Wright State University

EE480/680
Micro-Electro-Mechanical Systems (MEMS)
Summer 2006

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Transducers: Actuators

Overview

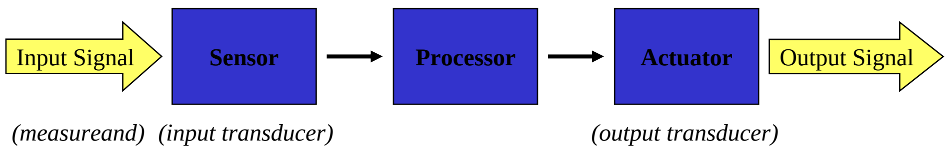
- Transducers
- Basic Mechanics
- Actuators
  - Electrostatic
  - Electro-Thermal
  - Bimorph Electro-Thermal
  - Residual Stress
  - Mechanical Components

Transducers

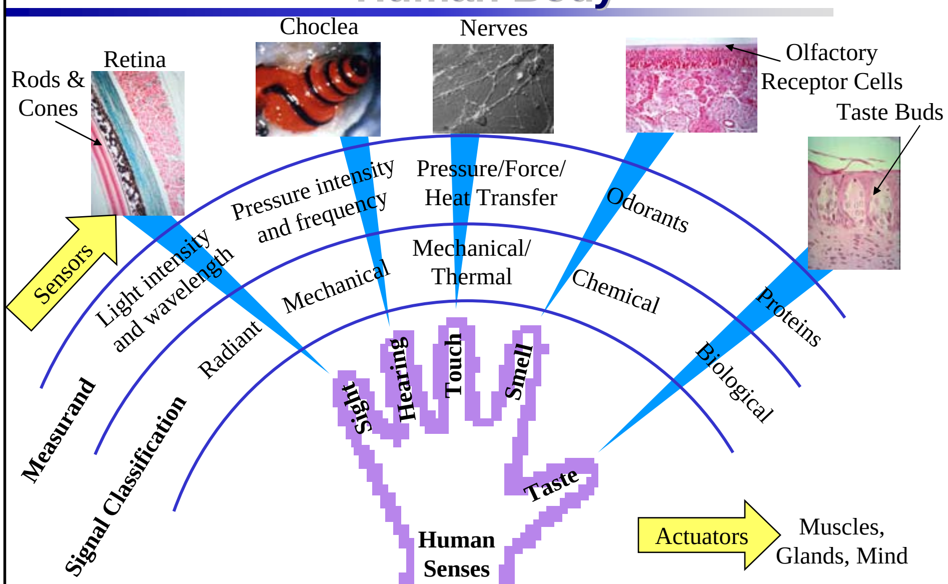
- Transducer: a device that transfers power from one form to another
- Transducers can be divided into two categories
  - Sensors – reacts to environment
  - Actuators – acts on environment
- Can you think of common examples of sensors and actuators?

Transducers

- Transducer Schemes
  - One or more of the below components may or may not be utilized
  - A transducer can perform a dual role as sensor and actuator



Transducers: Examples from the Human Body



Transducers

- Sensor Classification

After Gardner, *Microsensors*, 1994.

Signal Classification	Measurands
Thermal	Temperature, heat, heat flow, entropy, heat capacity, and etc.
Radiation	Gamma rays, X-rays, ultra-violet, visible, infra-red, micro-waves, radio waves, phase, and etc.
Mechanical	Position, displacement, velocity, acceleration, force, torque, pressure, mass, flow, acoustic wavelength and amplitude, and etc.
Magnetic	Magnetic field, flux, magnetic moment, magnetization, magnetic permeability, and etc.
Chemical	Humidity, pH level and ions, concentration of gases, vapors and odors, toxic and flammable materials, pollutants, and etc.
Biological	Sugars, proteins, hormones, antigens, and etc.
Electrical	Charge, current, voltage, resistance, conductance, capacitance, inductance, dielectric permittivity, phase, frequency, and etc.

Transducers

- Actuator Classification

Signal Classification	Action
Thermal	heat, cool, radiate, and etc.
Radiation	emit light and other radiation
Mechanical	Provide displacement, velocity, acceleration, force, torque, pressure, mass, flow, and etc.
Magnetic	Provide magnetic field, flux, magnetic moment, magnetization, magnetic permeability, etc.
Chemical	Change/Provide humidity, pH level and ions, concentration of gases, vapors and odors, muscle stimulation, and etc.
Biological	Provide mechanical actuation, computing, etc.
Electrical	Provide charge, current, voltage, and etc.

Transducers

- Ideal Sensor Characteristics
  - Linear Operation
  - Noise Free Response
  - Zero Baseline
  - Fast Response Time
  - Large Frequency Bandwidth
  - No Saturation
  - High Sensitivity
  - High Resolution
  - Reliable and Rugged
  - No Performance Drift
  - Intolerant to Interference
  - No Hysteresis, Repeatable
  - Low Power Consumption
  - Simple Construction

- Ideal Actuator Characteristics
  - Aforementioned, plus ….

  - High Force Per Unit Volume
  - Large Deflections
  - Simplicity of Drive and Control
  - Simple Interface

Overview

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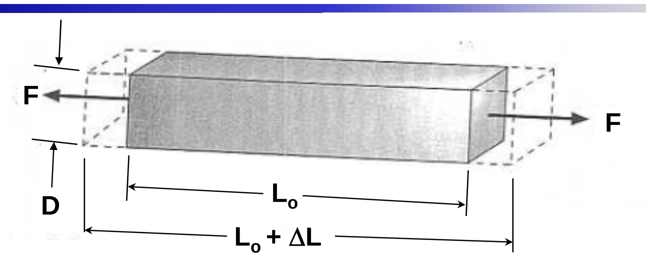
  - Bimorph Electro-Thermal
  - Residual Stress
  - Mechanical Components

Axial Stress & Strain

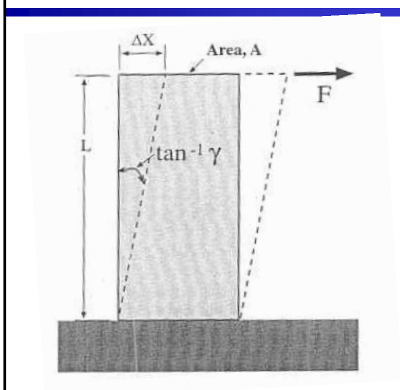


- Strain, ε, is the deformation of a solid (ΔL/L) due to stress
- Stress, σ, is the force acting on a unit area of a solid (F/A)
- The Young's Modulus, E, is the ratio of stress over strain
  - describes the "firmness" of a material (hard, E Large, soft, E small)

$$E = \frac{stress}{strain} = \frac{\sigma}{\varepsilon}$$ (typically in N/m^2)

Micromachined Transducers Sourcebook G. Kovacs ©1997

Shear Stress & Strain



- Shear stress is force applied to an object in the plane of an opposing force
  - Such as an anchor point
- The shear modulus of elasticity, G, represents the degree of displacement an object will allow under shear stress.
- Shear strain, γ, is related to the angle that a deformed element's sides make with respect to its original shape

$$G = \frac{\text{shear stress}}{\text{shear displacement angle (rad)}} = \frac{\tau}{\gamma} = \frac{\frac{F}{A}}{\frac{\Delta X}{L}}$$ (typically in N/m^2)

Micromachined Transducers Sourcebook G. Kovacs ©1997

Shear Stress & Strain Cont.

For isotropic materials (those having identical properties in every direction, generally not the case for most single-crystal materials, Shear modulus, G, is related to the elastic modulus, E, by

$$E = 2G(1+\mu) = 3K(1-2\mu)$$

μ is Poisson's ratio
K is the bulk modulus

The bulk modulus is defined as the ratio of hydrostatic stress to volume compression

$$K = \frac{\text{hydrostatic stress}}{\text{volume compression}} = \frac{\frac{F}{A}}{\frac{\Delta V}{V}}$$ in N/m^2

The bulk modulus of a material represents its volume change under uniform pressure. In general, solids are less compressible than liquids due to their rigid atomic lattices

For Ex.
- Water – K = 2.0 x 10^9 N/m^2
- Aluminum – K = 7 x 10^{10} N/m^2
- Steel – K = 14 x 10^{10} N/m^2

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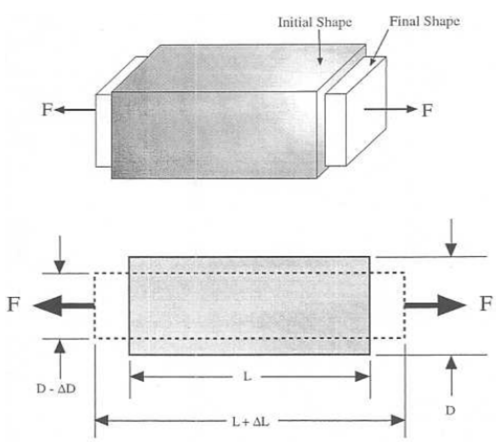
Poisson's Strain



$$\varepsilon_a = \frac{\Delta L}{L_o}$$ axial strain

$$\varepsilon_t = \frac{\Delta D}{D_o}$$ transverse strain

$$\mu = \frac{\text{transverse strain}}{\text{longitudinal strain}} = -\frac{\varepsilon_t}{\varepsilon_a} = -\frac{\frac{\Delta D}{D_o}}{\frac{\Delta L}{L_o}}$$

Poisson's ratio ν or μ always defined as a positive value

- Typical values are 0.2 to 0.5 for most materials
- For most metals, Poisson's ratio is ~ 0.3
- Rubber's have a Poisson's ratio closer to 0.5
- Cork has a Poisson's ratio close to 0

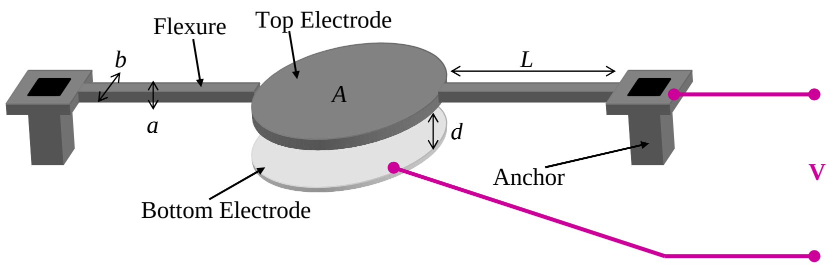
Micromachined Transducers Sourcebook G. Kovacs ©1997

Actuators: Electrostatic

- Advantages
  - Simple Designs
  - Simple Fabrication
  - High Frequency Operation
  - Low Power
- Disadvantages
  - Low Force Per Unit Volume
  - High Drive Voltages
  - Nonlinear Operation

Actuators: Electrostatic

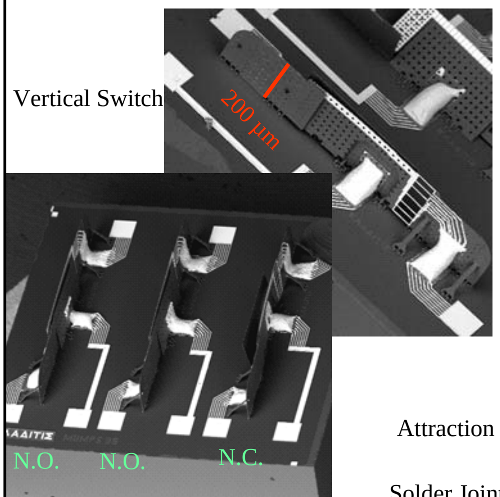
- Parallel Plate
  - Two plate like structures facing each other, with a potential difference between them, will be drawn together due to the force of electrostatic attraction.

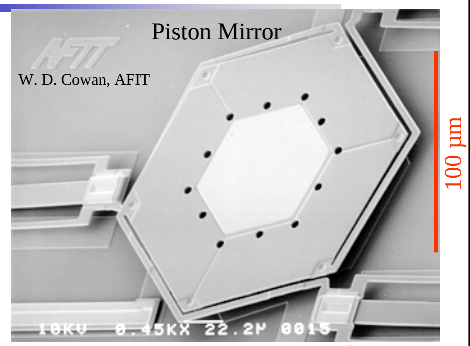


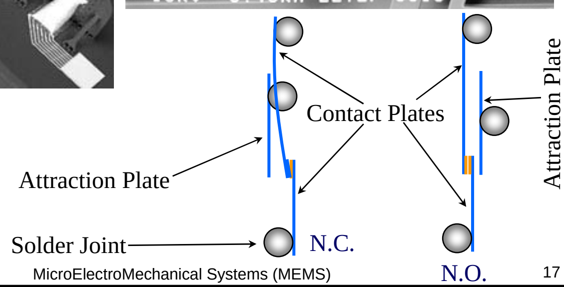
Actuators: Electrostatic

- Parallel Plate Examples

Vertical Switch

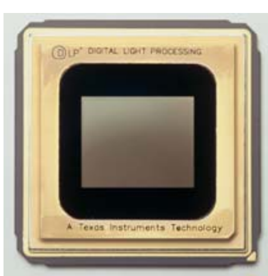






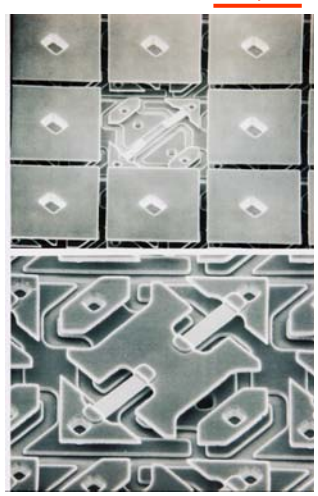
Actuators: Electrostatic

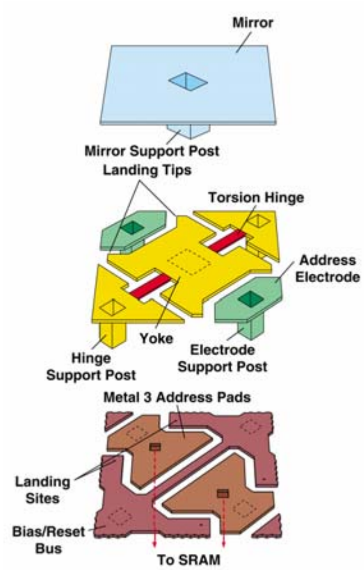
- Parallel Plate Examples: Texas Instruments Digital Micromirror Device™



SXGA device with black aperture: 1280x1024; 1,310,720 mirrors

16 μm



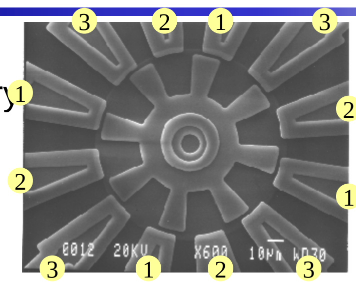


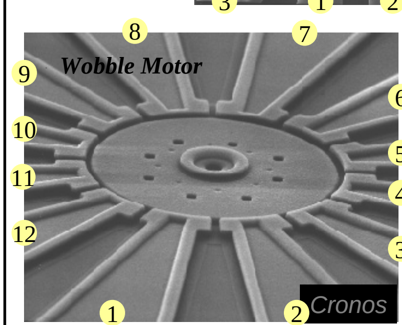
Actuators: Electrostatic

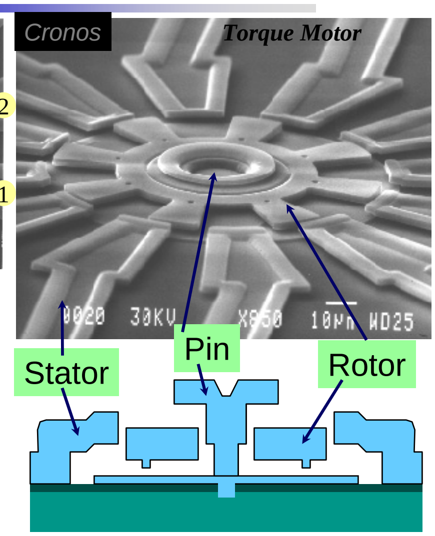
- Notes:
  - Displacement vs. Actuation Voltage
  - Spring Constants
  - Damping Coefficient
  - Lumped Element Dynamic Model

Actuators: Electrostatic

- Rotary



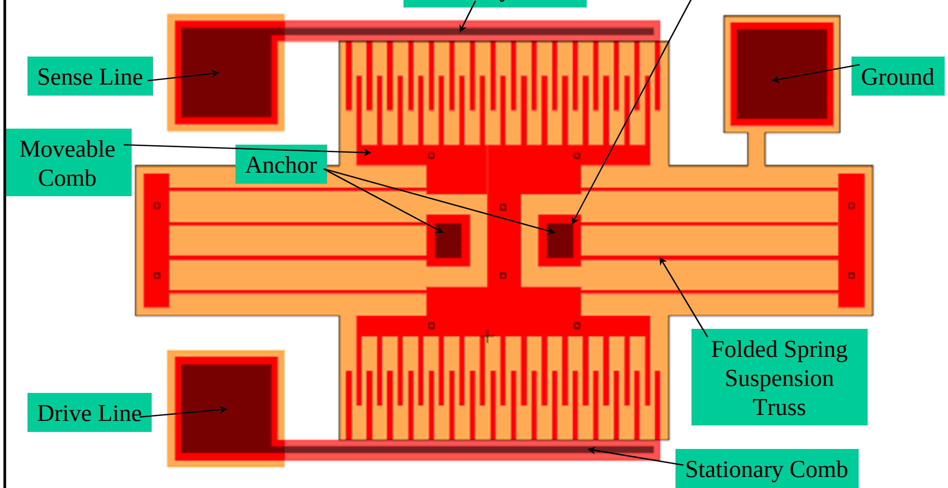




Cross section of motor

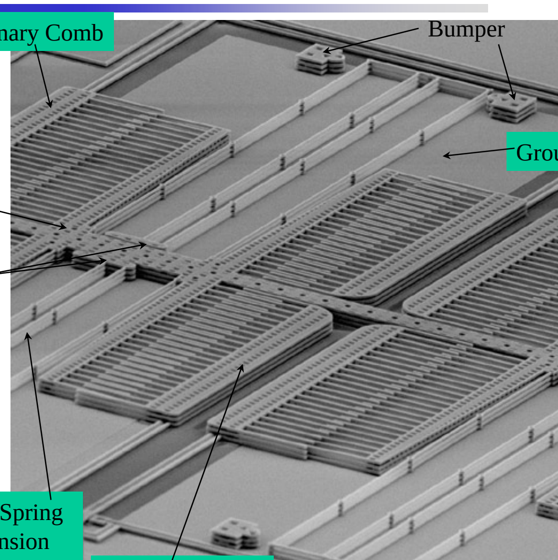
Actuators: Electrostatic

- Comb Drive



Actuators: Electrostatic

- Comb Drive
  - Sandia Example

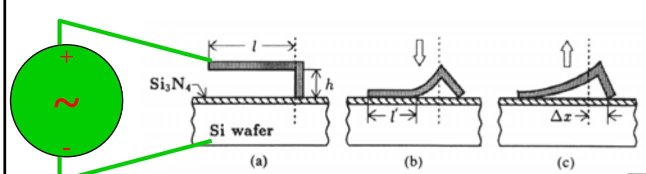


Actuators: Electrostatic

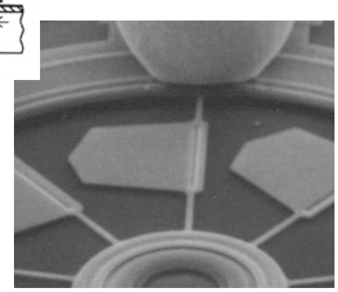
- Comb Drive Notes:
  - Displacement vs. Actuation Voltage
  - Spring Constants

Actuators: Electrostatic

- Scratch Drive
  - First demonstrated by:
    - T Akiyama and K. Shono, "Controlled Stepwise Motion in Polysilicon Microstructures, Journal of Microelectromechanical Systems, vol. 2, pp. 106-110, Sept 1993.

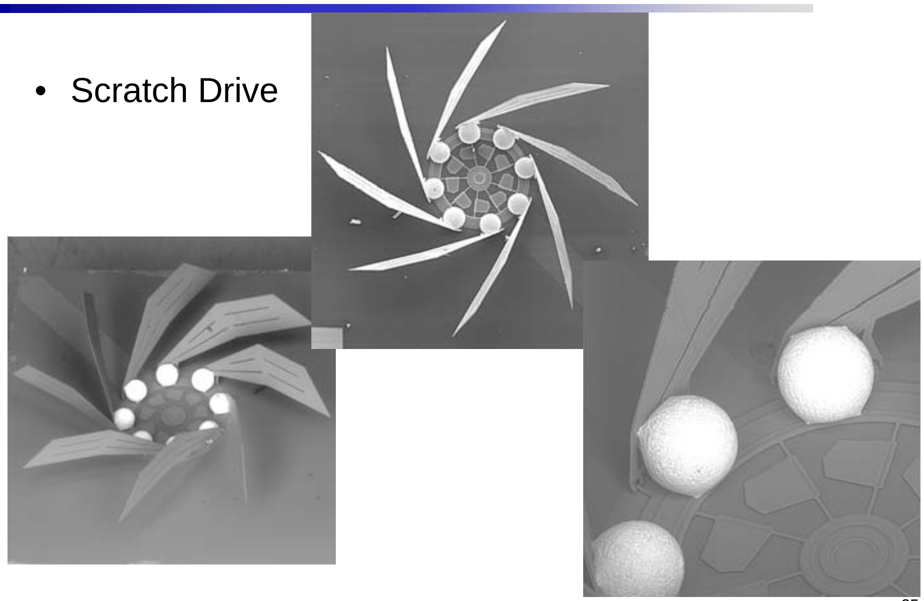


Δx ~ few nm
strong force



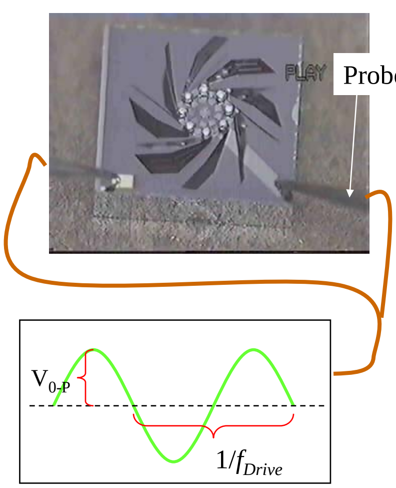
Actuators: Electrostatic

- Scratch Drive

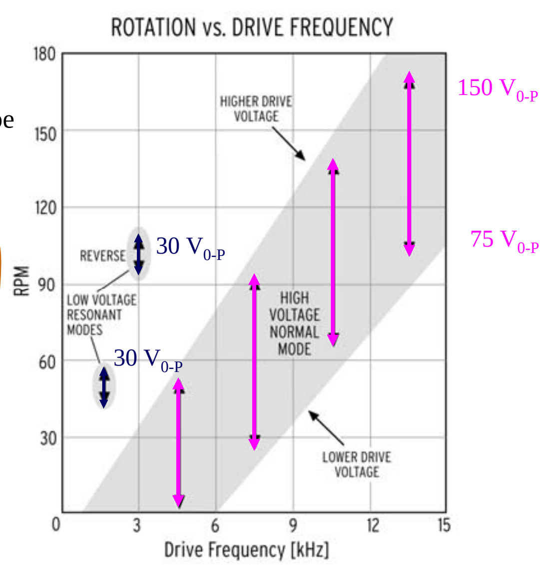


Actuators: Electrostatic

- Scratch Drive

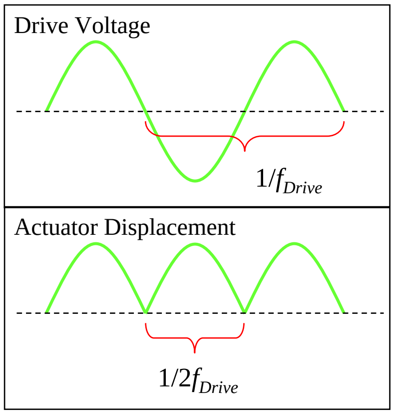


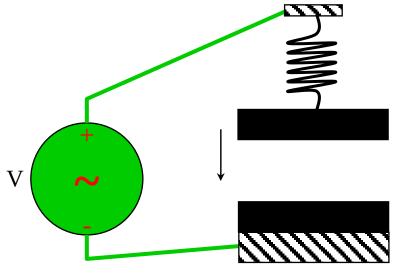
Function Generator & Amplifier



Actuators: Electrostatic

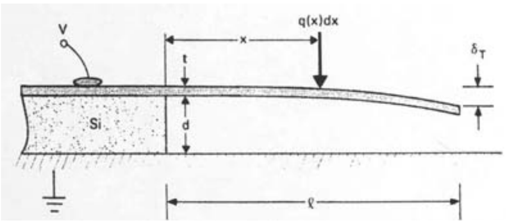
- When driving with a zero-bias input signal, the frequency of operation is twice the input signal frequency!

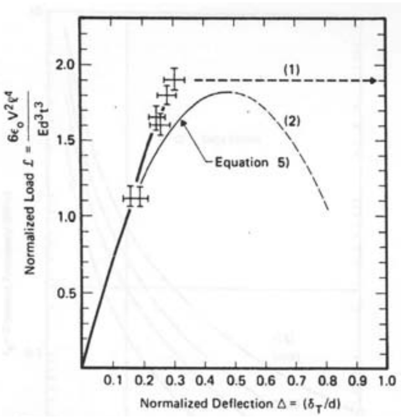




Actuators: Electrostatic

- Cantilever
  - Simpler Structure
  - Modeling Voltage vs. Deflection more complicated.



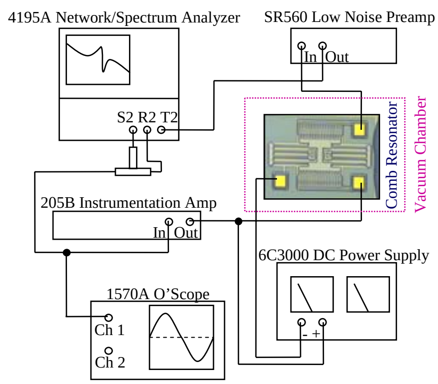


K. E. Petersen, "Dynamic Micromechanics on Silicon: Techniques and Devices," *IEEE Transactions on Electron Devices*, vol. ED-25, no. 10, 1978.

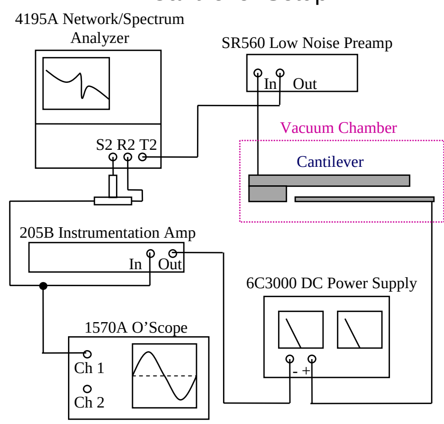
Actuators: Resonant Frequency

- Best and Easiest: By Eye
- 2nd Best: Electrically (Network/Spectrum Analyzer/Impedance Analyzer)

Comb Setup



Cantilever Setup



W. D. Cowan, V. M. Bright, and G. C. Dalton, "Measuring Frequency Response of Surface-Micromachined Resonators," *The Proceedings of SPIE*, vol. 3225, pp. 32-43, 1997. Figures formatted by Victor Bright.

Actuators

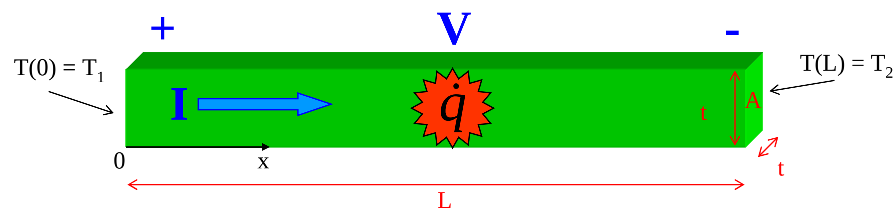
- Transducers
- Actuators
  - Electrostatic
  - Electro-Thermal
  - Bimorph Electro-Thermal
  - Residual Stress
  - Mechanical Components

Actuators: Electro-Thermal

- Advantages
  - Simple Designs
  - Simple Fabrication
  - High Force Per Unit Volume
  - Low Voltage
- Disadvantages
  - Temperature Dependent
  - High Electric Power Consumption
  - Low Frequency Operation

Actuators: Electro-Thermal

- Material expands due to Ohmic or Joule Heating causing motion of actuator structure.



$$q = \text{Power} = I^2 R = \frac{I^2 L \rho}{A} \text{ - or - } \frac{V^2}{R} = \frac{V^2 A}{L \rho} \qquad \dot{q} = \frac{\text{Power}}{\text{Volume}} = \frac{I^2 \rho}{A^2} \text{ - or - } \frac{V^2}{L^2 \rho}$$

Heat Transfer

$$k \frac{\partial^2 T}{\partial x^2} + \dot{q} = 0$$

$$T(x) = \frac{1}{2}\frac{\dot{q}}{k}\left(Lx - x^2\right) + \frac{1}{L}\left(T_2 - T_1\right)x + T_1$$

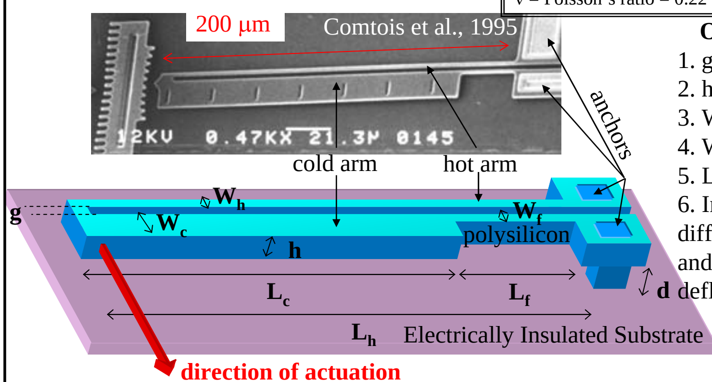
Thermal Expansion

$$L_{new}(x) = \int_0^x \left[1 + \alpha\left(T(\chi) - T_0\right)\right] d\chi$$

Actuators: Electro-Thermal

- Laterally/Horizontally Deflecting
  - Motion that is parallel to the plane of the substrate

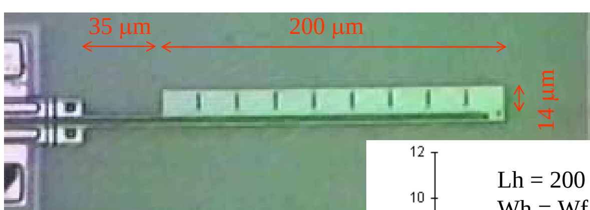
Example properties needed for modeling an electro-thermal actuator:
ρ = electrical resistivity = $2.3 \times 10^{-5}\ \Omega m$
α = coefficient of thermal expansion = $29 \times 10^{-7}\ K^{-1}$
α_r = temperature coefficient of resistance = $1.25 \times 10^{-3}\ K^{-1}$
k = thermal conductivity = 32 W/mK
E = Young's modulus = 169 GPa
ν = Poisson's ratio = 0.22



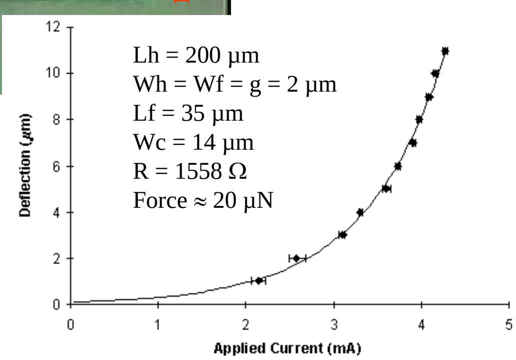
Optimum Dimensions:
1. g = as small as possible
2. h = as tall as possible
3. $W_c/W_h = 7$
4. W_h = as small as possible
5. $L_f \approx L_h/4$
6. Increasing the temp. difference between the cold and hot arm increases deflection.

Actuators: Electro-Thermal

- Laterally (Horizontally) Deflecting



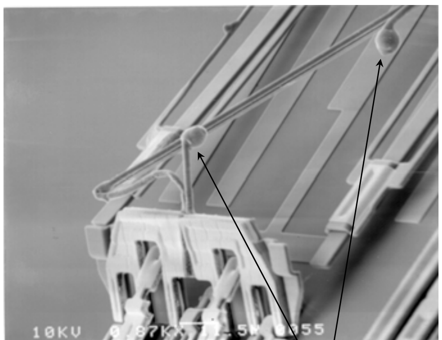
V. Bright et al., AFIT, 1996

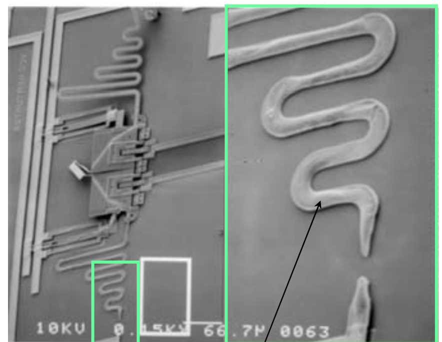


Comtois et al., 1995

Actuators: Electro-Thermal

- Low resistance wiring and Si/Au eutectic



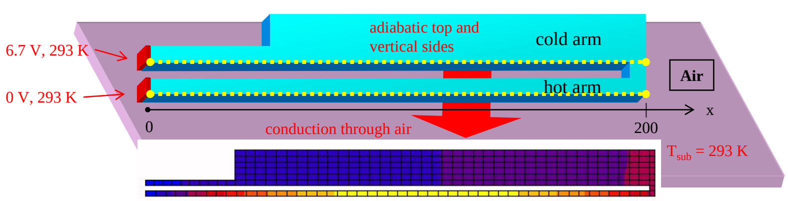


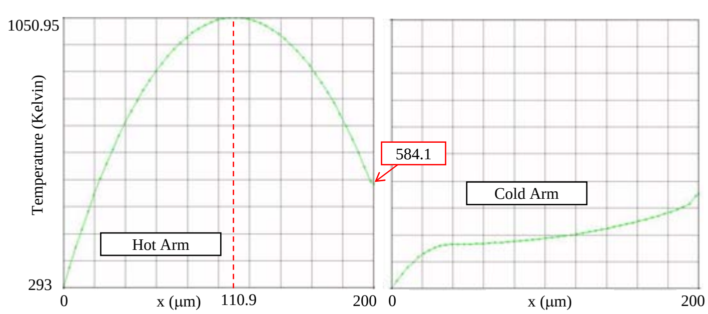
“Burned out” electro-thermal actuator hot arm

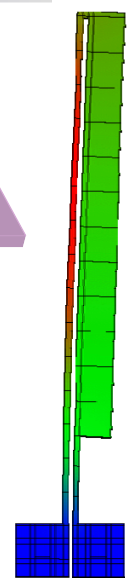
Eutectic Compound 18.6%Si/81.4%Au with melting temperature of 363 °C

Actuators: Electro-Thermal

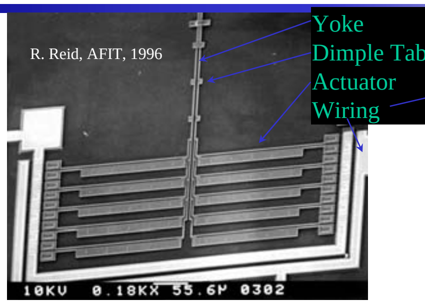
- Temperature Distribution (Relative Magnitude)

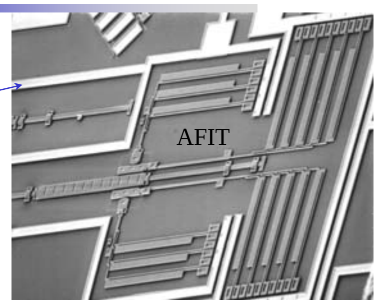


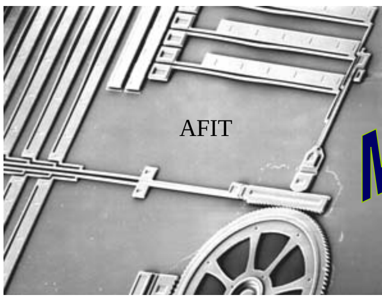




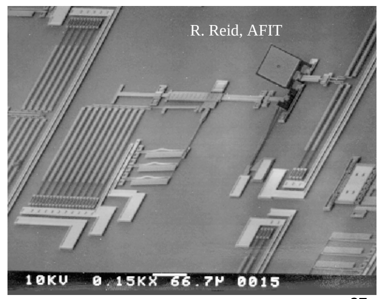
Actuators: Electro-Thermal







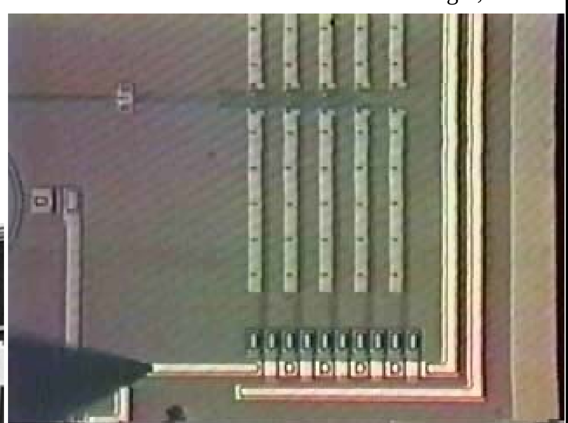
Motors

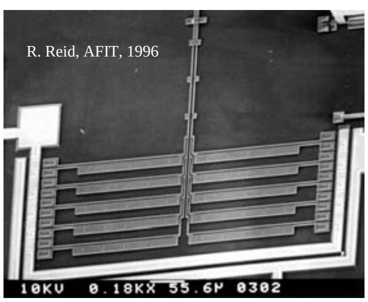


Actuators: Electro-Thermal

Motor Movie

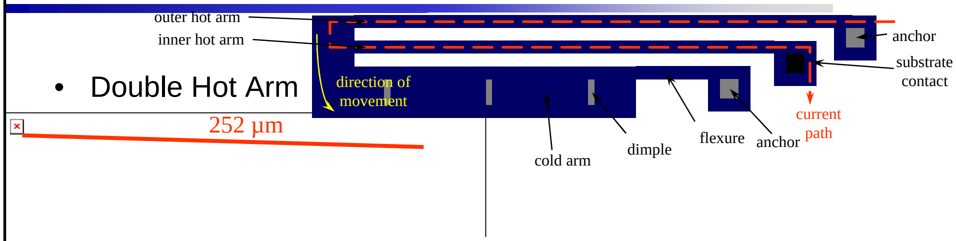
V. Bright, AFIT





Actuators: Electro-Thermal

- Double Hot Arm



D. Burns et al., AFIT

Design measurements for thermal actuators

	1-H actuator	2-H actuator
Cold arm length	162 µm	162 µm
Cold arm width	14 µm	14 µm
Flexure length	38 µm	38 µm
Flexure width	2.5 µm	2.0 µm
Inner hot arm length	200 µm	221 µm
Outer hot arm length	not applicable	252 µm
Hot arm width	2.5 µm	2.5 µm
Separation between inner hot arm and cold arm	3 µm	3 µm
Separation between hot arms	not applicable	3 µm

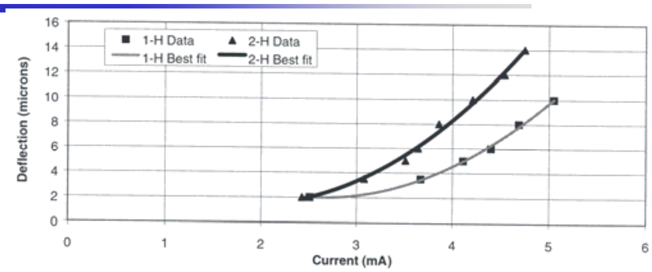
Comparison of single hot-arm (1-H) and double hot-arm (2-H) actuator operating properties

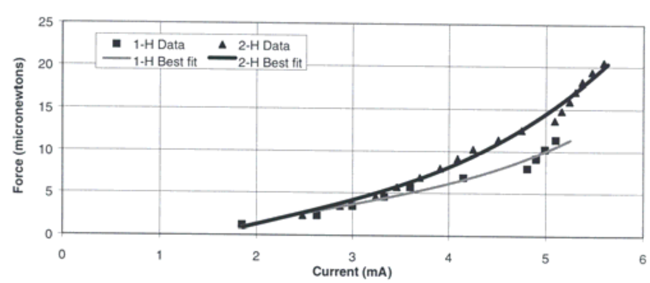
	1-H actuator	2-H actuator
Electrical resistance	1.510 KΩ	2.413 KΩ
Maximum deflection (positive)	10 µm	14 µm
Maximum deflection (backbending)	8 µm	12 µm
Maximum force	11.4 µN	20.5 µN
Maximum current before backbending (under load)	5.12 mA	5.59 mA
Maximum operating frequency (air)	12 KHz	17 KHz
Maximum operating frequency (40 mTorr)	4 KHz	27 KHz

Actuators: Electro-Thermal

- Double Hot Arm

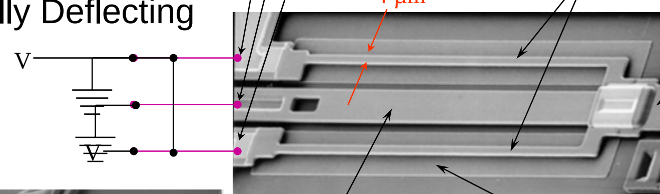
D. Burns et al., AFIT

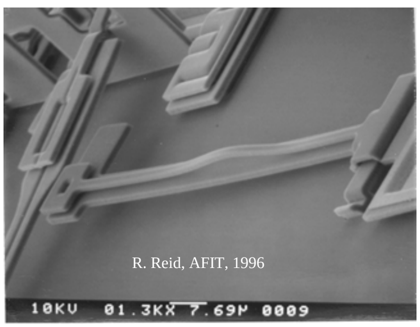




Actuators: Electro-Thermal

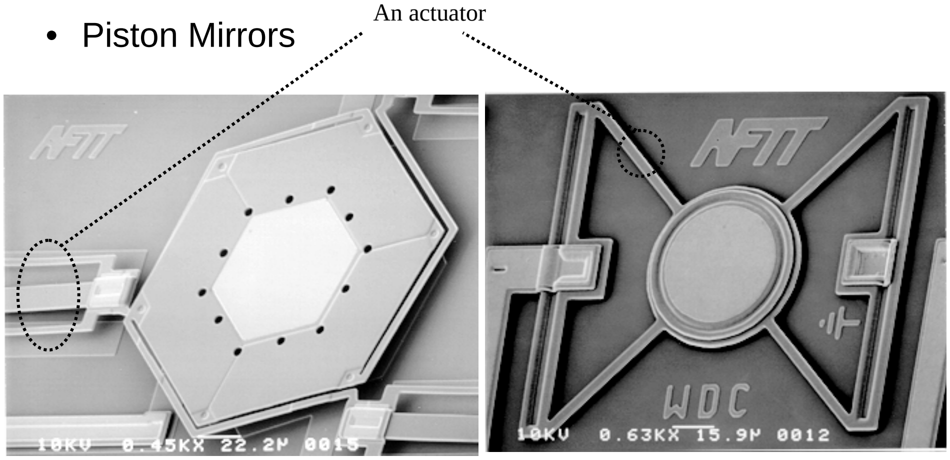
- Vertically Deflecting





Actuators: Electro-Thermal

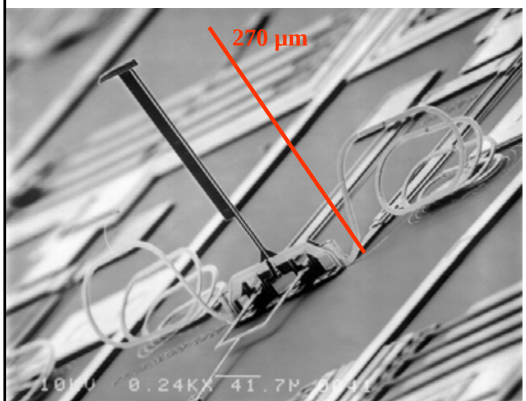
- Piston Mirrors

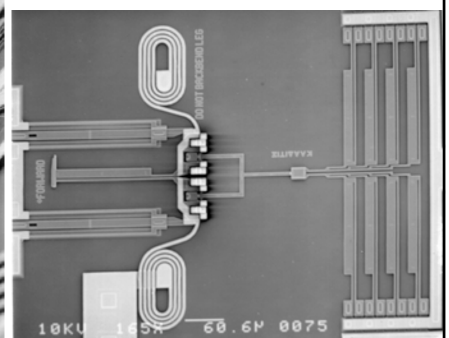


W. D. Cowan, AFIT

Actuators: Electro-Thermal

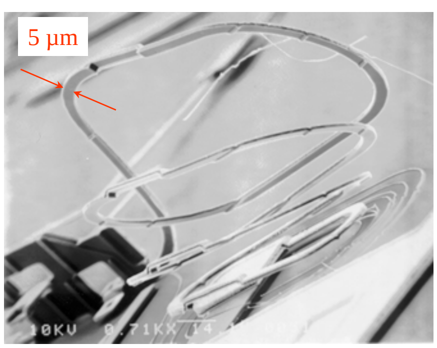
- Assembled Devices: Micro-Robot Leg



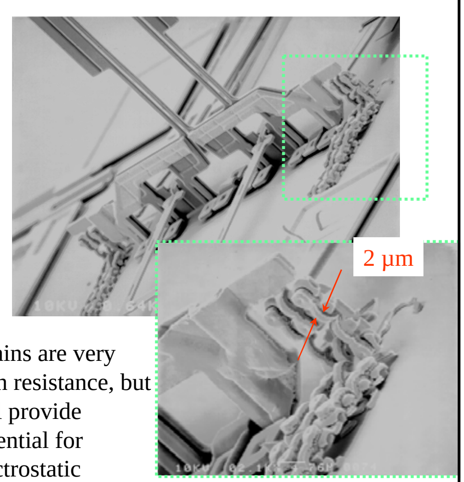


Actuators: Electro-Thermal

- Low resistance wire necessary for electro-thermal actuation



Spring wire is a good low resistance electrical path

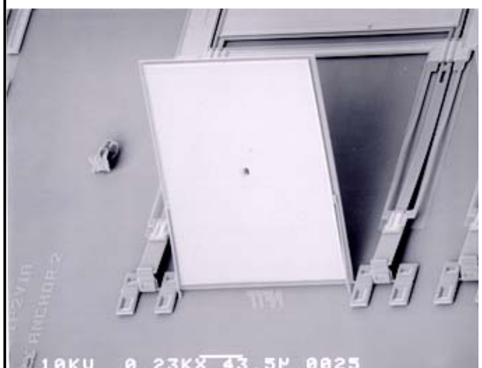


Chains are very high resistance, but will provide potential for electrostatic actuators

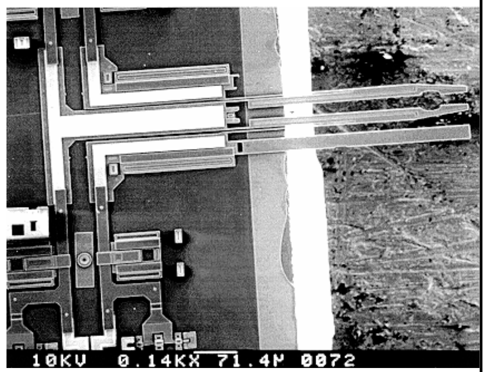
Does not work for electro-thermal

Actuators: Electro-Thermal

- Assembled Devices: Mirror & Micro-Grippers



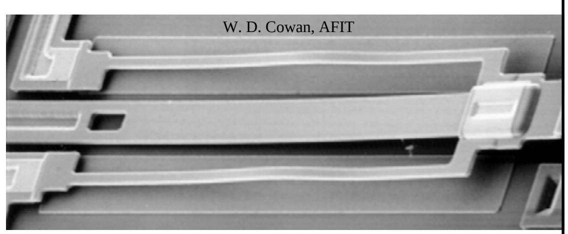
W. D. Cowan, AFIT



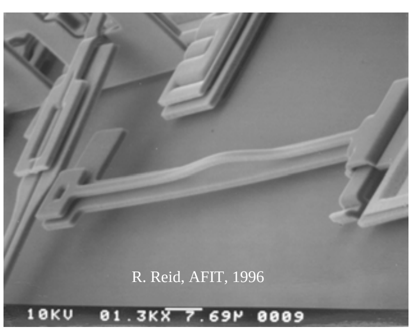
J. Comtois, AFIT

Actuators: Electro-Thermal

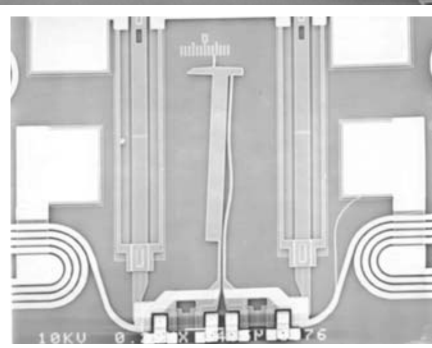
- Back bending
  - The permanent plastic deformation of a “hot arm”.
  - Performed once before beginning normal operation.



W. D. Cowan, AFIT

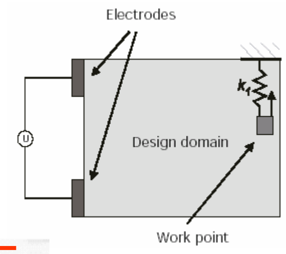


R. Reid, AFIT, 1996

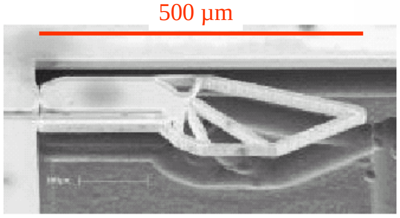


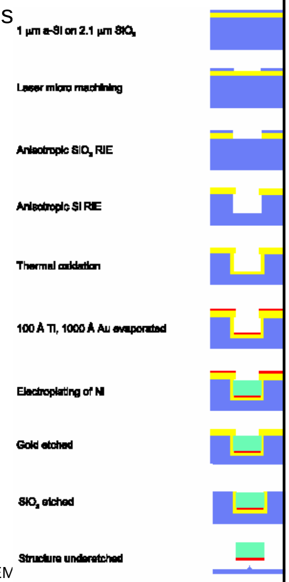
Actuators: Electro-Thermal

- The design of an electro-thermal actuator is a compromis between thermal and mechanical efficiency!
- Optimized design by J. Jonsmann et al., "Compliant Electro-thermal Microactuators," 1999.
  - Design domain size
  - Location of electrodes
  - Location of work point
  - Electrical resistance
  - Amount of material used
  - Available voltage



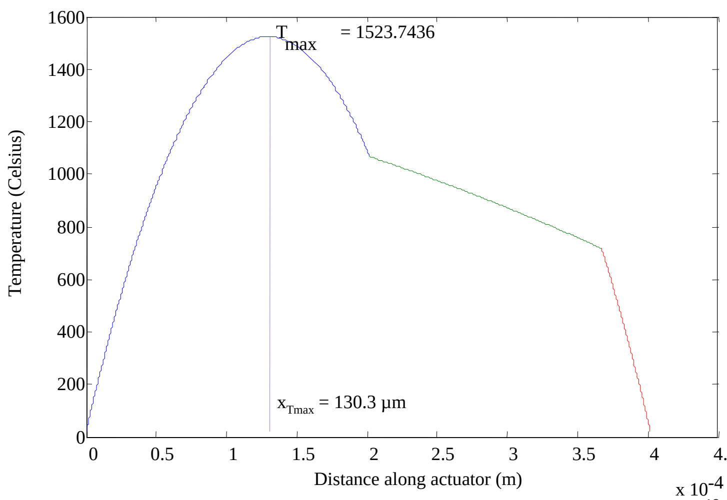
500 µm





Actuators: Electro-Thermal

- Optional:
  - Analytical modeling of the temperature distribution of a laterally deflecting electro-thermal actuator.

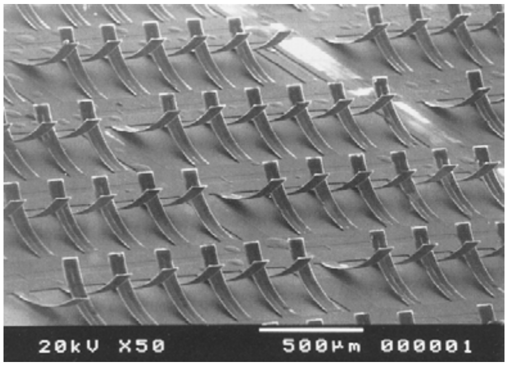


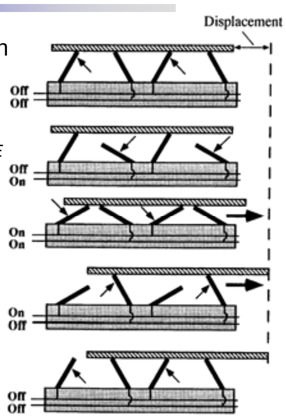
Overview

- Transducers
- Actuators
  - Electrostatic
  - Electro-Thermal
  - Bimorph Electro-Thermal
  - Residual Stress
  - Mechanical Components

Actuators: Bimorph Electro-Thermal

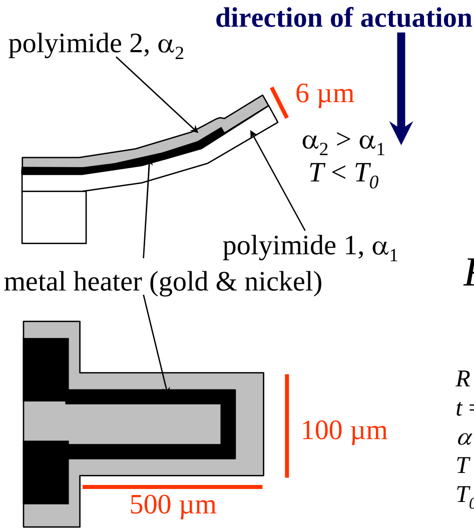
- An actuator made up of a sandwich of at least two layers with different coefficients of thermal expansion and an internal electric heater.
  - Ex. M. Ataka, S. Omofsks, N. Takeshima, and H. Fujita, "Fabrication and operation of polyimide bimorph actuators for a ciliary motion," *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 2, no. 4, pp. 146-150, Dec. 1993.





Vanderbilt

Actuators: Bimorph Electro-Thermal



Actively moves when heated by an internal electric heater.

Error!

$$R = \frac{(t_1 + t_2)^2}{6(\alpha_1 - \alpha_2)(T - T_0)t_1 t_2}$$

Kovacs

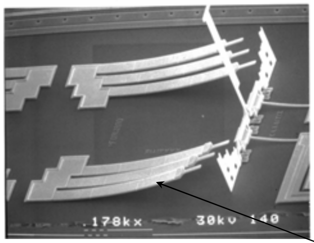
R = Radius of Curvature
t = thickness
α = coefficient of thermal expansion
T = temperature
T_0 = reference temperature

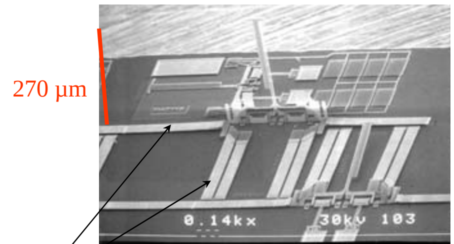
Overview

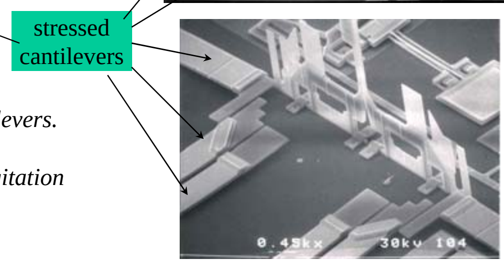
- Transducers
- Actuators
  - Electrostatic
  - Electro-Thermal
  - Bimorph Electro-Thermal
  - Residual Stress
  - Mechanical Components

Actuators: Residual Stress

- A passive actuator, usually in the form of a cantilever, made up of a sandwich of at least two layers with different coefficients of thermal expansion.







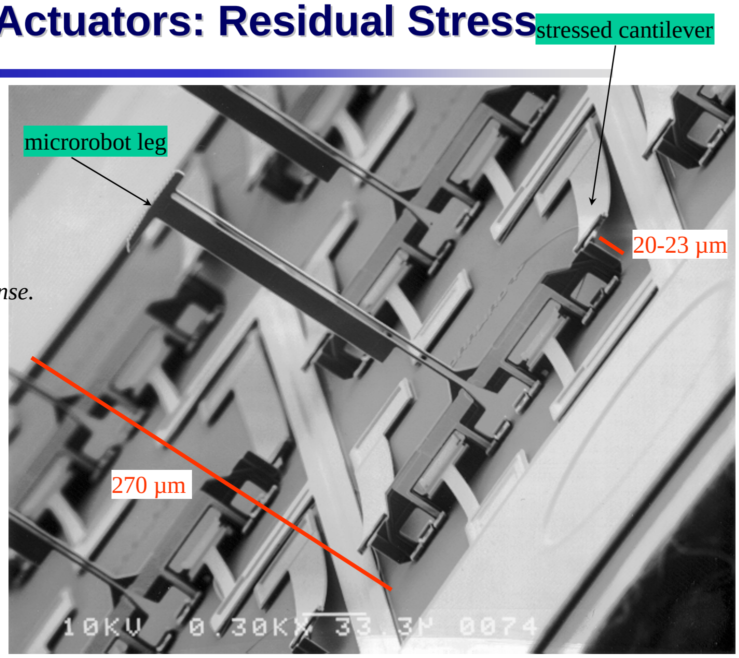
Assembled with residual stress cantilevers.

Possibly assisted by unintentional agitation during release, rinse, and/or dry.

Actuators: Residual Stress

Assembled with intentional agitation during release and rinse.

Assisted by stressed cantilevers.

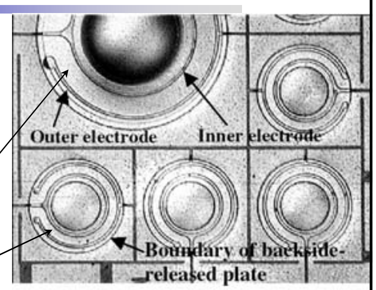


Actuators: Other

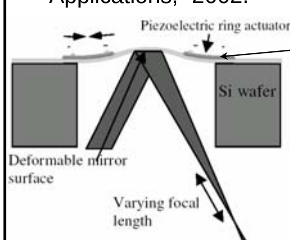
- Most other actuators are further extensions of the basic examples covered in the previous slides.
- Other types of actuation include:
  - Piezoelectric
  - Magnetic / Electro-Magnetic
  - Pneumatic
  - Shape Memory Alloy

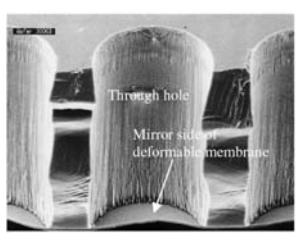
Actuators: Piezoelectric

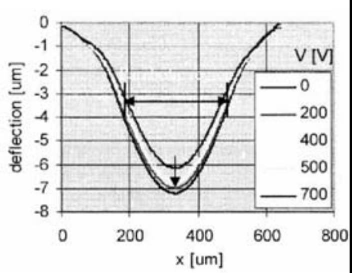
- In a piezoelectric material, an applied voltage induces an internal stress, resulting in an expansion of the material.
- Conversely, for sensor use, the application of an external force induces an electric field across the material.
- Ex. M. J. Mescher et al., “A Novel High-speed Piezoelectric Deformable Varifocal Mirror For Optical Applications,” 2002.



PZT

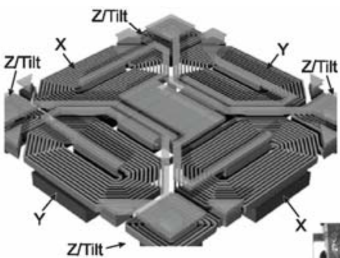


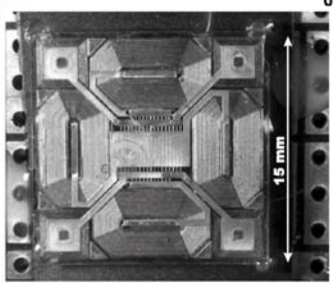


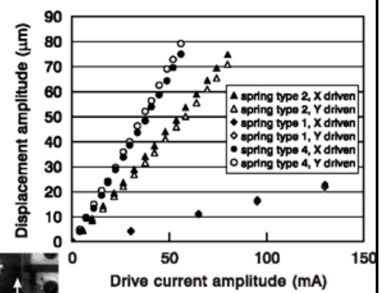


Actuators: Magnetic / Electro-Magnetic

- Ex. H. Rothuizen et al., "Compact Copper/epoxy-based Electromagnetic Scanner for Scanning Probe Applications," 2002

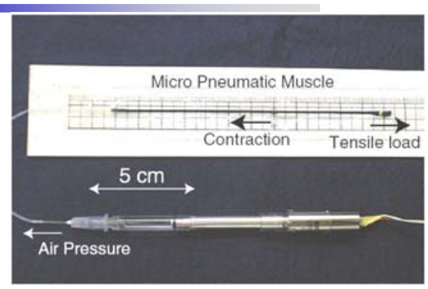






Actuators: Pneumatic

- Ex. Y. K. Lee et al., "A Multi-channel Micro Valve for Micro Pneumatic Artificial Muscle," 2002.



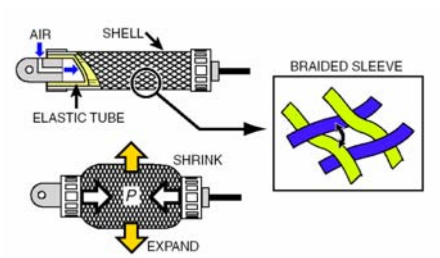
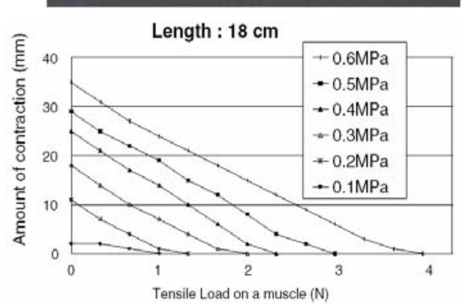
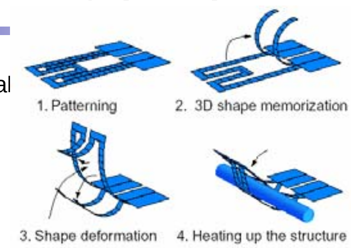


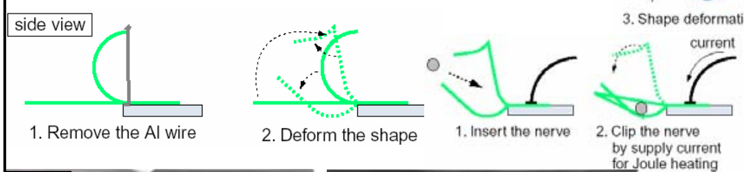
Figure 1. Structure of Mckibben pneumatic muscle

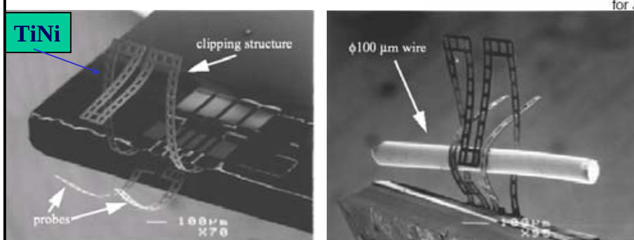


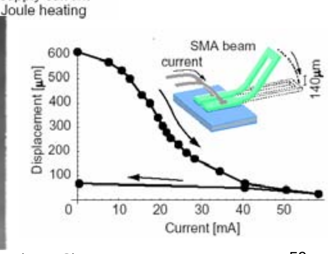
Actuators: Shape Memory Alloy (SMA)

- Ex.: S. Takeuchi, "Three Dimensional SMA Microelectrodes with Clipping Structure for Insect Neural Recording," 1999.





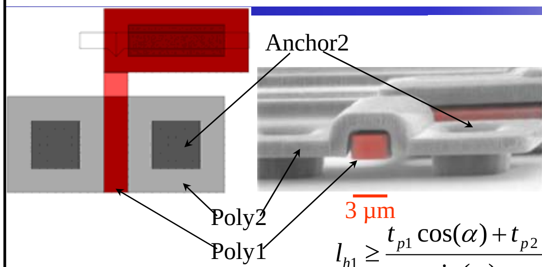




Overview

- Transducers
- Actuators
  - Electrostatic
  - Electro-Thermal
  - Bimorph Electro-Thermal
  - Residual Stress
- Mechanical Components

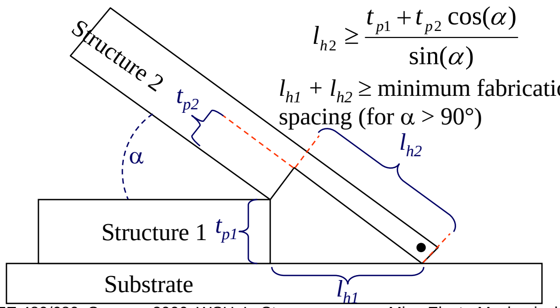
Mechanical Components: Substrate or Staple Hinges

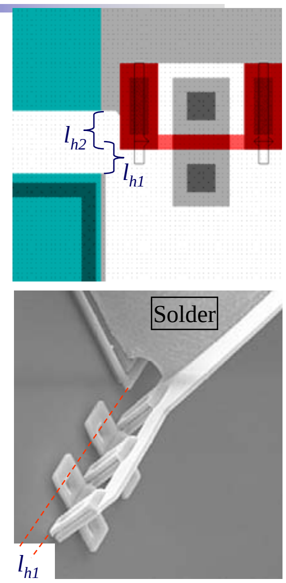


$$l_{h1} \geq \frac{t_{p1}\cos(\alpha) + t_{p2}}{\sin(\alpha)}$$

$$l_{h2} \geq \frac{t_{p1} + t_{p2}\cos(\alpha)}{\sin(\alpha)}$$

$l_{h1} + l_{h2} \geq$ minimum fabrication spacing (for α > 90°)

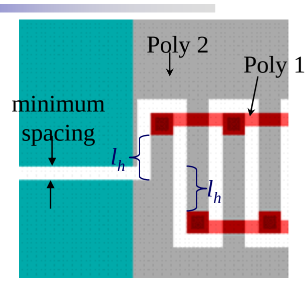


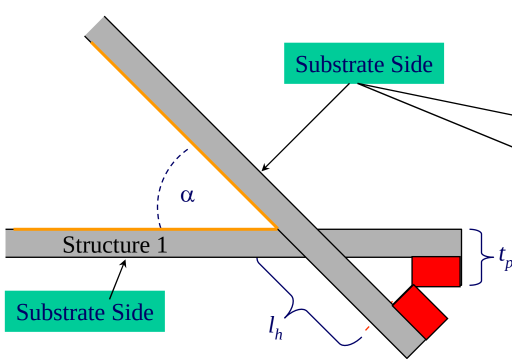


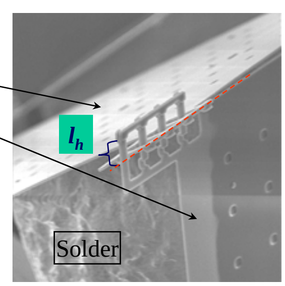
Mechanical Components: Scissor Hinges

- "Up - Folding" $l_h \geq t_p \cot\left(\frac{\alpha}{2}\right)$

$l_h \geq$ minimum fabrication spacing (for α > 90°)

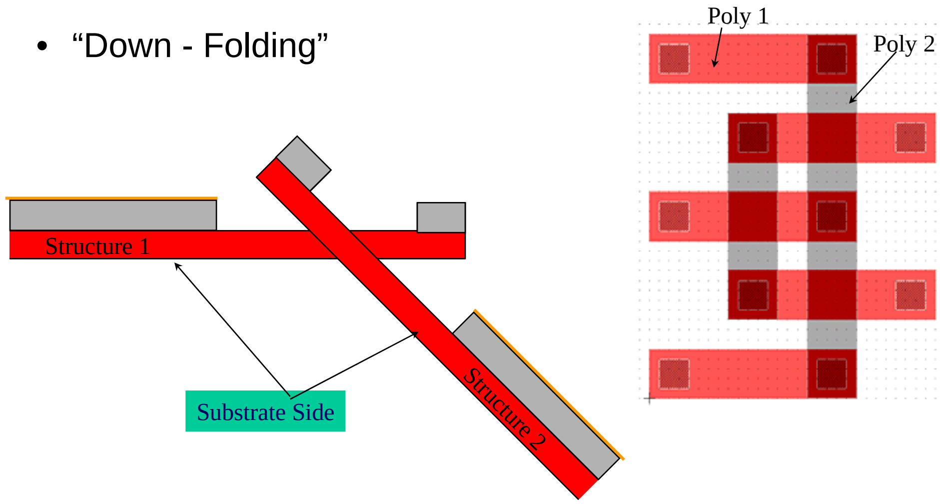




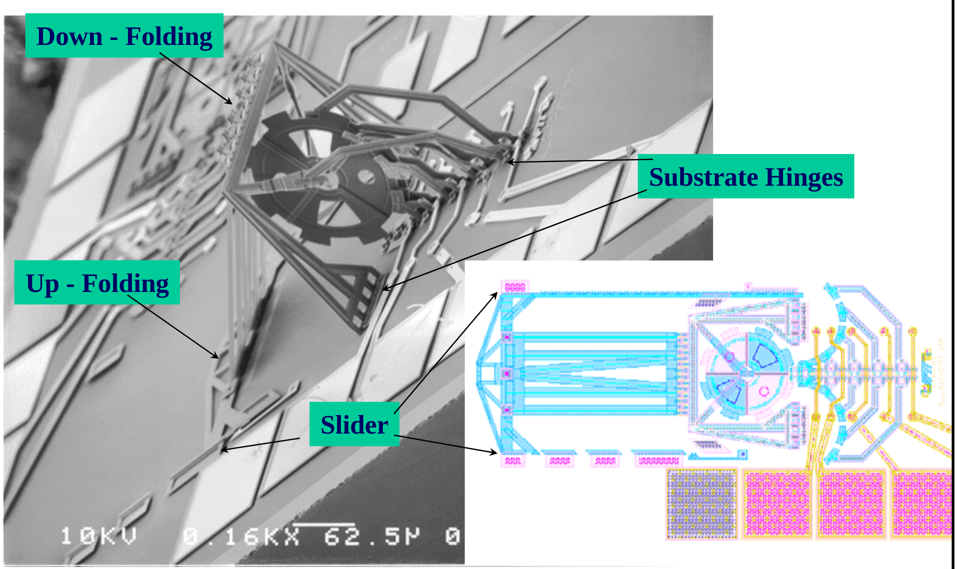


Mechanical Components: Scissor Hinges

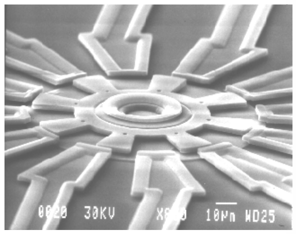
- "Down - Folding"

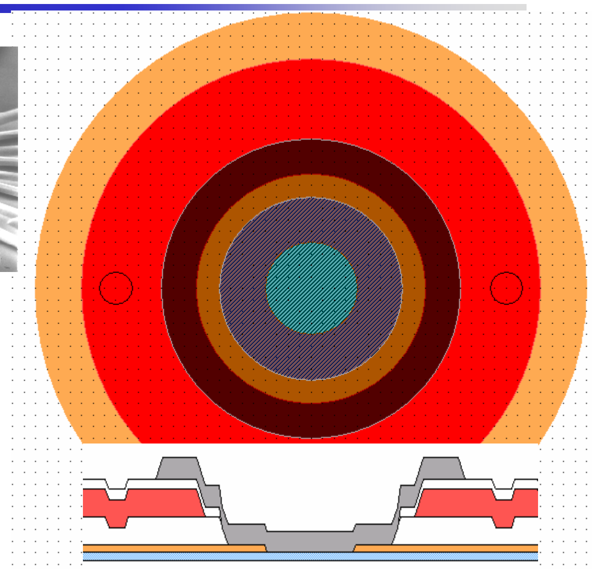


Mechanical Components: Hinges

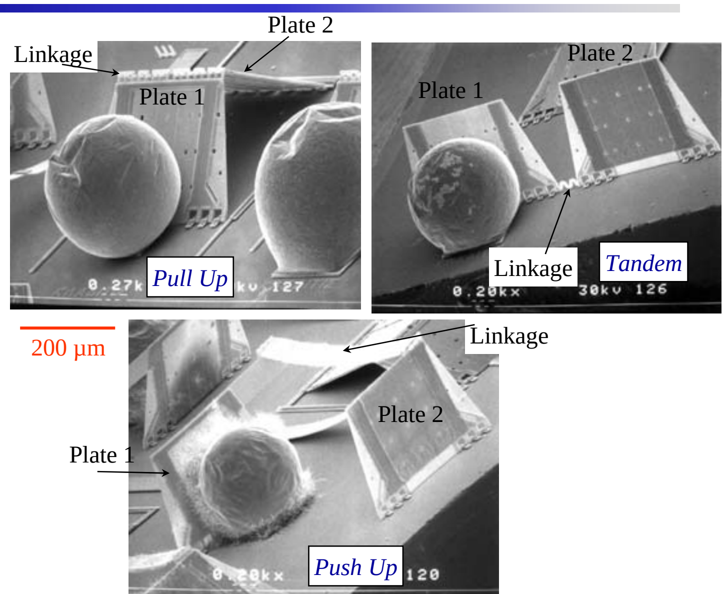


Mechanical Components: Pin Joint

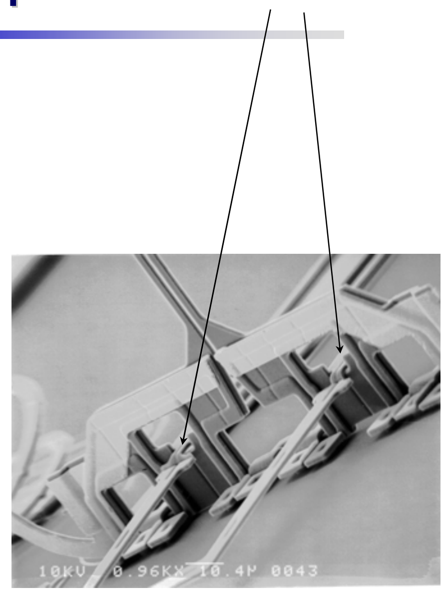




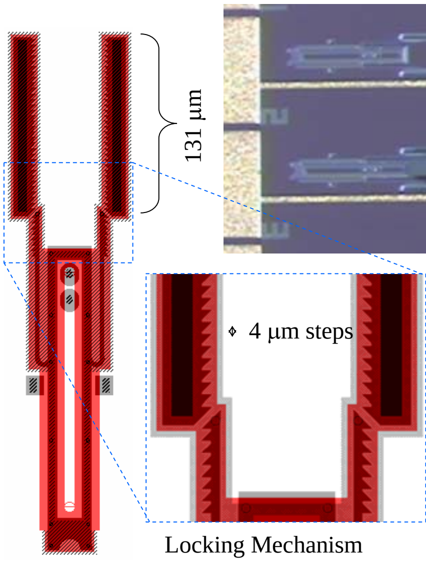
Mechanical Components: Linkages

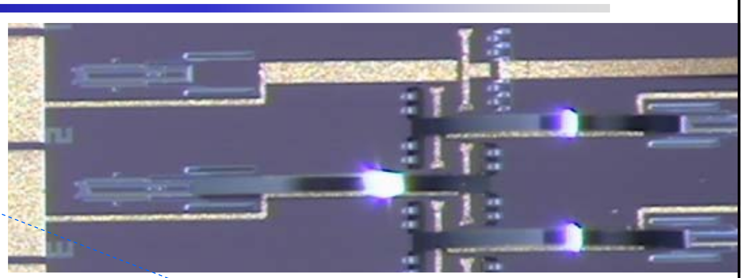


Mechanical Components: Locks

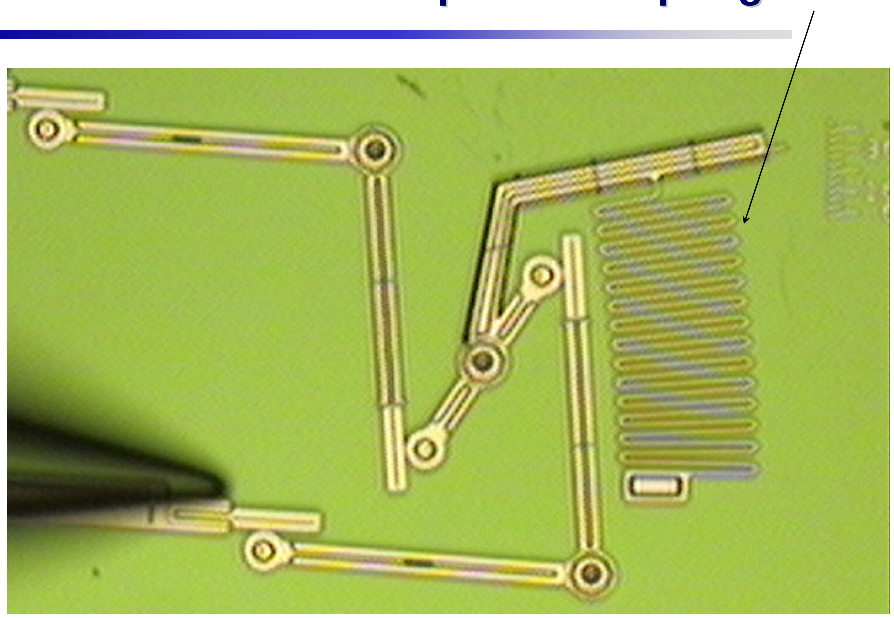


Mechanical Components: Locks





Mechanical Components: Springs



Mechanical Components: Other

- Gears
- Flexible Hinges
- Corrugation or Stiffening

………