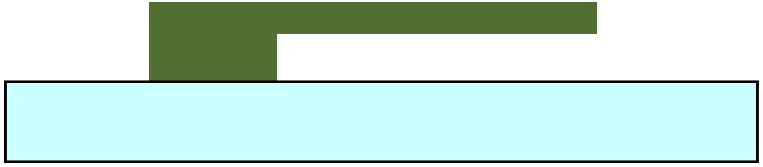
Etch using a mask

Boron doping using a mask

Flip and bond to a glass



Dissolve undoped silicon

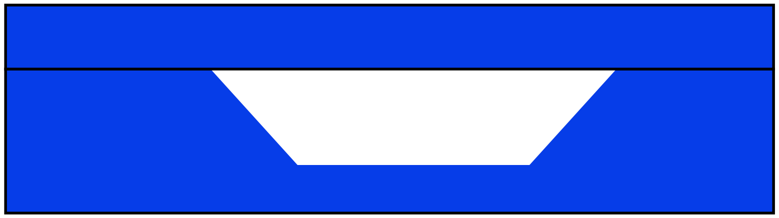


Boron doped dissolved wafer process (Michigan)

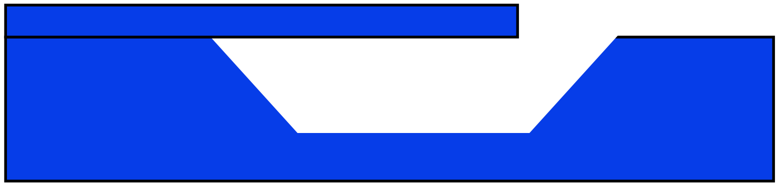
Wafer bonding

Etch a cavity in a wafer

Bond another wafer



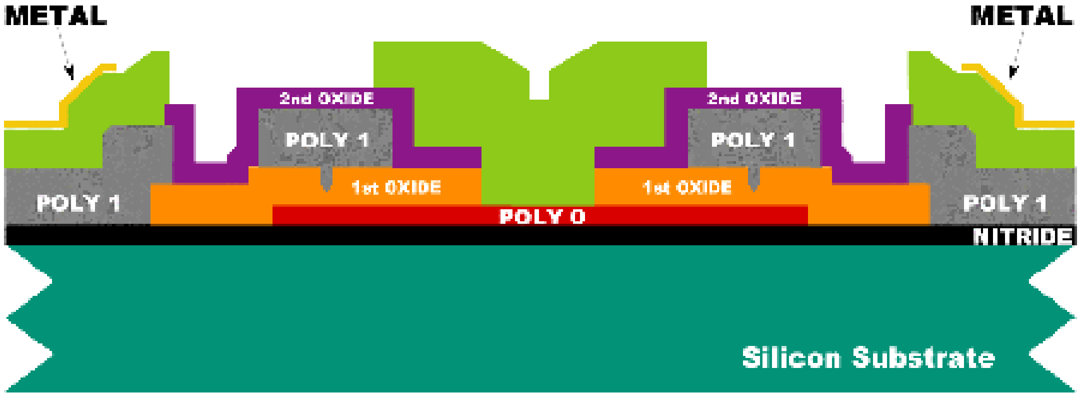
Thin down / polish and etch



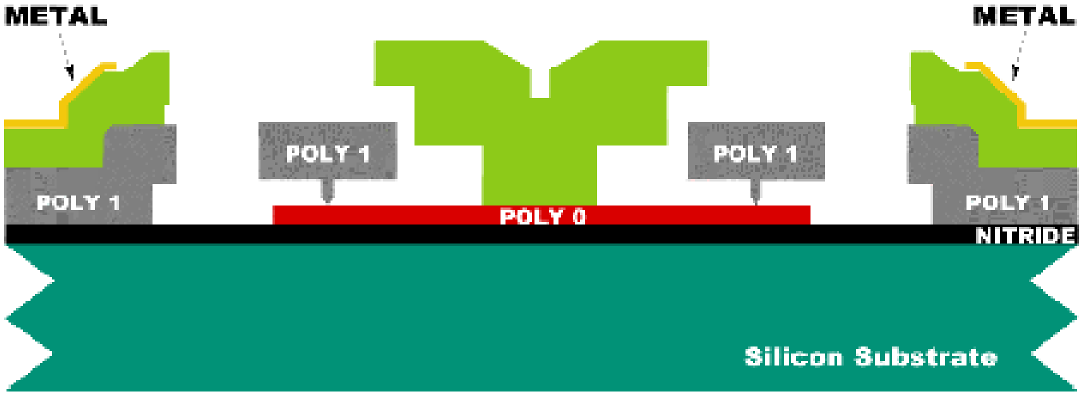
Released cantilever using MIT's wafer bonding process

Making an electrostatic micromotor using surface micromachining

Side view

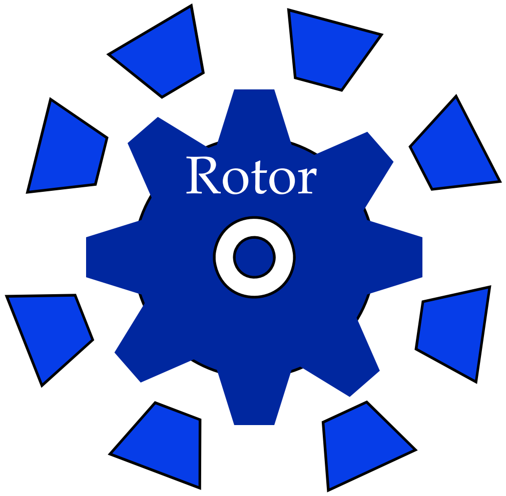


After sacrificing oxide layers…



Cronos MUMPs (formerly MCNC MUMPs)

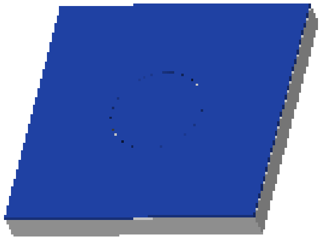
Top view



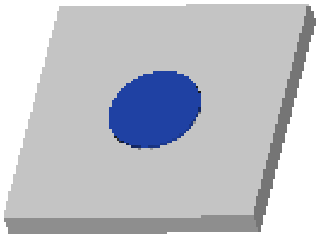
Stator poles

Making a micromotor

Deposit poly0

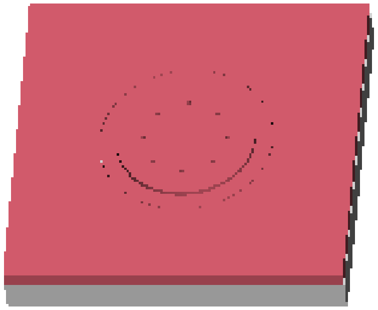


Etch poly0

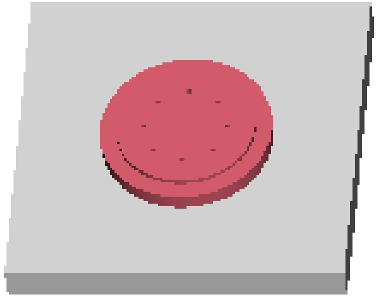


Deposit oxide1

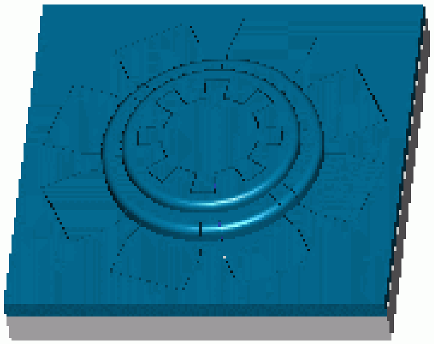
Dimples in oxide1



Etch oxide1

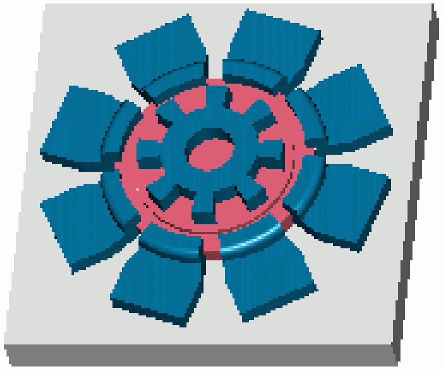


Deposit poly1

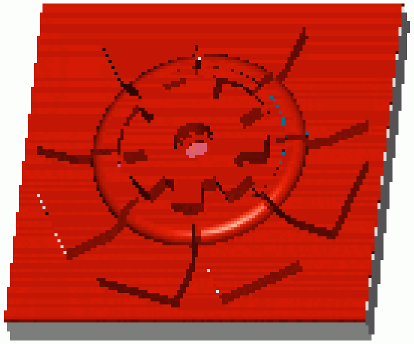


Making a micromotor (contd.)

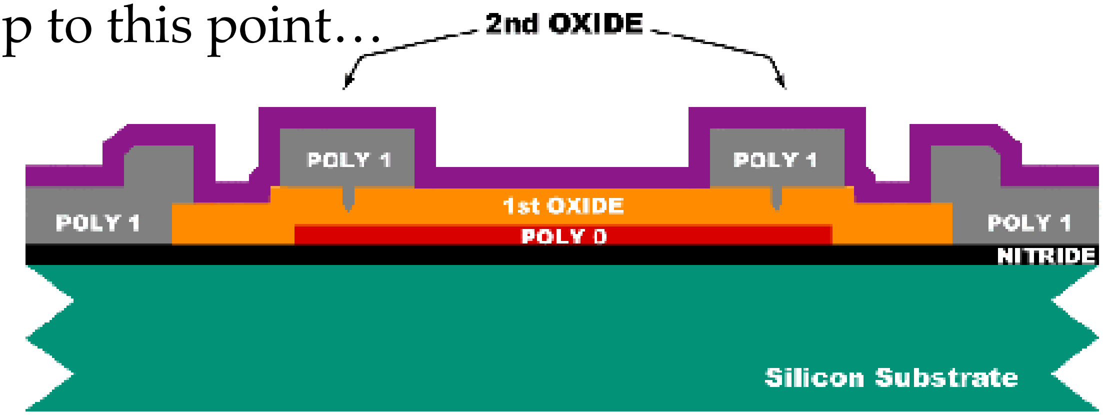
Etch poly1



Deposit oxide2



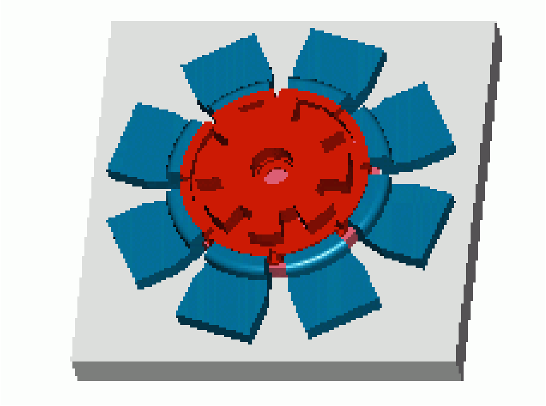
Cross-section up to this point…



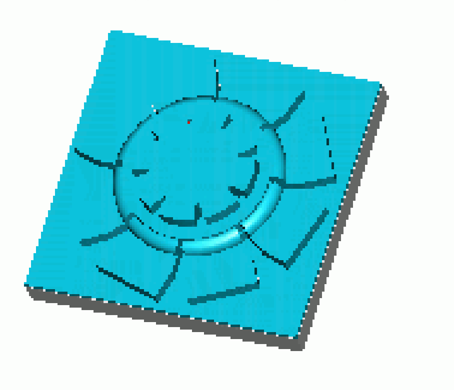
Cronos MUMPs (formerly MCNC MUMPs)

Making the micromotor (contd.)

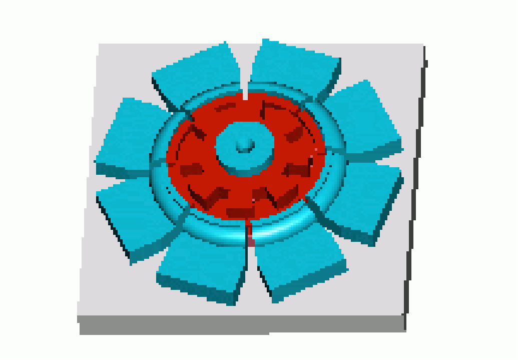
Etch oxide2



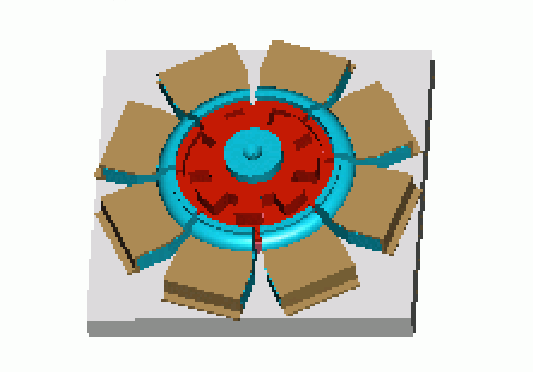
Deposit poly2

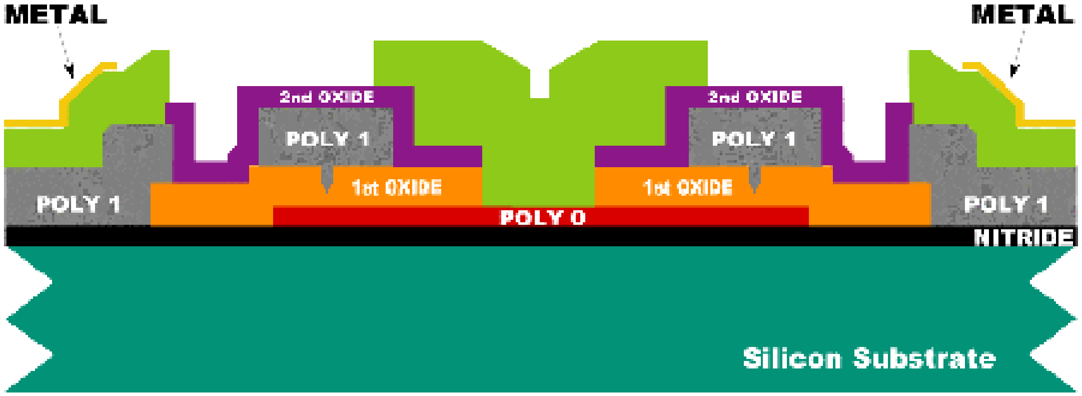


Etch poly2



Deposit and etch metal

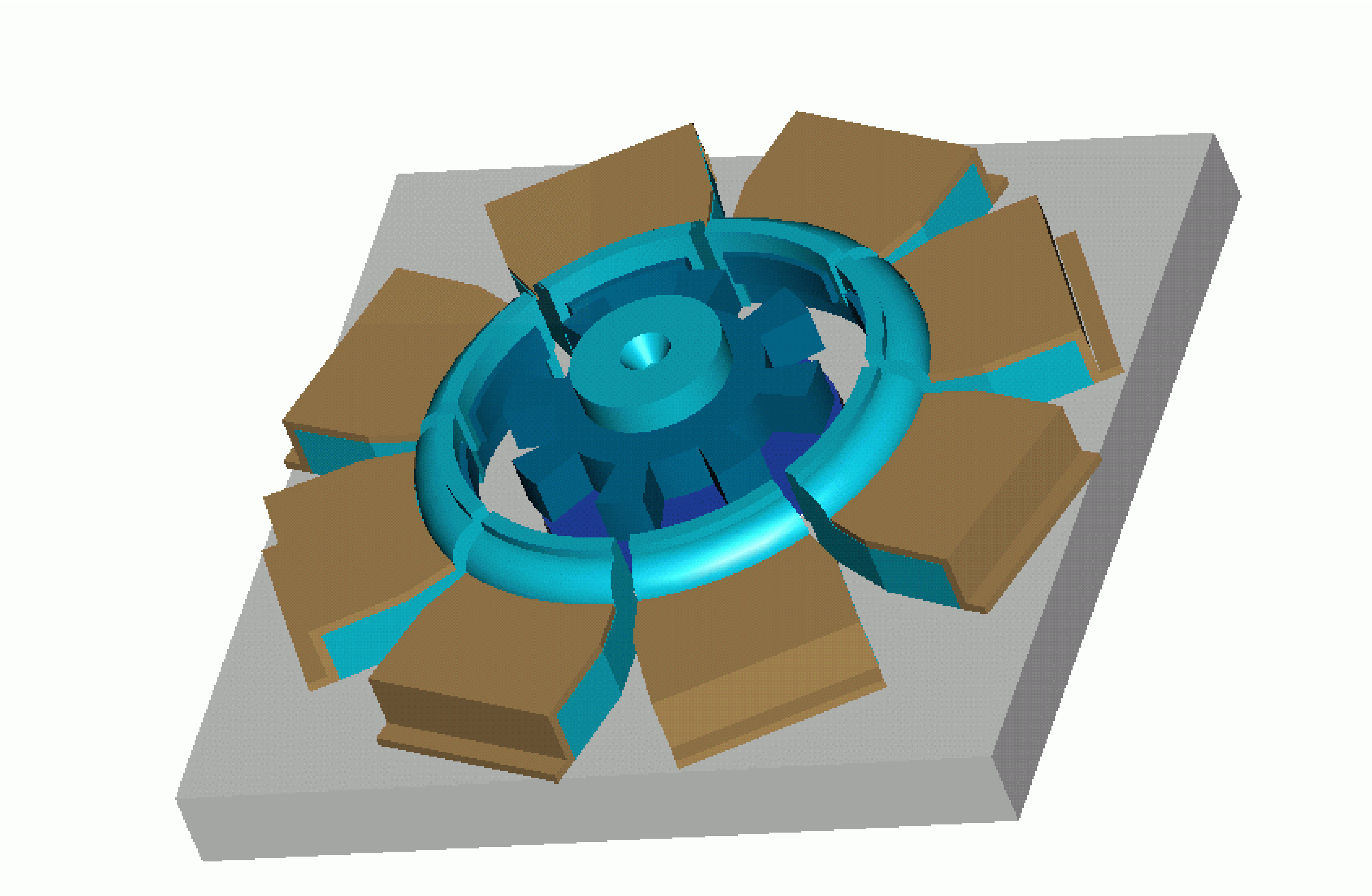




Cronos MUMPs (formerly MCNC MUMPs)

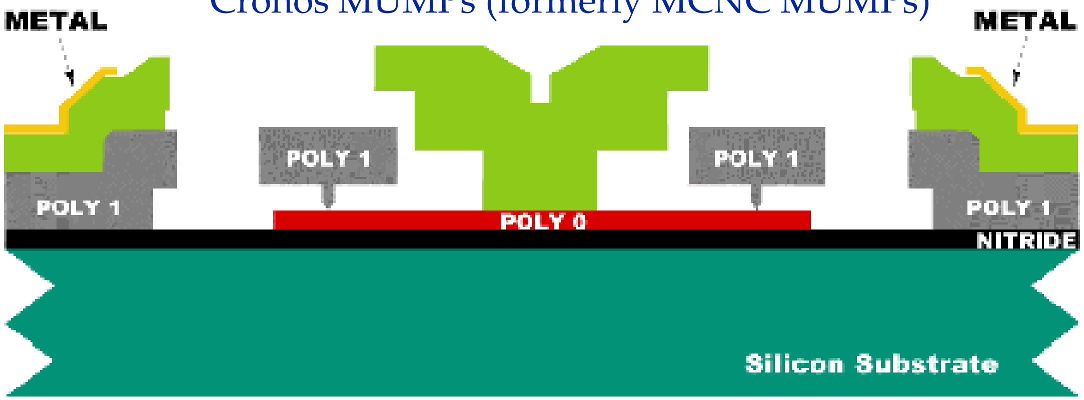
Cross-section before sacrificing oxide layers

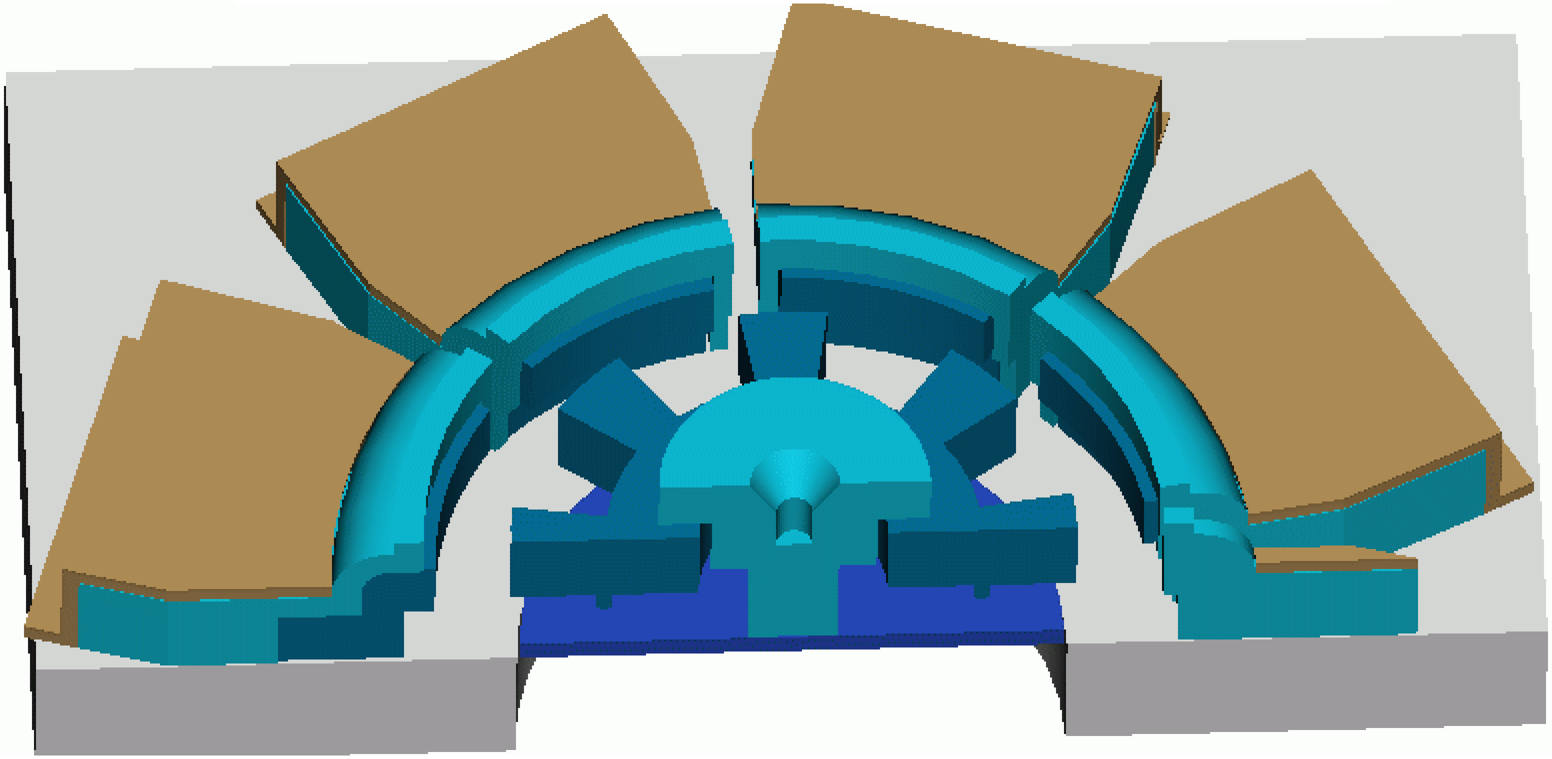
Finished micromotor



Micromotor after “release”

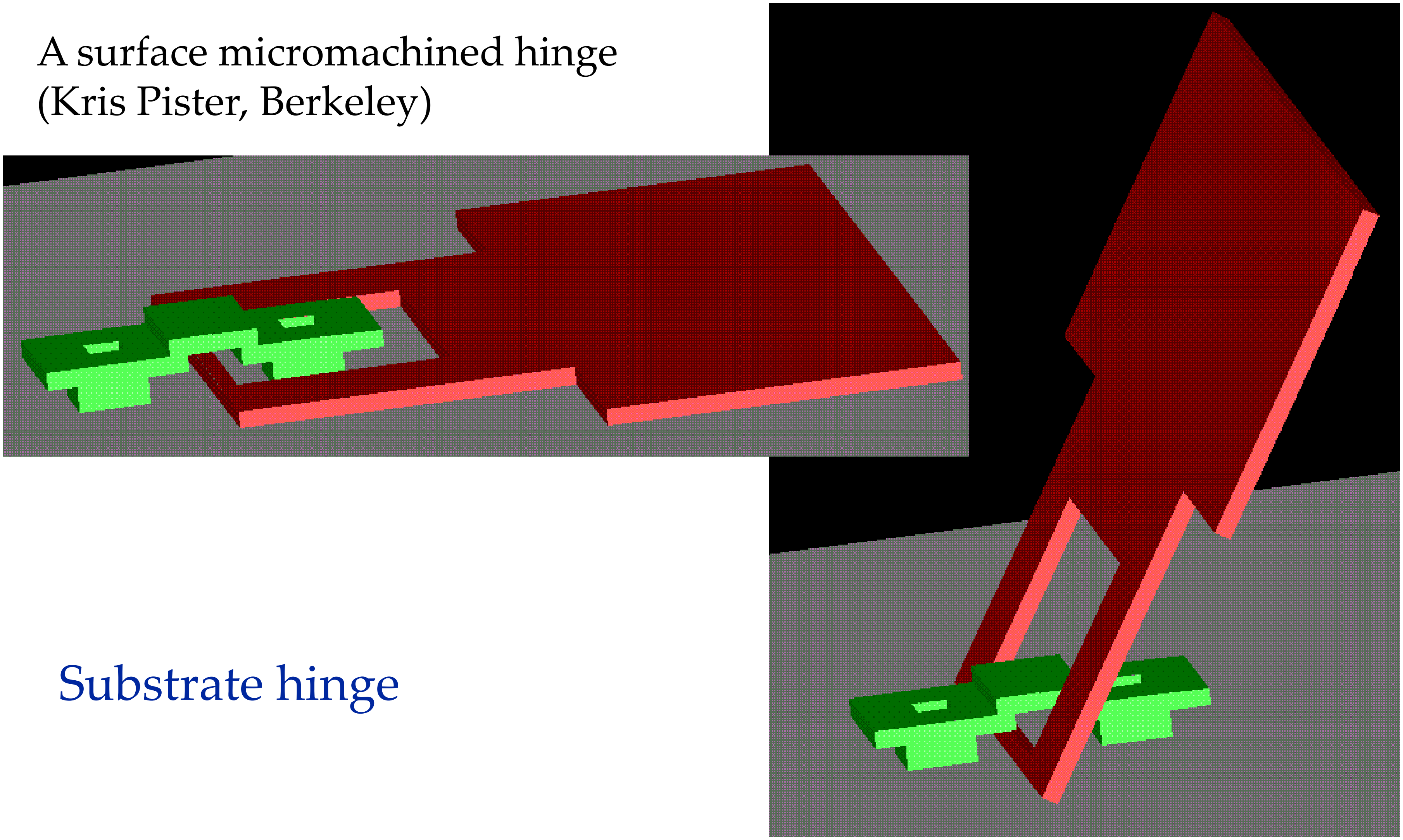
Cronos MUMPs (formerly MCNC MUMPs)





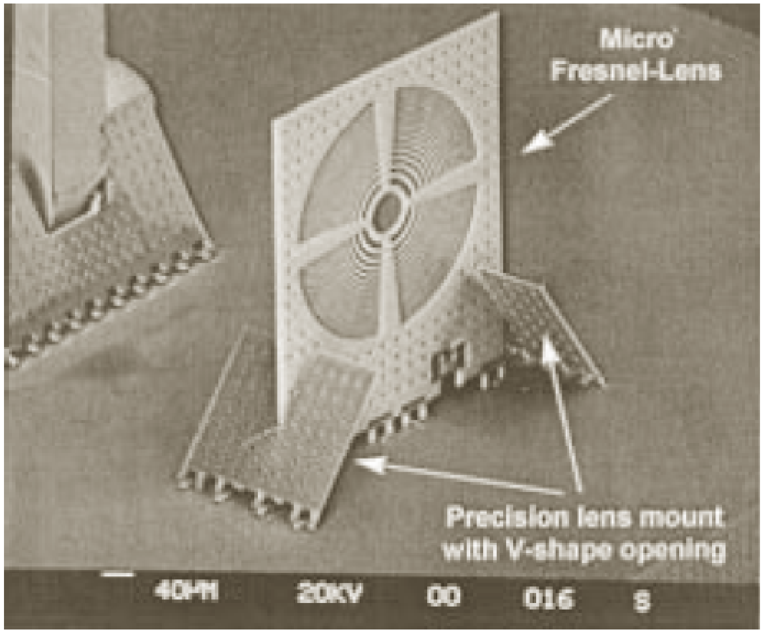
Out-of-plane hinges

A surface micromachined hinge
(Kris Pister, Berkeley)



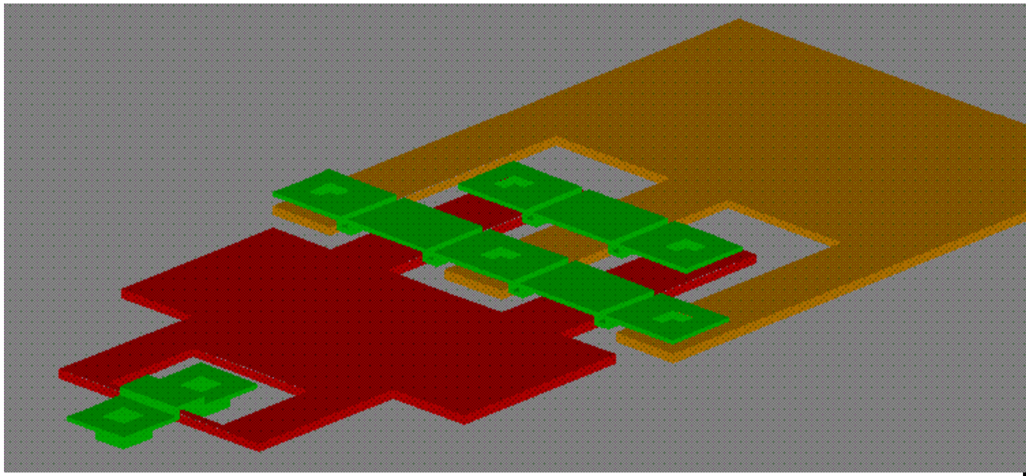
Substrate hinge

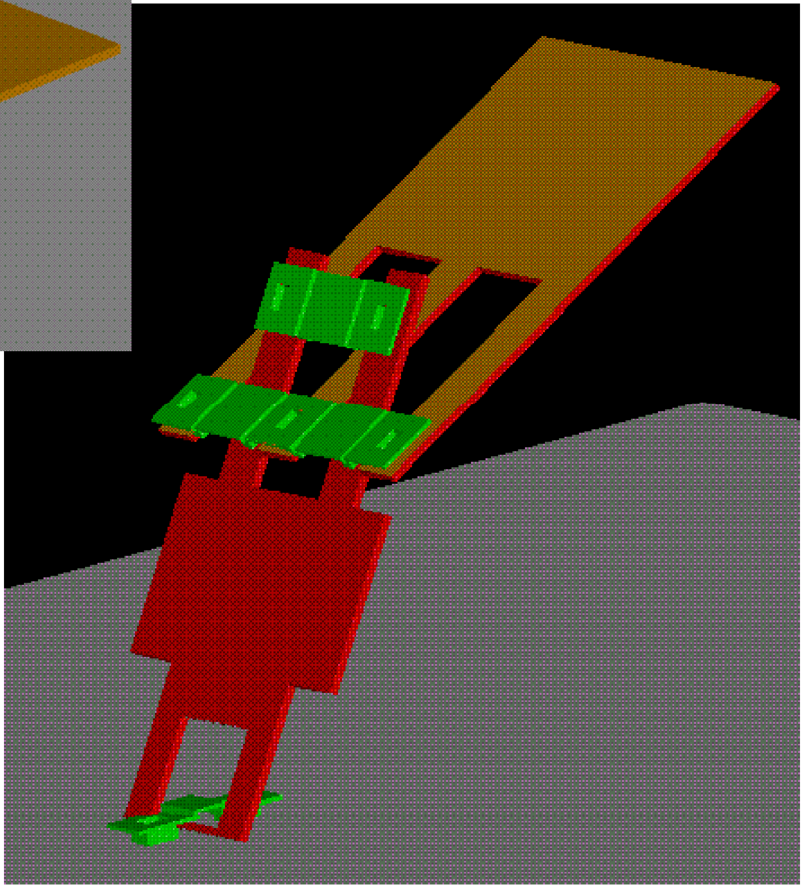
Optics on a chip



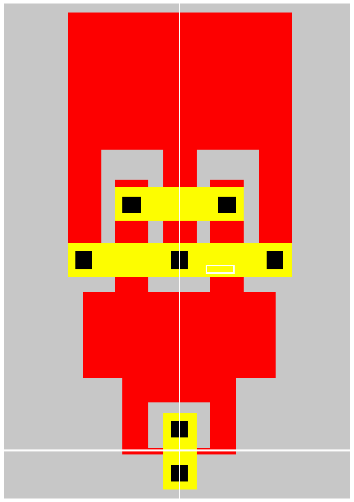
Lin et al., 1995; Proc. IEEE MEMS workshop.

Floating out-of-plane hinge



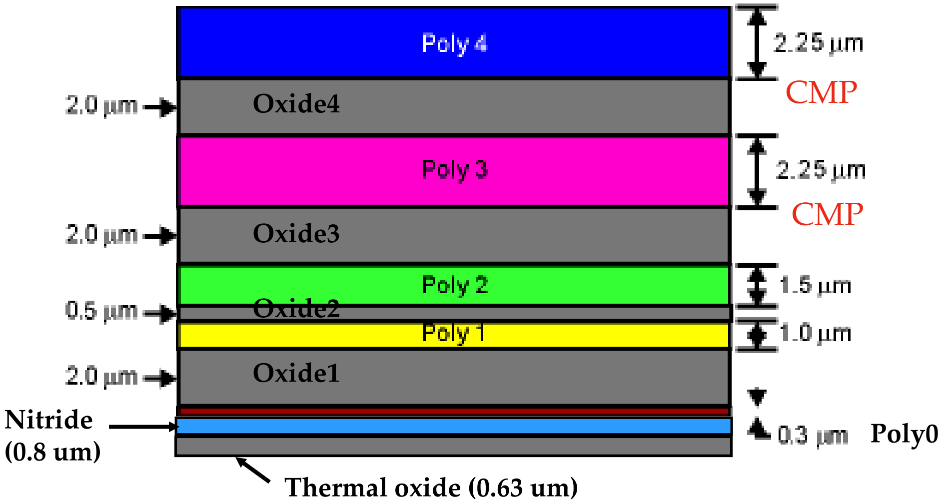


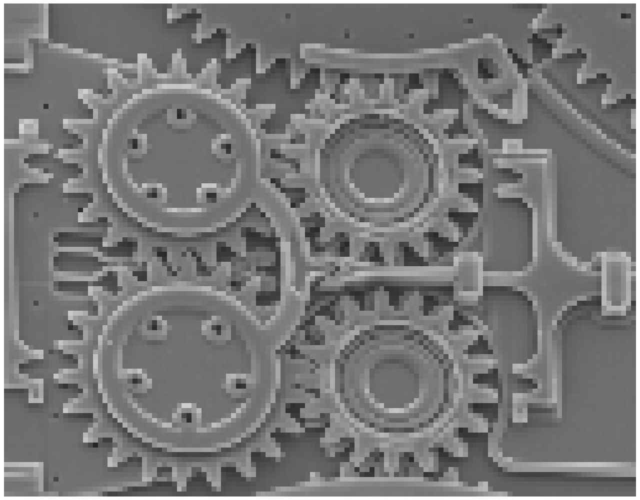
Mask layout



SUMMiT V

Sandia Ultra-planar Multi-layer Micromachining Technology

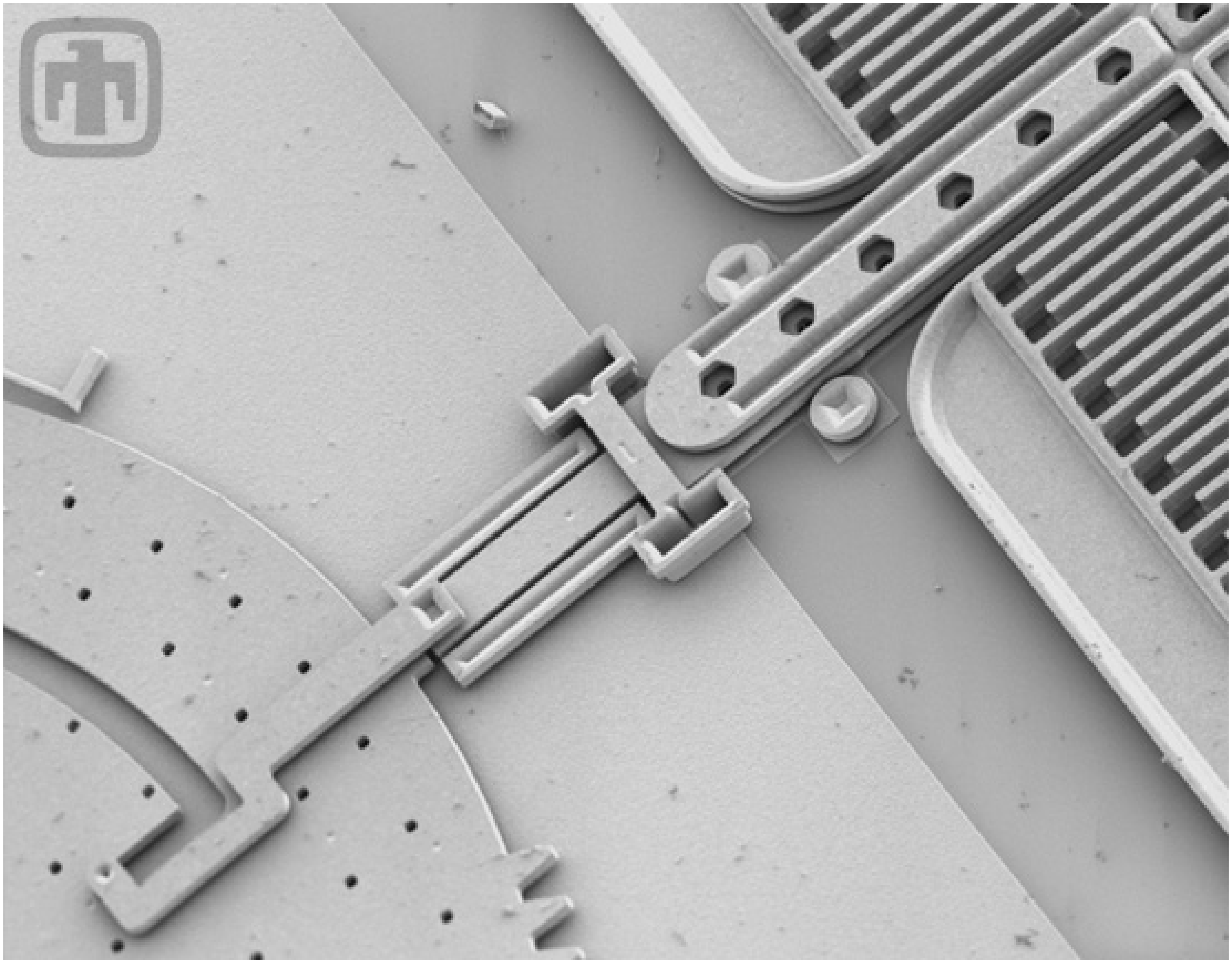




Figures: courtesy of Sandia National Laboratory

A gear train on a moving platform.

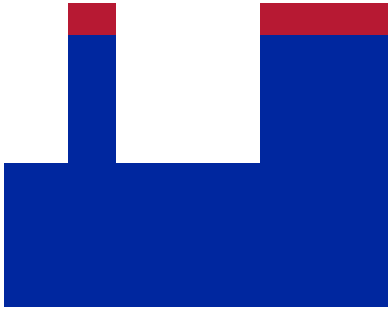
Close-up of Sandia's micro lock



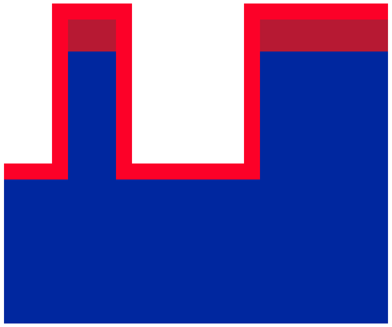
SCREAM process (MacDonald, Cornell)

Deposit and pattern mask oxide

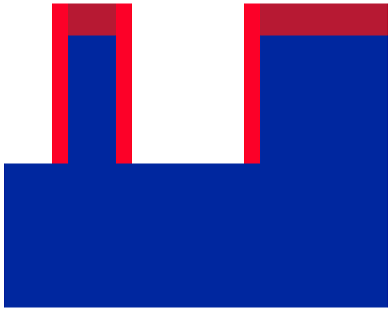
Deep RIE silicon etch



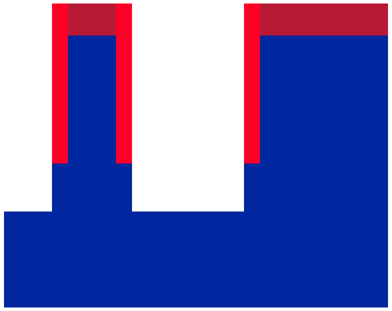
Deposit sidewall oxide



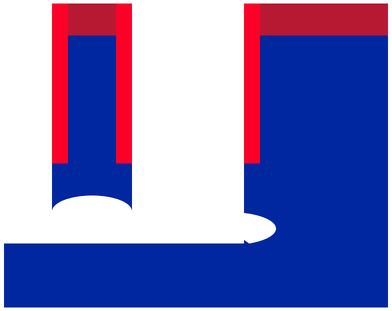
Etch bottom sidewall oxide



Second deep RIE silicon etch



Isotropic silicon etch

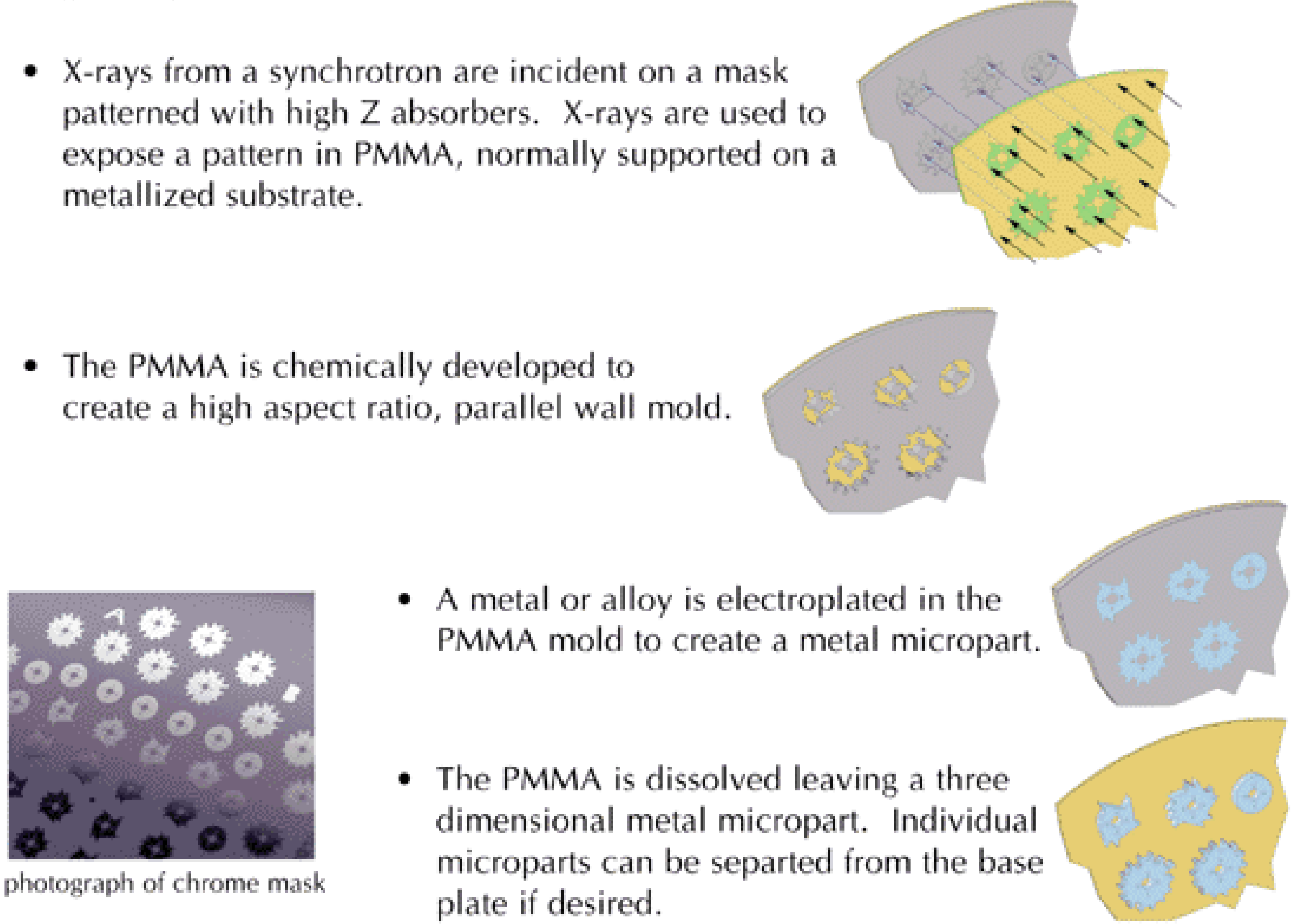


HARM processes

- **High Aspect Ratio Micromachining (HARM)**
  - Useful for most devices and essential for some
  - Good out-of-plane stiffness
- **LIGA**
- **HEXSIL**

LIGA

LIGA: German acronym for lithography, electroplating, and moulding
Developed by Karlsruhe Nuclear Research center in late 1980's.

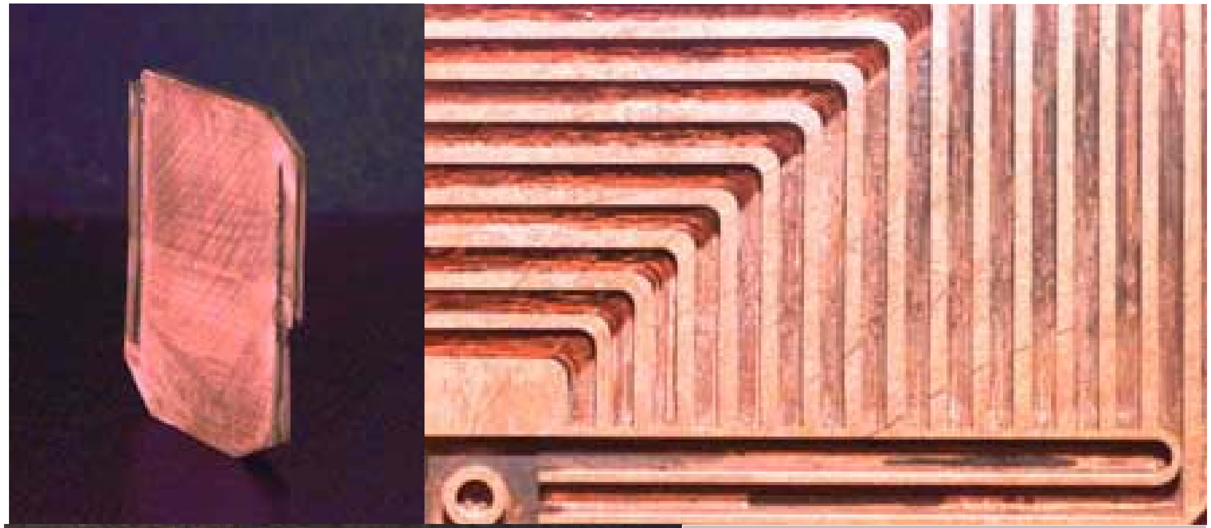


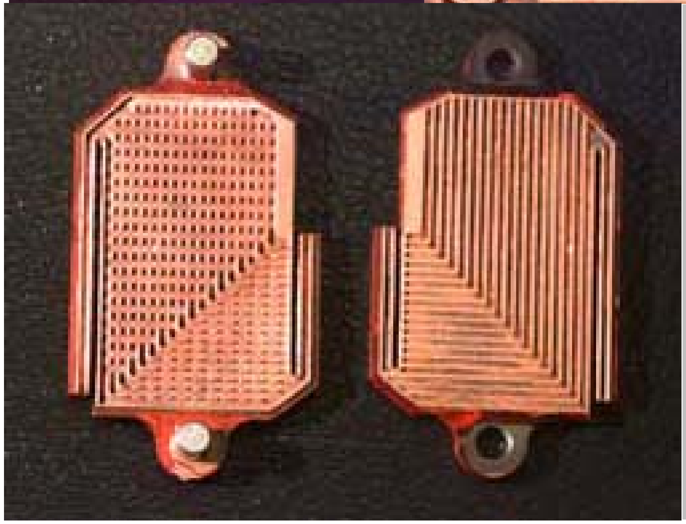
- X-rays from a synchrotron are incident on a mask patterned with high Z absorbers. X-rays are used to expose a pattern in PMMA, normally supported on a metallized substrate.
- The PMMA is chemically developed to create a high aspect ratio, parallel wall mold.
- A metal or alloy is electroplated in the PMMA mold to create a metal micropart.
- The PMMA is dissolved leaving a three dimensional metal micropart. Individual microparts can be separted from the base plate if desired.

photograph of chrome mask

Figure: courtesy of Sandia National Laboratory

Sandia's LIGA product

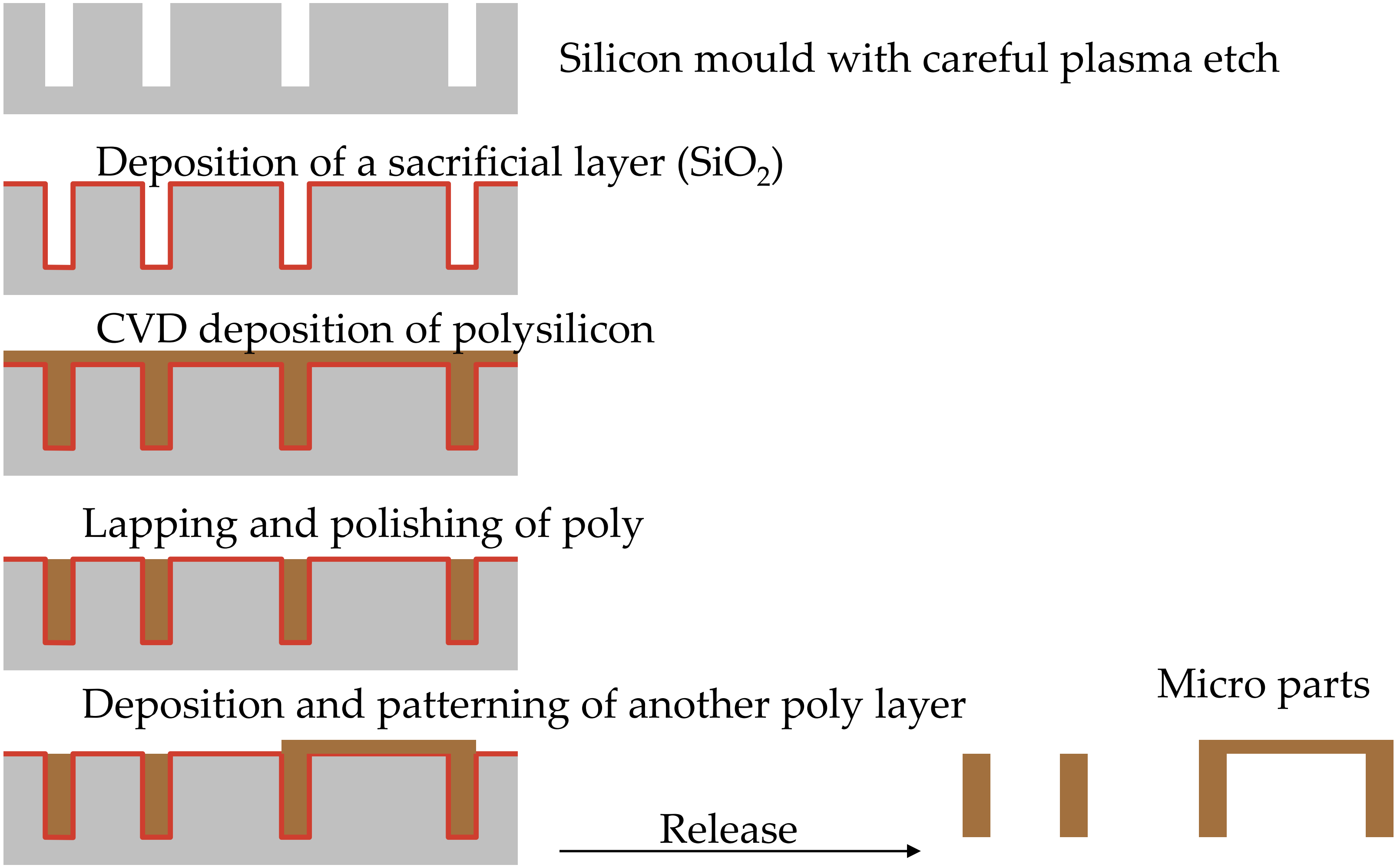




A heat exchanger that had overall dimensions of 1.7 x 2.3 inches designed by Lockheed Martin Missles and Space. The feature sizes were as small as 23µm and the finished product was vacuum tight.

HEXSIL

A polysilcion template-based moulding process (Keller and Ferrari, 1994)



Silicon mould with careful plasma etch

Deposition of a sacrificial layer (SiO_2)

CVD deposition of polysilicon

Lapping and polishing of poly

Deposition and patterning of another poly layer

Release

Micro parts

G.K. Ananthasuresh, Indian Institute of Science, Aug. 2014

How much should we know about u-fab?

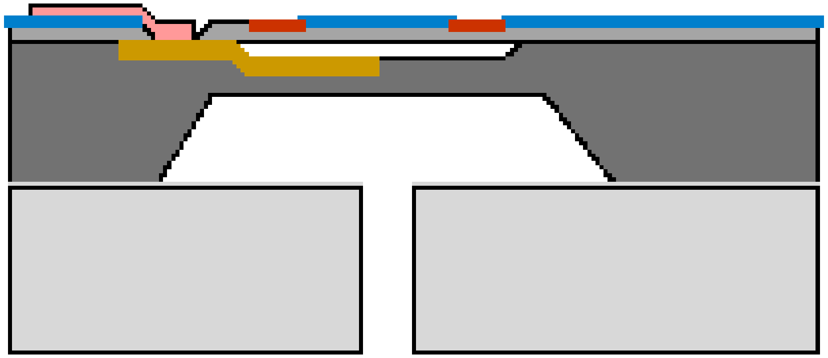
Being able to draw the process flow diagrams from a description.

Visualizing a process from a cross-section.

Visualize device
from a verbal description of the process

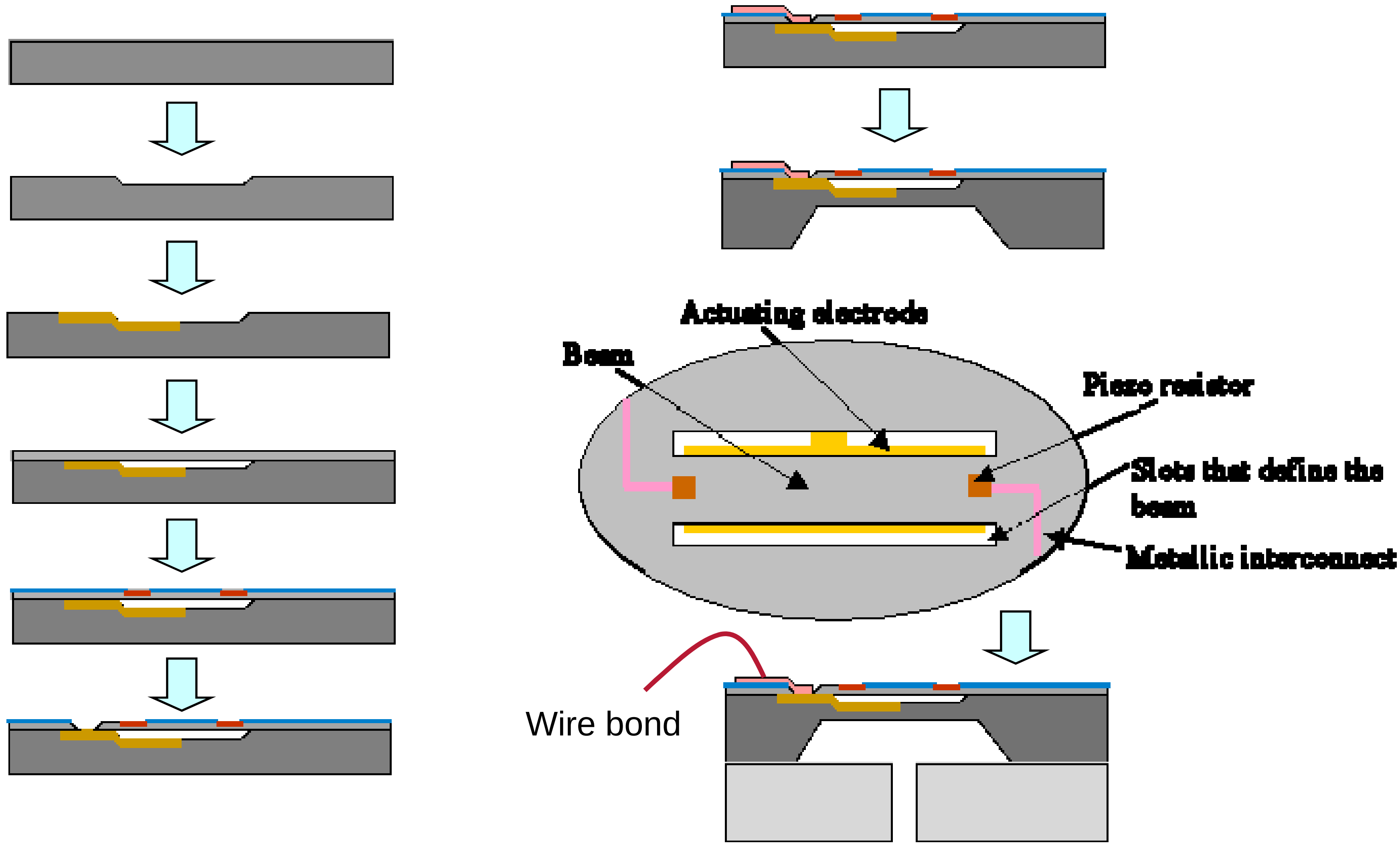
Being able to draw the process flow diagrams from a description.

Shallow pits were etched into n-type substrates, and p-type deflection electrodes were diffused in the above pits, followed by fusion bonding of a second wafer above the first. The top wafer was then ground and polished down to a thickness of 6 um. A passivation layer was then formed on the top wafer and sensing piezoesistors were formed using ion implantation, after which contact holes for metallization to connect to the diffused deflection electrodes were etched. Bond pads and interconnect metallization were then deposited and patterned, followed by etching of the diaphragm from the back of the wafer. Finally, two slots were etched next to the beam to release it over the buried cavity.



(Petersen et al., 1991)

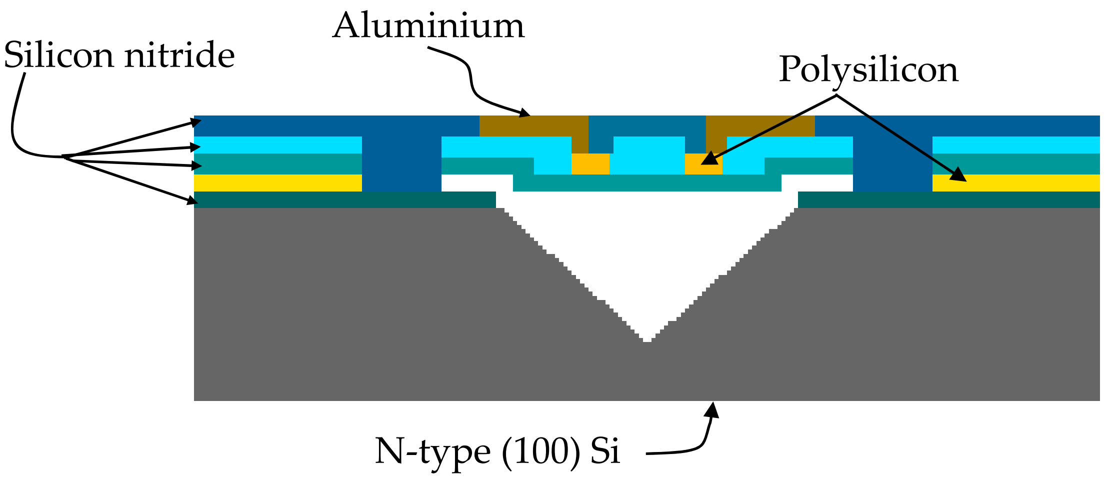
Process flow



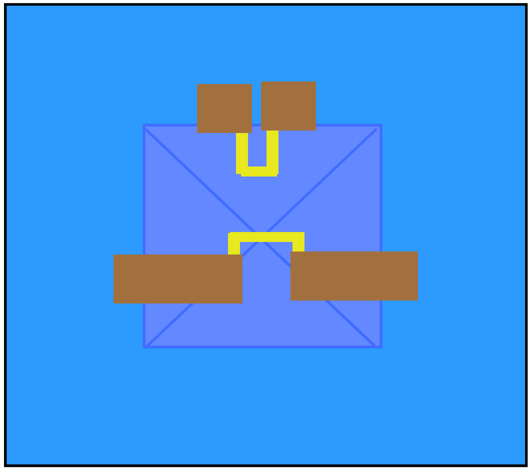
"Verbalize" the process steps from a device cross section

"Verbalizing" a process from a cross-section and then visualizing it geometrically.

A micro-diaphragm pressure sensor (Sugiyama et al., 1986)



Top view



What process was used to make this?

(IEEE Int. Electron Devices Meeting, 1986, pp. 184-187)

Visualizing a process flow

Deposit a nitride layer using LPCVD

Etch the nitride layer to leave a square window

Deposit polysilicon using LPCVD

Deposit a thick nitride layer

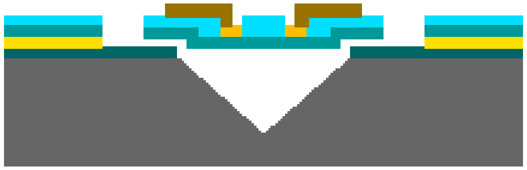
Deposit polysilicon piezoresistors

Deposit another nitride layer

Etch nitride layers

Etch polysilicon and silicon using KOH

Deposit Al using vacuum evaporation and pattern

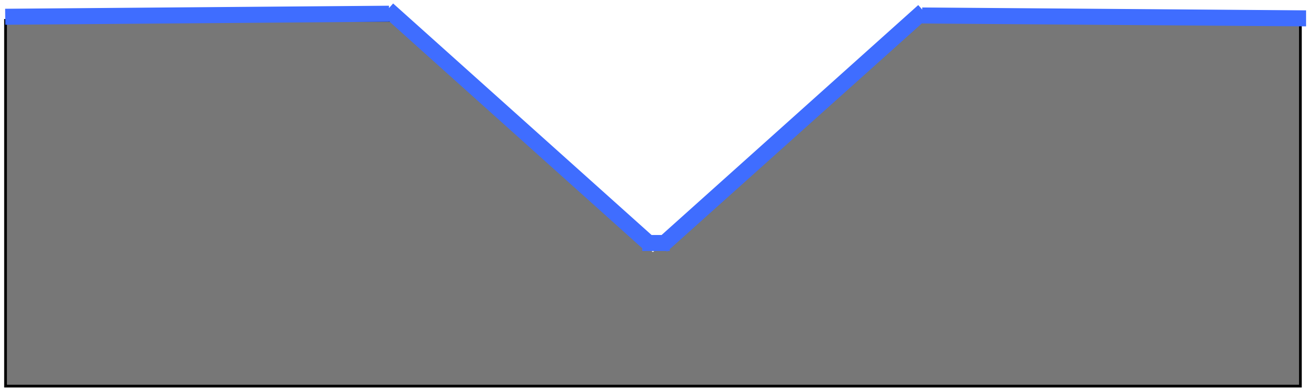


Seal using a nitride layer using plasma CVD

G.K. Ananthasuresh, Indian Institute of Science, Aug. 2014

Order of the process steps is important!

We should not etch the pyramidal pit first.
This is because the subsequent layers conform to the pit's surface and it will not be possible to get a membrane.



Other ("unconventional") processes

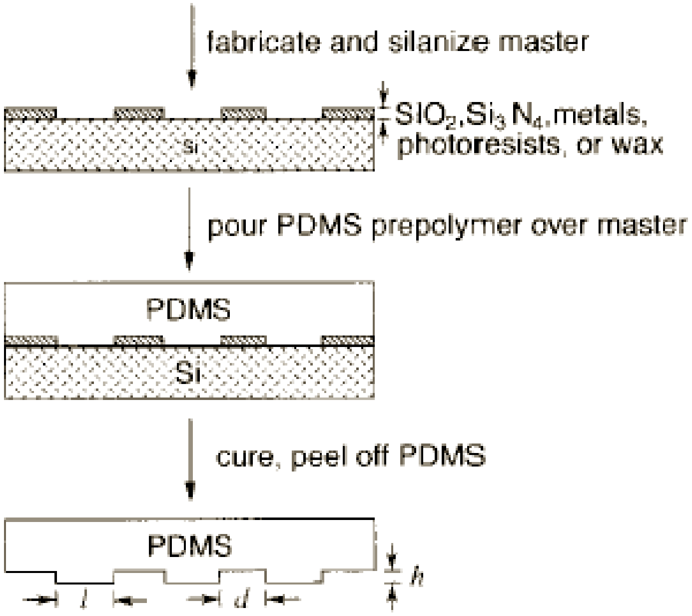
- Soft-lithography (embossing)
- Precision machining
- Micro-EDM (electro-discharge machining)
- Abrasive cutting
- Laser micromachining
- Ion milling, focused ion beam (FIB) milling
- Micro stereo lithography
- Ink-jet type deposition
- FIB deposition
- Laser-assisted CVD
- Hot embossing
- Etc.

Soft lithography

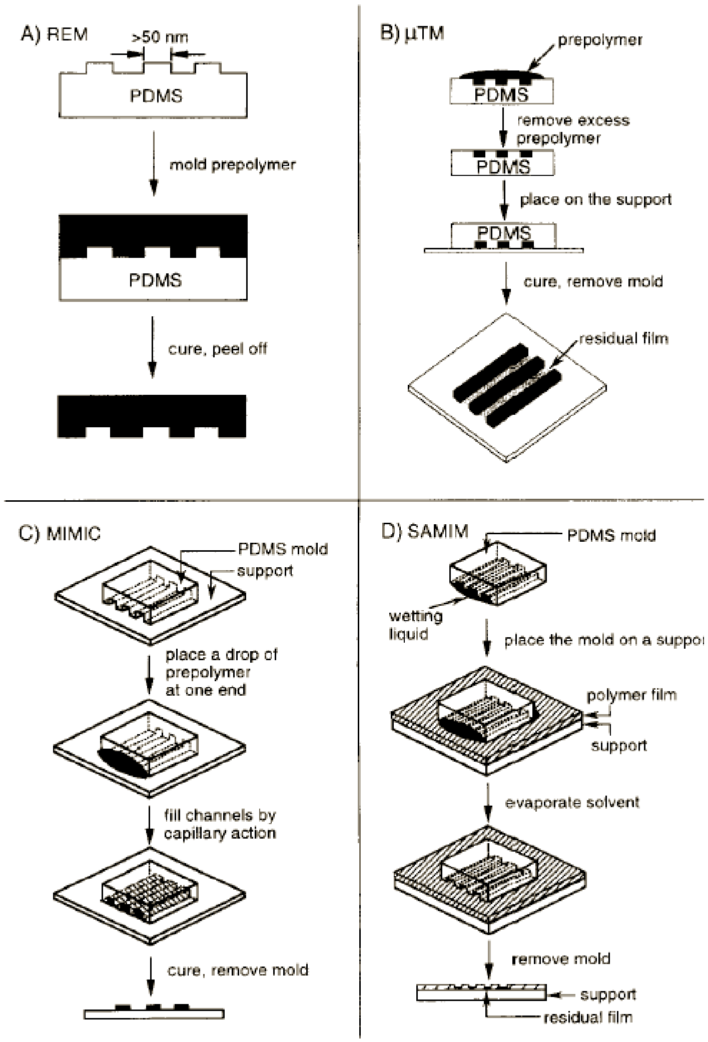
A new high-resolution lithography using an elastomeric stamping mould.

George Whitesides, Harvard

PDMS
Polydemethylsiloxane

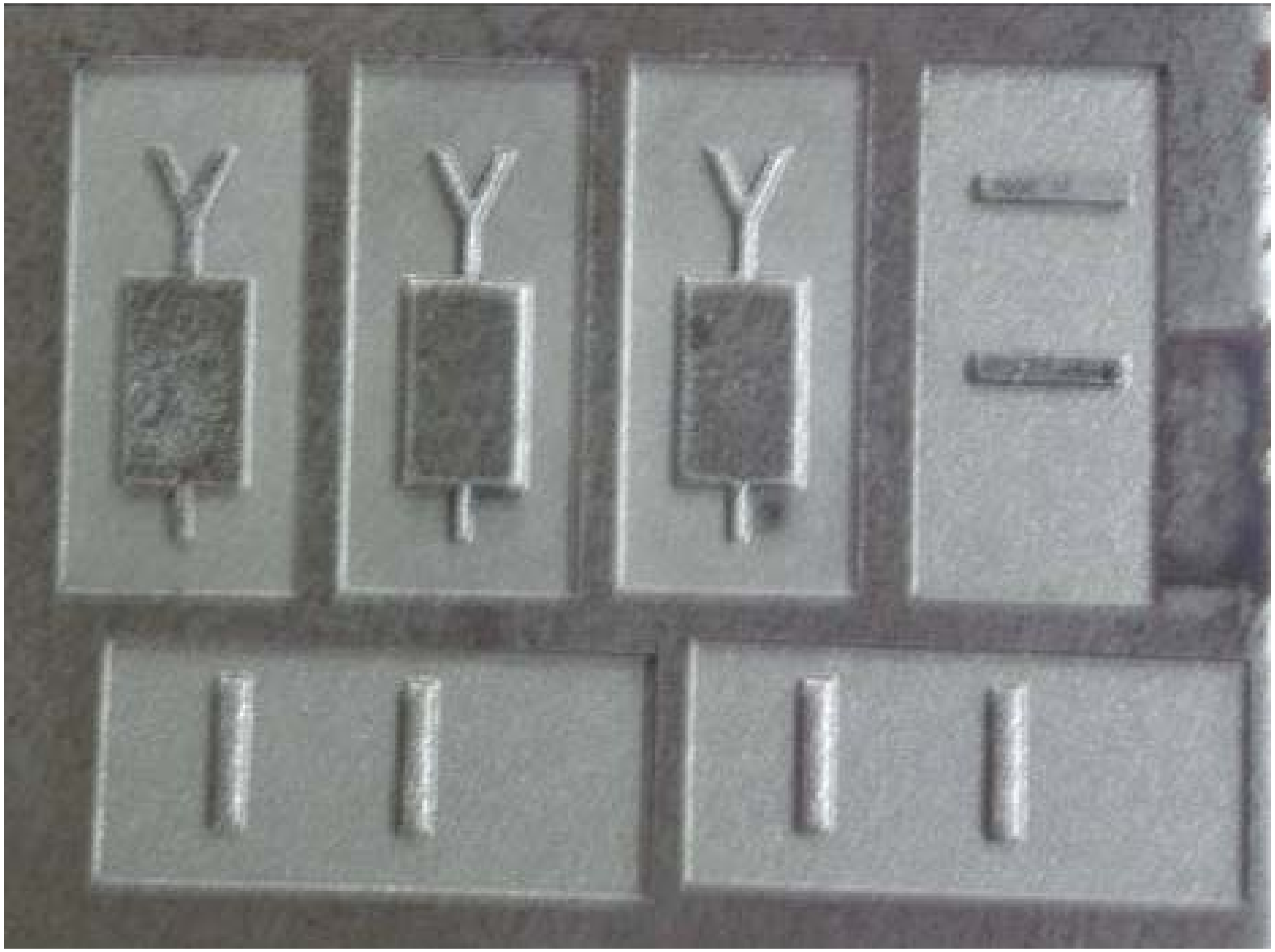


Making the PDMS mould



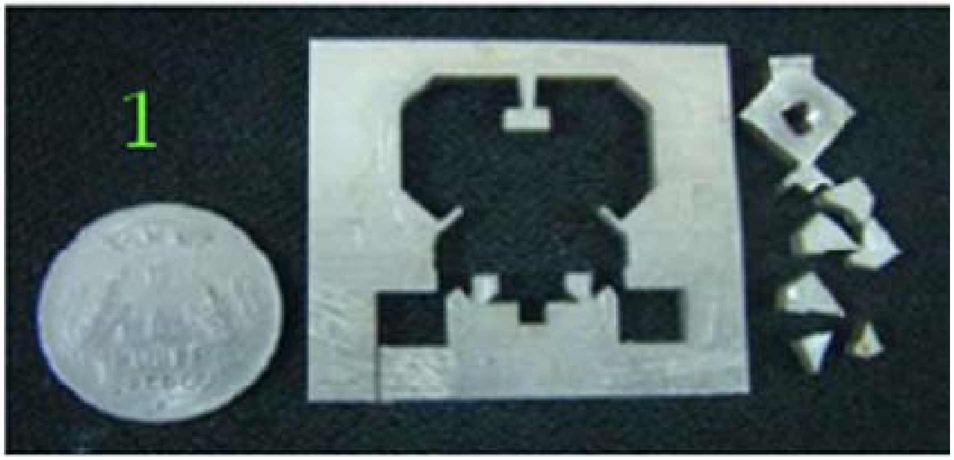
G.K. Ananthasuresh, Indian Institute of Science, Aug. 2014

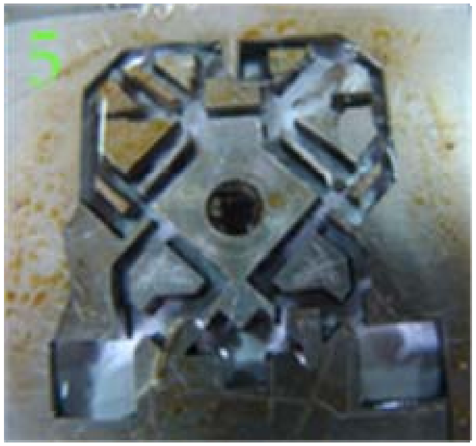
A metal mould for PDMS vacuum casting



Work in progress, Ravi Kumar in M2D2 Lab, IISc, for Raman Research Institute.

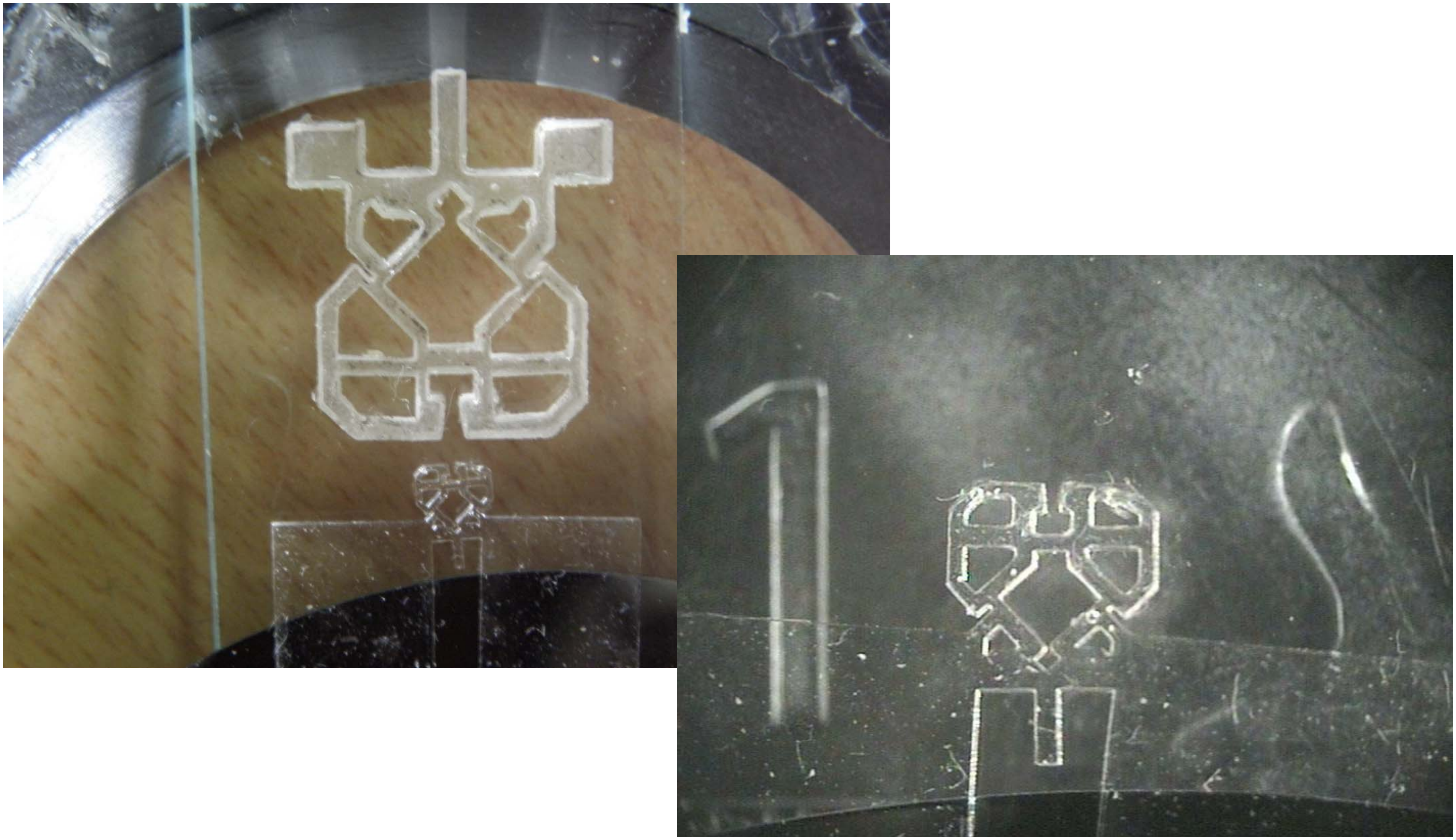
Vacuum-casting of PDMS miniature grippers





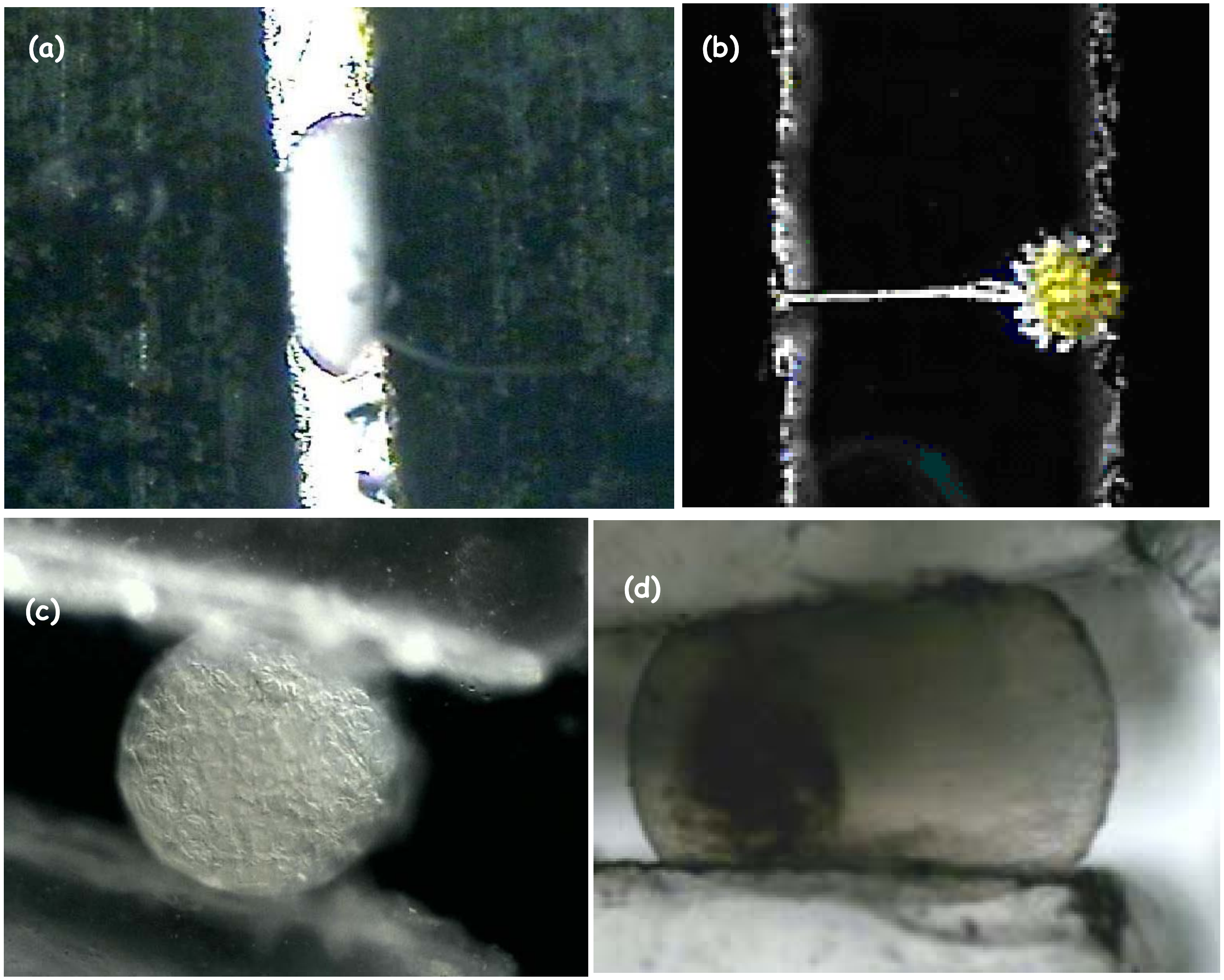
Sahu, M2D2 Lab, IISc.

Smaller and smaller grippers…



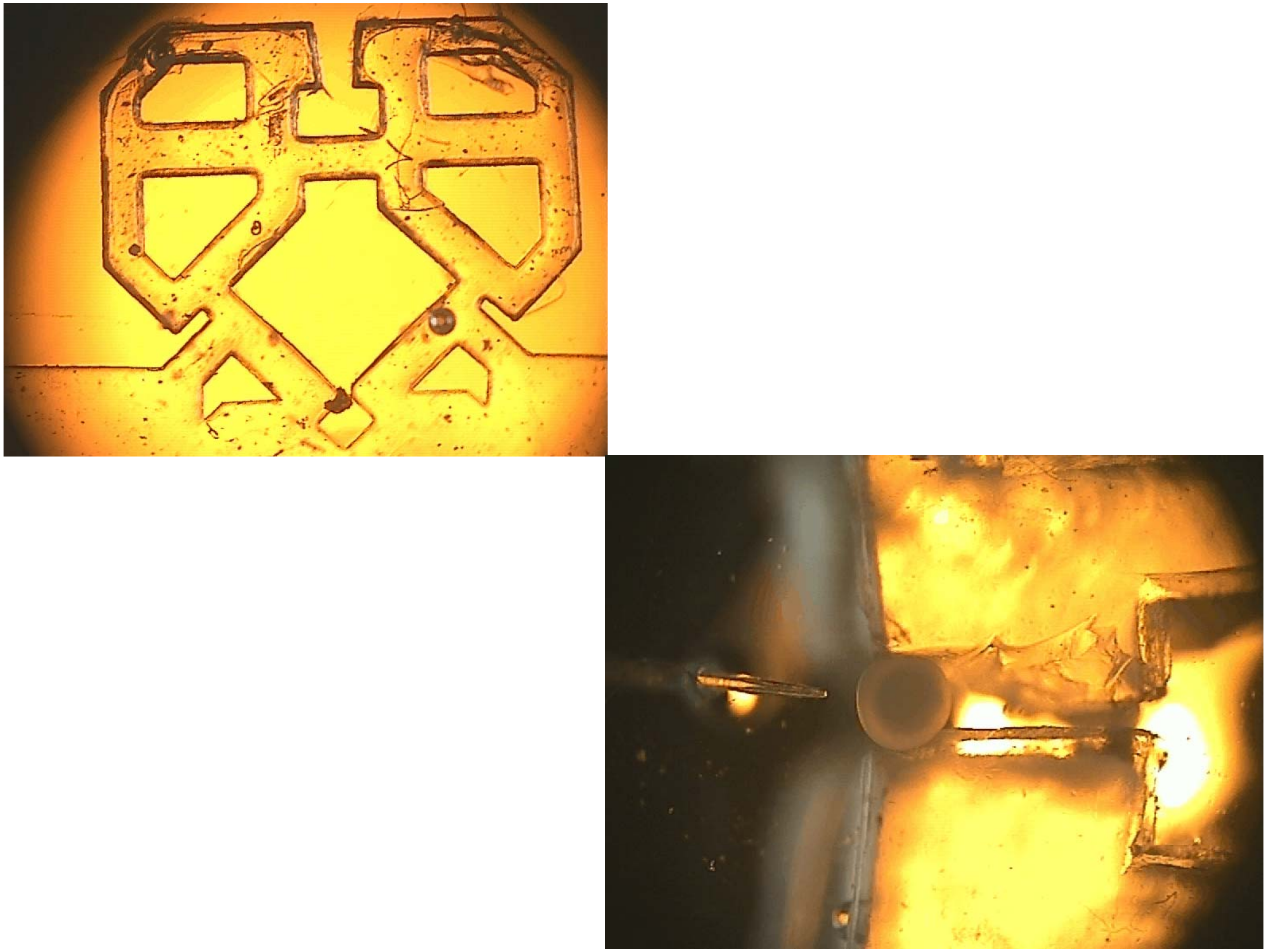
Ramu, M2D2 Lab, IISc.

Bio-manipulation in the M2 lab



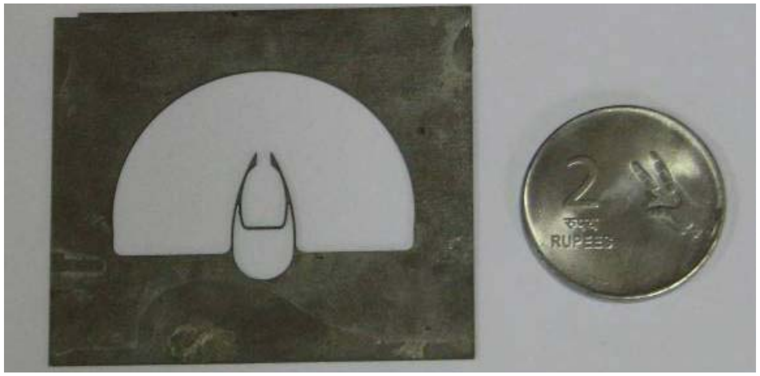
Sahu and Maheswari, M2D2 Lab, IISc.

Cell-injection with miniature grippers



Ramu, Bhargav, and Chakravarthy, M2D2 Lab, IISc.

Wire-cut Electro Discharge Machining



Ravi Kumar, M2D2 Lab, IISc.

Punching and blanking

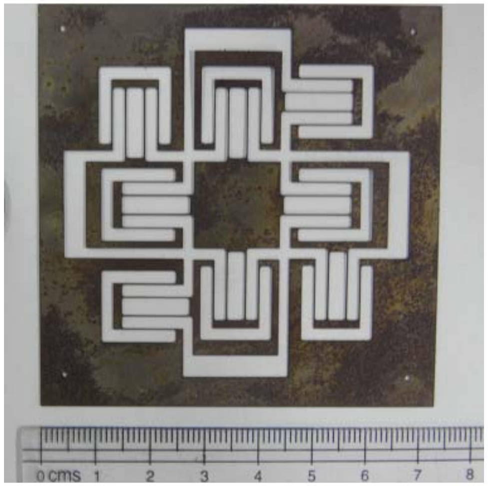
Card-board

Plastic film

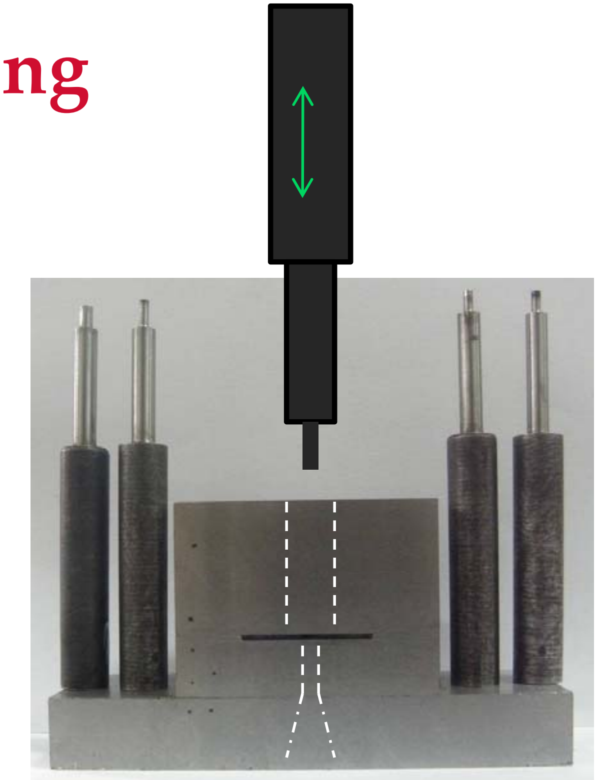
Aluminium foil

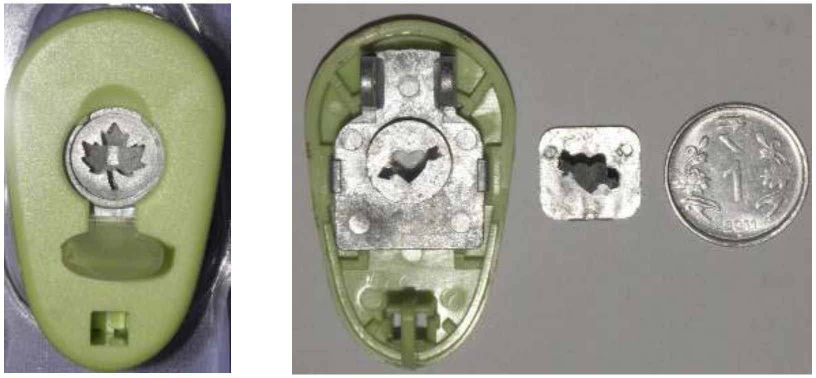
Ravi Kumar, M2D2 Lab, IISc.

A spring-steel gripper by punching



Manufacturing of a Meso-scale Dual-axis Accelerometer

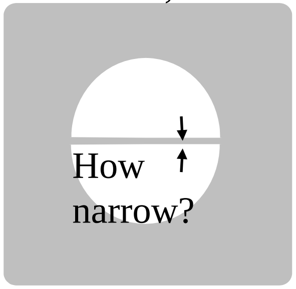




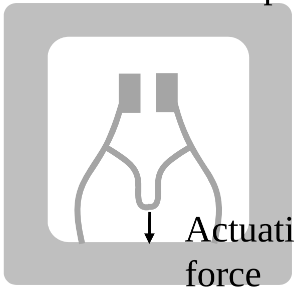
Craft punches

Al foil, 0.025 mm thick

Paper, 0.150 mm thick



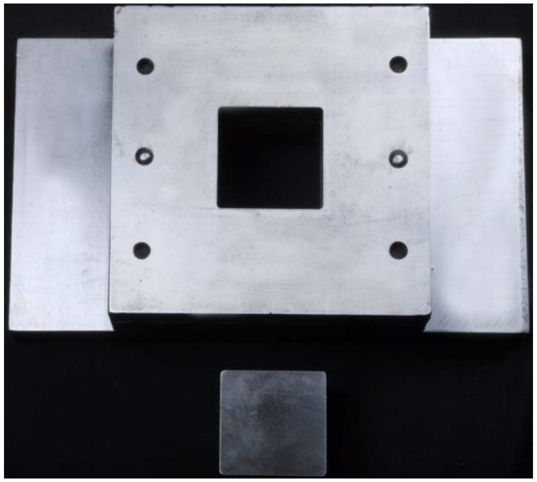
How narrow?



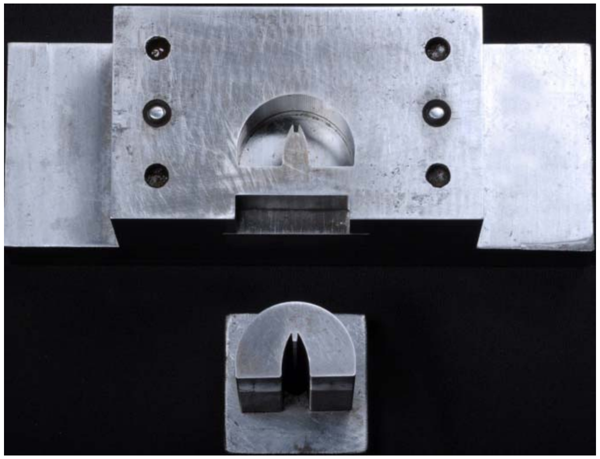
Actuation force

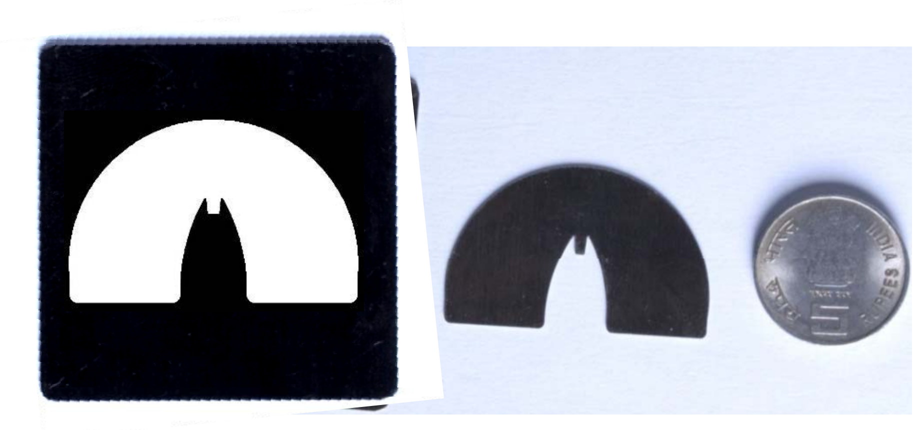
Fabrication details

- Workpiece material is Ssring steel sheet of 0.5 mm thickness
- Dies are made of oil-hardened nitride steel (OHNS)

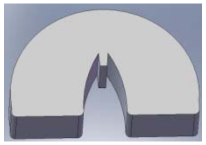


First stage

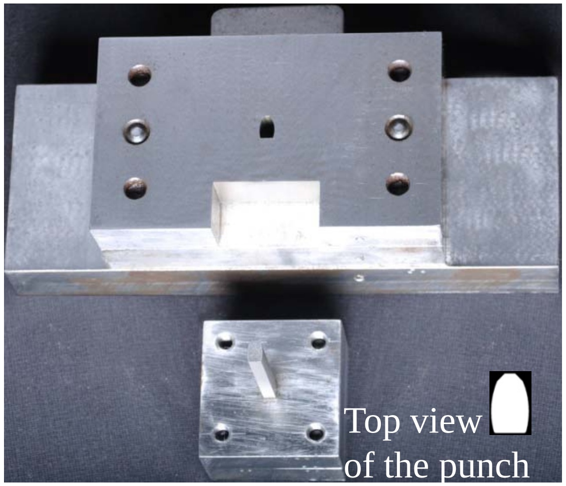




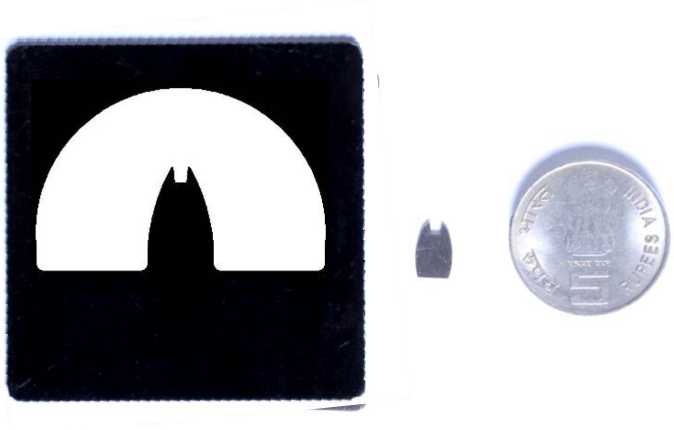
Second stage



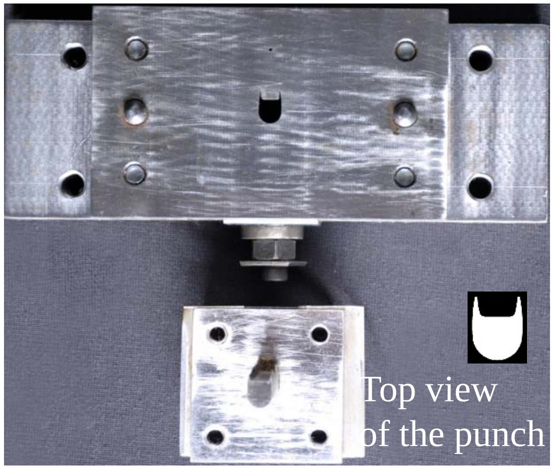
Top view of the punch



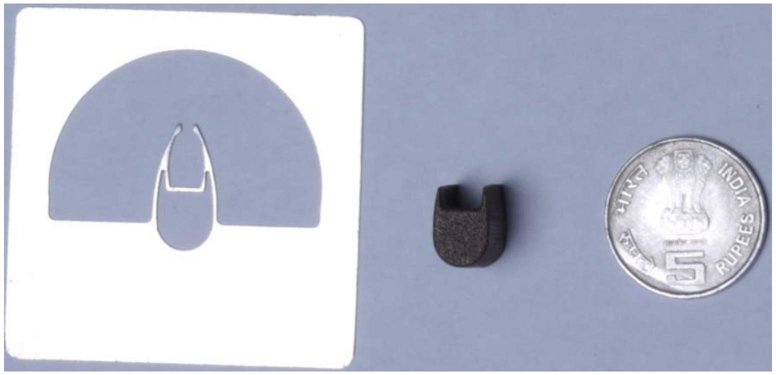
Top view of the punch



Third stage



Top view of the punch



Fourth stage on spark erosion

More questions

- ✓ What are they?
- ✓ How small are they?
- ✓ How are they useful
- ✓ How do they work?
- ✓ What are they made of?
- ✓ How are they made?
- ✓ How are they modeled and simulated?
- ✓ How are they designed?

ME 237/NE 211 will try to answer these questions.