Mechanical MEMS

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Fundamentals of Micromachining

Mechanical Actuators

- Actuation mechanisms:
  - electrostatic = electrostatic attraction of charged plates
  - thermal = expansion of solids or fluids
  - shape memory alloy = considerable change in length
  - pneumatic/hydraulic = fluid pressure
  - piezoelectric = electrically induced strain
  - magnetic
  - chemical
  - biological

Electrostatic Actuators

- Based on attraction of two oppositely charged plates
- Typically low power
- Simple to fabricate
- Coulomb's law:

$$F_{elec} = \frac{1}{4\pi\varepsilon_r\varepsilon_o}\frac{q_1 q_2}{x^2}$$

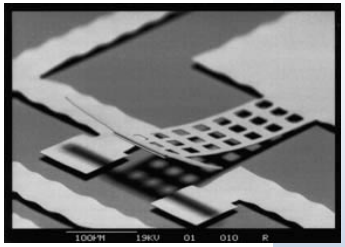
Electrostatic Actuation

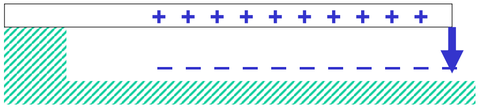
- Cantilever Actuators
  - electrostatic force

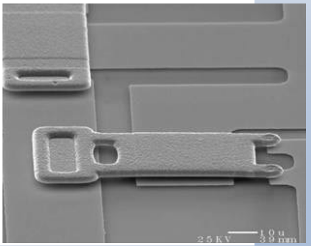
$$q(x) = \frac{\varepsilon_o}{2}\left(\frac{V}{d - d(x)}\right)^2$$

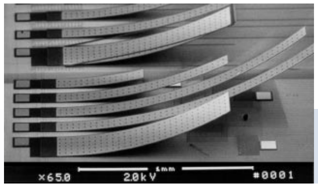
  - tip deflection

$$(d\delta)_T = \frac{x^2}{6EI}(3L - x)wq(x)dx$$



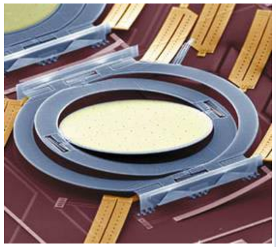


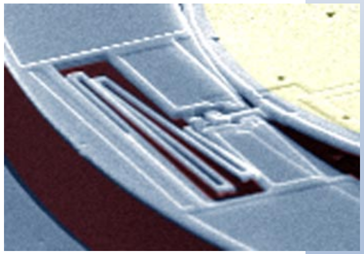




Electrostatic Actuation

- Fabrication
  - polysilicon with sacrificial oxide
  - electroplated metal with sacrificial organic layer
  - sputtered metal with sacrificial organic layer
- Torsional Actuators
  - dual deflection electrodes
  - small deflection

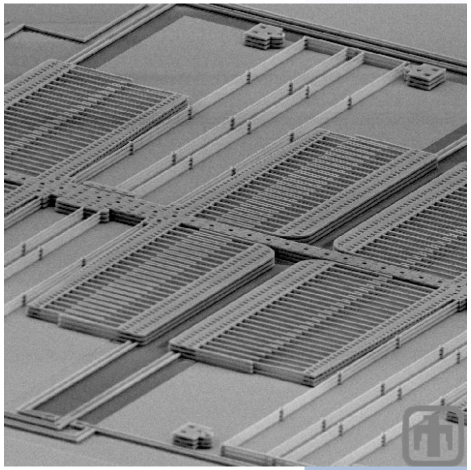


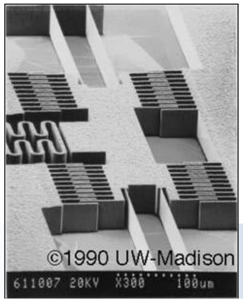


Torsional spring for mirror application

Electrostatic Actuation

- Comb Drives
  - use large number of electrostatically actuated fine “fingers”
  - attractive force is mainly due to fringing fields
  - generate large movements





Electrostatic Actuation

- Rotary Micromotors
  - use freely moving central rotor with surrounding capacitive plates
  - up to 300,000 rpm
  - up to 300 V
  - Fabrication:
    - polysilicon/oxide
    - metal/resist

Electrostatic Actuation

- Linear Micromotors (Scratch Drive Actuators)
  - uses flexible conductive plate with small bushing at one end
  - velocities up to > 1mm/s

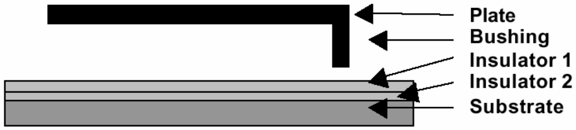


Figure 1 Schematic view of a representative SDA

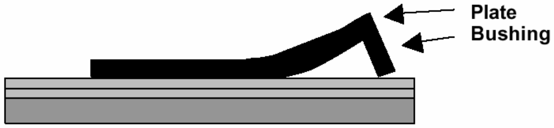
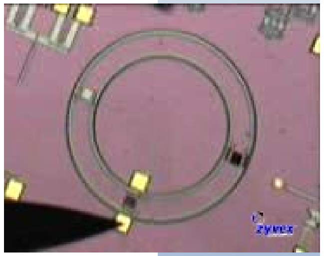
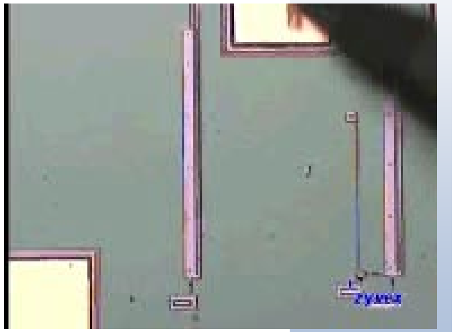


Figure 2 Schematic view of the SDA under the applied load



Thermal Actuation

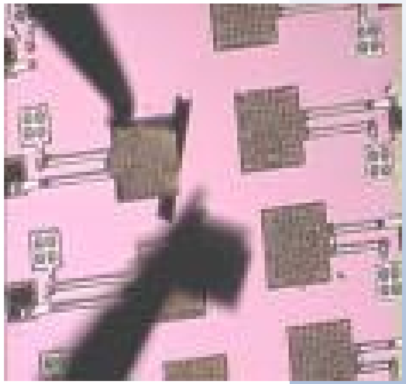
- Linear Thermal Expansion
- Volume Expansion/Phase-Change
- Bimorph Thermal Actuators
  - uses difference in thermal coefficients of expansion
  - heater is sandwiched between two “two” active materials
  - environmental ruggedness (+)
  - high power, low bandwidth (-)



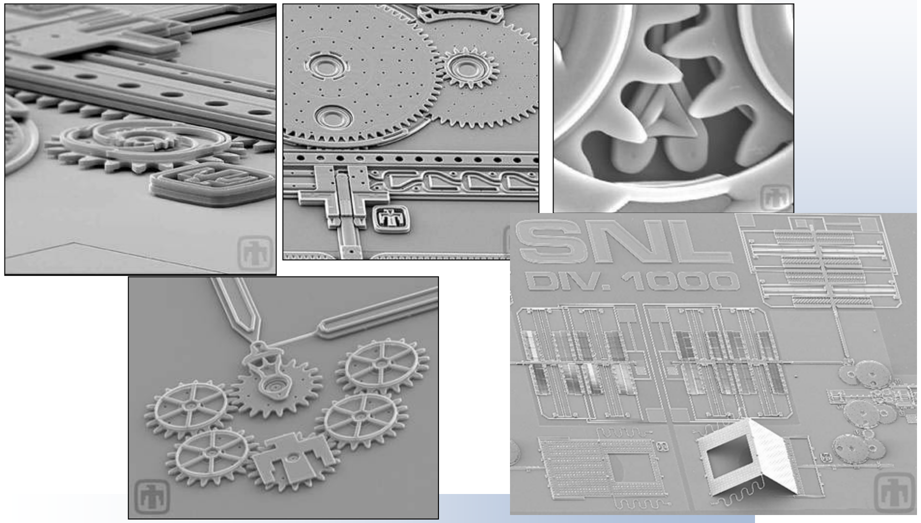
Thermal Bimorph Video

SMA Actuators

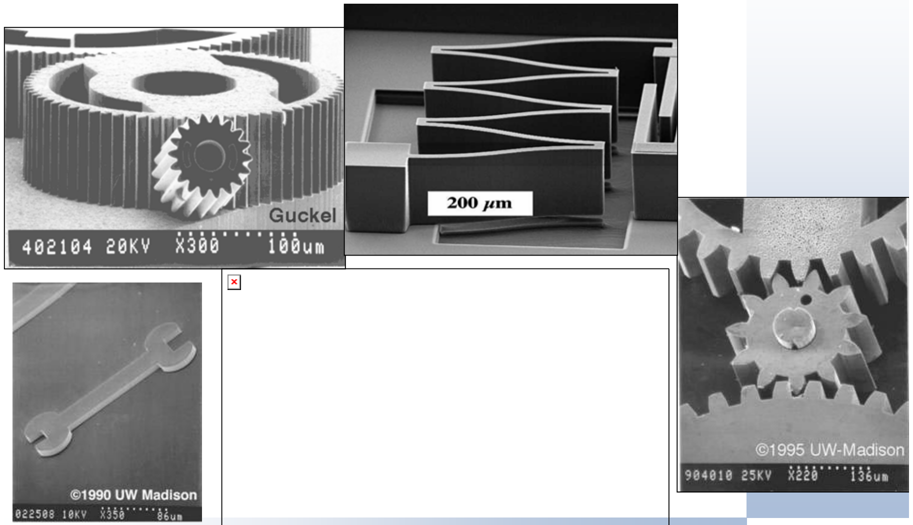
- Shape Memory Alloy (SMA) Actuators
  - use alloys that exhibit considerable changes in length when heated
  - heat causes material transition from one crystal phase to another
  - alloys: Au/Cu, In/Ti, Ni/Ti



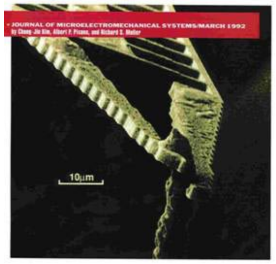
Gears from Sandia

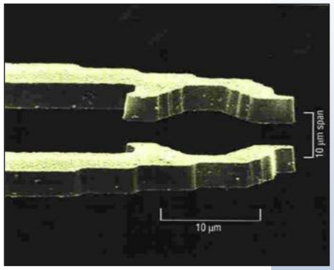


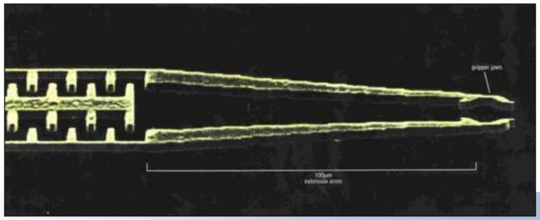
Random Mechanical Items



Micro-Grippers

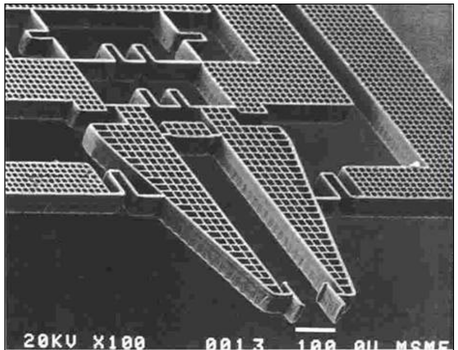


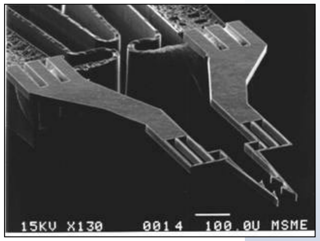


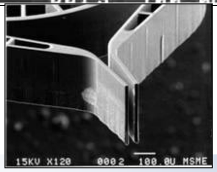


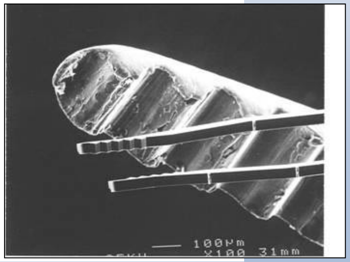
Source: Berkeley

Micro-Tweezers







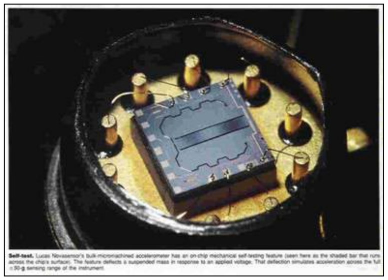


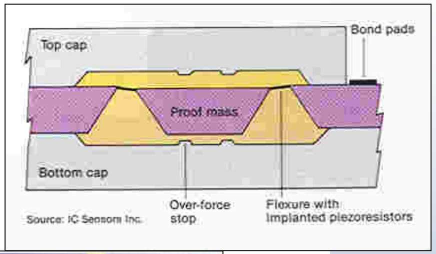
Source: MEMS Precision Instruments

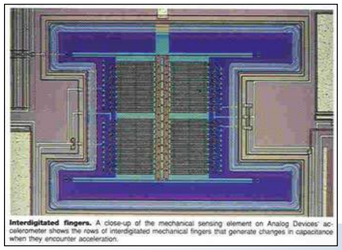
Strain Gages

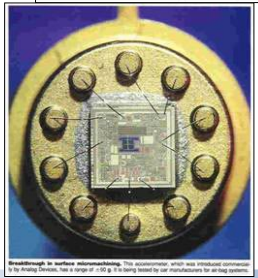
- Gage factor is defined as relative resistance change over strain
- Types include:
  - Metal foil
  - Thin-film metal
  - Bar semiconductor
  - Diffused semiconductor
- Implantable strain gages
- Penetrating micro-strain gage probe

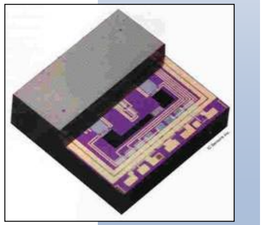
Accelerometers











Sources: Analog Devices, Lucas NovaSensor, and EG&G IC Sensors

Accelerometers

- F=ma is basic concept
- Force measured by deflection or strain
- Can be related to spring constant, F=kx
- Generally displacement of proof mass is measured relative to frame
- Dynamic system as described previously
- Strain gage type most basic
  - Strain in beam measured as proof mass deflects beam
  - Lots of configurations

Accelerometers

- Capacitive accelerometers most commercialized
  - Torsion bar with assymetric plates
- Force-balanced capacitive used in autos
  - Comb of capacitors measures differential capacitance
  - Highly sensitive, typical displacement only 10 nm
  - Force feedback to maintain central location of proof mass
  - Force required to maintain equilibriumgenerates signal

Accelerometers

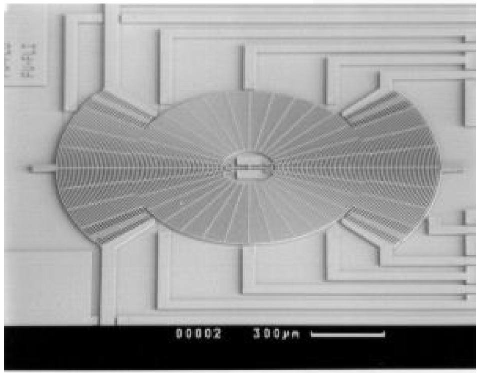
- Piezoelectric accelerometers
  - Generally show no DC response
    - Special circuitry to create DC response
  - Typically use ZnO
- Tunneling accelerometers
  - Highly sensitive
  - More difficult to fabricate
  - Requires closed loop control
  - Long term drift
- Latching accelerometers
  - Lock in place if acceleration exceeded

Accelerometers

- Switch arrays
  - Array of switches sensitive to increasing levels of acceleration
  - Simple to build
  - Optimizes range of accelerometer in use
- Multi-axis acclerometers
  - Only one example to date
  - Cross-axis sensitivity problem
  - Precise alignment and low cost are advantages
- All require extensive circuitry

Gyroscopes

- Measure rotation
- Couple energy from one vibrational axis to another due to Coriolis effect
- Two micromachined modes: Open loop vibration and Force-to-rebalance mode
- Vibrating prismatic beams
  - Beam driven in one direction, deflection measured in orthogonal direction



Gyroscopes

- Tuning forks
  - Large inertial mass, increased sensitivity
  - Metallic ring structure
- Dual accelerometer
- Vibrating shells
  - Two-axis
  - Vibration in z direction
  - Output in both x and y

Pressure Sensor (conventional)

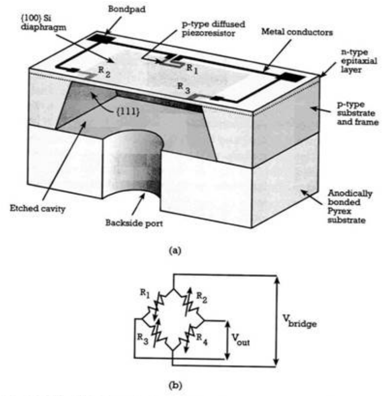


Figure 4.5 (a) Schematic illustration of a pressure sensor with diffused piezoresistive sense elements. (b) The four sense elements form a Wheatstone bridge configuration.

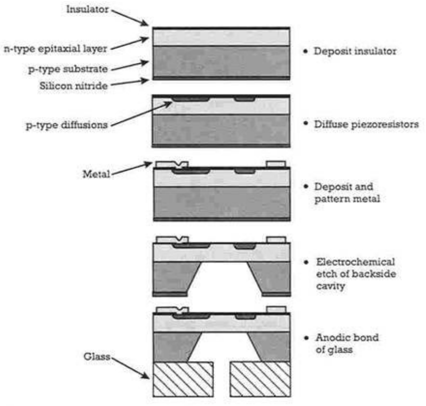
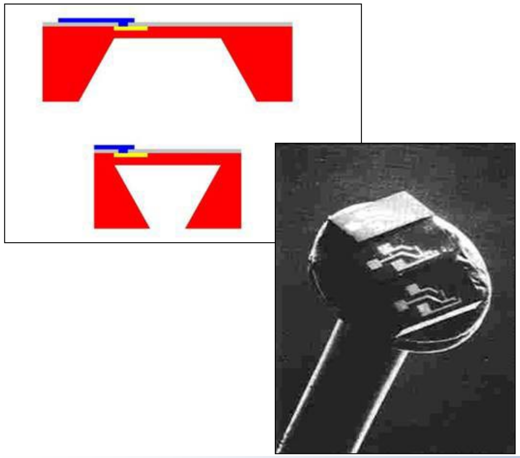
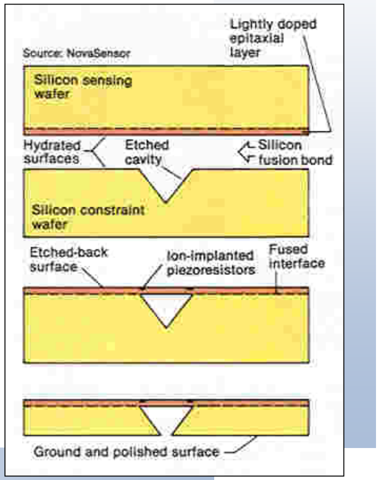


Figure 4.6 Fabrication steps for a piezoresistive gauge, or differential, bulk micromachined pressure sensor.

Source: Maluf

Pressure Sensor (ultra-miniature)





Source: NovaSensor

Piezoresistive Pressure Sensors

- Piezoresistivity is a material property where bulk resistivity is influenced by mechanical stress applied to material
- Common piezoresistors: Si, poly Si, SiO2, ZnO
- Typical design: 4 piezoresistors in a Wheatstone bridge on a diaphragm
- Pressure sensitivity (mV/V-bar): $S = (\Delta R/\Delta P)(1/R)$

Capacitive Pressure Sensors

- Capacitive sensors convert charge into change in capacitance
- Advantages:
  - more sensitive than piezoresistive
  - less temperature dependent
- Disadvantages:
  - gap fabrication
  - diaphragm mechanical properties

Capacitive Pressure Sensors

- Basic concept: $C = \varepsilon A/d$
- Sensitivity: $\Delta C/\Delta d = -\varepsilon A/d2$
- Small Gaps:
  - larger capacitance
  - easier capacitance detection
  - plates may stick together
- Large Gaps:
  - small capacitance
  - may require wafer bonding

Microphones

- Convert acoustic energy into electrical energy
- High sensitivity pressure sensors
- Types:
  - Capacitive
    - variable gap capacitor; most common
    - require DC bias
    - sensitivity: 0.2 to 25 mV/Pa
    - response: 10 Hz to 15 kHz

Microphones (cont)

- Piezoresistive
  - diaphragm with 4 pezoresistors in a Wheatsone bridge
  - sensitivity: ~25 μV/Pa
  - response: 100 Hz to 5 kHz
- Piezoelectric
  - use piezoelectric material mechanically coupled to diaphragm
  - sensitivity: 50 to 250 μV/Pa
  - response: 10 Hz to 10 kHz