

Microelectromechanical Systems (MEMS)

An introduction

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Outline

- **Introduction**
 - **Applications**
 - *Passive structures*
 - *Sensors*
 - *Actuators*
 - **Future Applications**
 - **MEMS micromachining technology**
 - *Bulk micromachining*
 - *Surface micromachining*
 - *LIGA*
 - *Wafer bonding*
 - **Thin film MEMS**
 - *Motivation*
 - *Microresonators*
 - **MEMS resources**
 - **Conclusions**
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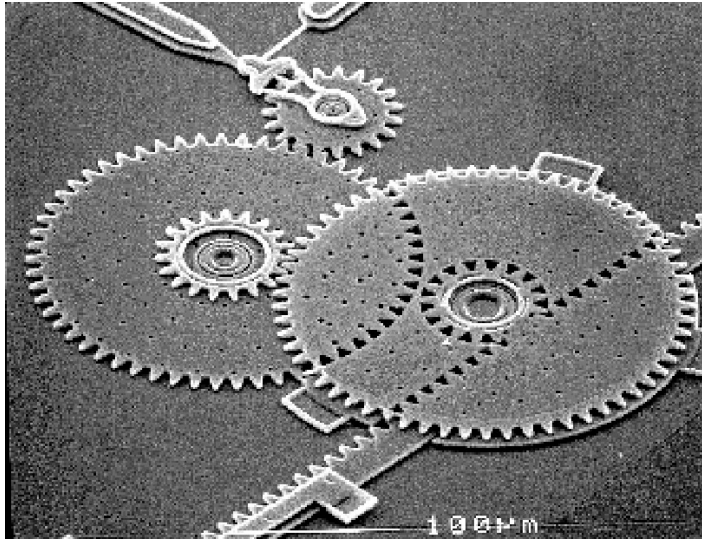
What are MEMS?

(Micro-electromechanical Systems)

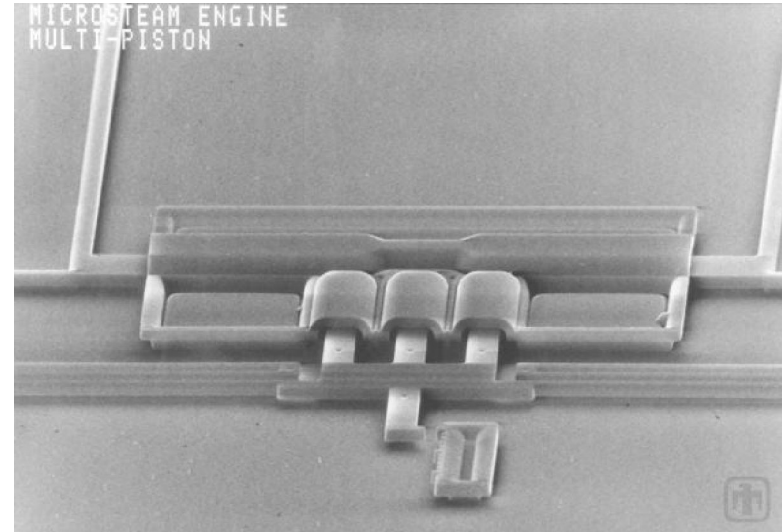
- Fabricated using micromachining technology
- Used for sensing, actuation or are passive micro-structures
- Usually integrated with electronic circuitry for control and/or information processing



3-D Micromachined Structures



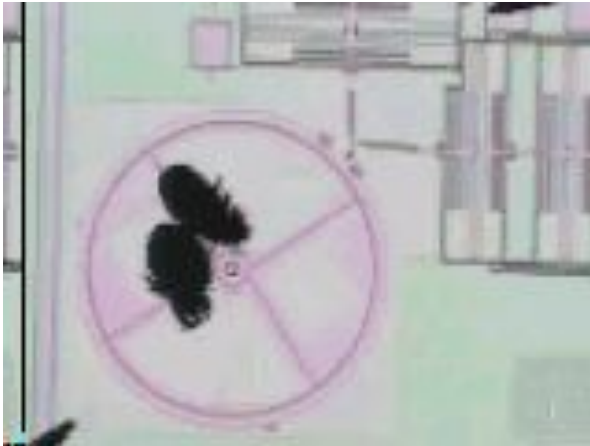
Linear Rack Gear Reduction Drive



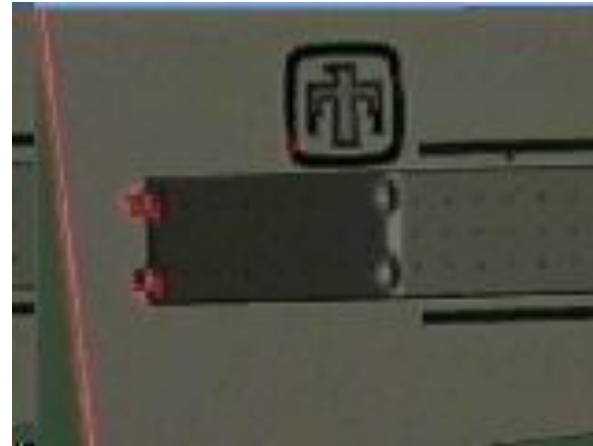
Triple-Piston Microsteam Engine

Photos from Sandia National Lab. Website: <http://mems.sandia.gov>

3-D Micromachined Structures



2 dust mites on an optical shutter

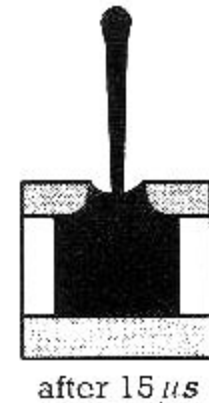
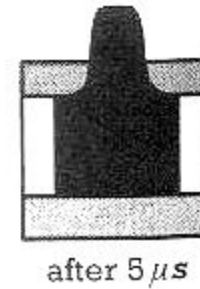
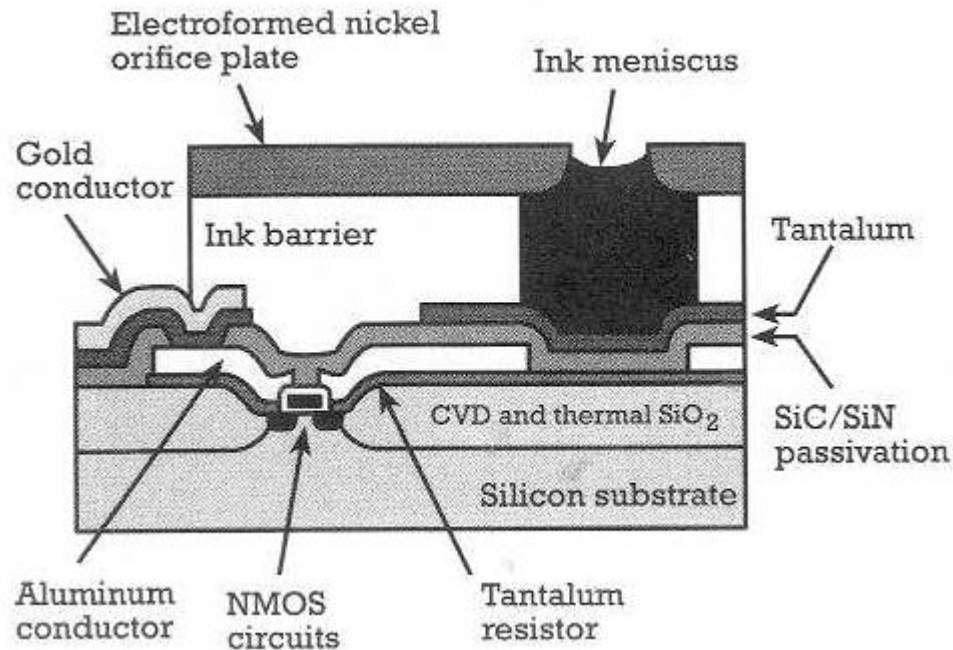


Deflection of laser light using a hinged mirror

Movies from Sandia National Lab. Website: <http://mems.sandia.gov>

Applications: Passive Structures

Inkjet Printer Nozzle



Applications: Sensors

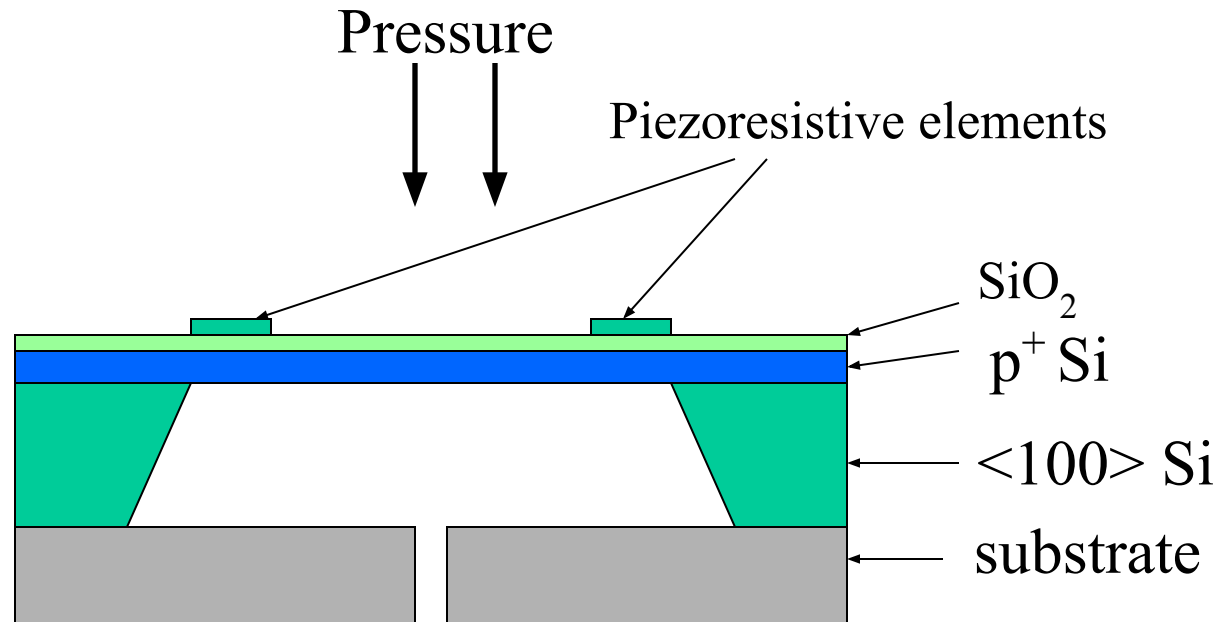
Pressure sensor:

- Piezoresistive sensing
- Capacitive sensing
- Resonant sensing

Application examples:

- Manifold absolute pressure (MAP) sensor
 - Disposable blood pressure sensor (Novasensor)
-

Piezoresistive Pressure Sensors



Piezoresistive Pressure Sensors

Wheatstone Bridge configuration

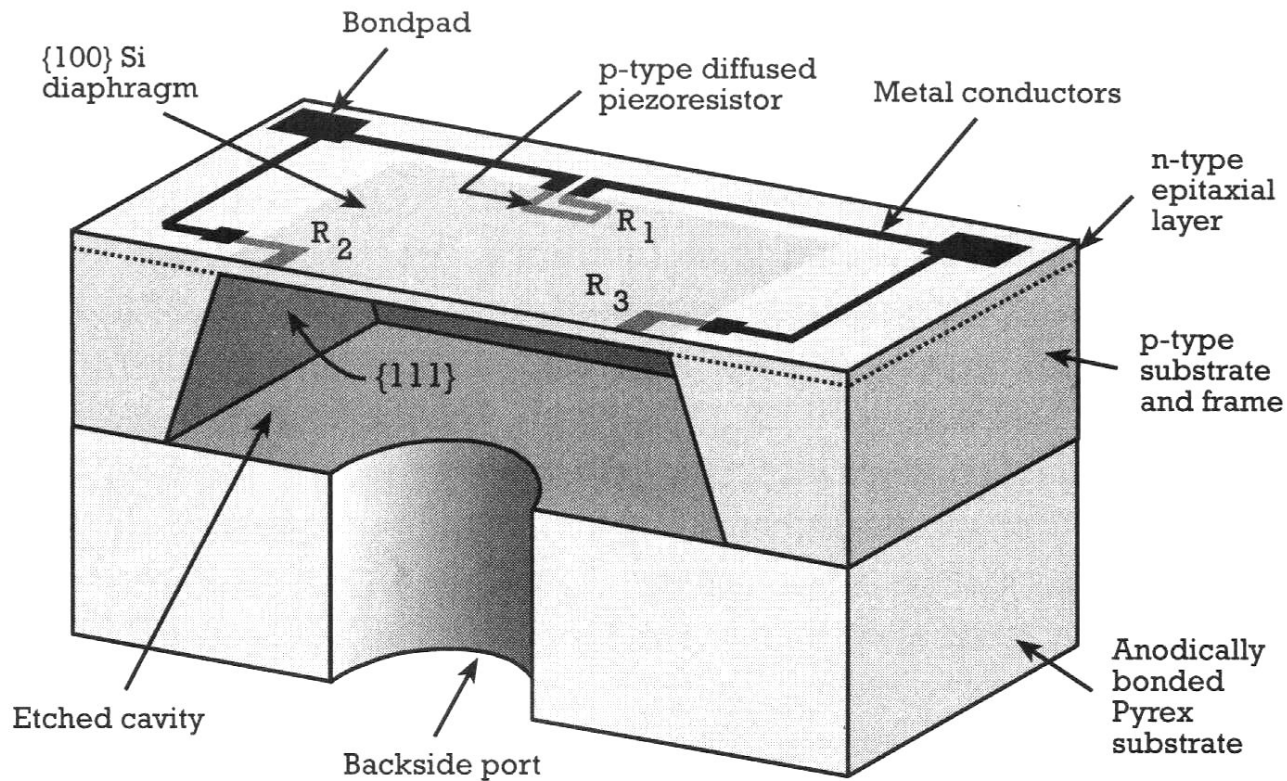


Illustration from "An Introduction to MEMS Engineering", N. Maluf

Applications: Sensors

Inertial sensors

- Acceleration



- Air bag crash sensing
- Seat belt tension
- Automobile suspension control
- Human activity for pacemaker control

- Vibration

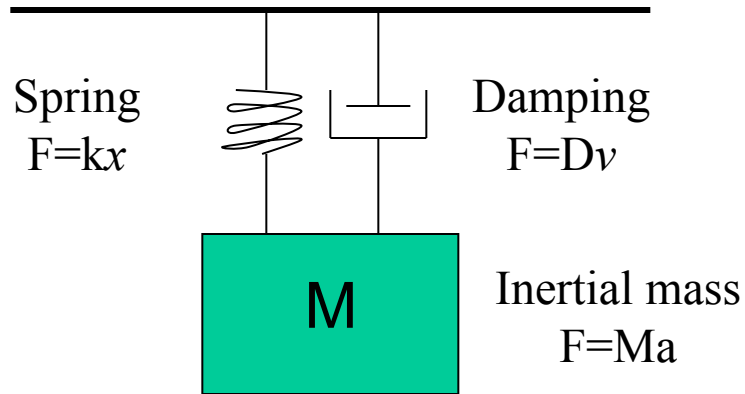
- Engine management
- Security devices
- Monitoring of seismic activity

- Angle of inclination

- Vehicle stability and roll



Accelerometers



Static deformation:

$$d_{static} = \frac{F}{k} = \frac{Ma}{k}$$

Dynamic behavior

$$M \frac{d^2 x}{dt^2} + D \frac{dx}{dt} + kx = F_{ext} = Ma$$

$$\omega_r = \sqrt{\frac{k}{M}} \quad \text{Resonance frequency}$$

$$Q = \frac{\omega_r M}{D} \quad \text{Quality factor}$$

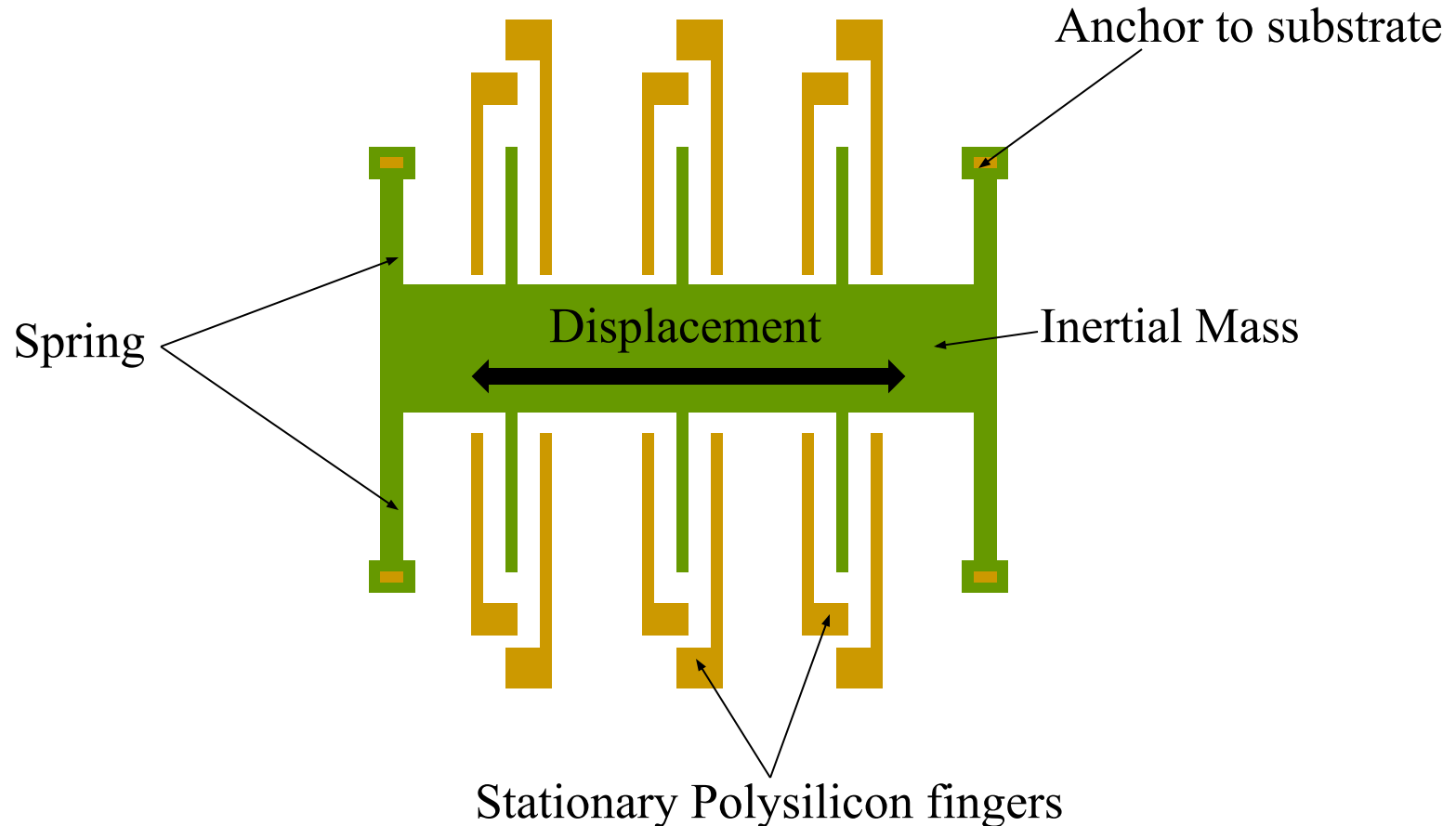
Accelerometers

Accelerometer parameters

- acceleration range (G) ($1\text{G}=9.81\text{ m/s}^2$)
- sensitivity (V/G)
- resolution (G)
- bandwidth (Hz)
- cross axis sensitivity

Application	Range	Bandwidth	Comment
Air Bag Deployment	$\pm 50\text{ G}$	$\sim 1\text{ kHz}$	
Engine vibration	$\pm 1\text{ G}$	$> 10\text{ kHz}$	resolve small accelerations ($< 1\text{ micro G}$)
Cardiac Pacemaker control	$\pm 2\text{ G}$	$< 50\text{ Hz}$	multiaxis, ultra-low power consumption

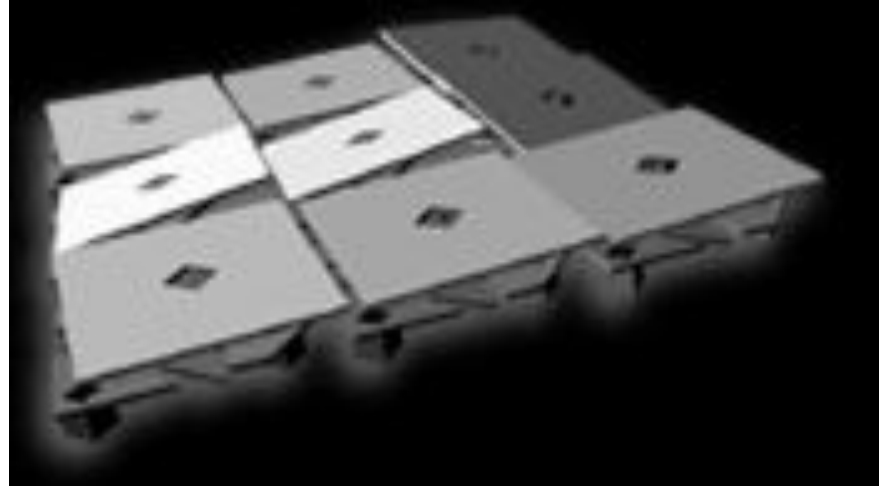
Capacitive Accelerometers



Based on ADXL accelerometers, Analog Devices, Inc.

Applications: Actuators

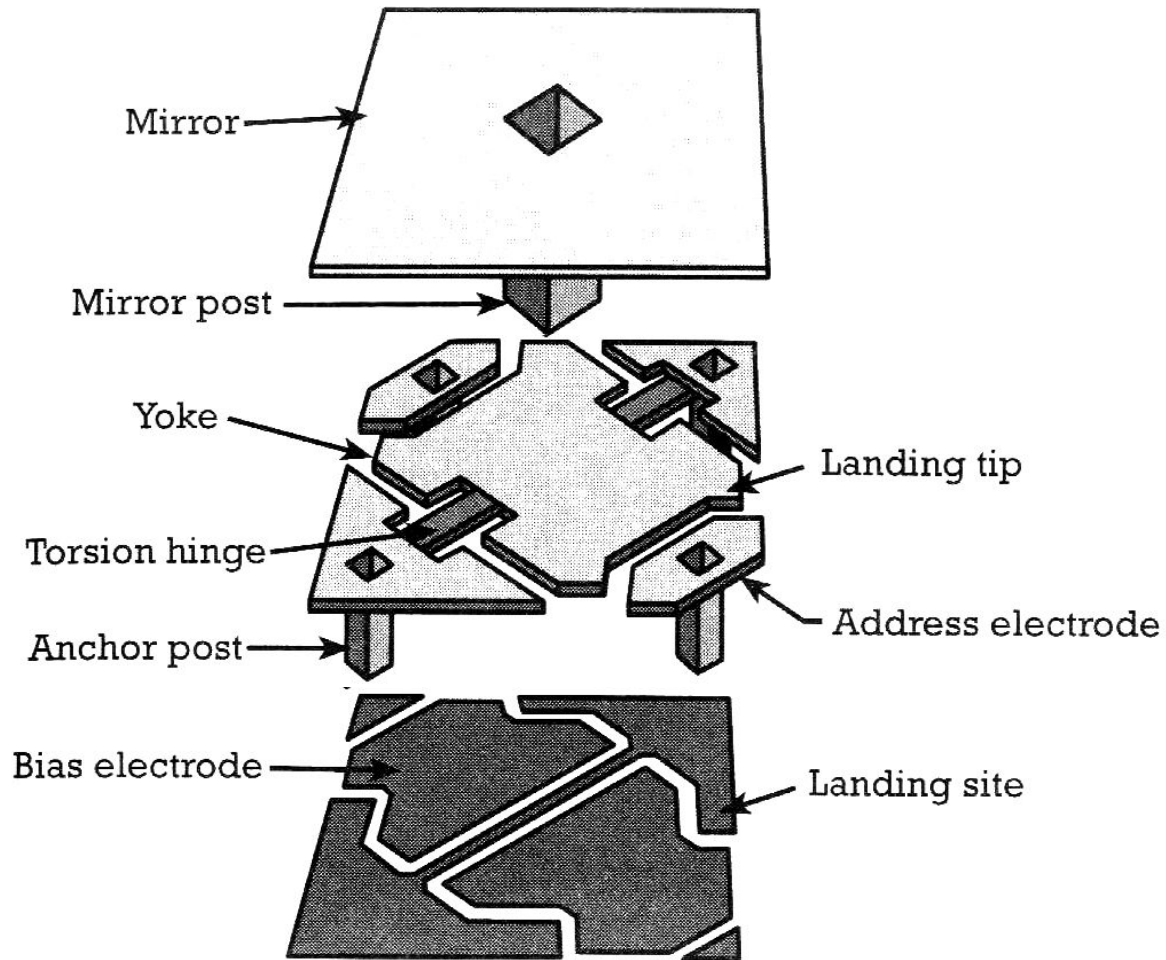
Texas Instruments Digital Micromirror Device™



- Invented by Texas Instruments in 1986
- Array of up to 1.3 million mirrors
- Each mirror is 16 μm on a side with a pitch of 17 μm
- Resolutions: 800x600 pixels (SVGA) and 1280x1024 pixels (SXGA)

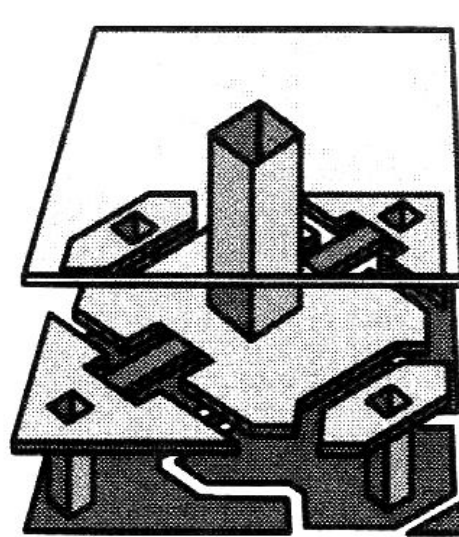
For an animated demo of this device, go to
http://www.dlp.com/dlp_technology/

Digital Micromirror Device

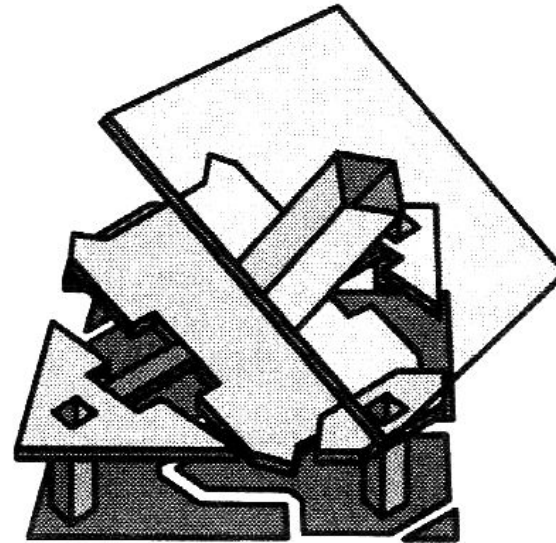


From "An Introduction to Microelectromechanical Systems Engineering" by Nadim Maluf

Digital Micromirror Device



Unactuated state



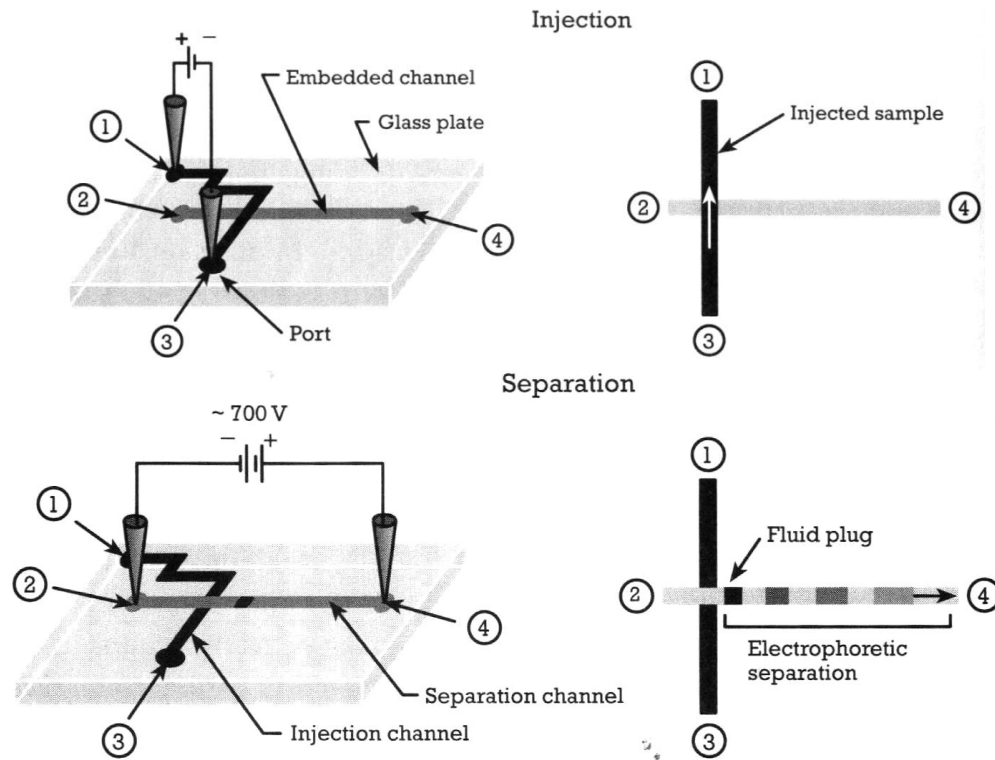
Actuated state

- Mirror is moved by electrostatic actuation (24 V applied to bias electrode)
- Projection system consists of the DMD, electronics, light source and projection optics
- Switching time: 16 μs (about 1000 times faster than the response time of the eye)
 - => Achieve grey scale by adjusting the duration of pulse*
- Placing a filter wheel with the primary colors between light source and the micromirrors
 - => Achieve full color by timing the reflected light to pass the wheel at the right color*

Some future applications

- **Biological applications:**
 - Microfluidics
 - Lab-on-a-Chip
 - Micropumps
 - Resonant microbalances
 - Micro Total Analysis systems
 - **Mobile communications:**
 - Micromechanical resonator for resonant circuits and filters
 - **Optical communications:**
 - Optical switching
-

Microfluidics / DNA Analysis



In the future, a complete DNA sequencing systems should include:

- Amplification (PCR)
- Detection (electrophoresis)
- Fluid preparation and handling (pumps, valves, filters, mixing and rinsing)

➡ MEMS !

Basic microfabrication technologies

- **Deposition**
 - Chemical vapor deposition (CVD/PECVD/LPCVD)
 - Epitaxy
 - Oxidation
 - Evaporation
 - Sputtering
 - Spin-on methods
 - **Etching**
 - Wet chemical etching
 - Isotropic
 - Anisotropic
 - Dry etching
 - Plasma etch
 - Reactive Ion etch (RIE, DRIE)
 - **Patterning**
 - Photolithography
 - X-ray lithography
-

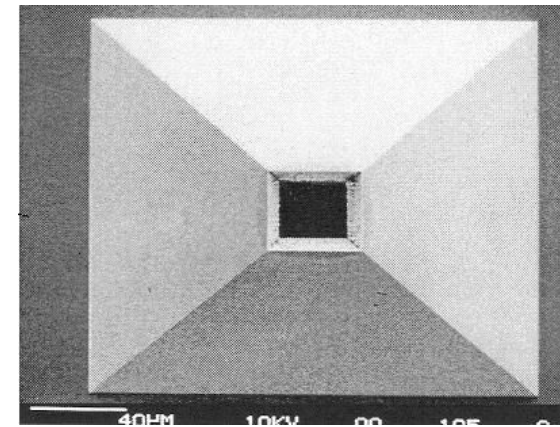
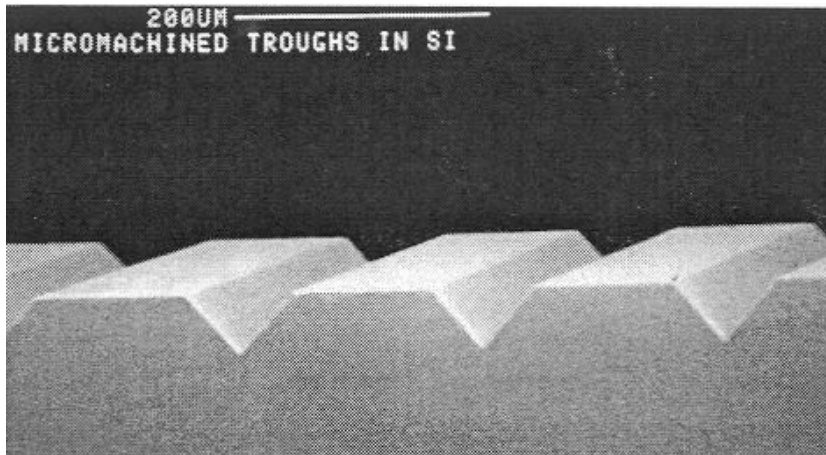
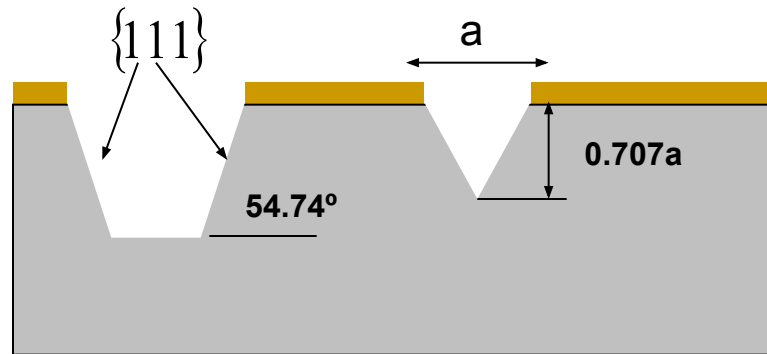
Bulk micromachining

Anisotropic etching of silicon

Etchant	$\frac{r_{etch} \langle 100 \rangle}{r_{etch} \langle 111 \rangle}$	Selectivity to p ⁺ - Si	Disadvantages
Potassium Hydroxide (KOH)	100	Yes	-Highly corrosive -Not CMOS compatible
Tetramethyl ammonium hydroxide (TMAH)	30-50	yes	-formation of pyramidal hillocks at bottom of cavity
Ethylenediamine pyrochatechol (EDP)	35	Yes	-carcinogenic vapors

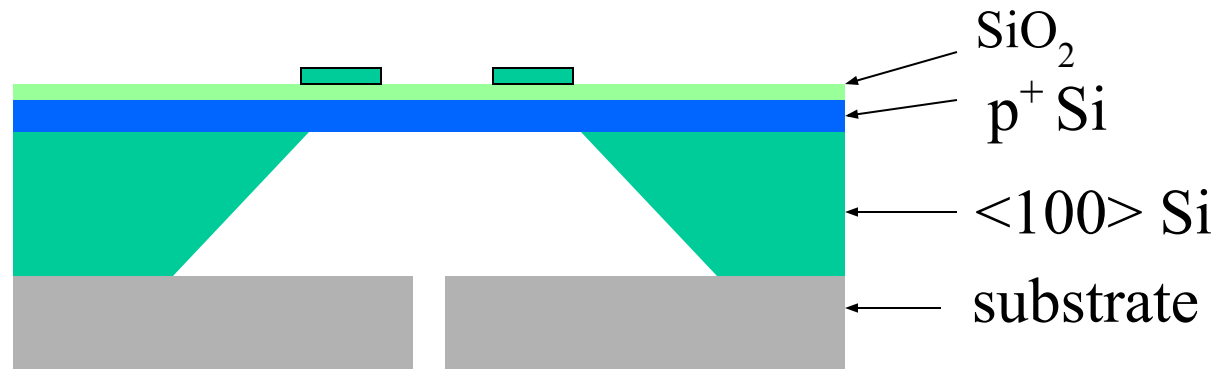
Bulk micromachining

Anisotropic etch of $\{100\}$ Si

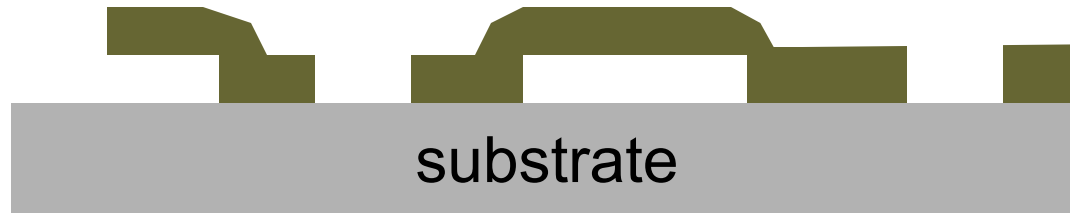


Bulk micromachining: Pressure sensors

Piezoresistive elements



Surface Micromachining



Important issues:

- selectivity of structural, sacrificial and substrate materials
- stress of structural material
- stiction

Surface Micromachining

Most commonly used materials for surface micromachining:

- substrate: silicon
- sacrificial material: SiO_2 or phosphosilicate glass (PSG)
- structural material: polysilicon

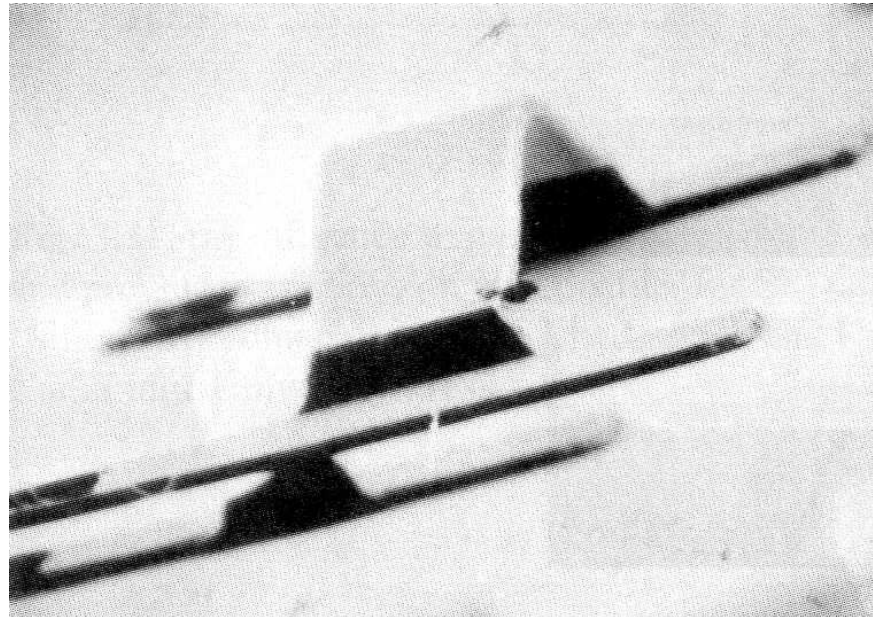
Alternative materials

Substrates	Sacrificial	Structural
Glass Plastic metals	Polymer Metals silicon nitride	Thin film silicon (a-Si:H, $\mu\text{c-Si}$) silicon nitrides Silicon carbide Metals polymers bilayer composites

Surface Micromachining

Stress

- Polysilicon deposited by LPCVD ($T \sim 600^\circ\text{C}$) usually has large stress
- High T anneal ($600\text{-}1000^\circ\text{C}$) for more than 2 hours relaxes the strain



➡ Low temperature, thin film materials has much less intrinsic stress

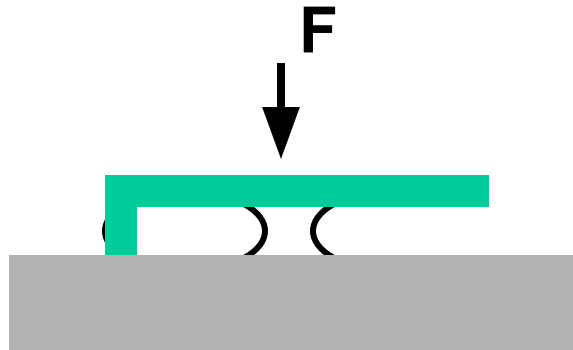
Photo from R.T. Howe, Univ. of Calif, Berkeley, 1988



Surface Micromachining

Stiction

Surface tension of liquid during evaporation results in capillary forces that causes the structures to stick to the substrate if the structures are not stiff enough.



To avoid this problem

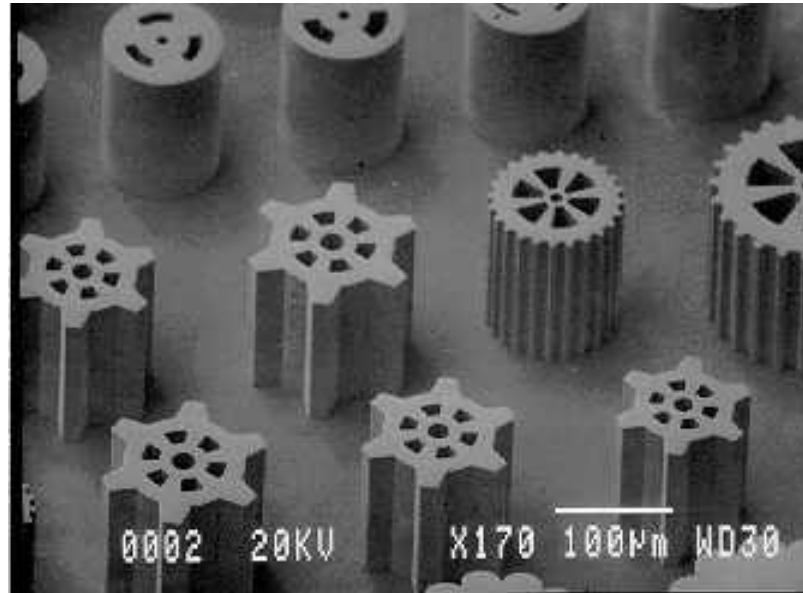
- make the structures stiffer (ie, shorter, thicker or higher Young's modulus)
 - use super-critical drying in CO_2 (liquid $\rightarrow$ supercritical fluid $\rightarrow$ gas)
 - roughen substrate to reduce contact area with structure
 - coat structures with a hydrophobic passivation layer
-

LIGA – X-ray Lithography, Electroplating (Galvanoformung), Molding (Abformung)



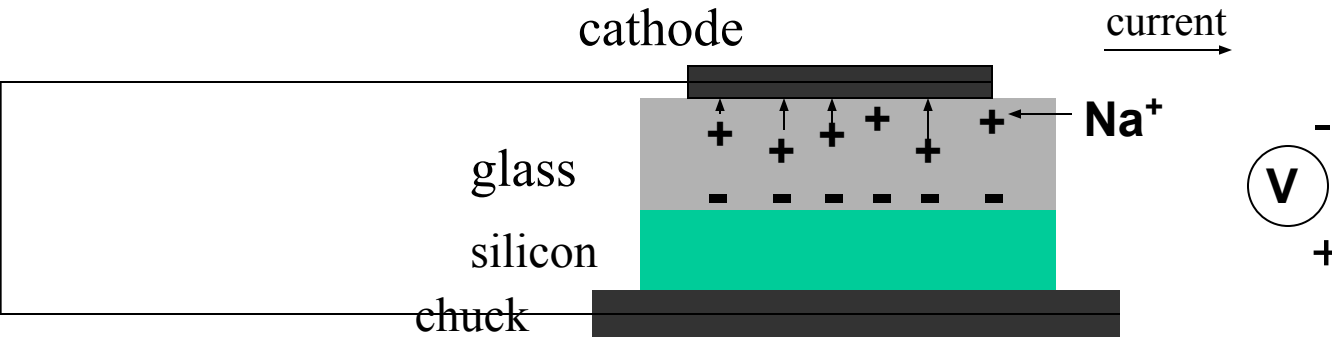
Remove mold
Immerse in chemical bath and
electroplate the metal
Expose and develop photoresist
Deposit photoresist
Deposit plating base

LIGA



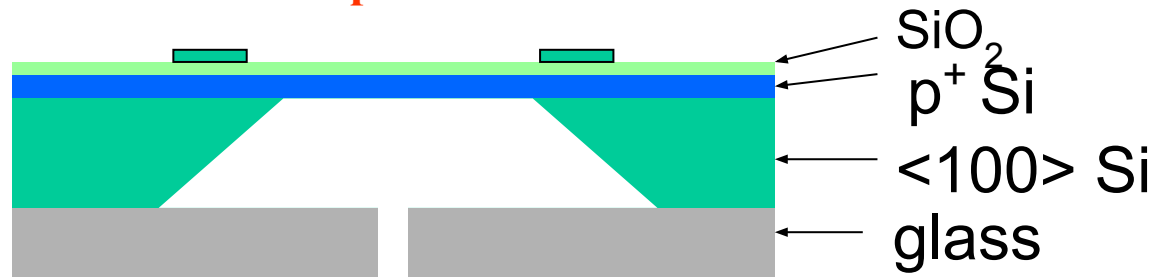
Photos from MCNC – MEMS group

Wafer bonding- Anodic



- bring sodium containing **glass (Pyrex)** and **silicon** together
- heat to **high temperature** (200-500 °C) in vacuum, air or inert ambient
- apply **high electric field** between the 2 materials ($V \sim 1000V$) causing mobile **+ ions** to **migrate** to the cathode leaving behind fixed negative charge at glass/silicon interface
- bonding is complete when current vanishes
- **glass and silicon held together by electrostatic attraction** between - charge in glass and + charges in silicon

Piezoresistive pressure sensor



Summary: MEMS fabrication

- MEMS technology is based on silicon microelectronics technology
 - Main MEMS techniques
 - Bulk micromachining
 - Surface micromachining
 - LIGA and variations
 - Wafer bonding
-

Thin-film MEMS

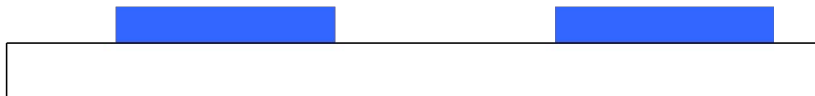
Thin films allows:

- Low-temperature processing
- Large area, low cost, flexible or biocompatible substrates
- Possibility to integrate with a CMOS or thin film electronics based back plane
- Control of structural material film properties (mechanical, electronic, optical and surface)

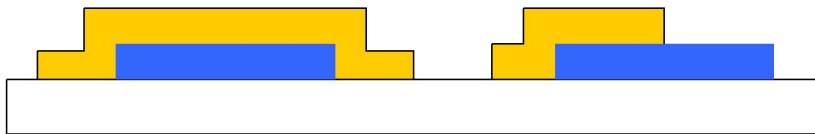


Surface micromachining on glass

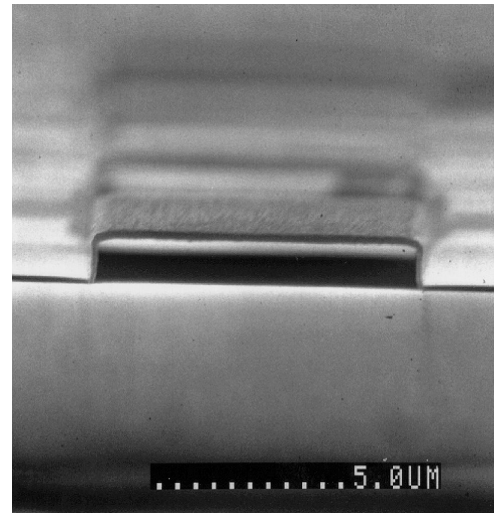
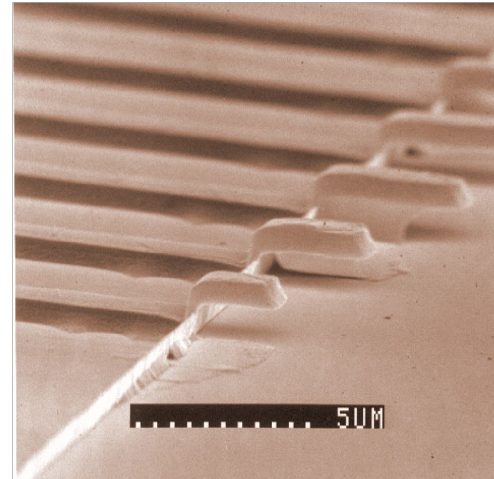
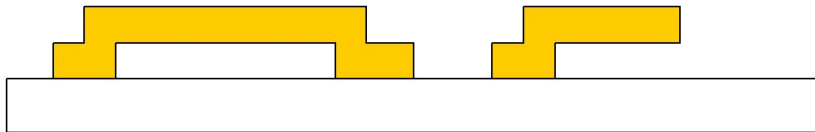
Sacrificial Layer Deposition and Patterning



Structural Layer Deposition and Patterning



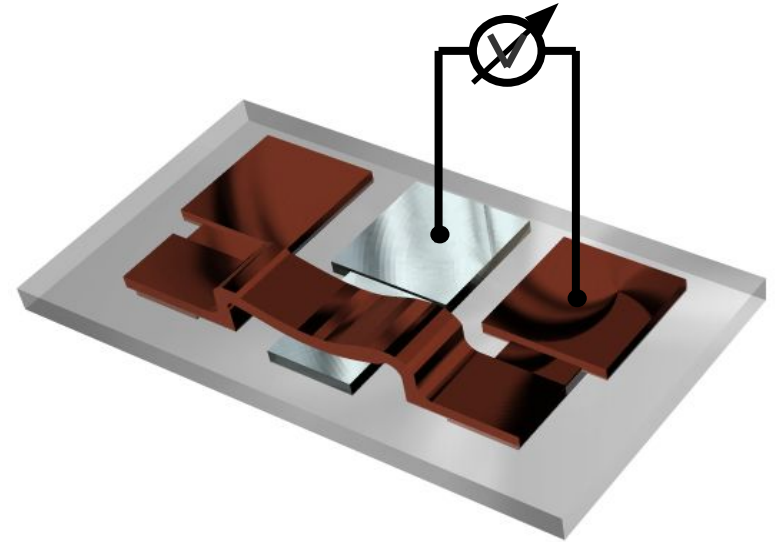
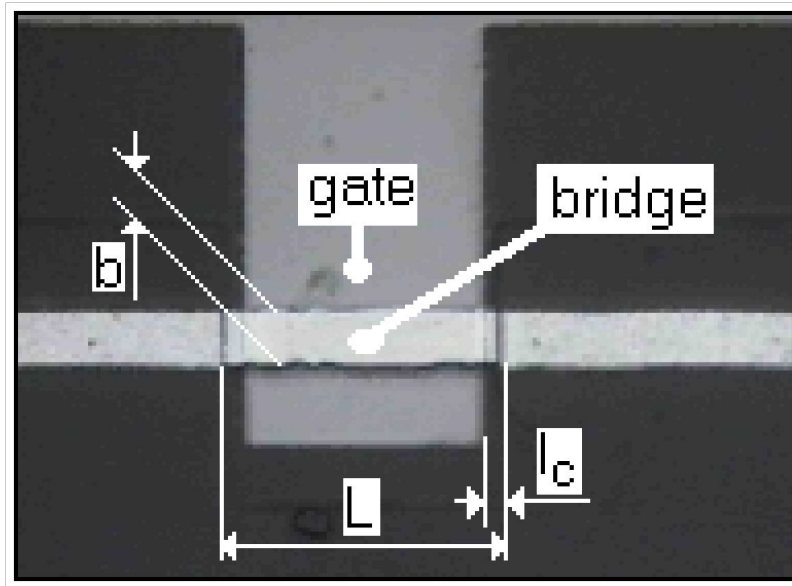
Sacrificial Layer Removal



$d=1\text{ }\mu\text{m}$; $h=500\text{ nm}$; $b=10\text{ }\mu\text{m}$

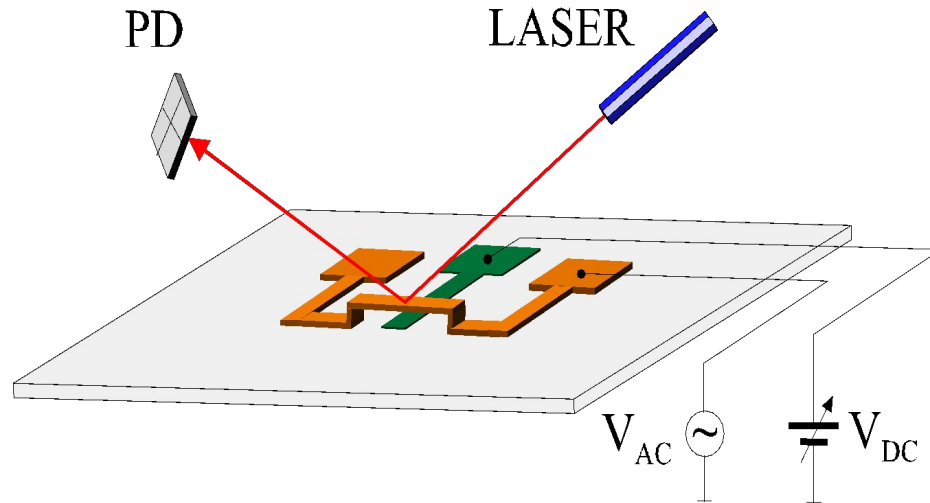
L_{max} (bridge) $\sim 60\text{ }\mu\text{m}$; L_{max} (cantilever) $\sim 30\text{ }\mu\text{m}$

Electrostatic Actuation



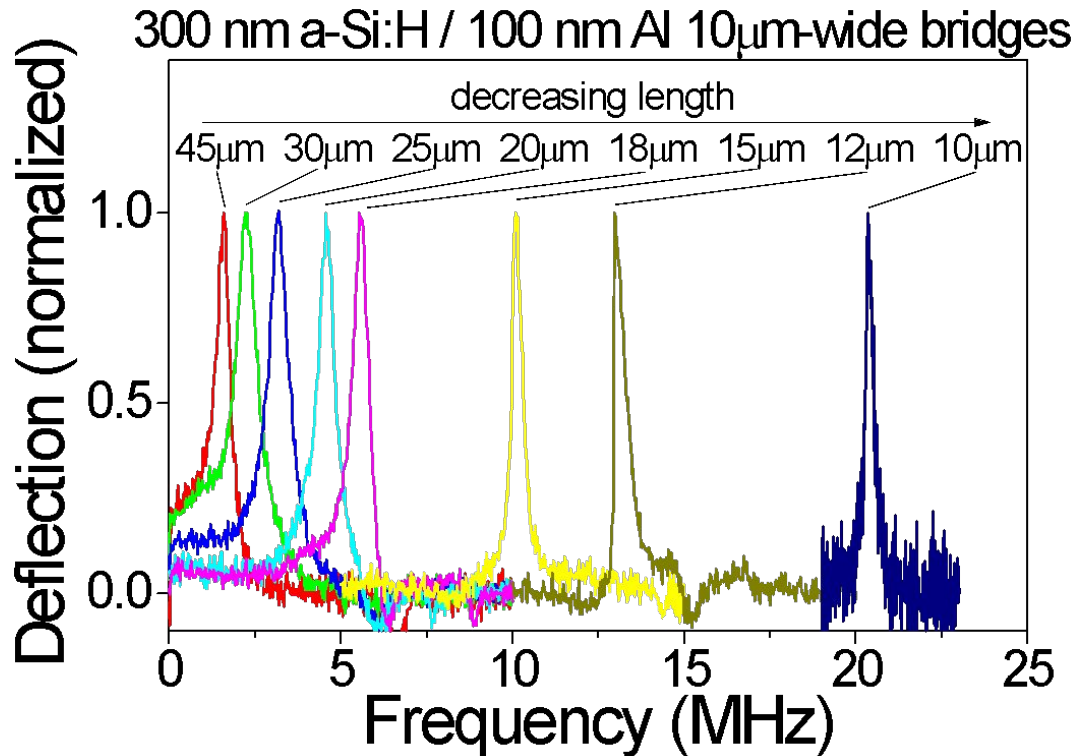
- **Electrostatic force between gate and counter-electrode**
- **Electrostatic force is always attractive**

Optical detection



- A laser beam is focused on the structure and the reflected light is collected with an intensity (or quadrant) detector.
- The deviation of the beam is proportional to the deflection

Resonance frequency



$$f_r = \frac{3.52}{2\pi L^2} \left(\frac{EI}{\rho A} \right)^{1/2}$$

- Optical detection of electrical actuation
- Resonance is inversely proportional to square of the length
- 20 MHz resonances measured with 10 μ m-long a-Si:H bridges ($Q \sim 100$ in air; Q up to 5000 in vacuum)

MEMS Resources

Reference Books

- Nadim Maluf, An Introduction to Microelectromechanical Engineering (Artech House, Boston, 2000)
- M. Elewenspoek and R. Wiegerink, Mechanical Microsensors (Springer-Verlag, 2001)
- Héctor J. De Los Santos, Introduction to Microelectromechanical (MEM) Microwave Systems (Artech House, Boston, 1999)

Websites

- Sandia National Lab: <http://mems.sandia.gov>
- Berkeley Sensors and Actuators Center: <http://www-bsac.eecs.berkeley.edu>
- MEMS Clearinghouse: <http://www.memsnet.org/>

Some companies with MEMS products

- Accelerometers – Analog Devices:
<http://www.analog.com/technology/mems/index.html>
 - Digital Light Processing Projector- Texas Instruments: <http://www.dlp.com>
 - Micro-electrophoresis chip – Caliper Technologies: <http://www.calipertech.com>
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