# 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**
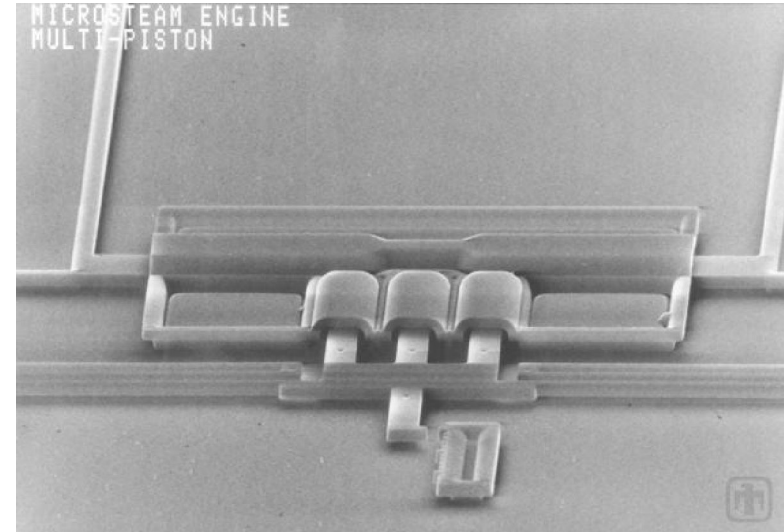- **Conclusions**

# 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
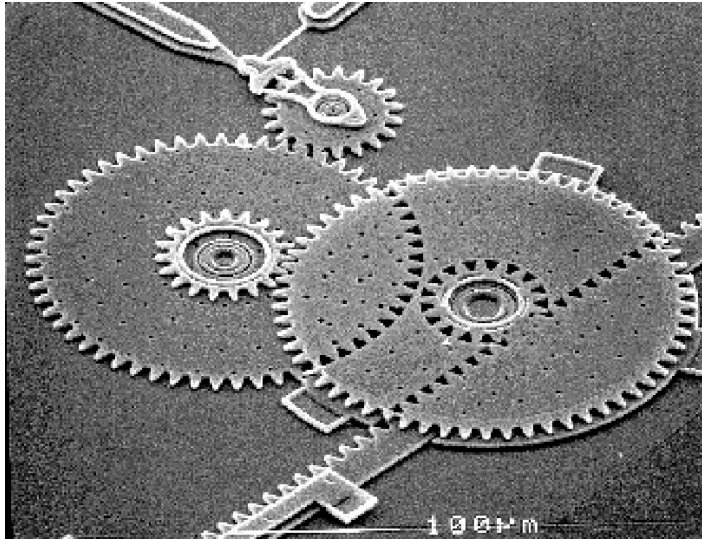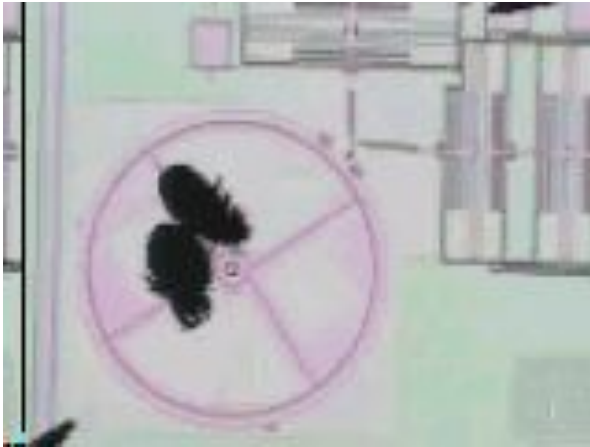


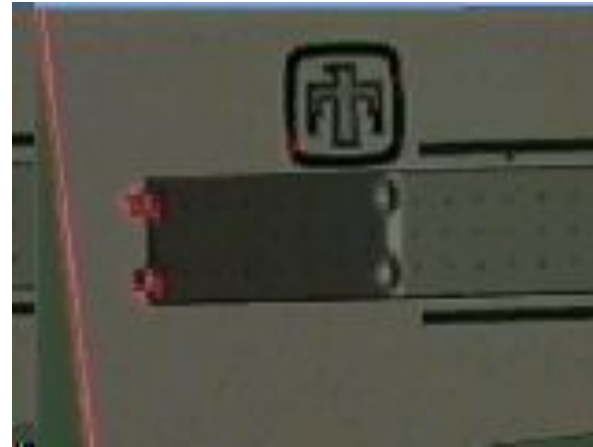**Linear Rack Gear Reduction Drive**



**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



Electroformed nickel orifice plate

Ink meniscus

Gold conductor

Ink barrier

Tantalum

Aluminum conductor

NMOS circuits

Tantalum resistor

CVD and thermal SiO$_2$

SiC/SiN passivation

Silicon substrate

after 5 $\mu s$

after 15 $\mu s$

after 24 $\mu s$
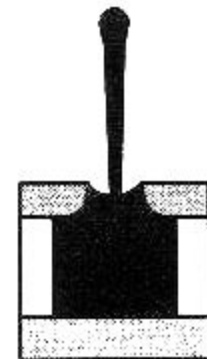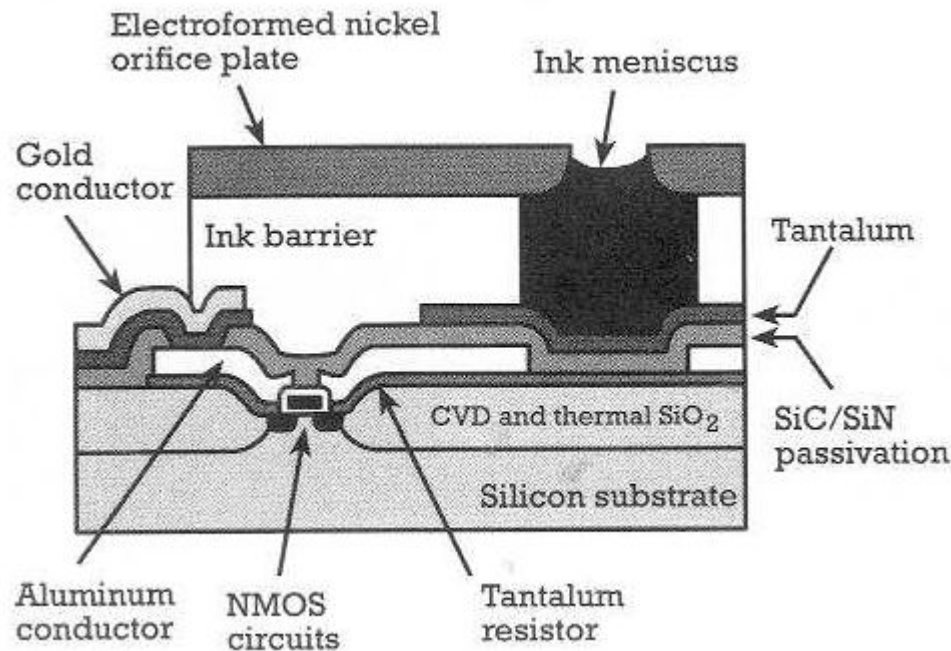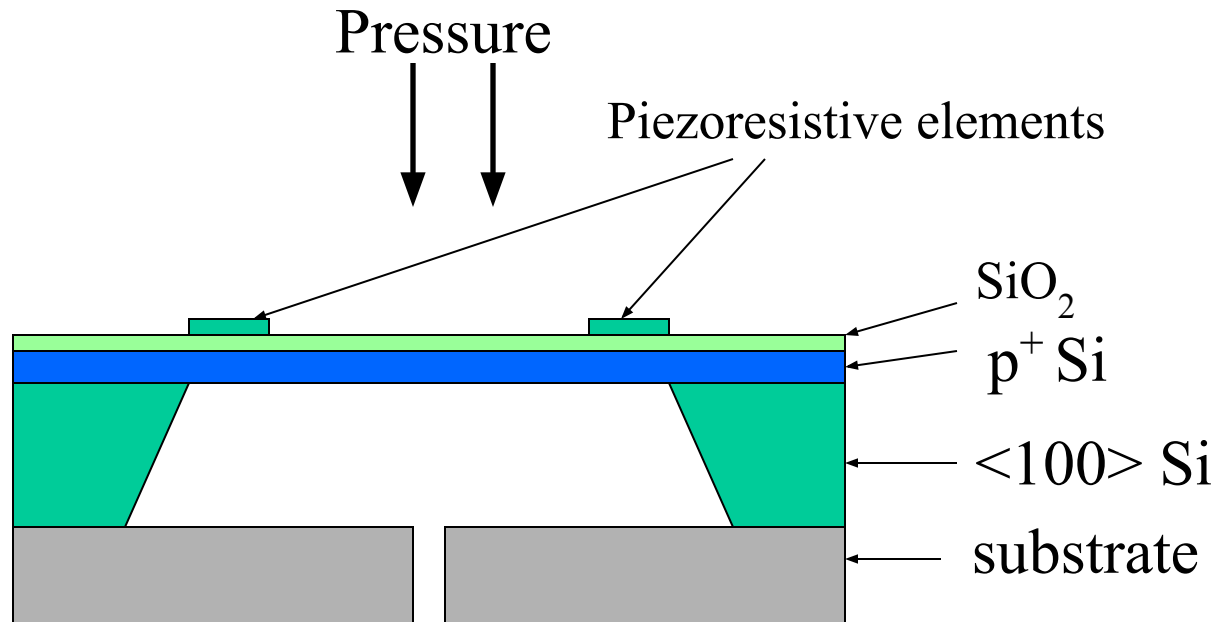
# Applications: Sensors

Pressure sensor:

- Piezoresistive sensing
- Capacitive sensing
- Resonant sensing

Application examples:

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

# Piezoresistive Pressure Sensors

Pressure

Piezoresistive elements

SiO$_2$

p$^+$ Si

<100> Si

substrate

# Piezoresistive Pressure Sensors
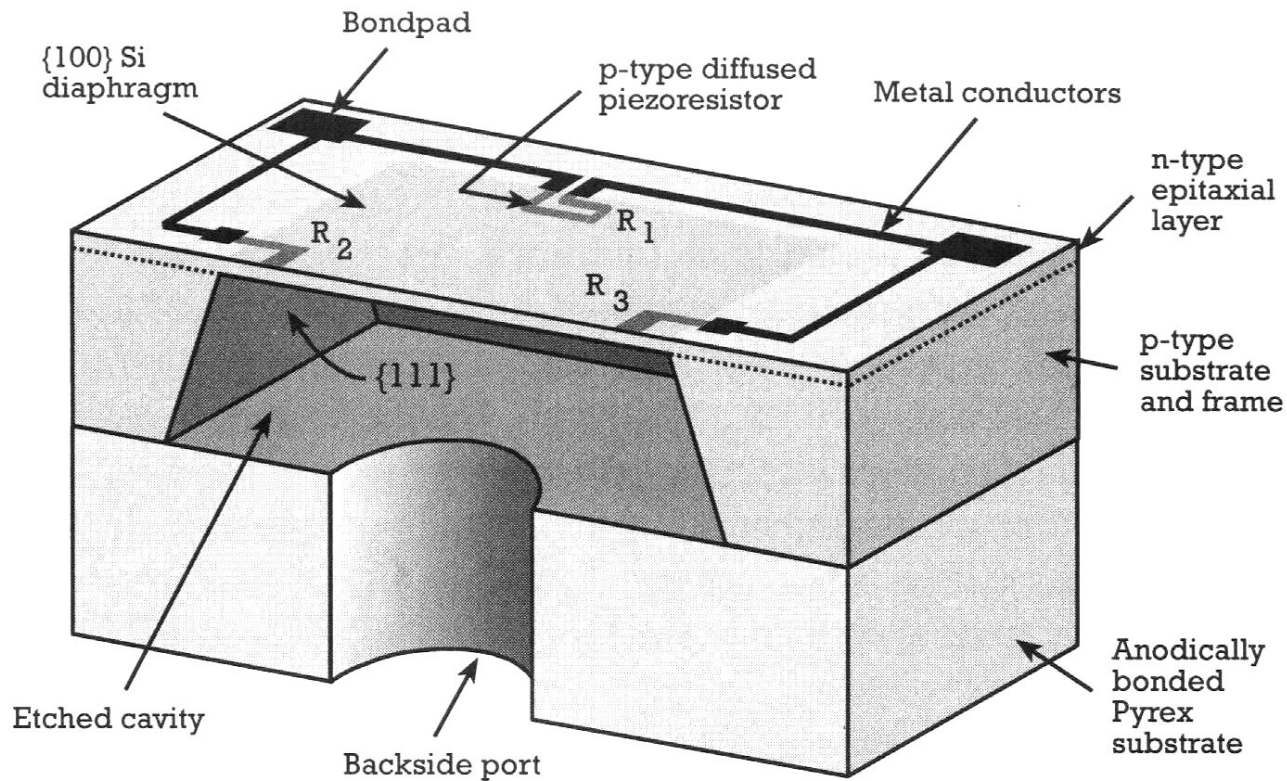
Wheatstone Bridge configuration



*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



Spring
F=k$x$

Damping
F=D$v$

Inertial mass
F=Ma
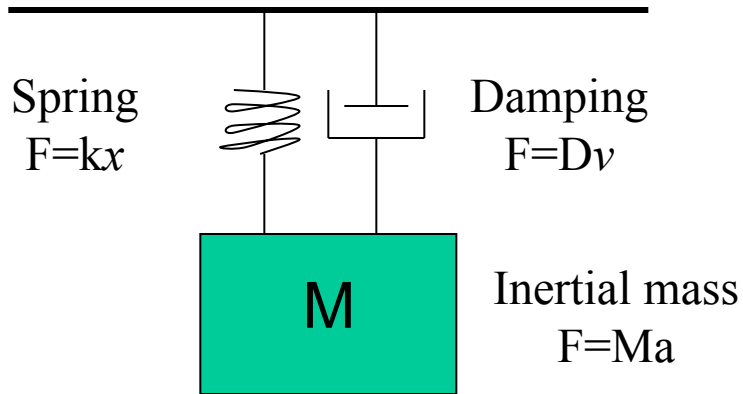
Static deformation:

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

Dynamic behavior

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

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

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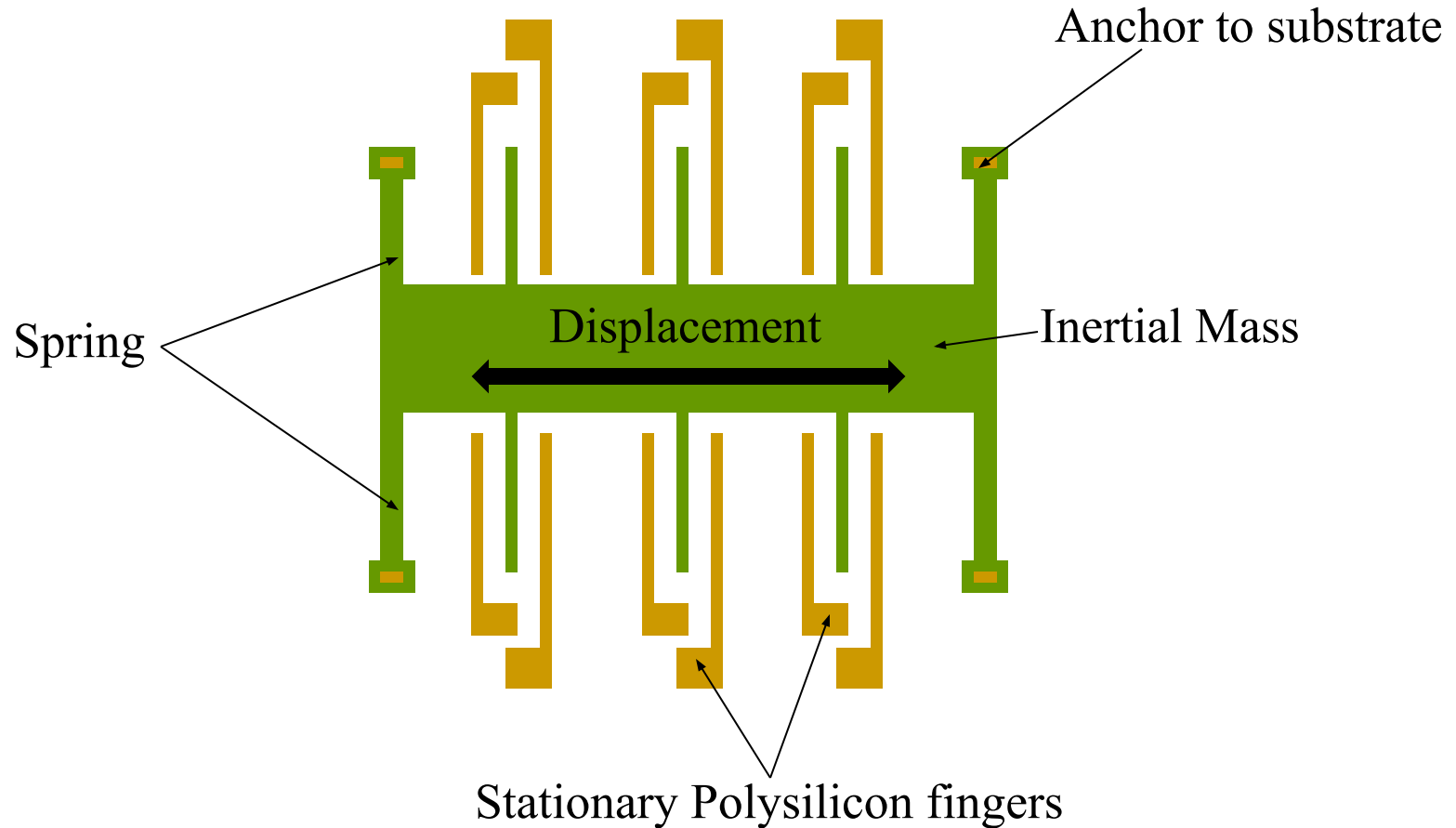
# Accelerometers

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

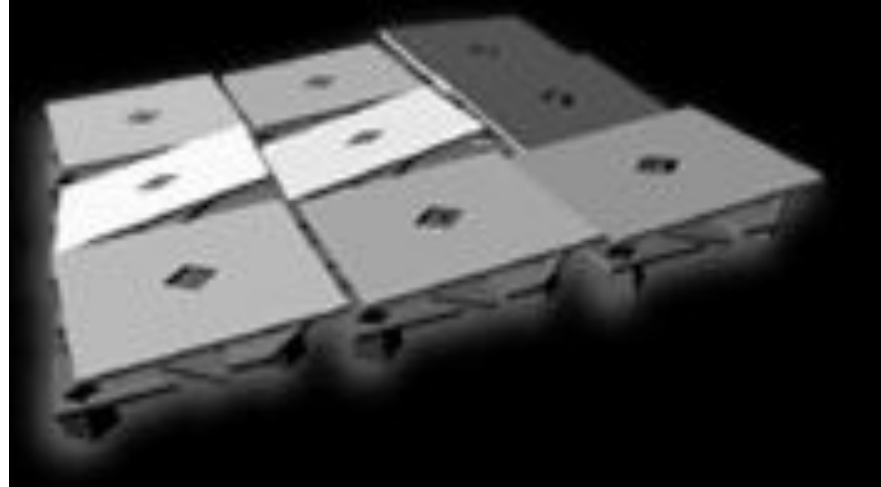| Application | Range | Bandwidth | Comment |
|---|---|---|---|
| Air Bag Deployment | ± 50 G | ~ 1 kHz | |
| Engine vibration | ± 1 G | > 10 kHz | resolve small accelerations (< 1 micro G) |
| Cardiac Pacemaker control | ± 2 G | < 50 Hz | multiaxis, ultra-low power consumption |

# Capacitive Accelerometers



Based on ADXL accelerometers, Analog Devices, Inc.
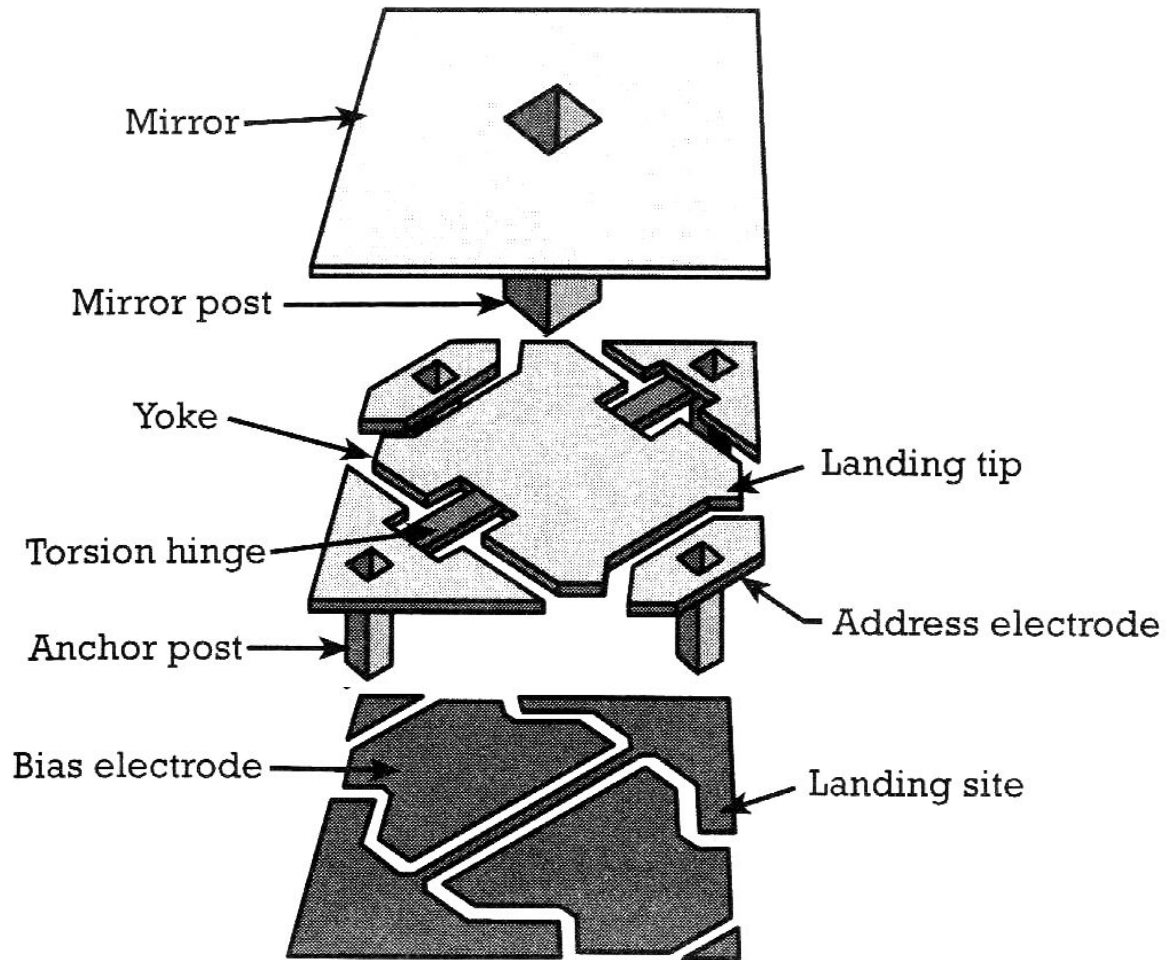
# Applications: Actuators

## Texas Instruments Digital Micromirror Device$^{TM}$



- 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

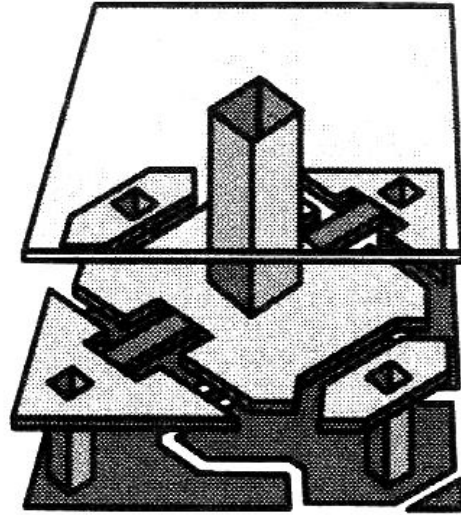- Resolutions: 800x600 pixels (SVGA) and 1280x1024 pixels (SXGA)

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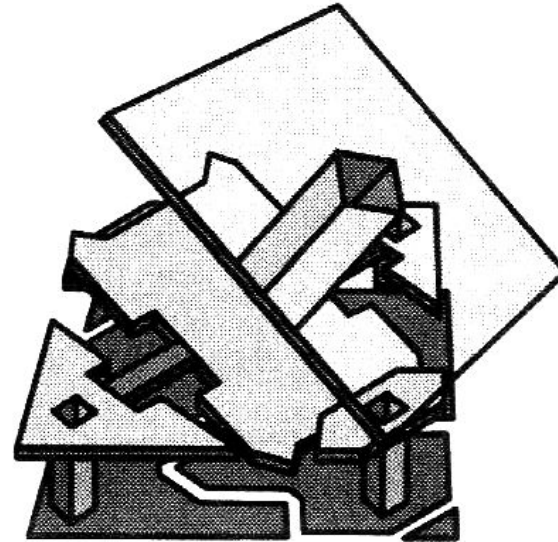**http://www.dlp.com/dlp_technology/**

# Digital Micromirror Device



Mirror

Mirror post

Yoke

Torsion hinge

Anchor post

Bias electrode

Landing tip

Address electrode

Landing site

# 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
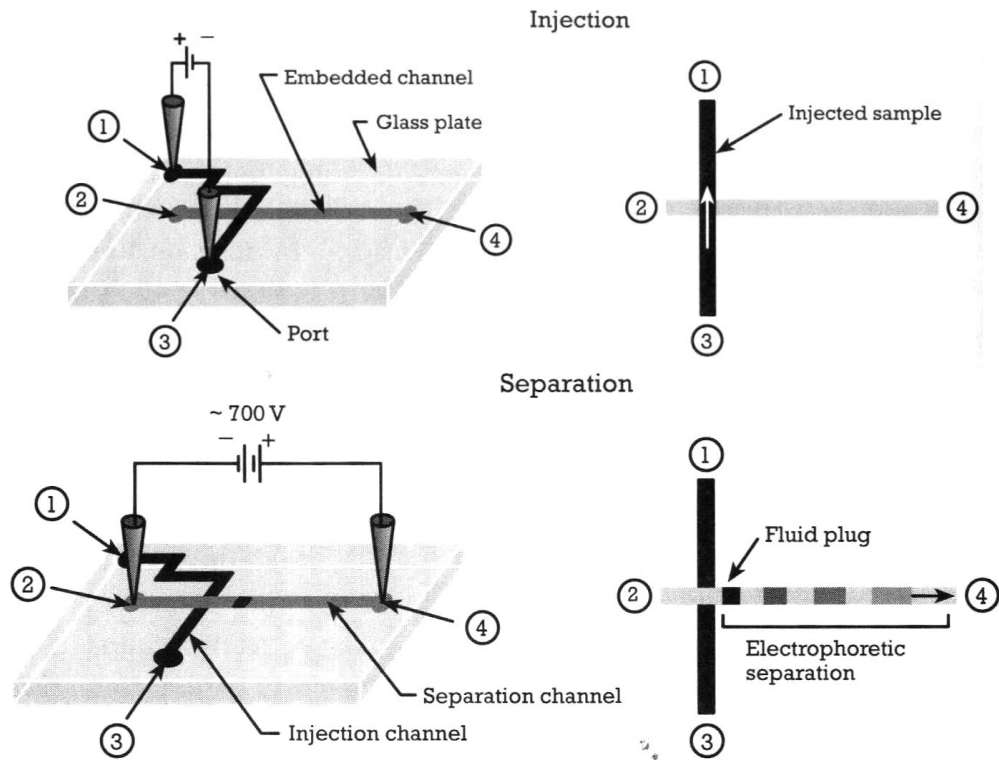


In the future, a complete DNA sequencing systems should include:
- Amplification (PCR)
- Detection (electrophoresis)
- Fluid preparation and handling (pumps, valves, filters, mixing and rinsing)

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 | $\dfrac{r_{etch}\langle 100\rangle}{r_{etch}\langle 111\rangle}$ | Selectivity to $p^+$- Si | Disadvantages |
|---|---|---|---|
| Potassium Hydroxide (KOH) | 100 | Yes | -Highly corrosive<br>-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
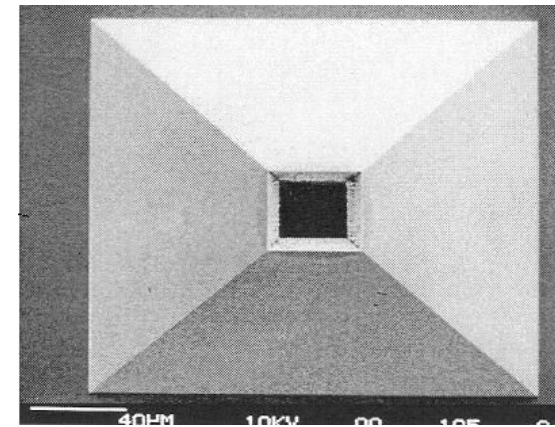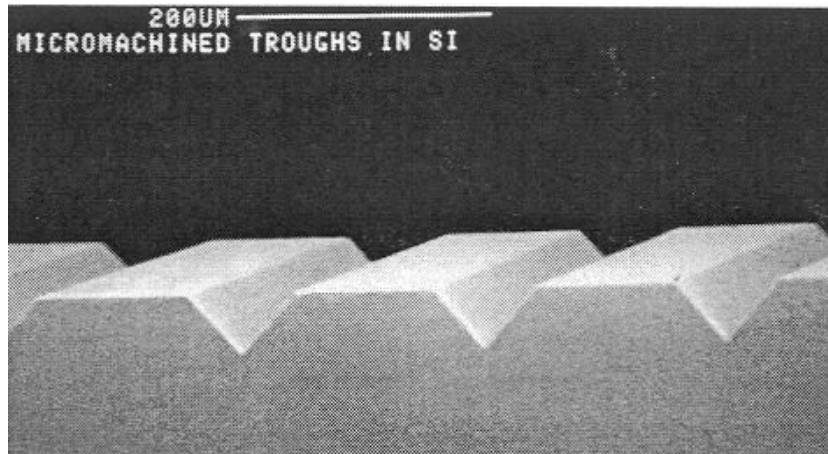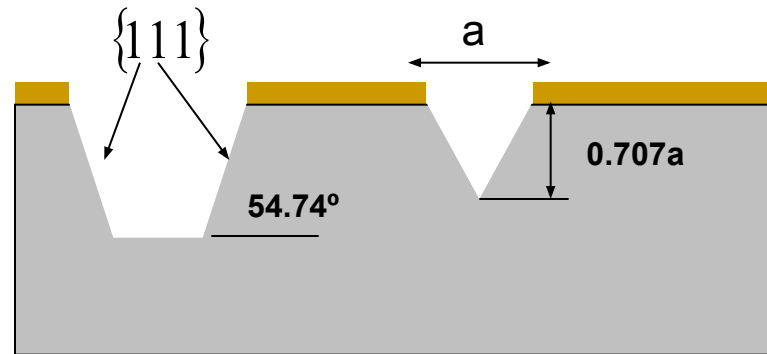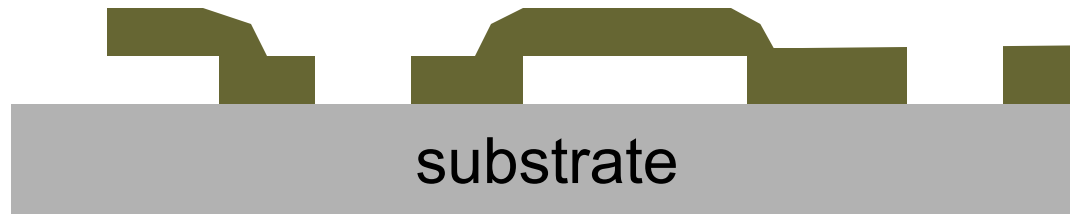
# Bulk micromachining: Pressure sensors

Piezoresistive elements

SiO$_2$

p$^+$ Si

<100> Si
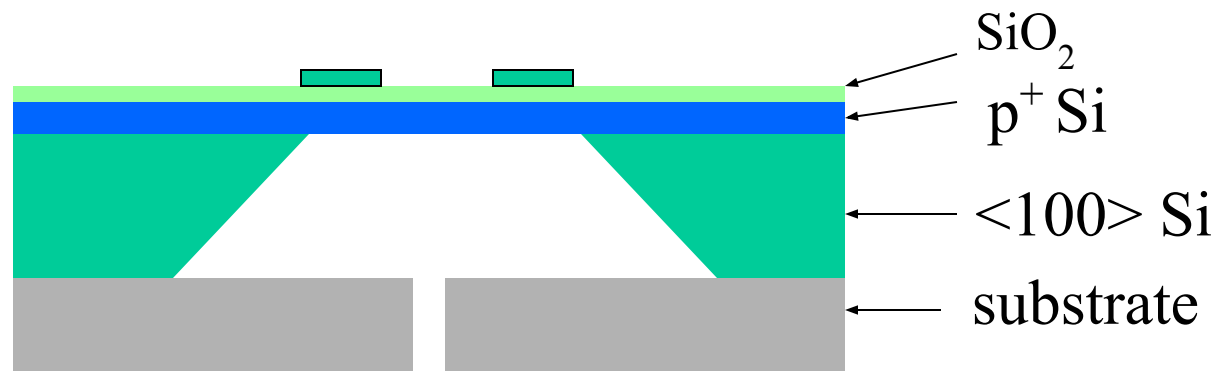
substrate

# 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<br>Plastic<br>metals | Polymer<br>Metals<br>silicon nitride | Thin film silicon (a-Si:H, μc-Si)<br>silicon nitrides<br>Silicon carbide<br>Metals<br>polymers<br>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
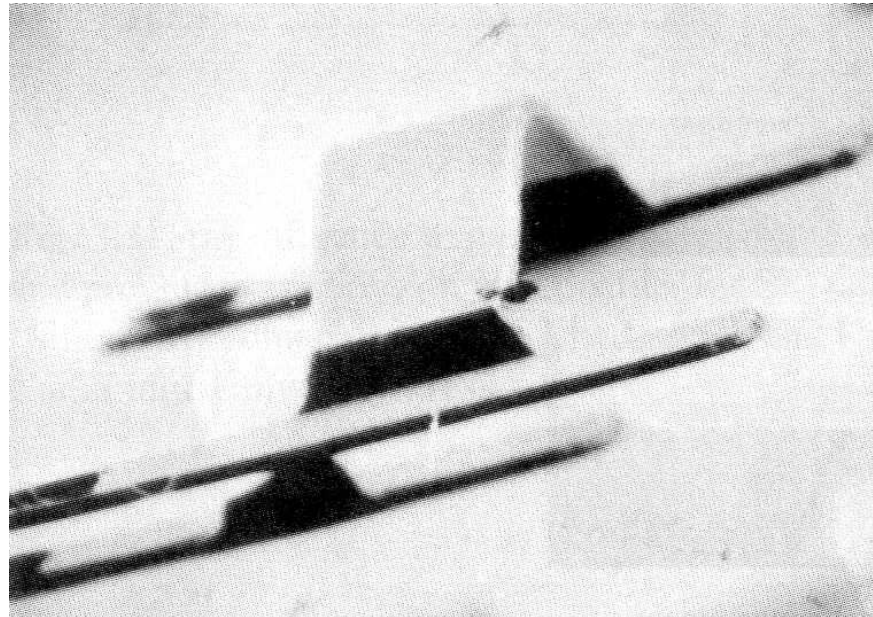


➡ Low temperature, thin film materials has much less intrinsic stress

*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.
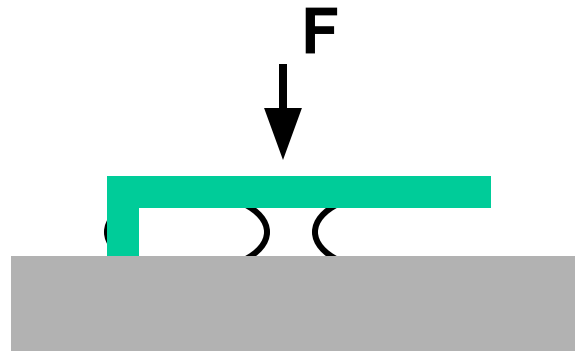


**To avoid this problem**
- make the structures stiffer (ie, shorter, thicker or higher Young's modulus)
- use super-critical drying in $CO_2$ (liquid $\rightarrow$ supercritical fluid $\rightarrow$ gas)
- roughen substrate to reduce contact area with structure
- coat structures with a hydrophobic passivation layer
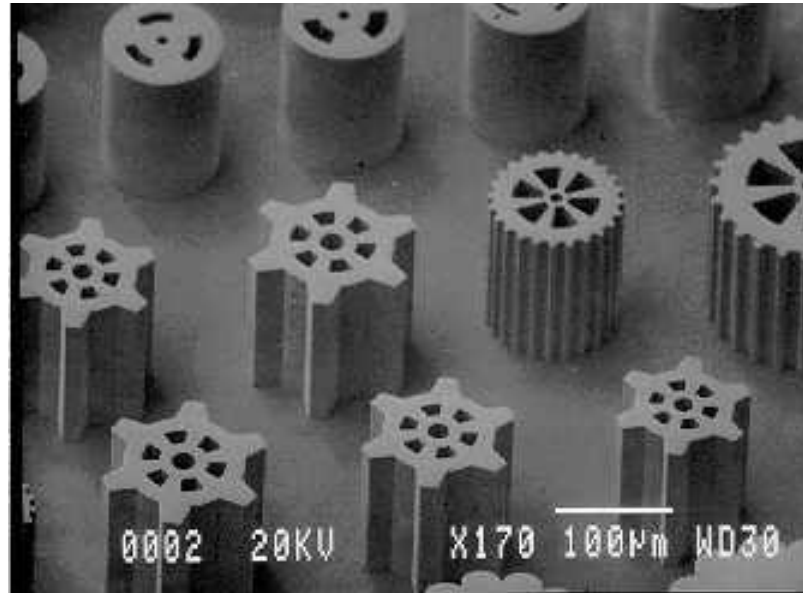
# LIGA – X-ray Lithography, Electroplating (Galvanoformung), Molding (Abformung)



Remove mold

Immerse in chemical bath and electroplate the metal

Expose and develop photoresist
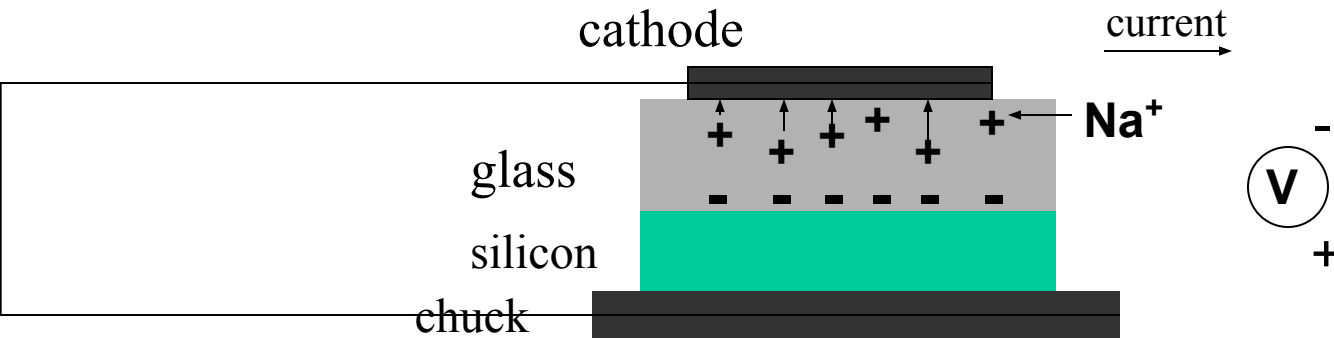
Deposit photoresist

Deposit plating base

# LIGA



*Photos from MCNC – MEMS group*

# Wafer bonding- Anodic



- bring sodium 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**
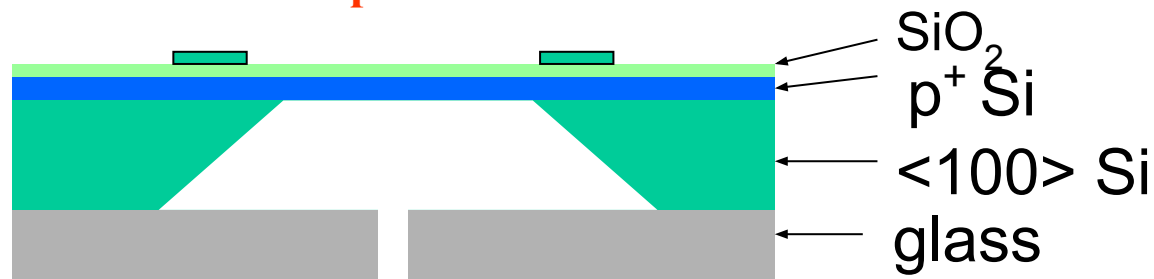
# Summary: MEMS fabrication

- 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)
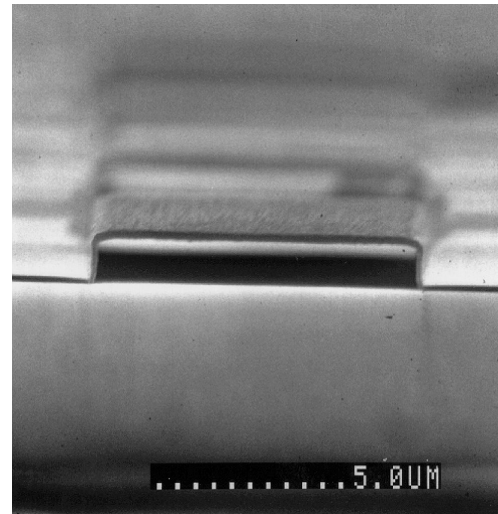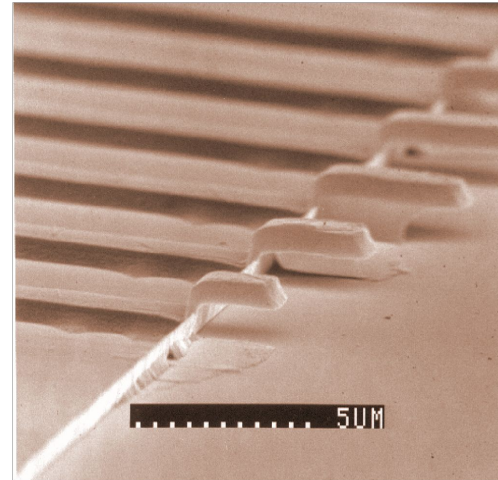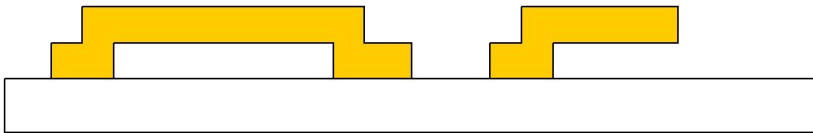
# Surface micromachining on glass



**Sacrificial Layer Deposition and Patterning**

**Structural Layer Deposition and Patterning**
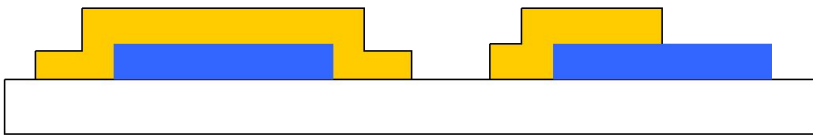
**Sacrificial Layer Removal**



5UM



5.0UM

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

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

# Electrostatic Actuation
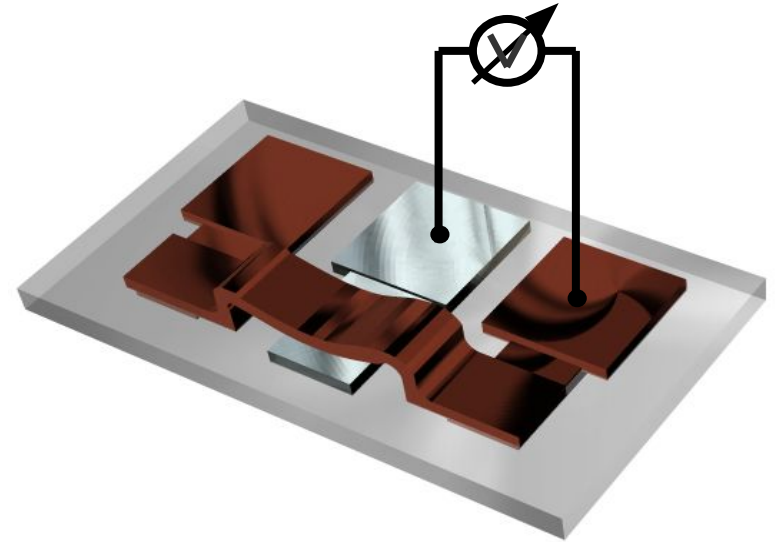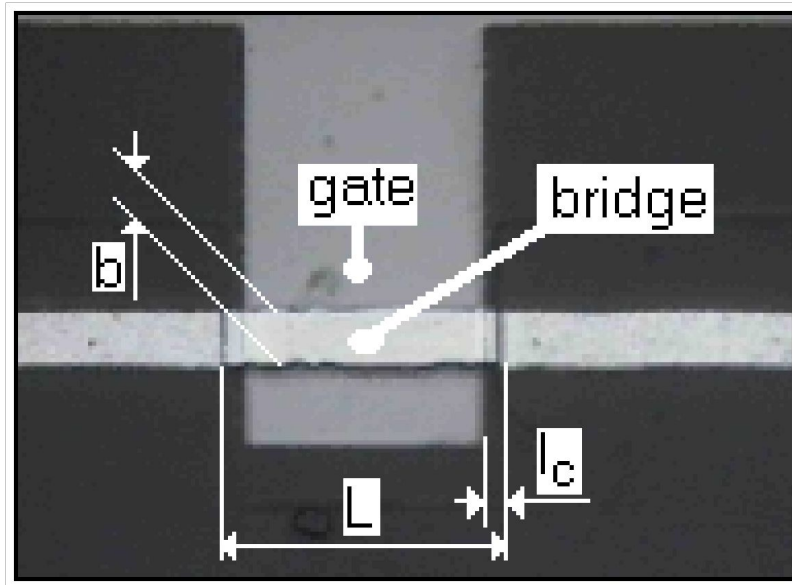


- **Electrostatic force between gate and counter-electrode**
- **Electrostatic force is always attractive**

# Optical detection
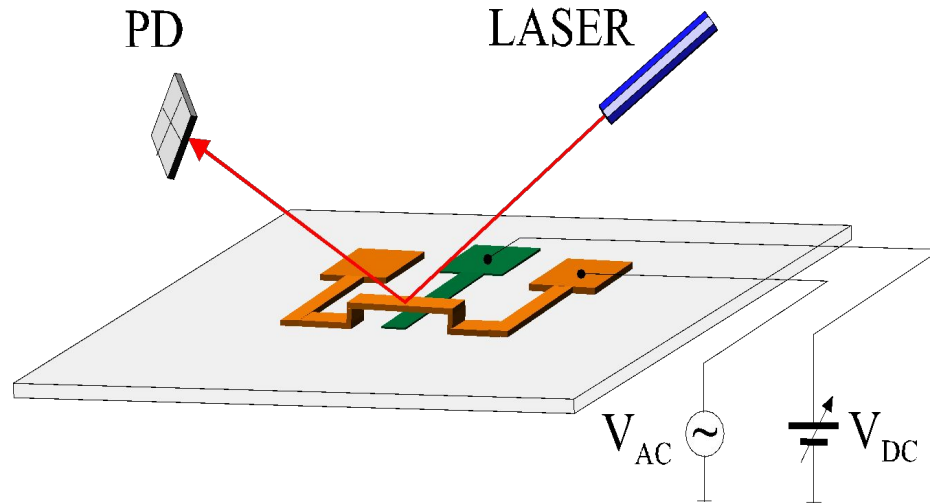


- A laser beam is focused on the structure and the reflected light is collected with an intensity (or quadrant) detector.

- The deviation of the beam is proportional to the deflection

# Resonance frequency



300 nm a-Si:H / 100 nm Al 10μm-wide bridges
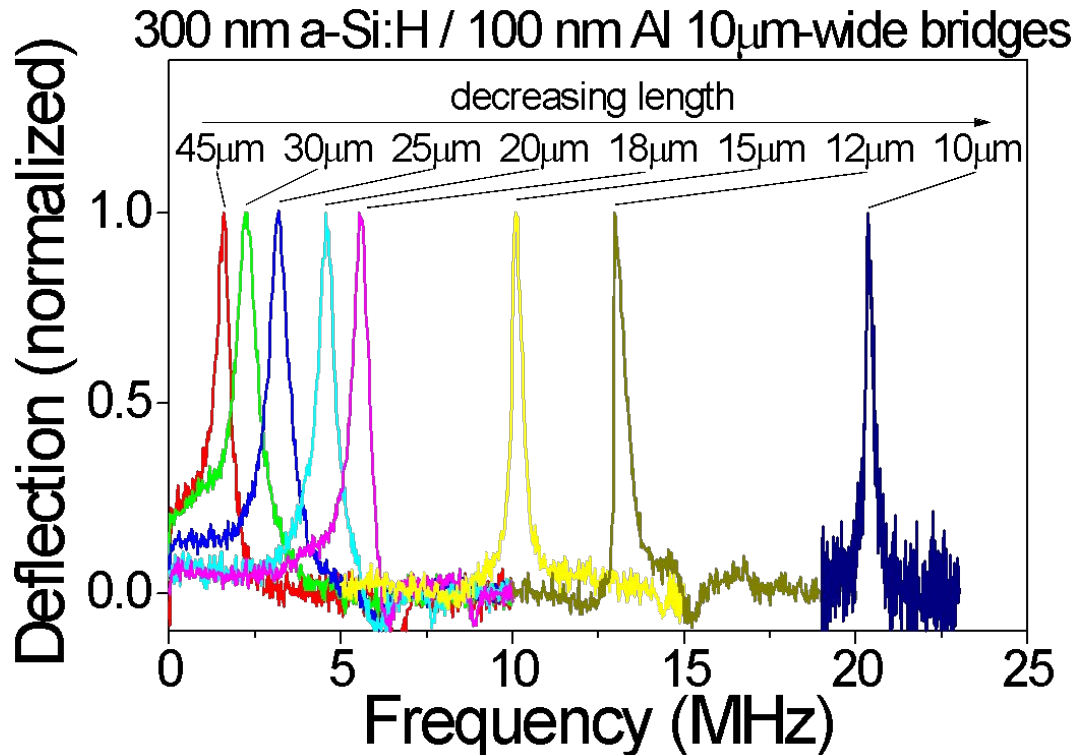
$$f_r = \frac{3.52}{2\pi L^2}\left(\frac{EI}{\rho A}\right)^{1/2}$$

- 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 ($Q\sim100$ in air; Q up to 5000 in vacuum)

# MEMS Resources

**Reference Books**

• Nadim Maluf, <u>An Introduction to Microelectromechanical Engineering</u> (Artech House, Boston, 2000)

• M. Elewenspoek and R. Wiegerink, <u>Mechanical Microsensors</u> (Springer-Verlag, 2001)

• Héctor J. De Los Santos, <u>Introduction to Microelectromechanical (MEM) Microwave Systems</u> (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