Microelectromechanical Systems (MEMS)

An introduction

Outline

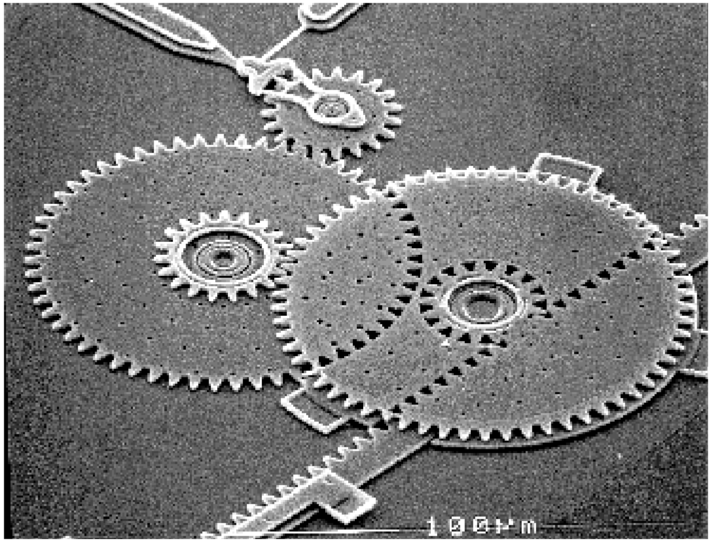
- **Introduction**
- **Applications**
  - *Passive structures*
  - *Sensors*
  - *Actuators*
- **Future Applications**
- **MEMS micromachining technology**
  - *Bulk micromachining*
  - *Surface micromachining*
  - *LIGA*
  - *Wafer bonding*
- **Thin film MEMS**
  - *Motivation*
  - *Microresonators*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

What are MEMS?

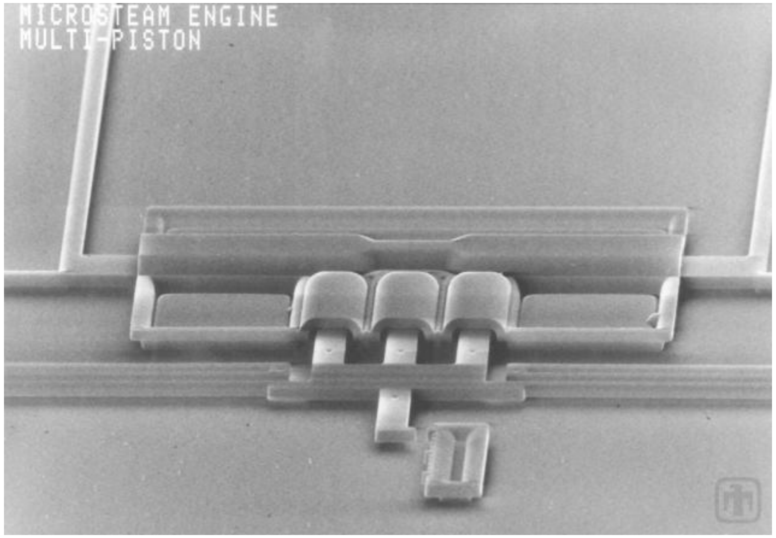
(Micro-electromechanical Systems)

- 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



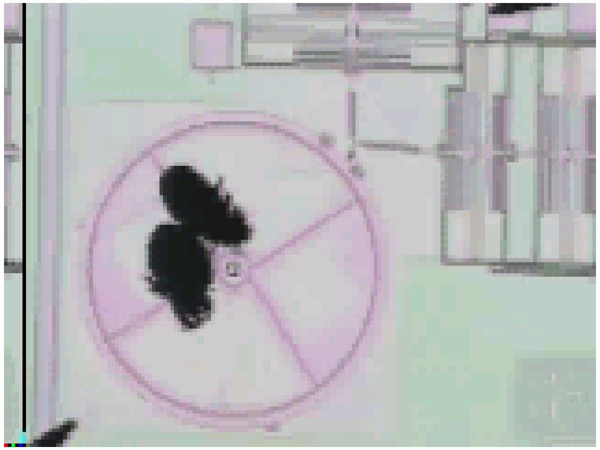
Linear Rack Gear Reduction Drive



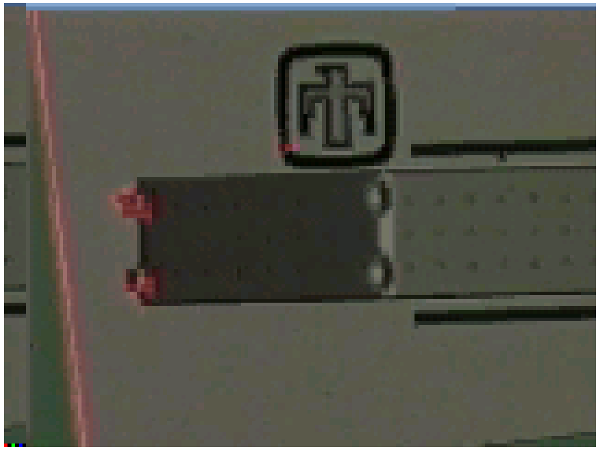
Triple-Piston Microsteam Engine

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

3-D Micromachined Structures



2 dust mites on an optical shutter

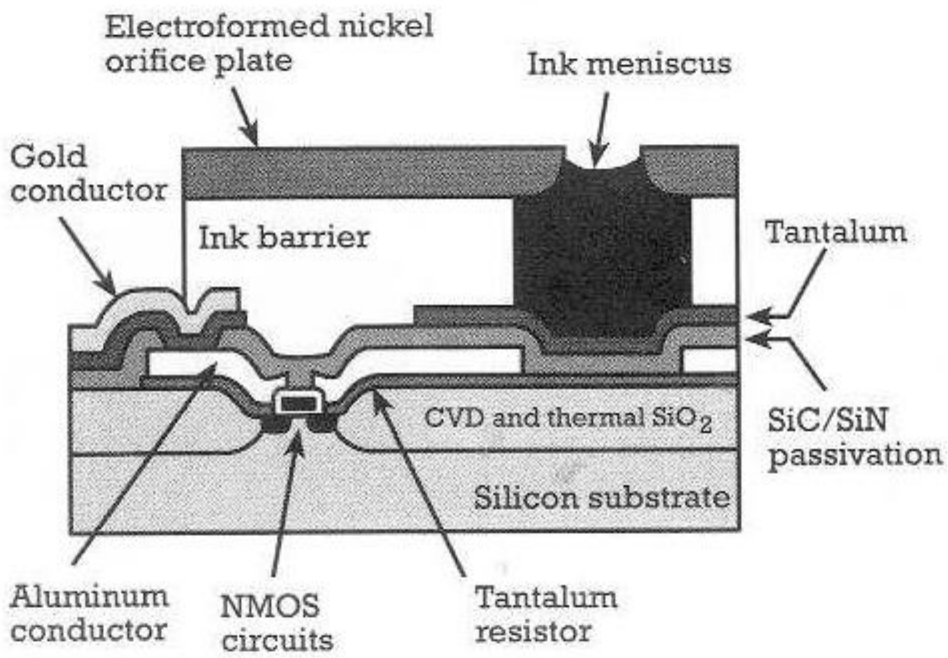


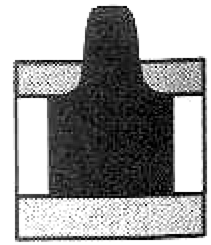
Deflection of laser light using a hinged mirror

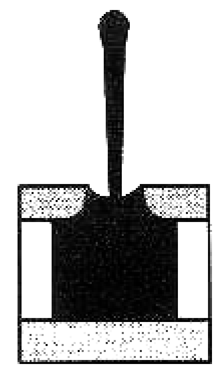
Movies from Sandia National Lab. Website: http://mems.sandia.gov

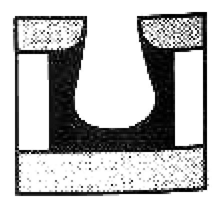
Applications: Passive Structures

Inkjet Printer Nozzle




after 5 μs


after 15 μs


after 24 μs

Applications: Sensors

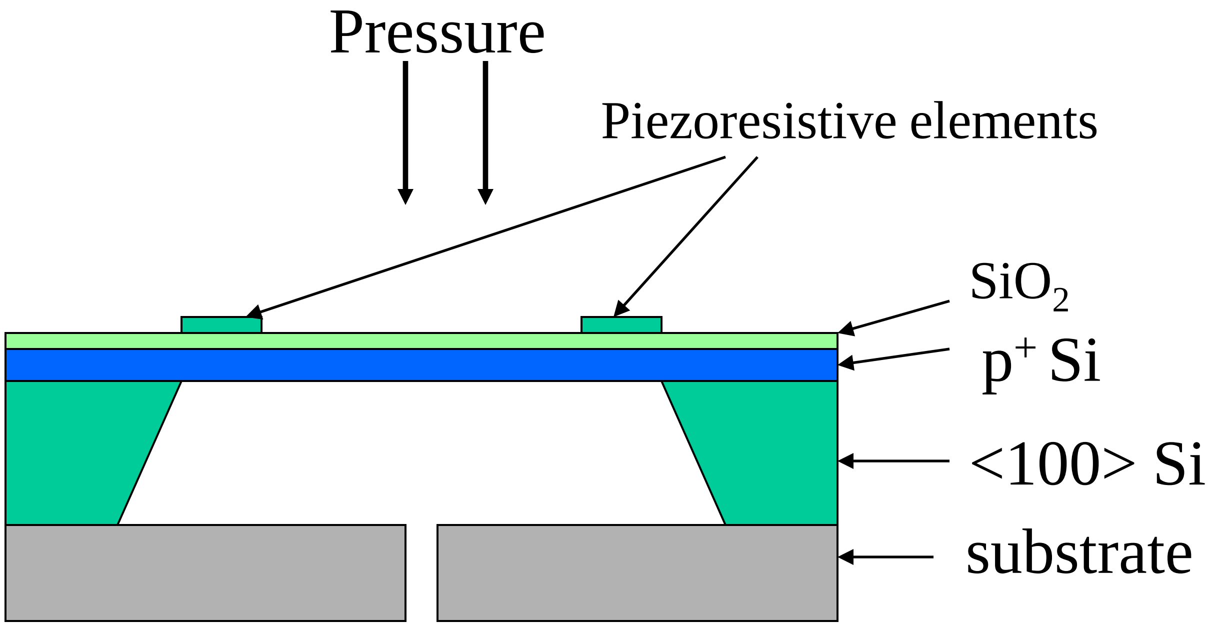
Pressure sensor:

- 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

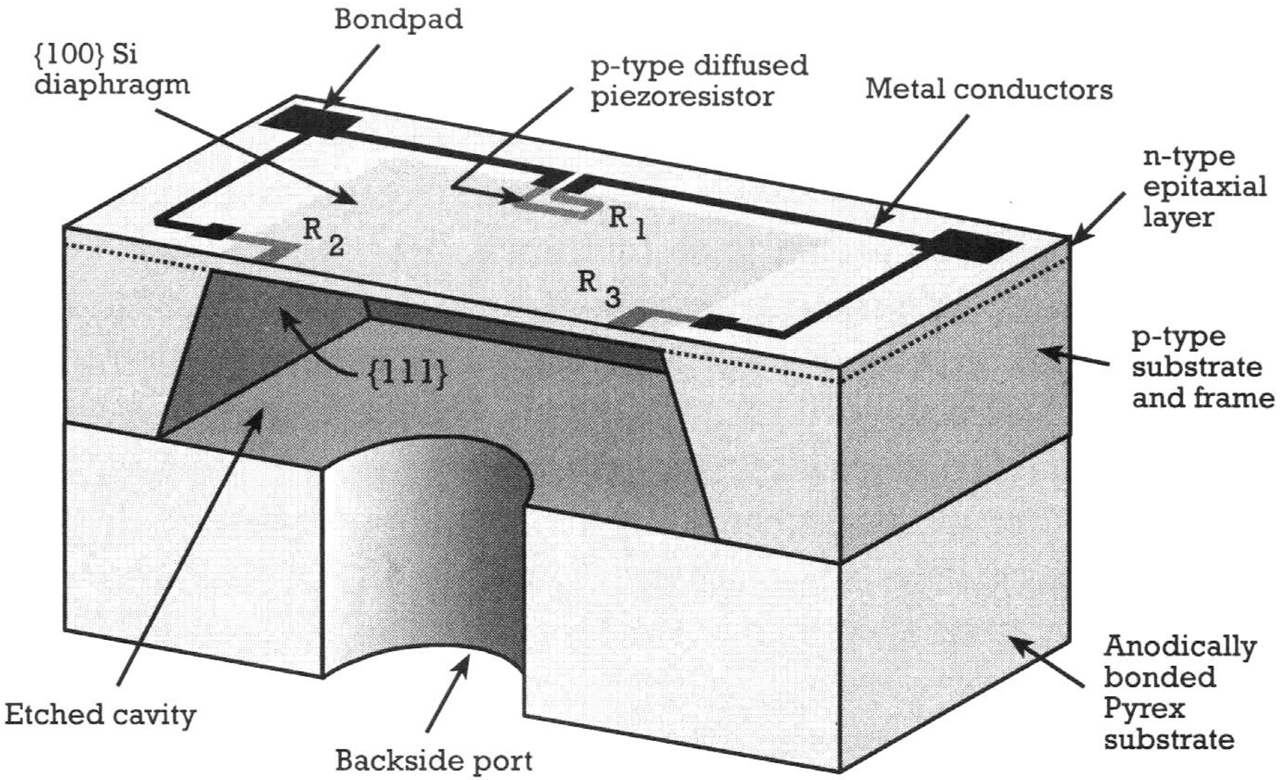


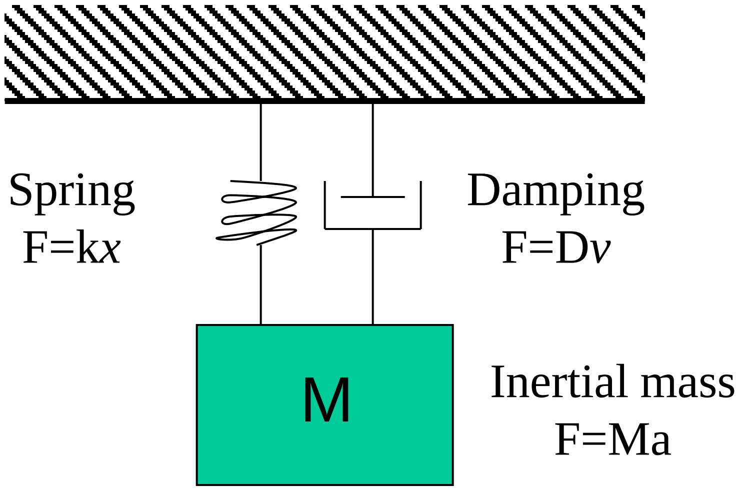
Illustration from "An Introduction to MEMS Engineering", N. Maluf

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

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

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

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

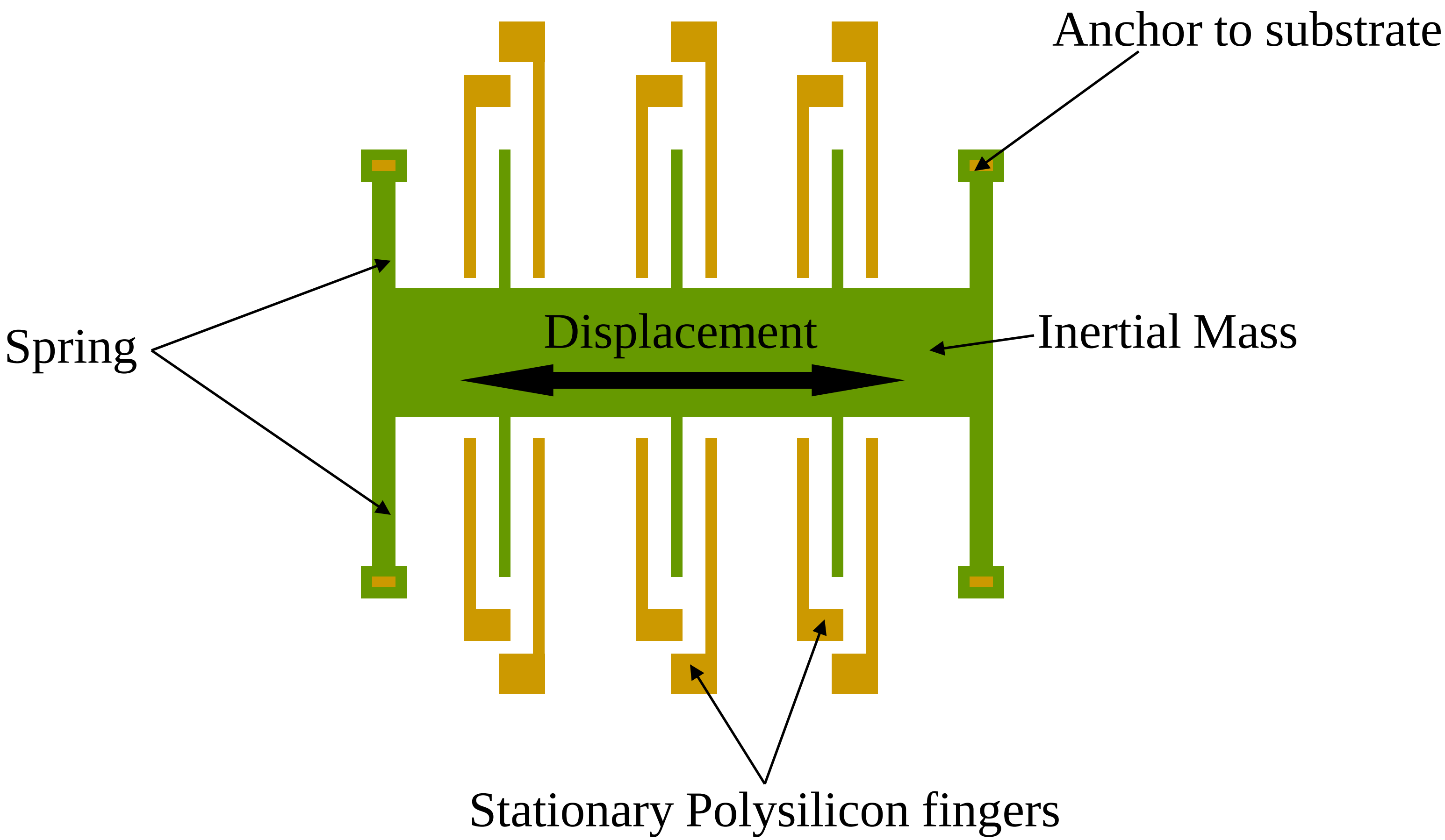
Accelerometers

Accelerometer parameters

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

Application	Range	Bandwidth	Comment
Air Bag Deployment	± 50 G	~ 1 kHz	
Engine vibration	± 1 G	> 10 kHz	resolve small accelerations (< 1 micro G)
Cardiac Pacemaker control	± 2 G	< 50 Hz	multiaxis, ultra-low power consumption

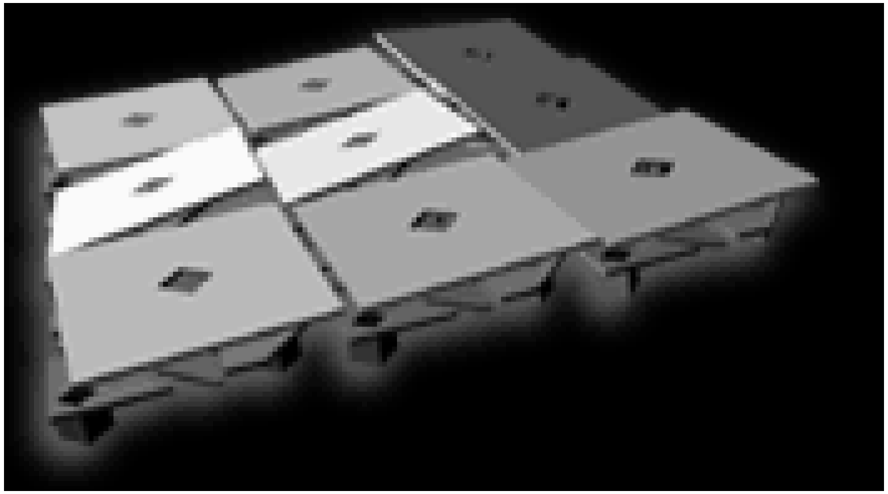
Capacitive Accelerometers



Based on ADXL accelerometers, Analog Devices, Inc.

Applications: Actuators

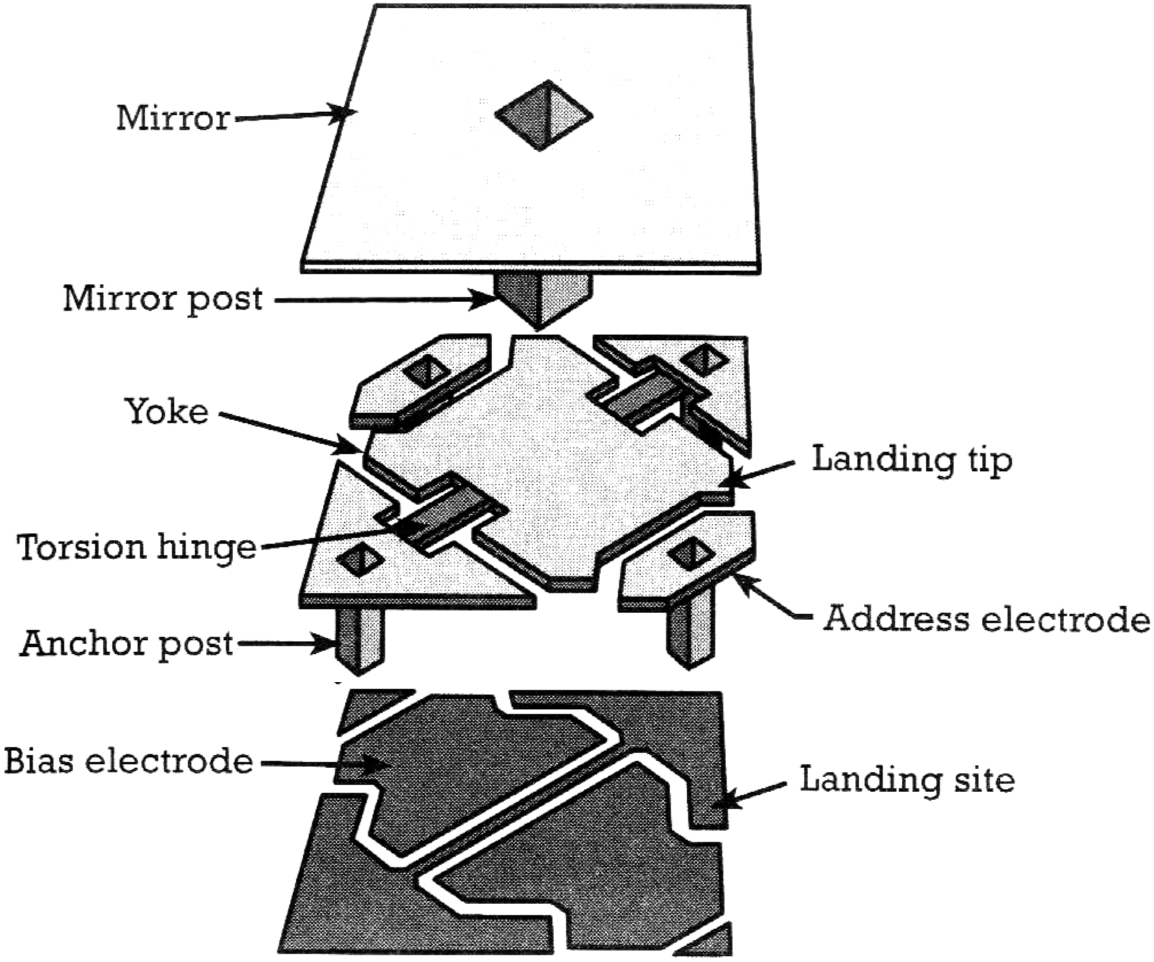
Texas Instruments Digital Micromirror Device™



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

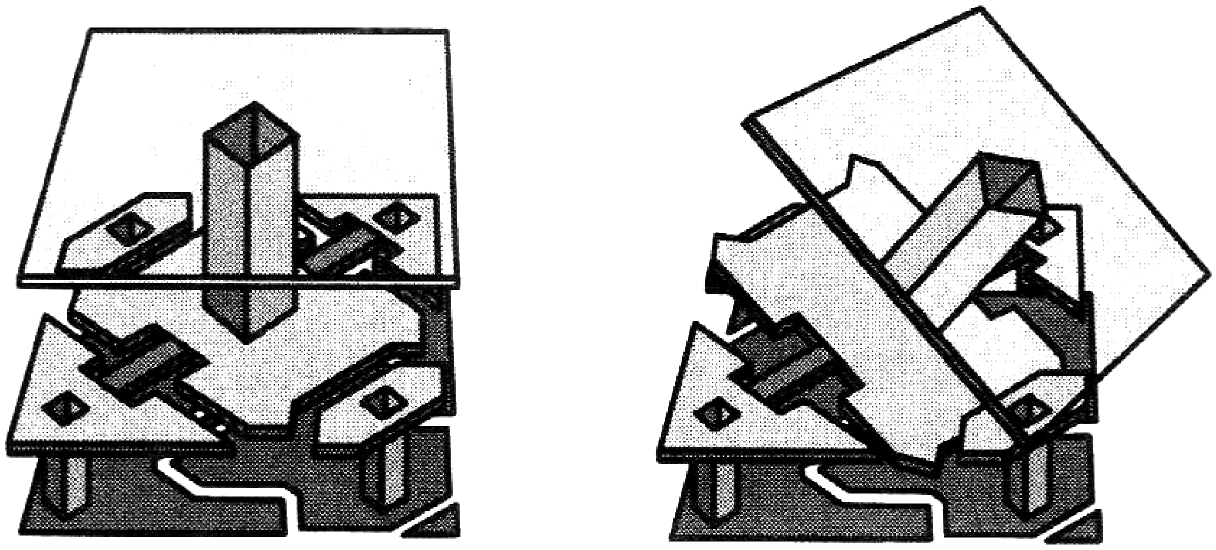
*For an animated demo of this device, go to **http://www.dlp.com/dlp_technology/***

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)

  => Acheive 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

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

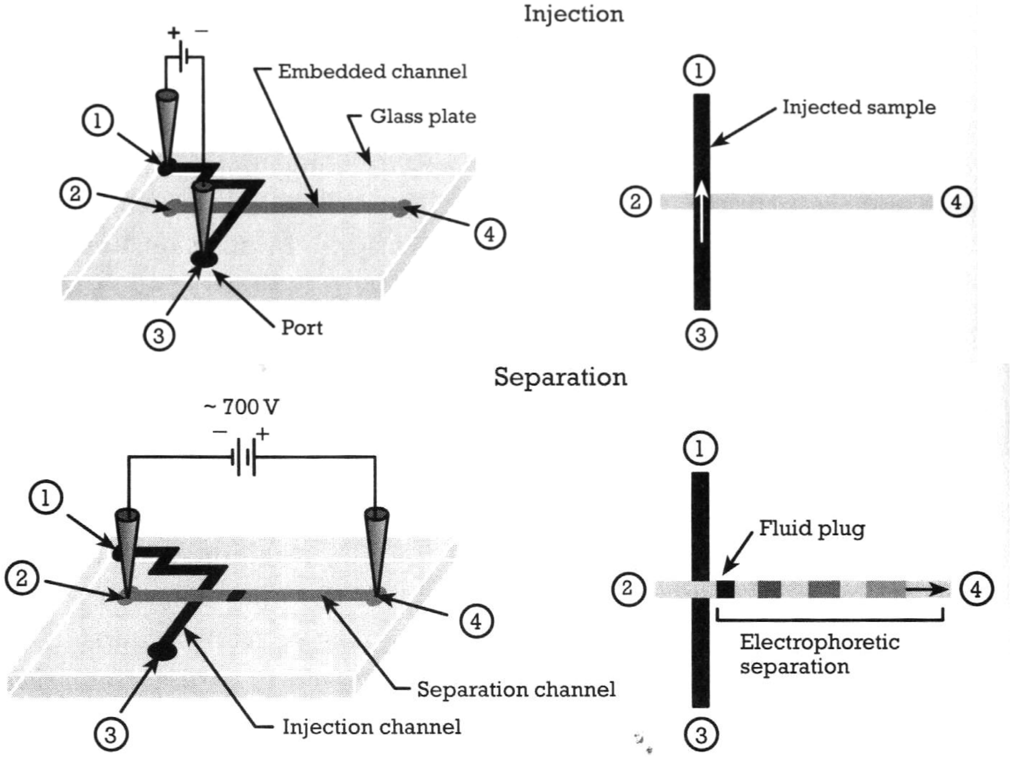
Some future applications

- 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
    - Istropic
    - Anisotropic
  - Dry etching
    - Plasma etch
    - Reactive Ion etch (RIE, DRIE)
- Patterning
  - Photolithography
  - X-ray lithography

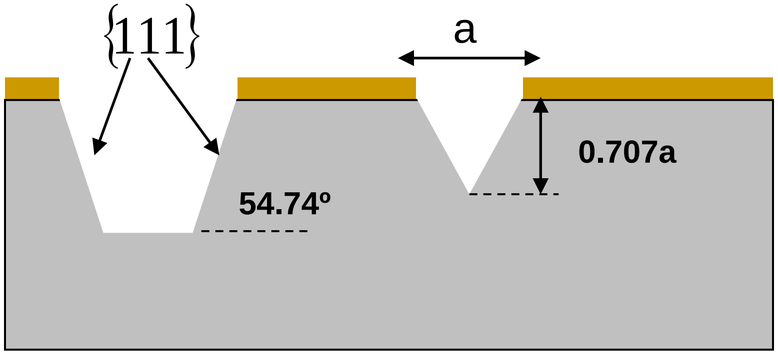
Bulk micromachining

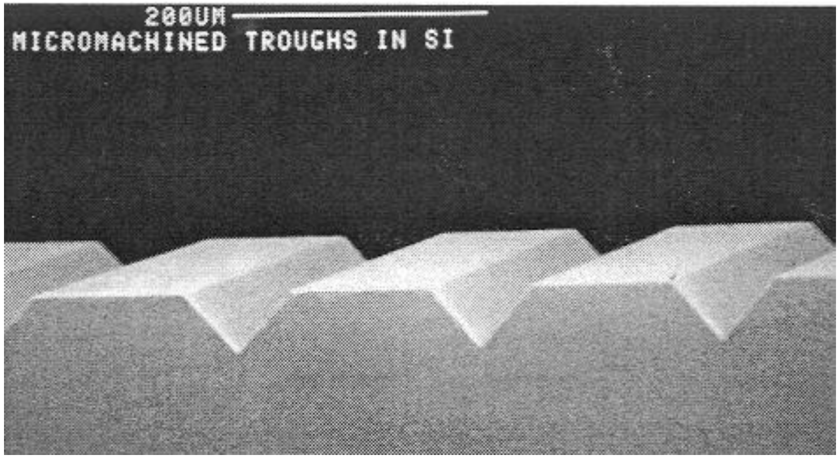
Anisotropic etching of silicon

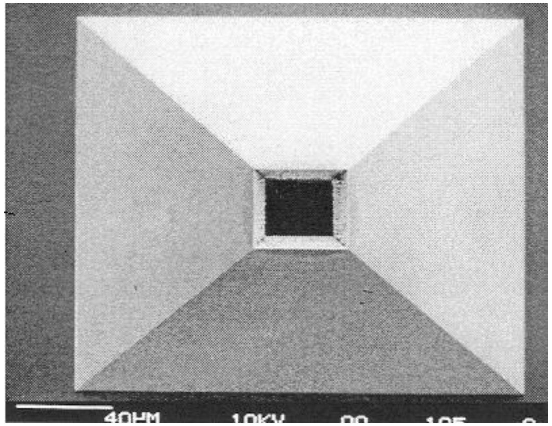
Etchant	$\frac{r_{etch}\langle 100\rangle}{r_{etch}\langle 111\rangle}$	Selectivity to p^{+}- Si	Disadvantages
Potassium Hydroxide (KOH)	100	Yes	-Highly corrosive -Not CMOS compatible
Tetramethyl ammonium hydroxide (TMAH)	30-50	yes	-formation of pyramidal hillocks at bottom of cavity
Ethylenediamine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

Bulk micromachining

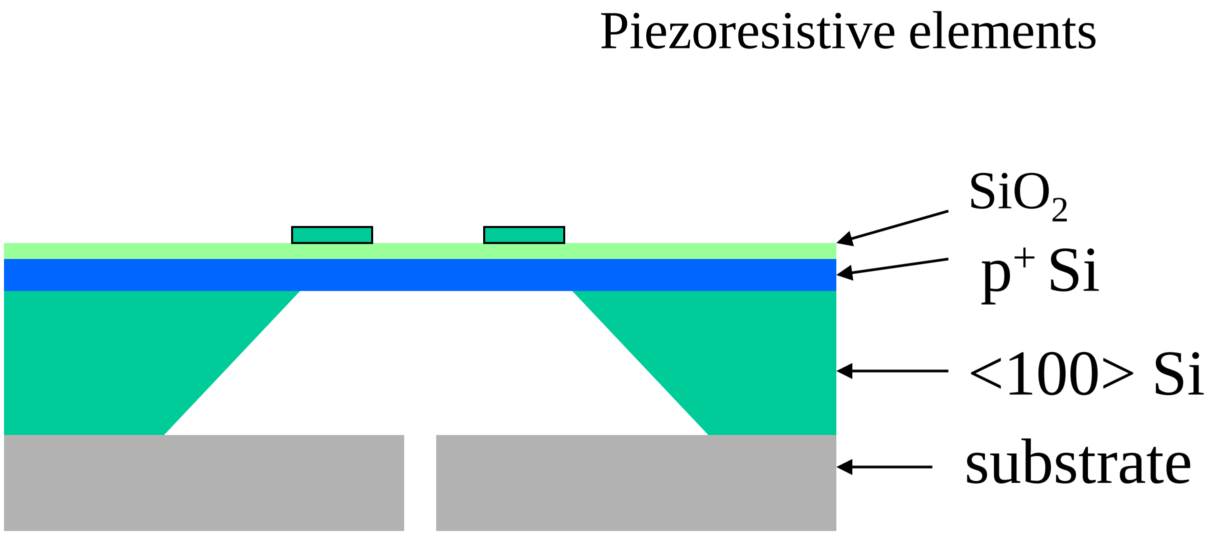
Anisotropic etch of {100} Si



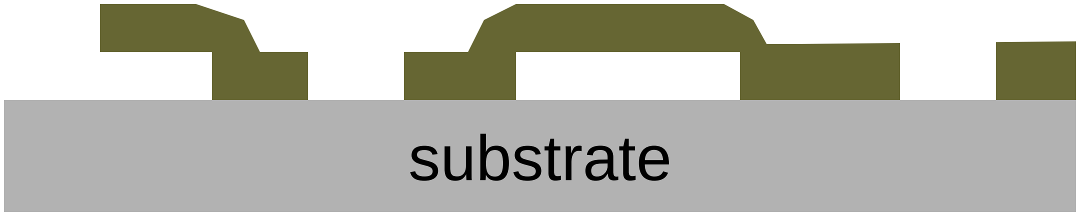




Bulk micromachining: Pressure sensors



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

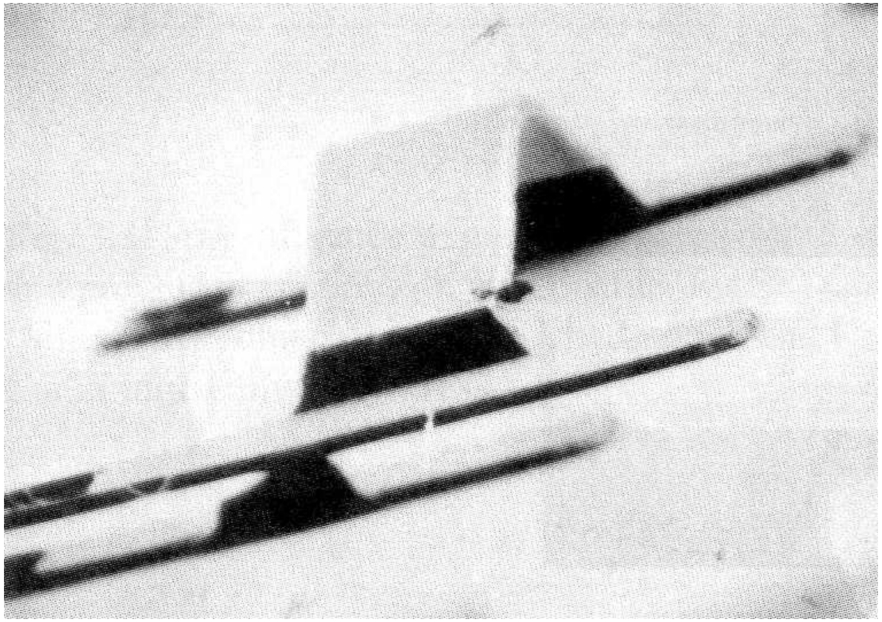
Alternative materials

Substrates	**Sacrificial**	**Structural**
Glass Plastic metals	Polymer Metals silicon nitride	Thin film silicon (a-Si:H, μc-Si) silicon nitrides Silicon carbide Metals polymers bilayer composites

Surface Micromachining

Stress

- Polysilicon deposited by LPCVD (T~600 ºC) usually has large stress
- High T anneal (600-1000 ºC) for more than 2 hours relaxes the strain



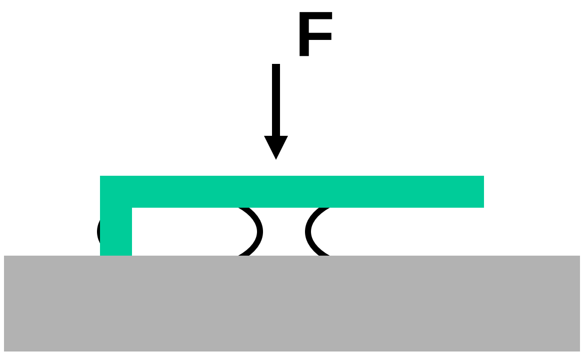
➡ Low temperature, thin film materials has much less intrinsic stress

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 → supercritical fluid → 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

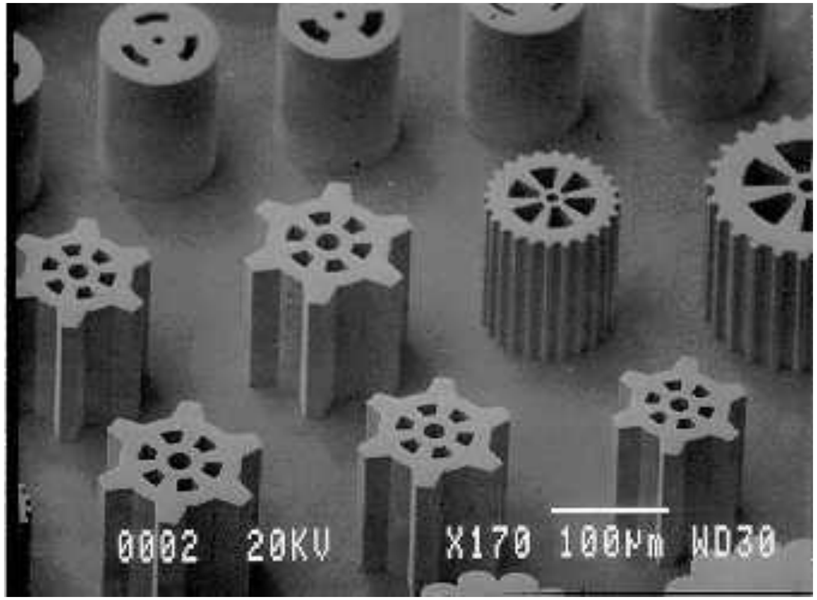
Immerse in chemical bath and electroplate the metal

Expose and develop photoresist

Deposit photoresist

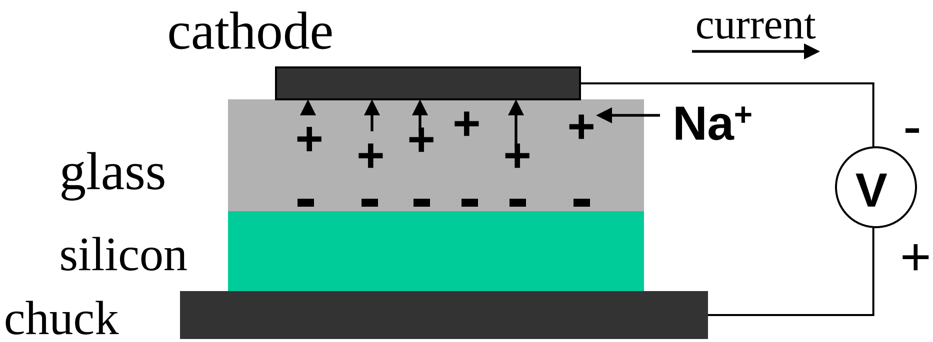
Deposit plating base

LIGA



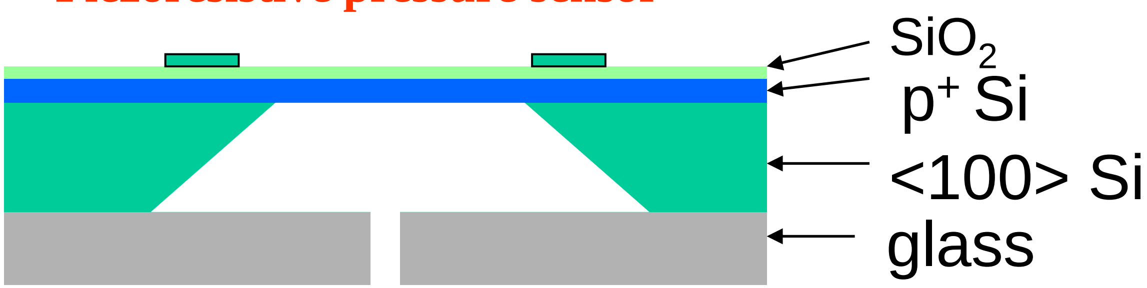
Photos from MCNC – MEMS group

Wafer bonding- Anodic



- bring sodium contating glass (Pyrex) and silicon together
- heat to high temperature (200-500 ºC) in vacuum, air or inert ambient
- apply high electric field between the 2 materials (V~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

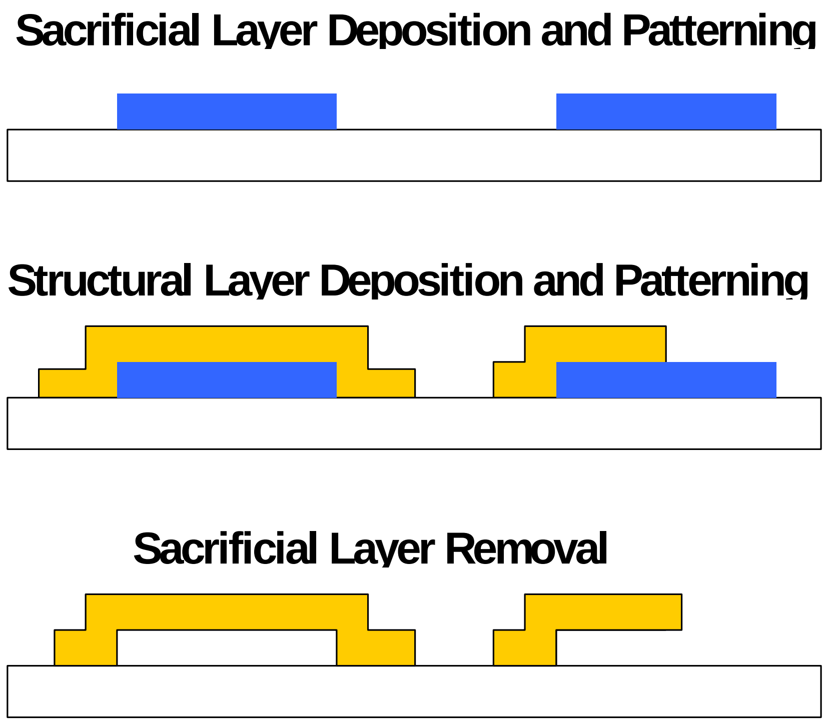
- MEMS technology is based on silicon microelectronics technology
- Main MEMS techniques
  - Bulk micromachining
  - Surface micromachining
  - LIGA and variations
  - Wafer bonding

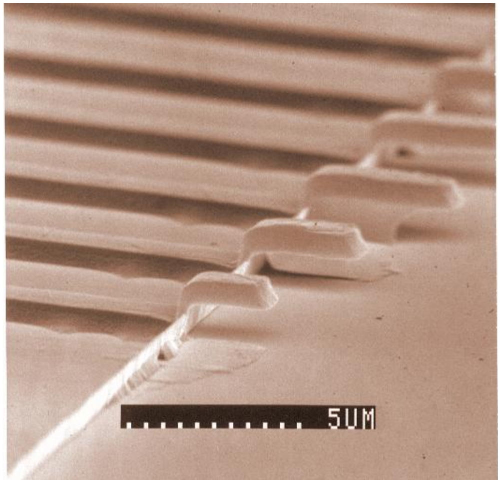
Thin-film MEMS

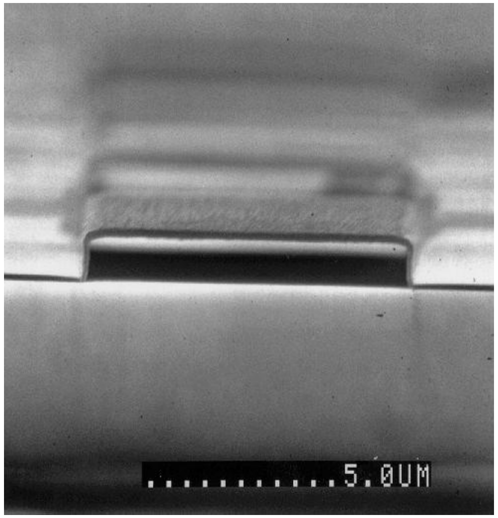
Thin films allows:

- 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



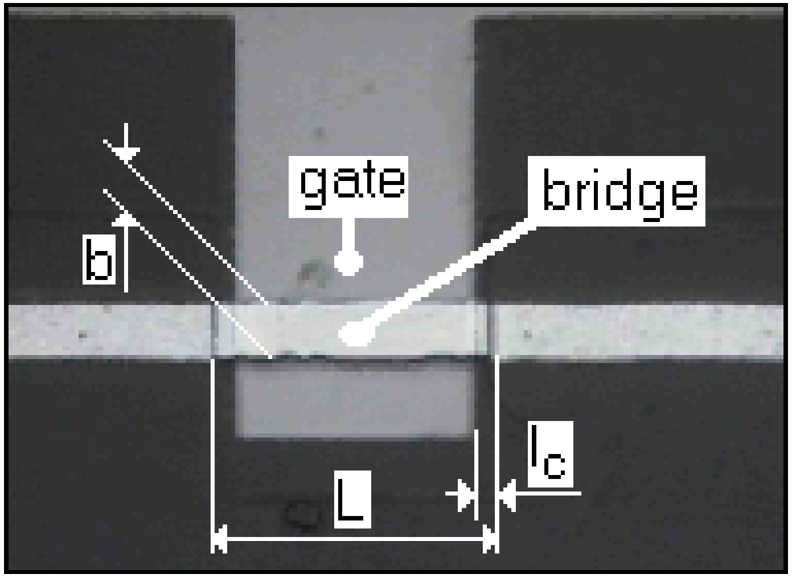


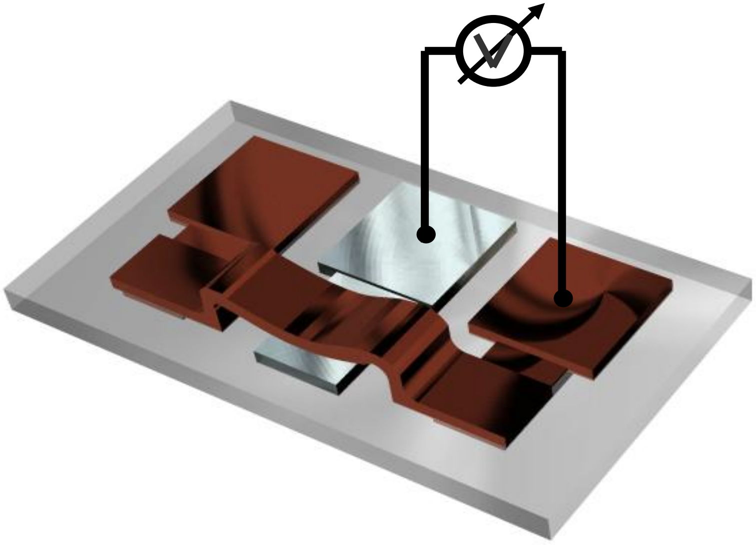


d=1 µm; h=500 nm; b=10 µm

L_{max}(bridge) ~ 60 µm ; L_{max}(cantilever) ~ 30 µm

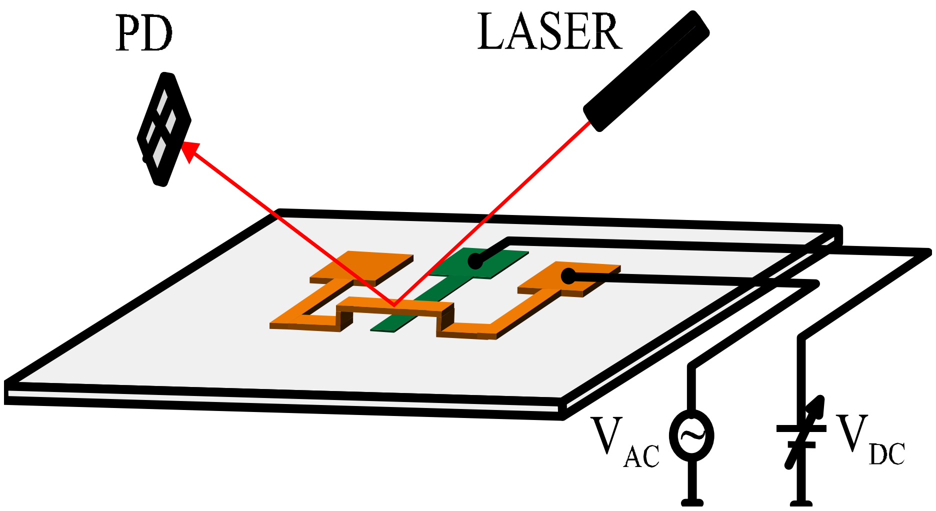
Electrostatic Actuation





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

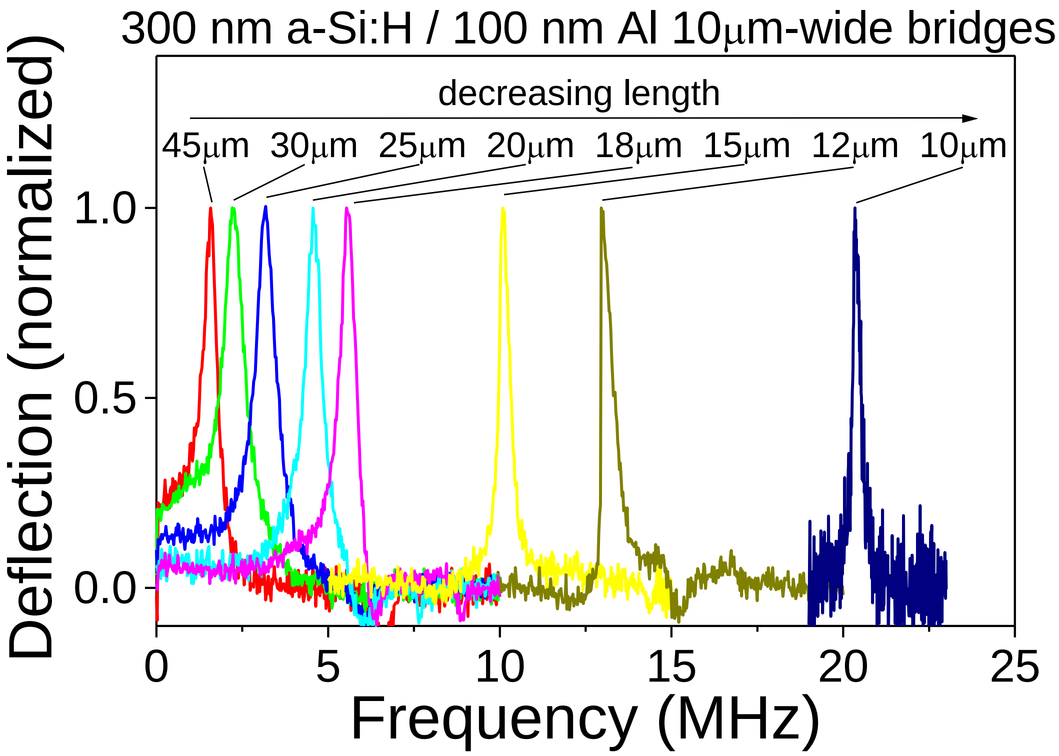
Optical detection



•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 μm-long a-Si:H bridges (*Q*~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