MEMS Devices

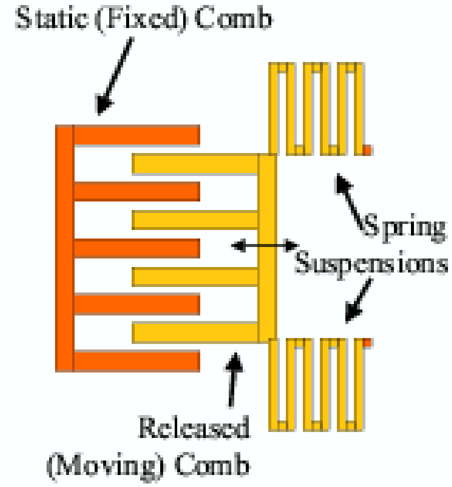
1. Basic devices and phenomena
2. Electrostatics
3. Stress and Strain (beams)
4. Thermal devices
5. Actuators
6. STMs and AFMs

Fundamental MEMS Processes and Devices

- Example: surface micromachined polysilicon comb drives
  - Mechanics for MEMS
    - Stress and strain
    - Cantilever beams
    - Resonance
  - Electrostatics for MEMS
    - Parallel-plate capacitors
    - Pull-in voltage
    - Comb drives

Electrostatic Comb Drives

Principle: interlacing comb fingers create large capacitor area; electrostatically actuated suspended microstructures (Tang, Nguyen and Howe, 1989)



Features:

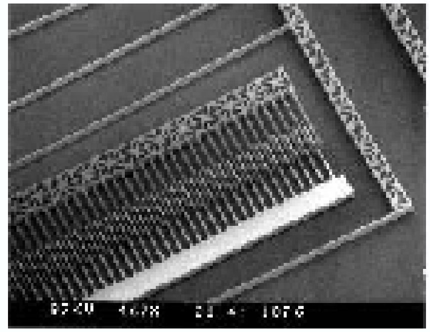
- Linear relationship between capacitance and displacement
- Higher surface area / capacitance than parallel plate capacitor
- Electrostatic actuation: low power (no DC current)

Electrostatic Comb Drives

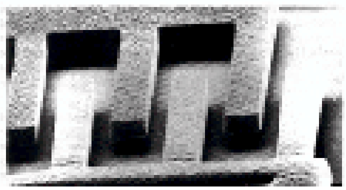
Comb drives combine mechanical and electrostatic issues:

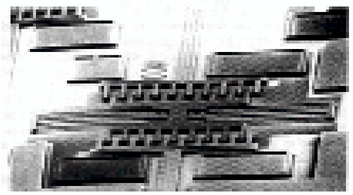
- Elasticity
- Stress and strain
- Resonance (natural frequency)

- Capacitance
- Electrostatic forces
- Electrostatic work and energy



Tang, Nguyen and Howe
JMEMS 1989





Axial Stress And Strain

Stress: force applied to surface

$\sigma = F/A$

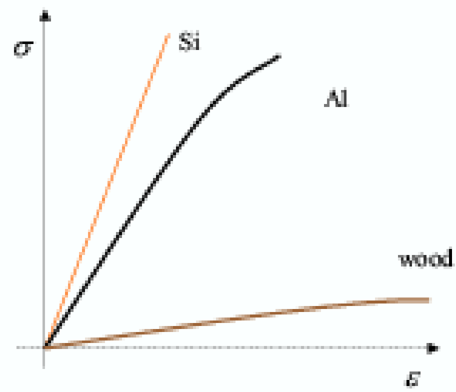
measured in N/m^2 or Pa

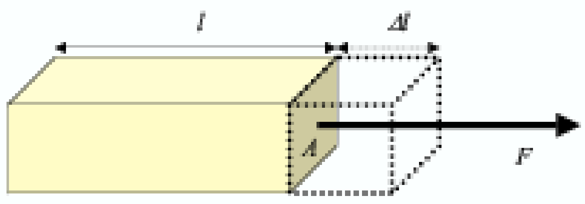
compressive or tensile

Strain: ratio of deformation to length

$\varepsilon = \Delta l / l$

measured in %, ppm, or microstrain





Young's Modulus:

$E = \sigma/\varepsilon$

Hooke's Law:

$K = F/\Delta l = E\, A/l$

Shear Stress And Strain

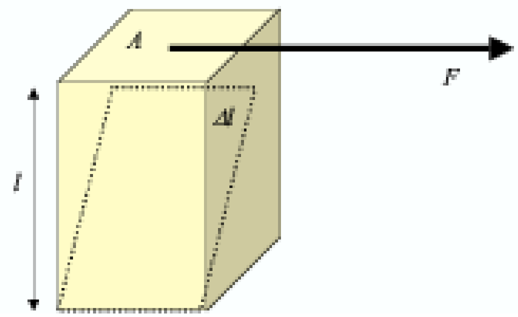
Shear Stress: force applied parallel to surface

$\tau = F/A$

measured in N/m^2 or Pa

Shear Strain: ratio of deformation to length

$\gamma = \Delta l / l$



Shear Modulus:

$G = \tau / \gamma$

Poisson's Ratio

Tensile stress in x direction results in compressive stress in y and z direction (object becomes longer and thinner)

Poisson's Ratio:

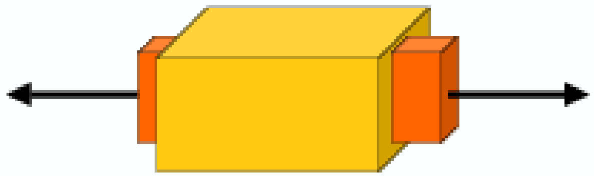
$\nu = -\varepsilon_y / \varepsilon_x$

$=$ - transverse strain / longitudinal strain

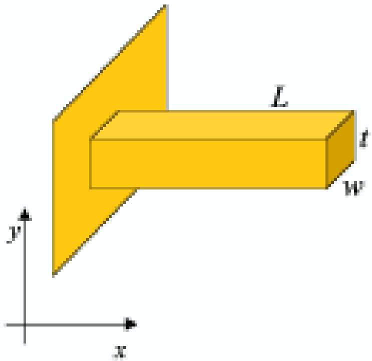
Metals: $\nu \approx 0.3$

Rubbers: $\nu \approx 0.5$

Cork: $\nu \approx 0$



Cantilever Beams



Assume that x axis lies in center of beam

Axial Strain: $\varepsilon(y) = y/\rho$

ρ radius of curvature

Axial Stress: $\sigma(y) = E\ \varepsilon(y)$

Axial Force: $dF = \sigma(y)\ w\ dy$

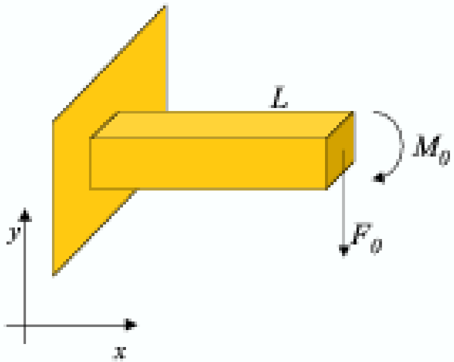
Bending Moment:

$$M = 1/12\ t^3\ w\,E / \rho$$
$$= E\,I / \rho$$

$I = 1/12\ t^3\ w$

(area moment of inertia)

Cantilever Beams



Assume that we apply a force F_0 and a moment M_0 on a beam with length L

$$F(x) = F_0$$

$$M(x) = M_0 + F(L-x)$$

For $M_0 = 0$

$$y(x) = F / (6EI)\,(3\,Lx^2 - x^3)$$

$$y(L) = FL^3 / 3EI$$

Spring Constant, K

$$= F/y = 3EI/L^3$$

$$= Et^3w / 4L^3$$

Cantilever Beams

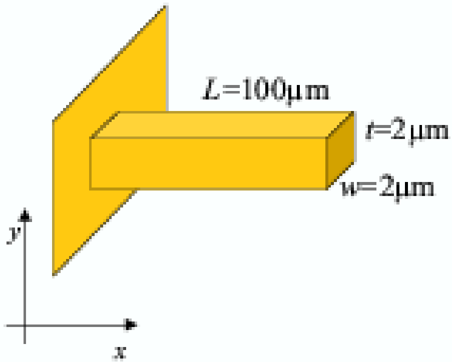
	Point Load	*Distributed Load*
Cantilever	$y(x) = F/(6EI)\,(3\,Lx^2 - x^3)$	$y(x) = \rho x^2/(24EI)\,(6L^2 - 4Lx + x^2)$
	$\sigma_{max} = FLt\,/\,2I$	$\sigma_{max} = \rho L^2 t\,/\,4I$
Bridge	$y(x) = Fx/(48EI)\,(3\,Lx - 4x^2)$	$y(x) = \rho x^2/(24EI)\,(L - x)^2$
	for $L/2 \geq x \geq 0$	
	$\sigma_{max} = FLt\,/\,8I$	$\sigma_{max} = \rho L^2 t\,/\,12I$

L length of beam, t thickness of beam, w width of beam

$I = wt^3/12$ bending moment of inertia

SCS Beam

Example:



$E = 100$ GPa

$K = Ea^3b\ /\ 4L^3$

$= 0.4$ N/m $= 0.4$ μN/μm

How much does beam bend in a $1g$ gravity field?

$m = \rho V$ (assume mass at end of beam)

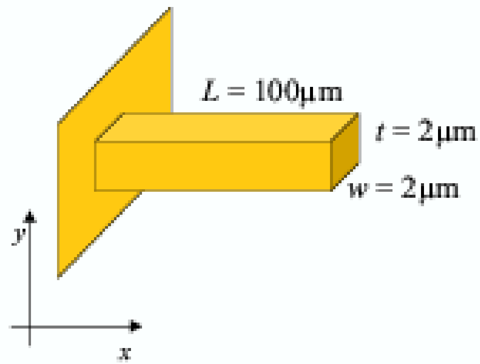
$= 2.3$ gram/cm^3 400 μm^3

$\approx 10^{-12}$ kg

$\Delta y \approx 2.5\ 10^{-11}$ m $= 0.25$ Å

detectable!

Resonators



$mx'' + bx' + Kx = F$

(Newton dynamics with damping and springs)

For $b = 0$:

$$\omega = \sqrt{\frac{K}{m}} = \frac{1}{2}\sqrt{\frac{Et^3 w}{mL^3}}$$

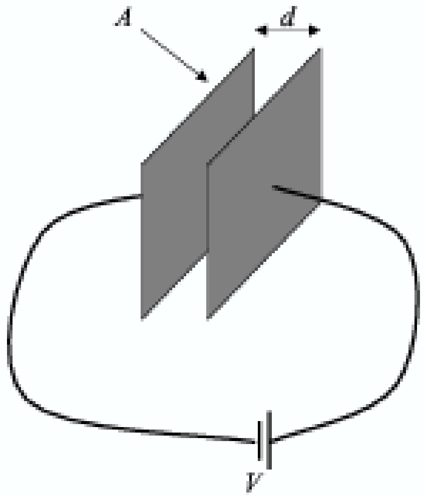
$$f_0 = \omega / 2\pi \approx 100 \text{ kHz}$$

Notice: if $t = 1\mu\text{m}$

$f_y = f_0 / 2$

$f_z = f_0$

Electrostatic Forces



Parallel Plate Capacitor:

Capacitance:

$C = Q/V = \varepsilon_0 \varepsilon_r A / d$

$\varepsilon_0 \approx 8.854 \; 10^{-12}$ F/m

dielectric constant of free space

ε_r dielectric permittivity

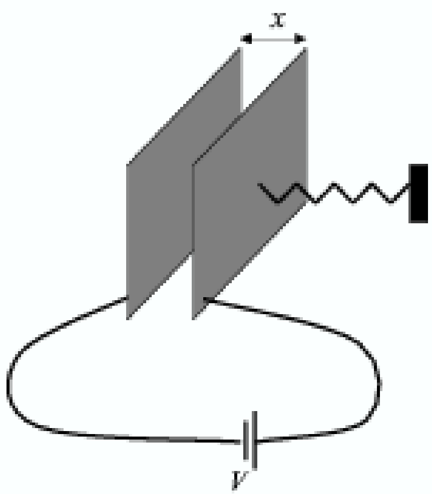
Stored energy:

$W = ½ \, C \, V^2 = ½ \, Q^2 / C$

Electrostatic force between plates:

$F = ½ \, C/d \; V^2$

Pull-In Point



The higher V, the closer the plate is pulled in. $F_{el} \rightarrow \infty$ when $d \rightarrow 0$. What is the closest stable distance x_{min}?

F_{el} and $-F_S$ must be tangential:

$-\varepsilon_0 \, \varepsilon_r \, A/x^3 \, V^2 = -K$, so

$V^2 = K x^3 / \varepsilon_0 \, \varepsilon_r \, A$

Substitute into $F_{el} = -F_S$ to get

$x_{min} = 2/3 \; d_0$

can control x only from $2/3 \; d_0$ to d_0

Electrostatic Comb Drive

Capacitance is approximately:

$C = \varepsilon_0 \, \varepsilon_r \, A/d$

$\quad = 2n \; \varepsilon_0 \, \varepsilon_r \, lh/d$

Change in capacitance when moving by Δx:

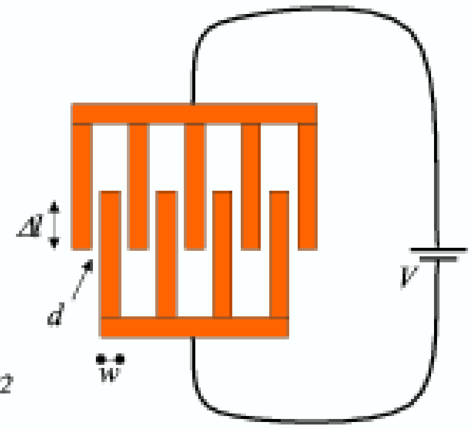
$\Delta C = \varepsilon_0 \; \varepsilon_r \, \Delta A \, / \, d$

$\quad = 2n \; \varepsilon_0 \; \varepsilon_r \, \Delta l \; h/d$

Electrostatic force:

$F_{el} = ½ \, V^2 \; dC/dx = n \; \varepsilon_0 \; \varepsilon_r \; h/d \; V^2$

Note: F_{el} independent of Δl over wide range (fringing field), and quadratic in V.



Electrostatic Accelerometer

Example: use MEMS comb structures as accelerometer

$h = 100\ \mu m$

$n = 100$

$d = 1\ \mu m$

Spring Constant: $K = 1$ N/m

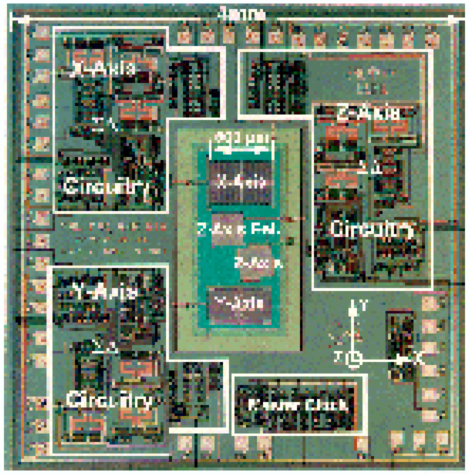
Proof Mass: $m = 0.1$ mg

Acceleration: $a = 0.1$ g

$\Delta x = 0.1\ \mu m$

$\Delta C = 17.7$ fF

Accelerometers

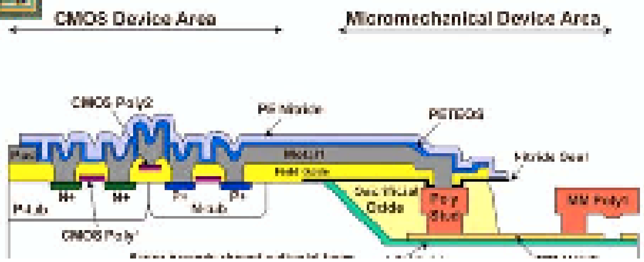


Three-axis accelerometer micrograph with labeling of functional units as reported by Lemkin et al, Proceedings ISSCC 1997.

SANDIA's IMEMS Process

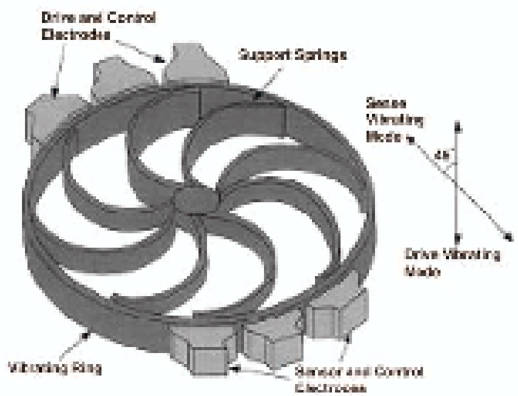
http://www.sandia.gov/mems/micromachine/pix/techinfo/cmos.gif

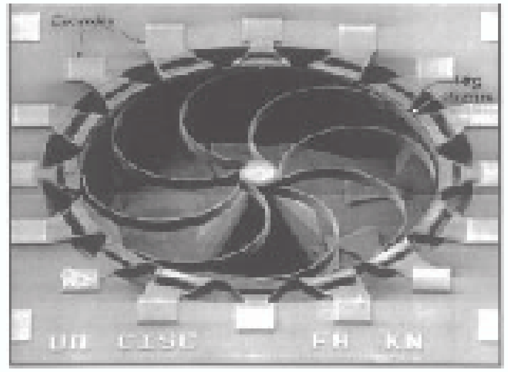
SNL Integrated Micromechanical/CMOS



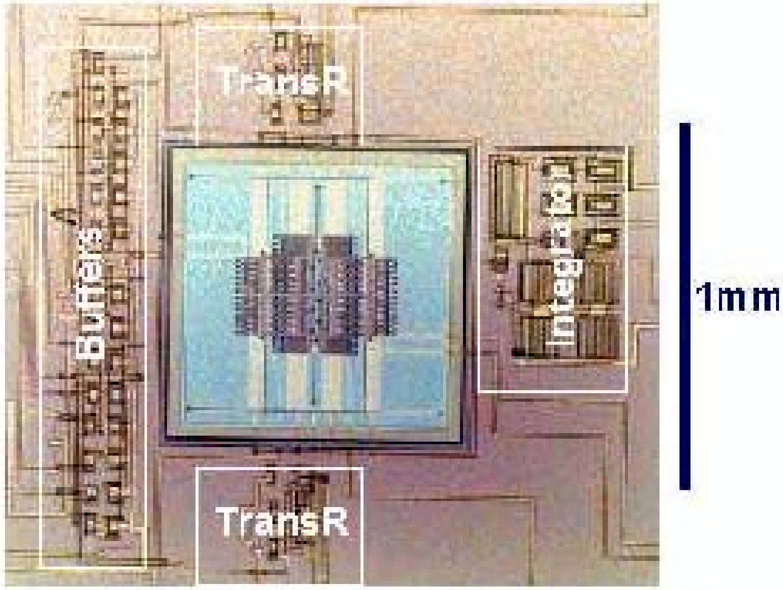
Gyroscopes

F. Ayazi and K. Najafi, “Design and fabrication of a high-performance polysilicon vibrating ring gyroscope,” in *Proc. IEEE Micro Electro Mechanical Systems Workshop (MEMS 1998)*, Heidelberg, Germany, February 1998, pp. 621–626.





MEMS Gyroscope

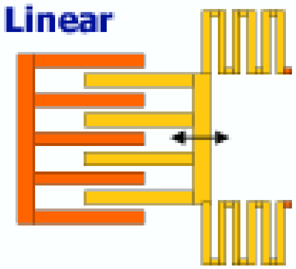


(B. Clark, R. Horowitz and R. T. Howe, 1996)

Comb Drive Design

Combs

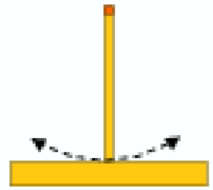
Linear



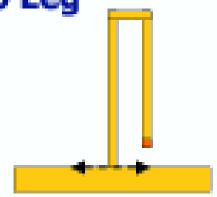
Rotational

Suspensions

Cantilever / Bridge



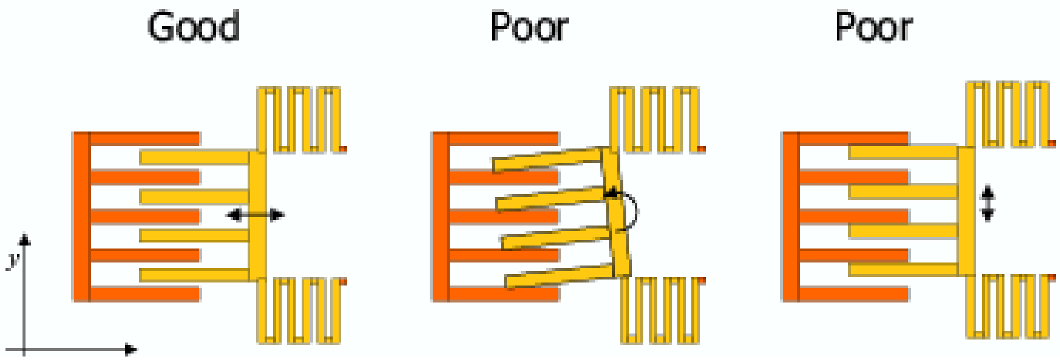
Crab Leg



Comb Drive Failure Modes

Comb drives require low stiffness in x direction but high stiffness in y, z direction as well as rotations.

Note: comb fingers are in unstable equilibrium with respect to the y direction.



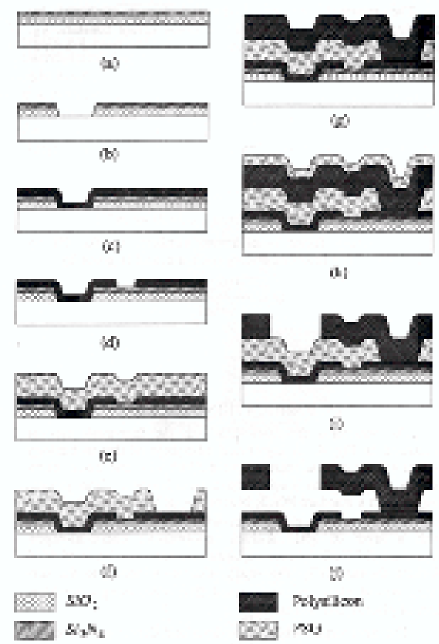
Comb Drive Fabrication

Surface micromachining with 1 released polysilicon layer

Tang, Nguyen and Howe (UC Berkeley)

This process formed basis for many subsequent MEMS designs

Figure: Tang, Nguyen and Howe, 1989.



Electrostatic Actuators

Ideas

- Comb drive
- Rotors
- Scratch drive
- T-drive
- Parallelogram
- Zipper
- DMD (torsional mirrors)
- Impact actuator
- Microengine
- Inchworm motors (see actin and myosin)

Issues

- Force, F
- Range, s
- Frequency, 1/t
  $P = F\ s/t$
- Linearity
- Efficiency

Translation	Rotation
Acceleration, velocity, distance	Angular acc., ang. vel., angle
$a = \dot{v} = \ddot{x}$	$\alpha = \dot{\omega} = \ddot{\phi}$
Force, momentum	Torque, angular momentum
F	$T = r \times F$
$p = mv = Ft$	$L = r \times p = I\omega = Tt$
Kinetic energy	Kinetic energy
$E = \frac{1}{2} mv^2$	$E = \frac{1}{2} I\omega^2$
Dynamics (spring,damper,mass)	Dynamics (moment of inertia)
$F = Kx + b\dot{x} + m\ddot{x}$	$T = \mathrm{K}\phi + \beta\dot{\phi} + I\ddot{\phi}$
Oscillation (assume $b=0$)	Oscillation (assume $\beta=0$)
$f = \frac{1}{2\pi}\sqrt{\mathrm{K}/m}$	$f = \frac{1}{2\pi}\sqrt{\mathrm{K}/I}$

Coriolis Force

Force generated when rotating a rotating system

Underlying principle: conservation of angular momentum.

Torque:

$$\vec{T} = \nabla\vec{L} = \nabla(I\vec{\omega}) = I\nabla\vec{\omega}$$

Time-dependent angular velocity:

$$\vec{\omega}(t) = \omega_0\begin{pmatrix}\sin\Omega t\\ \cos\Omega t\\ 0\end{pmatrix}$$

Gradient:

$$\nabla\vec{\omega}(t) = \omega_0\Omega\begin{pmatrix}-\cos\Omega t\\ \sin\Omega t\\ 0\end{pmatrix}$$

$$T = |I\nabla\vec{\omega}| = I\omega_0\Omega$$

Coriolis Force:

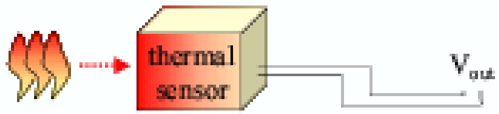
$$F_c = T/r = I\omega_0\Omega/r$$

$$\text{ring}: I = mr^2,\ F_c = mv_0\Omega$$

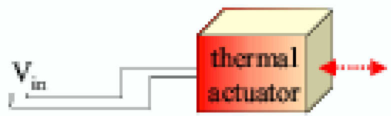
$$\text{disk}: I = \tfrac{1}{2}mr^2,\ F_c = \tfrac{1}{2}mv_0\Omega$$

Thermal Transducers

- ***Thermal sensor:*** heat causes measurable (electric) effect



  - Change in resistivity
  - Thermocouple
  - …
- ***Thermal actuator:*** heat causes motion
  - Thermal expansion
  - …

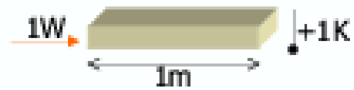


  - Advantages: small size, high force/volume, …
  - Disadvantages: high power, …

Thermal Transducers

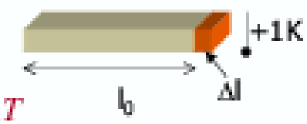
Heat capacity, c : ability to hold thermal energy; energy needed to change unit mass by unit temperature. Usually measured in J/kg·K. Analogous to electrical capacitor.

Thermal conductivity, κ : ability to transfer heat, usually measured in W/m·K. Analogous to electrical conductivity.



Coefficient of thermal expansion (CTE), α : relative change in length per unit temperature change, usually measured in 1/K.

$$\Delta l = l_0\, \alpha\, \Delta T$$



Note: thermal strain $\varepsilon_T = \alpha\, \Delta T$

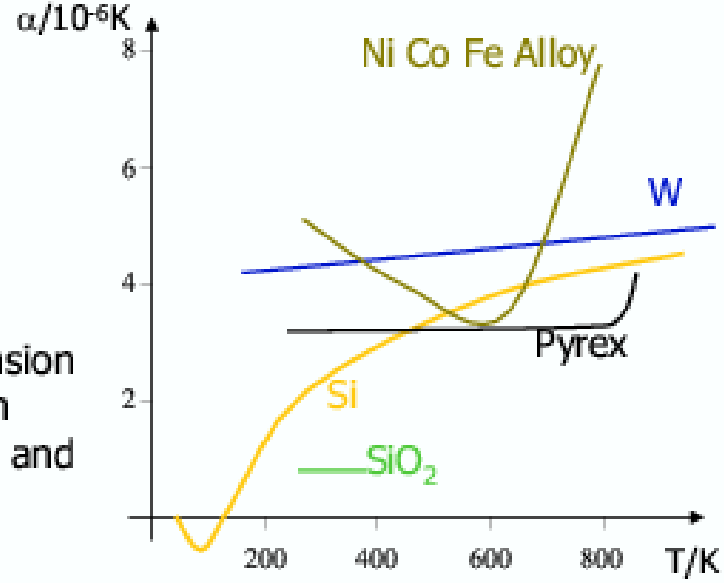
thermal stress $\sigma_T = E\, \varepsilon_T = E\, \alpha\, \Delta T$

Thermal Transducers

	c (J/kg·K)	κ (W/cm·K)	α (10^{-6}/K)
Si	712	1.49	2.6
Polysilicon	920 (?)	0.34	2.33
SiO_2	745	0.0138	0.35
Al	903	2.37	25.0
Au	129	3.18	14.2
GaAs	325	0.56	5.4
Polyimide (Dupont PI2611D)			3.00
Polyimide (Amoco Ultradel 1414)			191

Thermal Transducers

Note: Different coefficients of thermal expansion cause stress in bonded layers and thin films.



[After Madou 1997]

Thermal Transducers

Heat flux, q : thermal energy flowing across unit area per unit time ("heat current")

Fourier's law: $q = \frac{dQ}{dt} = -\kappa A \frac{dT}{dx}$ measured in W

more common: $\vec{q} = -\kappa \nabla T$ measured in $\frac{W}{m^2}$

Q = quantity of heat transferred (in J)

κ = thermal conductivity (in W/mK)

A = cross-sectional area (in m^2)

T = temperature (in K)

x = distance in direction of heat flow (in m)

Thermal Transducers

Temporal diffusion of thermal energy:

$$\text{Diffusion Equation}: \frac{dT}{dt} = \frac{\kappa}{\rho c}\nabla^2 T$$

κ = thermal conductivity (in W/m·K)

ρ = mass density (in kg/m^3)

c = heat capacity (in J/kg·K)

T = temperature (in K)

$\frac{\kappa}{\rho c}$ = thermal diffusivity (in m^2/s)

Thermal diffusivity: ratio of thermal conductivity to "normalized" thermal capacity

Thermal Pressure Sensor

Thermal conductivity changes with temperature

$\kappa = \frac{1}{3}\overline{m}\lambda n\overline{v}c_V$

$\overline{m}$ = average molecular mass (kg)

λ = mean free path (m)

n = number of molecules per unit volume ($1/m^3$)

$\overline{v}$ = mean velocity of gas molecules (m/s)

c_V = specific heat of gas (J/kg · K)

Want to measure pressure in volume with dimensions $< \lambda$:

- gas molecules collide mostly with heater/sensor
- linear relationship between conductivity κ and pressure P

[Kovacs 1998, p. 596]

Thermoresistive Effect

Resistivity changes with temperature

$R_T = R_0(1+\alpha_R \Delta T)$

R_0 = resistivity at temperature T_0

R_T = resistivity at temperature T

$\Delta T = T - T_0$ = temperature difference

α_R = temperature coefficient of resistivity

	Resistivity	TCR
C (graphite)	1390	-500
Al	2.83	3600
Au	2.4	8300
	(μΩ·cm)	(10^{-6}/K)

Shape Memory Alloy (SMA)

Materials that exhibit a temperature-dependent phase transition ("martensite" - "austensite" crystal structure)

Mostly Ni/Ti alloy, but also Au/Cu, In/Ti

Advantages:	**Disadvantages**:
• considerable temperature dependent expansion/contraction • relatively linear control • very high stress (> 200 MPa) • arbitrary shapes • simple actuation • life time: millions of cycles (?)	• special alloy material • high temperature annealing • low efficiency (≈3%) • thermal: long time constants (?)

Shape Memory Alloy (SMA)

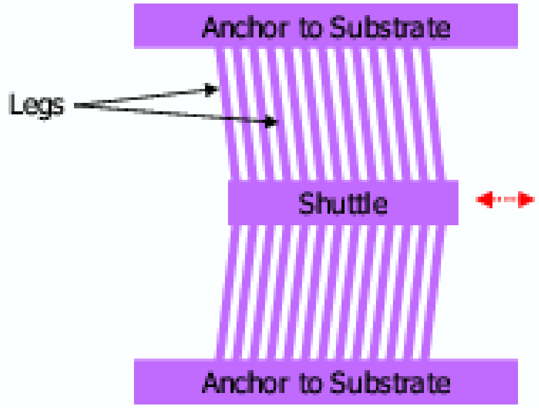
Energy densities for different actuation principles

Actuation	*Maximum Energy Density*	*Equation*
Magnetic	0.95	$\frac{1}{2} B^2 \mu_0$
SMA	10.4	-
Electrostatic	0.4	$\frac{1}{2} \varepsilon \cdot E_b^2$
Piezoelectric	52	$\frac{1}{2} \varepsilon_{\mathrm{PZT}} \cdot E_b^2$
	$[10^6 \mathrm{J/m^3}]$	

[After Madou 1997]

"Chevron" Actuator

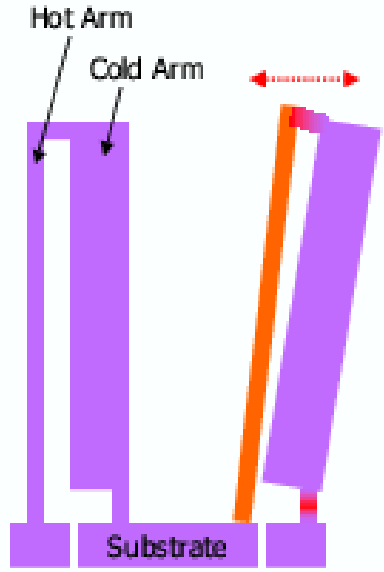
- Current flows through expansion members (legs)
- Legs expand and push shuttle towards right



[Cragun and Howell, ASME IMECE, 1999]

Thermal Actuator

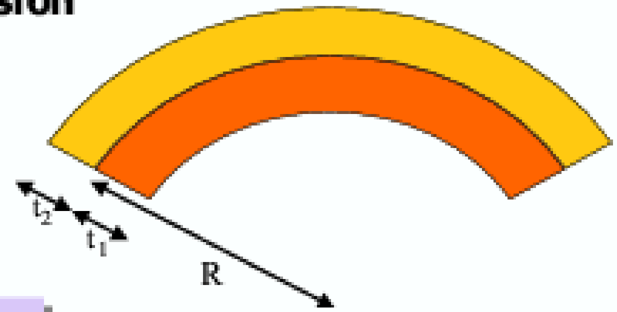
- "Pseudo bimorph"
- Current runs through loop of released structure (usually polysilicon, "cold arm" with gold layer)
- Regions with higher current density ("hot arm") are heated up more and expand more ("pseudo bimorph")



[Allen, Howard, Ruff and Kolesar, TCU, 1997]

Thermal Bimorph

Two layers of materials with different coefficients of thermal expansion



Approximation:

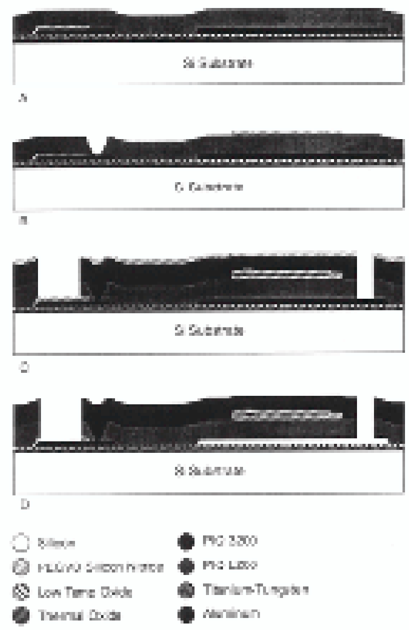
$$R = \frac{t_1 + t_2}{\varepsilon_2 - \varepsilon_1}$$

t_i = thickness of layer i

ε_i = thermal strain of layer i

Polyimide Bimorph MEMS

- Surface Micromachining of two polyimides with very different CTE
- Al connectors, bonding pads, and sacrificial layer for release of structures
- TiW heater loop
- Nitride masking material
- Spin-on deposition of polyimide layers
- Lower temperature → higher curvature



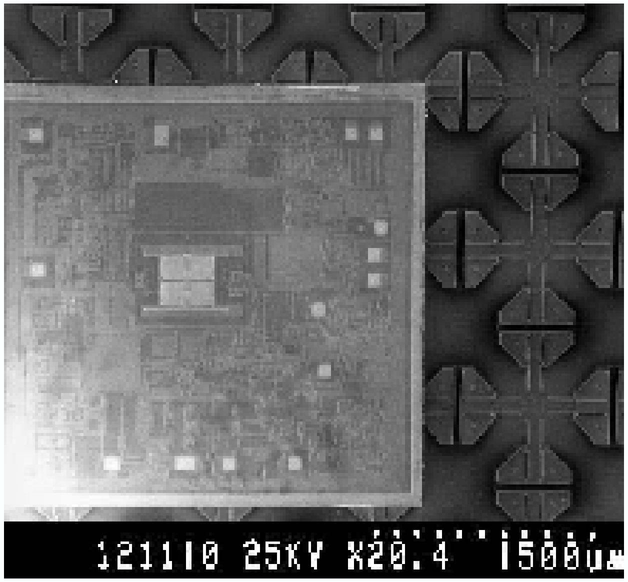
[Figure: Suh et al., 1996]

Polyimide Cilia Array

- 4 actuators per "motion pixel"
- 8 x 8 motion pixels per chip
- Up to 4 chips per array: 1024 cilia total

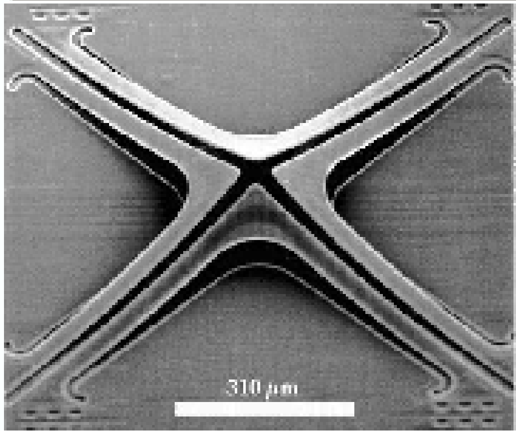
Right: MEMS cilia array moving an ADXL50 accelerometer chip.

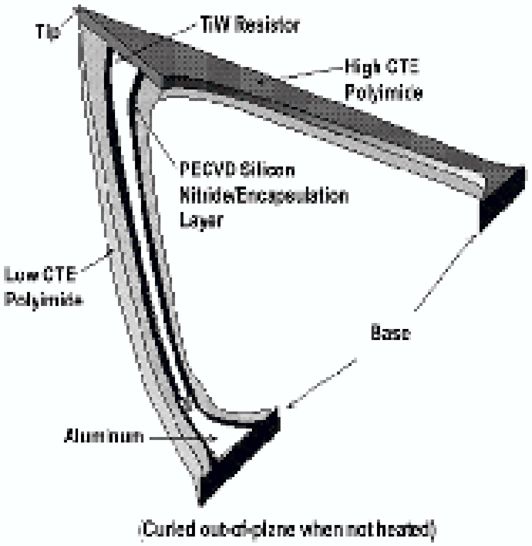
[From Suh et al., 1996]



Fully Addressable Cilia Array

- Polyimide on top of CMOS
- 8 x 8 motion pixels
- Serial / parallel PC interface
- Interactive control software





[From J. Suh et al., 1999]

Related Work

- **Micro Actuator Arrays**

  Pister, Fearing and Howe (UC Berkeley) 1990
  micro-air bearing

  Ataka, Omodaka, Konishi and Fujita (U. Tokyo) 1993 and 1995
  various μ-actuators

  Böhringer, Donald, Mihailovich and MacDonald (Cornell) 1994 and 1996
  electrostatic

  Liu and Will (USC ISI) 1995
  magnetic

  Suh, Glander, Darling, Storment and Kovacs (Stanford) 1996
  thermobimorph

  Yonezawa et al., 1997
  magnetic

  Hirata et al. (Neuchâtel) 1998
  micro-pneumatics

  Ebefors et al. (RIT Stockholm) 1999
  polyimide thermal actuator

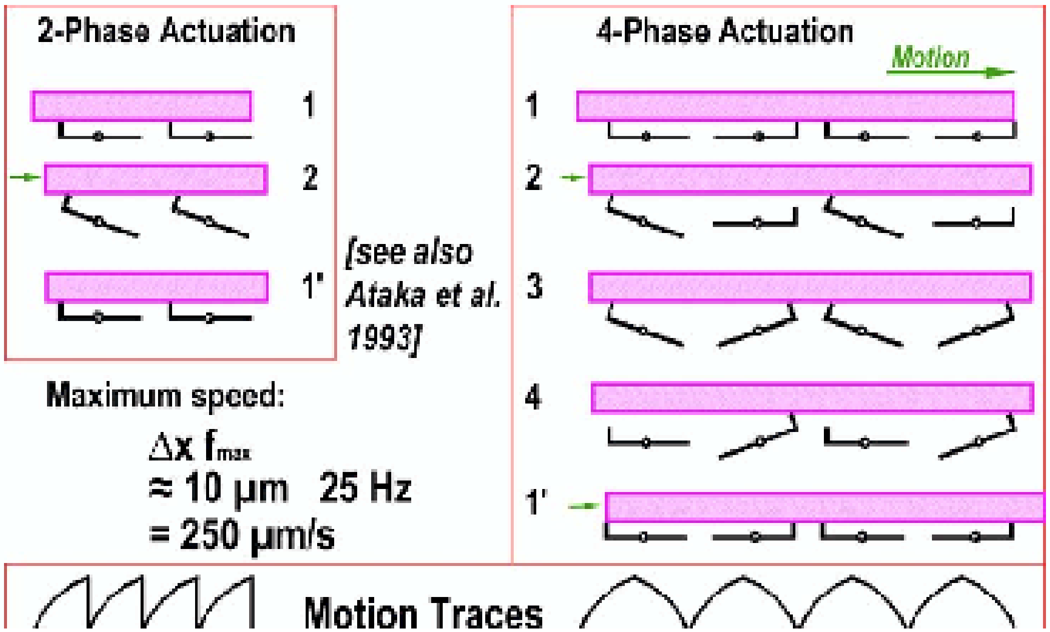
- **Macroscopic (Robotic) Actuator Arrays**

  Luntz, Messner and Choset (CMU) 1997
  macro-actuator array

  Berlin et al. (PARC) 1997
  air jets for paper transport

  Frei, Wiesendanger, Büchi and Ruf (ETH Zurich) 1998
  electromotors

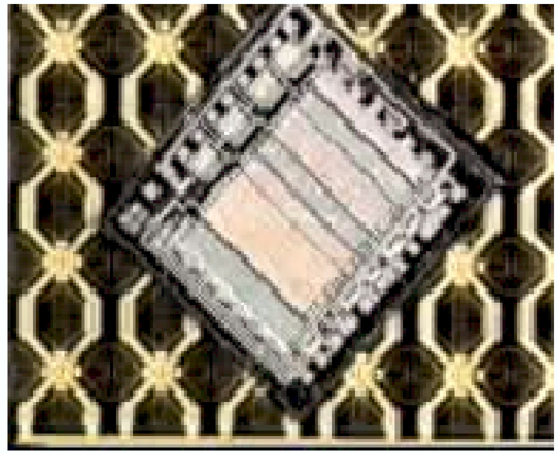
Kinematics of Actuation



MEMS Cilia Array in Action

MEMS cilia moving a 3 x 3 silicon chip

- Translation
- Rotation
- Centering and aligning



[Suh et al., SbA-A, 1997; JMEMS 12, 1999]
[Böhringer et al., IJRR 2, 1999]

Cilia Summary

- MEMS cilia actuator array with integrated control circuitry
- Electrostatic and thermal bimorph sensing and actuation
- High lifting capacity ($\approx$ 70 μN / per cilium)
- Large motion range (up to $\approx$ 25 μm horizontal and $\approx$ 125 μm vertical)
- Implementation of open-loop manipulation strategies (transport, rotate, position, orient, ...)
- Interactive PC control interface
- Abstraction: force vector field

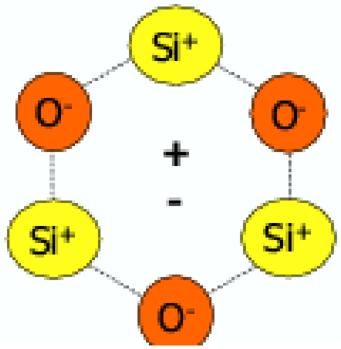
MEMS Robot Summary

- Thermal bimorph cilia arrays work for micro robot locomotion
- Maximum velocity of 635μm/s and carrying capacity of 1.4 g observed
- Each cilium has undergone close to 1 million actuations with no failures
- Accurate method for tracking robot investigated
- Linear plus negative exponential model closely describes movement of the robot
- Further work includes:
  - Temperature – velocity correspondence
  - Walking surface effects
  - Actuation voltage effects

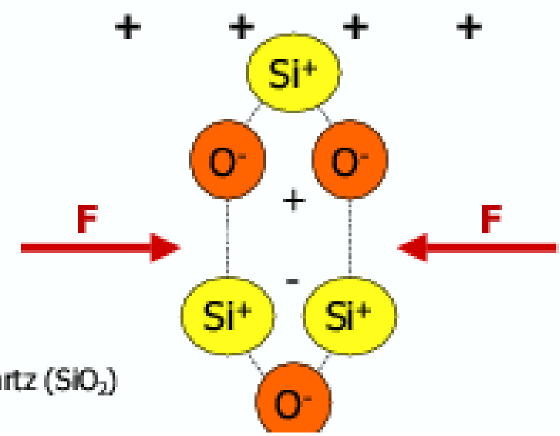
Piezoelectric Effect

Piezoelectricity: forces applied to a segment of material lead to the appearance of electrical charge on the surfaces of the segment.

The source of this phenomenon is the specific distribution of electric charges in the unit cell of a crystal.



Quartz (SiO_2)



Piezoelectricity

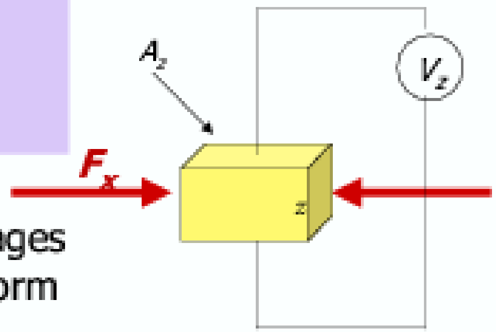
Force deforms crystals and displaces centers of positive and negative charge

$Q = d\,F = d\,\sigma\,A = d\,\varepsilon\,E\,A$

d = charge sensitivity coefficient (matrix)

for example:

$$V_z = \frac{Q_z}{C} = \frac{d_{zx}F_x}{C} = \frac{d_{zx}F_x z}{\varepsilon_0 \varepsilon_r A_z}$$



Effect is reversible: applying voltages causes the piezo crystal to deform

Typical values for d in the pC/N range

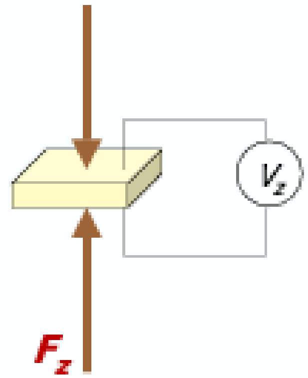
Piezoelectricity: Examples

Apply $F_z = 1\mathrm{N}$ force on a $1\mathrm{cm} \times 1\mathrm{cm} \times 1\mathrm{mm}$ slab of PZT (lead zirconate titanate)

$$V_z = \frac{d_{zz} F_z z}{\varepsilon_0 \varepsilon_r A_z} \approx 0.35V$$

$$V_x = \frac{d_{xz} F_z x}{\varepsilon_0 \varepsilon_r A_x} \approx 10V$$

$$d_{xz} = 110\,pC/N,\; d_{zz} = 370\,pC/N,\; \varepsilon_r = 1200$$



How much has the shape changed?

$$\sigma = \frac{F}{A} = E\varepsilon = E\frac{\Delta l}{l}$$

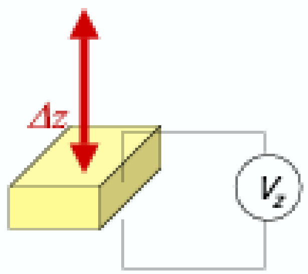
$$\Delta l_z = \frac{F_z z}{E A_z} \approx 0.12\,nm$$

$$E = 8.3 \cdot 10^{10}\,N/m^2$$

Piezoelectricity: Examples

Change in length per unit applied voltage:

$$\frac{\Delta l}{\Delta V} = \frac{C\Delta l}{\Delta Q} = \frac{\varepsilon_0 \varepsilon_r A \Delta l}{l dF} = \frac{\varepsilon_0 \varepsilon_r \Delta l}{l d\sigma} = \frac{\varepsilon_0 \varepsilon_r}{dE}$$



PZT:

$$\frac{\Delta l}{\Delta V} = \frac{\varepsilon_0 \varepsilon_r}{dE} \approx 1.23 nm / V$$

Note: Δl is independent of l ! It only depends on the voltage ΔV, and on material properties

⇒ piezo stacks

Piezoelectric Materials

Material	Type	Piezoelectric Constant (pC/N)	Relative Permittivity (ε_r)	Deposition
Quartz	single crystal	2.33	4.5	growth, oxidation
PVDF	polymer	20/2/-30	12	spin on
$BaTiO_3$	ceramic	78/190	1700	
PZT	ceramic	110/370	1200	spin-on
ZnO	metal oxide	246	1400	sputter

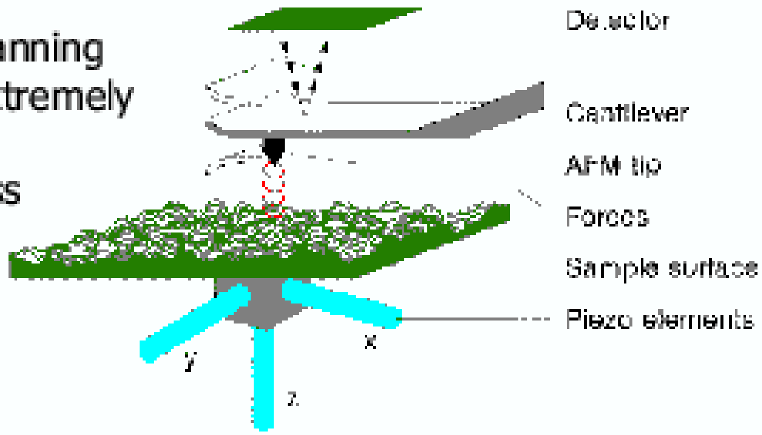
[After Kovacs, 1998, p. 217]

Scanning Probe Microscopy

Limitations of optical microscopy / lithography:

- Resolution (wavelength)
- Complexity / cost increases with decreasing scale

Instead: use scanning probe with extremely sharp tip ("aperture-less microscopy")



Scanning Probe Microscopy

Advantages:

- Not limited by optics / wavelengths
- Measure topography, and a wide range of phenomena such as electrostatic, magnetic, capillary, van der Waals forces, friction, conductivity, …

Disadvantages:

- Contact with sample
- Precise feedback required
- Very sharp tips required (µm … nm)
- Image convolution

Scanning Probe Microscopy

Tip Shape

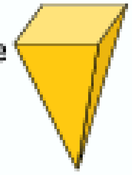
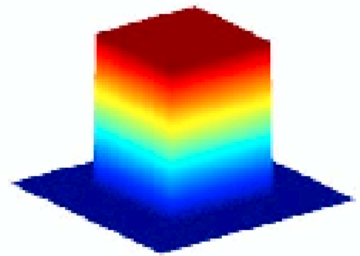


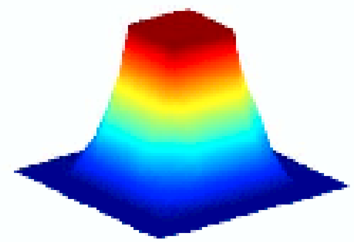
Image convolution:

let A be the sample surface
let B be the tip surface
then $A \oplus (-B)$ is the image that w
observe when scanning B over A



Original Feature

Definition: $A \oplus (-B) = \{a\text{-}b \mid a \in A$ and $b \in B\}$
("Minkovski sum")



Convoluted Feature

Question: Can we reconstruct A from $A \oplus (-B)$ and B?

Scanning Tunneling Microscope

(G. Binnig and H. Rohrer, IBM Zürich, Switzerland, Nobel Prize in Physics, 1986)

The electron cloud associated with surface atoms extends a small distance above the surface. When a very sharp tip is brought sufficiently close to such a surface, there is a strong interaction between the electron cloud on the surface and that of the tip atom.

When a small voltage is applied, an electric tunneling current flows. At a separation of a few atomic diameters, the tunneling current rapidly increases as the distance between the tip and the surface decreases.

Tunneling current: $I = I_0 e^{(-\beta\sqrt{\phi} z)}$

- I_0 scaling factor depending on materials and geometry
- β conversion factor (typical $10.25\,\mathrm{eV}^{-1/2}/\mathrm{nm}$)
- ϕ tunneling barrier height (typical 0.5eV)
- z tip/surface separation (typical 1nm)

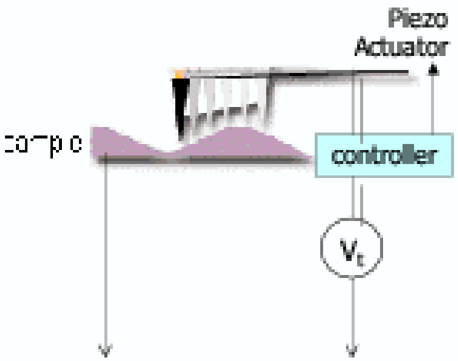
STM

Tunneling current $I = I_0 e^{(-\beta\sqrt{\phi}z)}$
is extremely sensitive to distance z:

$z = 1\text{nm}$ $\quad I = 7.1\ 10^{-4}\ I_0$

$z = 0.1\text{nm}$ $\quad I = 0.48\ I_0$

Feedback control for positioning of cantilever / tip to keep tunneling current constant.



Control signal gives extremely accurate position sensing (up to 0.001 Å)

Noise

- ***Johnson Noise:*** thermal noise across a resistor
  - White noise with flat frequency spectrum
  - Obeys Gaussian distribution
  - Reason: Brownian motion

- ***Shot Noise:*** fluctuations in current due to charge quanta
  - White Gaussian noise

Johnson and Shot noise set limitations on performance of STMs

$$V_{noise}(rms) = V_{nR} = \sqrt{4kTR\Delta f}$$

$k = 1.38 \cdot 10^{-23}$ J/K Boltzmann's constant

T absolute temperature

R resistance

Δf bandwidth

$$I_{noise}(rms) = I_{nR} = \sqrt{2qI_{dc}\Delta f}$$

$q = 1.60 \cdot 10^{-19}$ C electron charge

I_{dc} steady current

Δf bandwidth

Noise - Sample Calculations

- ***Johnson Noise:*** probe at room temperature

$$V_{noise}(rms) = V_{nR} = \sqrt{4kTR\Delta f} = \frac{0.1\mu\text{V}}{\sqrt{\text{Hz}}}$$

$k = 1.38 \cdot 10^{-23}\,\text{J/K}$ Boltzmann's constant

$T = 300\text{K}$

$R = 1\text{M}\Omega$

Δf bandwidth

- ***Shot Noise:*** calculate the ratio between noise and current response.

$$I_{nR} : \frac{dI_{dc}}{dz} = \frac{\sqrt{2qI_{dc}\Delta f}}{I_{dc}\beta\sqrt{\Phi}} = \frac{7.8 \cdot 10^{-7}\,\text{Å}}{\sqrt{Hz}}$$

$q = 1.60 \cdot 10^{-19}\,\text{C}$

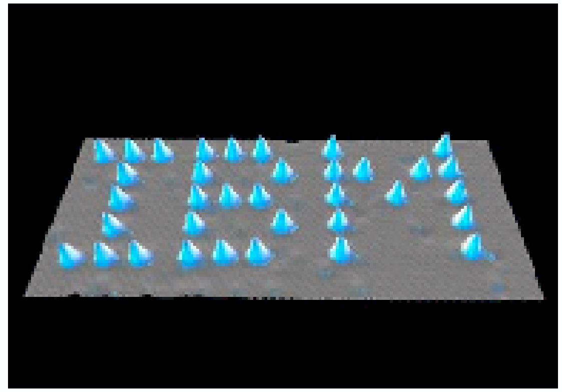
$I_{dc} = 1\mu\text{A}$

$\beta = 10.25\,\text{eV}^{-1/2}/\text{nm}$

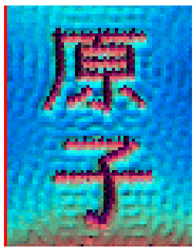
$\Phi = 0.5\text{eV}$

STM Gallery

Single atoms were accurately placed with an STM tip

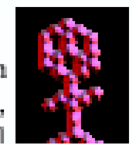


[“The Beginning” Xenon on Nickel (110), Eigler, IBM Zürich, 1990]



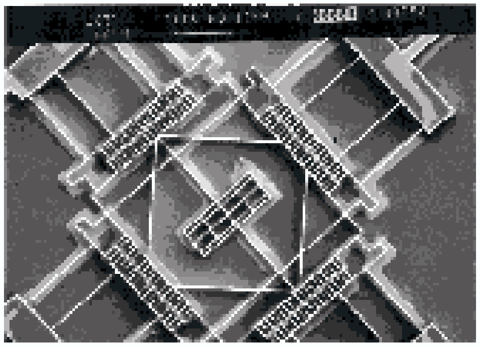
“Atom” Iron on Copper (111) [Lutz and Eigler, IBM Zürich]

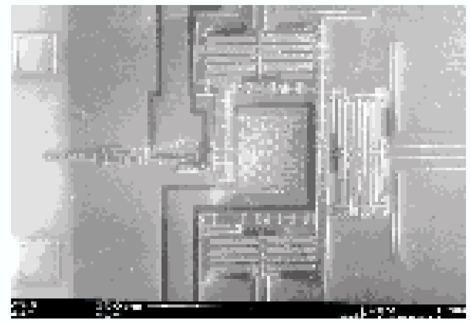
[“Carbon Monoxide Man” Carbon Monoxide on Platinum (111), Lutz and Eigler, IBM Zürich]



MEMS STM

Two Micro-STM Designs Have Been Fabricated





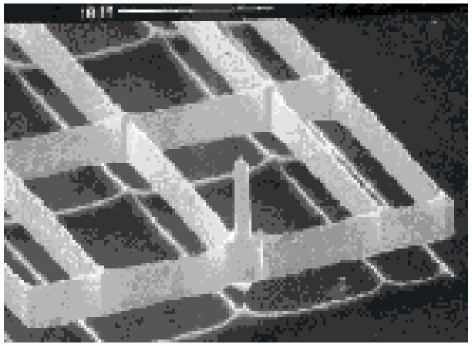
- Single Crystal Silicon (SCS) XYZ Actuators
  - Lateral (xy) motion provided by comb drives
  - Vertical (z) motion provided by torsional drive
- Integrated SCS Tip

MEMS STM

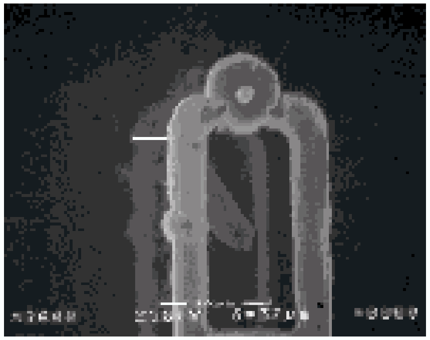
- The tunneling tip is fabricated along with the mechanical scanning stage
- The single crystal silicon tip may be silicided or metal-coated

Tip Dimensions:
Height = 5 μm
Shank Diameter = 1 μm
Tip Radius ≤ 10 nm

Lateral Motion:
Applied Voltage = 40 V
Displacement = 3.2 μm



Close-up of the tip on the stage

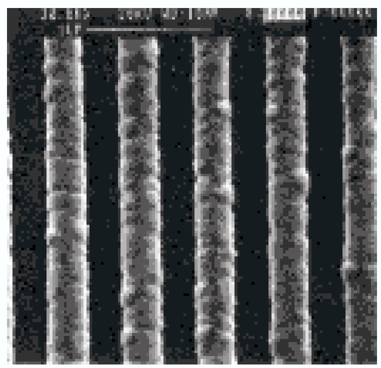


Lateral Displacement of the tip

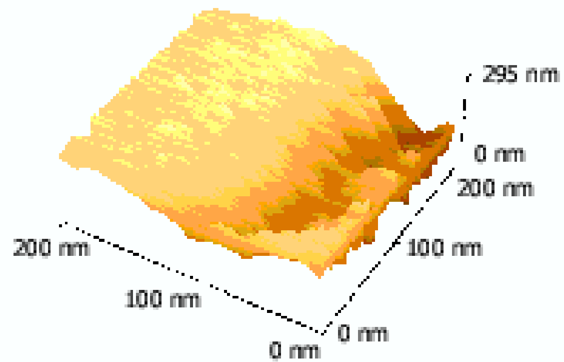
MEMS STM

Image Acquisition With The Micro-STM

- STM images acquired using commercial STM control electronics
- Z-Positioning of the tip provided by the torsional cantilever



SEM image of test sample



Micro-STM image of test sample

MEMS STM

Applications:

- Imaging with atomic resolution
- Data storage: 10^{12} bits/mm^2
- Sub-nanometer lithography

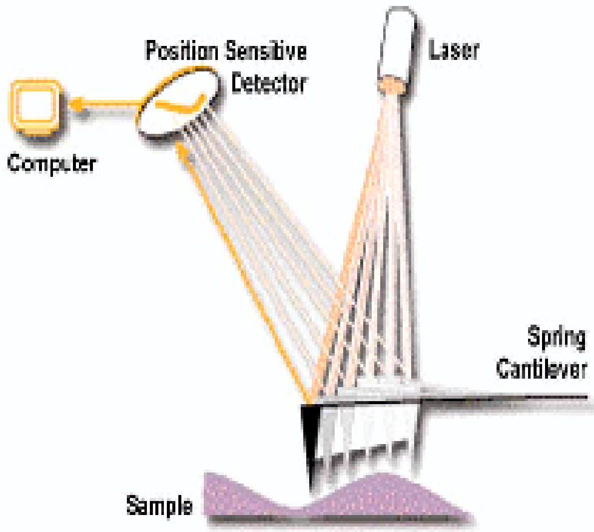
Problems:

- Conductive material only
- Tunneling current required
- Brownian motion (cooling)

Atomic Force Microscope

Similar to STM, but use forces (at atomic level) instead of tunneling current for feedback

Requires force feedback, usually with cantilever spring, and laser optical deflection detection or piezoresistors



AFM

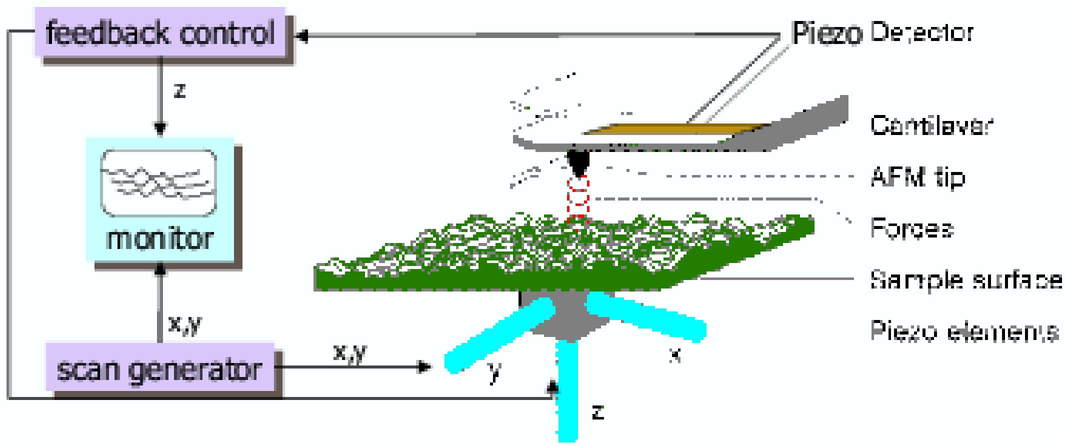
Advantages:

- Can be used in **contact mode** (atomic / ionic repulsion forces) or **non-contact mode** (> 10 Å; van der Waals, electrostatic, magnetic, capillary forces)
- Non-destructive probing:
  - Spring constants down to 1mN/m = 10^{-13} N/Å (compare with covalent bond 10^{-9} N)
  - Motion controllable down to 1/1000 of atomic radius
- Different environments:
  - Vacuum
  - Air
  - Liquid

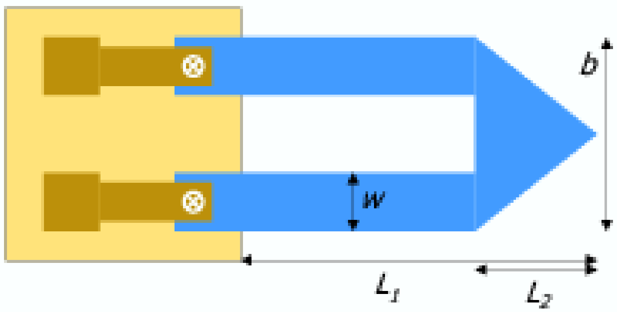
Piezoresistive AFM

Tortenese et al. 1991: first AFM with integrated piezo force sensor

- Scan generator moves sample in x and y direction
- Controller adjusts z motion to keep atomic force constant



Piezoresistive AFM



(Binding Force of a covalent bond: 10^{-9}N)

Spring constant :

$$K = \frac{Et^3wb}{(L_1^3 - L_2^3)b + 3L_2^3w}$$

Relative change in resistance :

$$\frac{\Delta R}{R} = \pi_1\sigma = \frac{3\pi_1(L_1 - L_2)}{4wt^2}F$$

$$= \frac{3\pi_1 Etb(L_1 - L_2)}{4((L_1^3 - L_2^3)b + 3L_2^3w)}z$$

Minimum detectable signal :

$$\left(\frac{\Delta R}{R}\right)_{\min} = \frac{2\sqrt{4kTR\Delta f}}{V} = 4\sqrt{\frac{kT\Delta f}{P}}$$

Minimum force : $F_{\min} = 5.4\ 10^{-10}\ N$

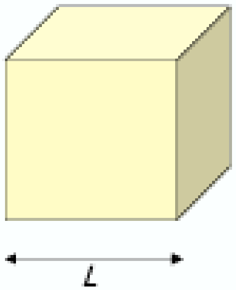
Scanning Probe Microscopes

The invention of the scanning tunneling microscope (STM) 15 years ago has produced new family of proximal probes:

- Atomic force microscope (AFM)
- Scanning thermal microscopes
- Scanning capacitance microscopes
- Magnetic force microscopes
- Surface probing and analytical tools for a wide variety of phenomena and materials
- Nanoassembly, nanomanipulators, and nanorobots
- Nanolithography
- Ultra-high density storage: towards pick-and-place of single atoms as bits

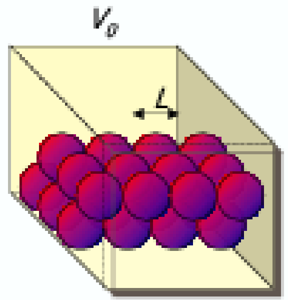
Scaling Effects

Scaling of a 3D Object



- Surface area $A \propto L^2$
- Volume $V \propto L^3$
- Mass (weight) $m = \rho V \propto L^3$
- Moment of inertia $I \propto mR^2 = L^5$
- Torque (weight acting on a moment arm) $\tau = R \times mg \propto L^4$

Scaling Effects



Example:
Densely packed spheres

Spheres per fixed volume:
$N = V_0 / L^3 \propto L^{-3}$

Total mass: $m \propto L^0$

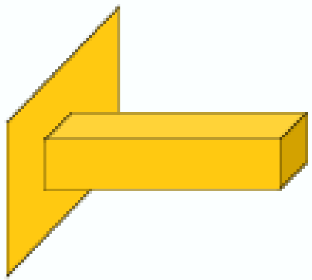
Total surface area: $A = N\, 4\pi\, (L/2)^2 \propto L^{-1}$

Scaling down spheres keeps total mass equal but increases total surface area by a linear factor

Useful, for example, for chemically active surfaces

Mechanical Resonance

- ***Cantilever Beam:***

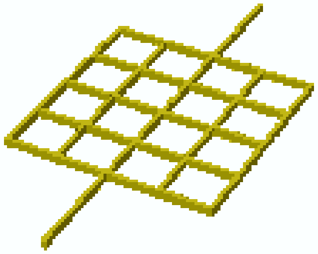


$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K}{m}}$$

$$K \propto L^1,\ m \propto L^3$$

$$f_0 \propto L^{-1}$$

- ***Torsional Resonator:***



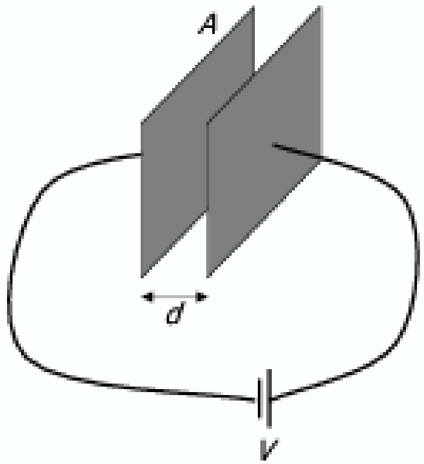
$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{I}}$$

$$k \propto L^3,\ I \propto L^5$$

$$f_0 \propto L^{-1}$$

Note consequences for life span

Electrostatics

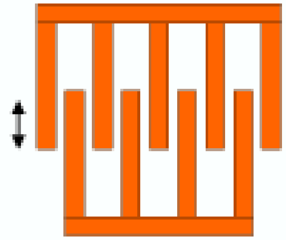


- Parallel-plate capacitor:
  $\boldsymbol{F = \frac{1}{2}\, \varepsilon A\, V^2 / d^2}$

- Electrostatic force is scale-independent:
  $F \propto L^0\, V^2$

Example: Comb Drives

- $F = n\,\varepsilon\,h\,V^2 / d$
  - n number of fingers
  - h height
  - d distance between fingers
  - V voltage



- Straightforward analysis for fixed n:
  $F \propto L/L \propto L^0$
- Height is given by process:
  $F \propto 1/L \propto L^{-1}$
- For given voltage V, d_{min} is fixed (breakdown):
  $F \propto L^0$
- If operating close to breakdown voltage, $V \propto d$, hence:
  $F \propto n\,\varepsilon\,h \propto L^1$ (or L^2?)

Example: Cube in Electrostatic Field

Electrostatic force acting on a small cube:

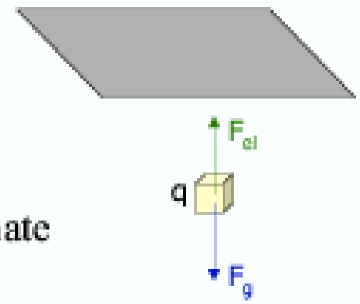
$$C = \frac{Q}{V} = \varepsilon \frac{A}{d} \text{ hence } \varepsilon E = \frac{Q}{A} = \sigma \text{ (charge density)}$$

Charge density in air / atm. pressure: $\sigma_{max} = Q/A = 3\ 10^{-5} \mathrm{C/m^2}$
(corresponds to a breakdown voltage of about 3 MV/m)

$$F_g = g\rho V = g\rho L^3$$

$$F_{el} = \frac{1}{2}\varepsilon A E^2 = \frac{\sigma^2}{2\varepsilon} L^2$$

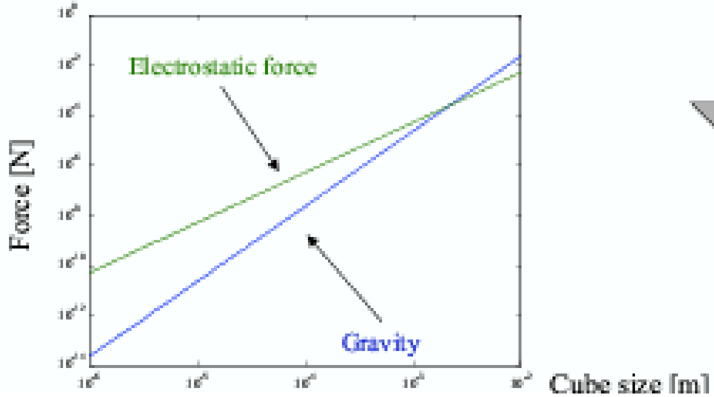
$$\text{hence for } L < \frac{\sigma^2}{2\varepsilon g \rho} \text{ electrostatics dominate}$$

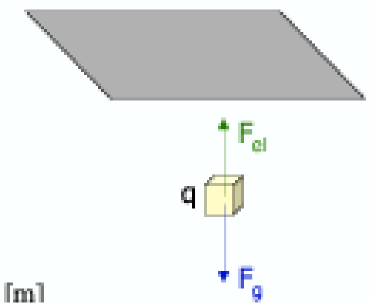


Example: Cube in Electrostatic Field

$$F_g = g\rho V = g\rho L^3, \quad g\rho \approx 22.6\frac{kN}{m^3}$$

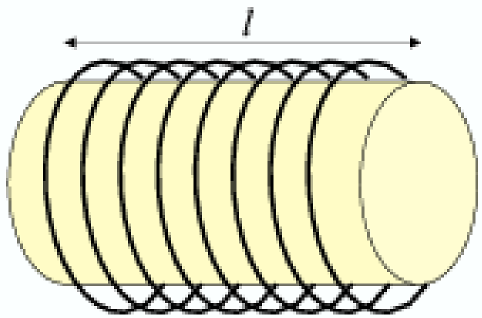
$$F_{el} = \frac{1}{2}\varepsilon E^2 L^2 = \frac{\sigma^2}{2\varepsilon}L^2, \quad \frac{\sigma^2}{2\varepsilon} = 50.8\frac{N}{m^2}$$





Electromagnetic Actuators

- Lorentz force: $F_m = q \cdot v \times B = l \; I \times B$
  $F_m \propto L^3$
- Coil: $B = \mu_0 \, \mu_r \, n/l \; I_{coil}$
  $B \propto L^2$
- Lorentz force on wire inside coil: $F_m \propto L^5$

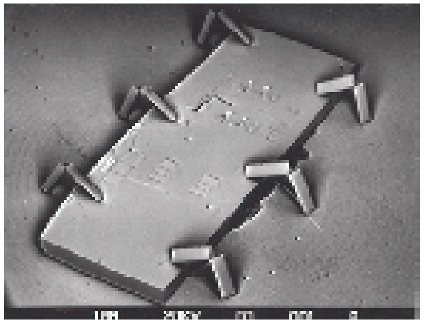


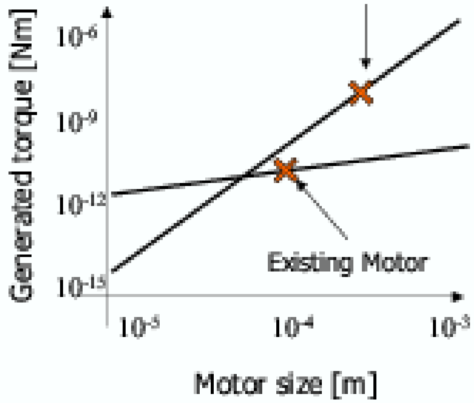
→ Lorentz force / coil not well-suited for MEMS

Microrobotic Ant

- Actuator torque $\tau = 10^{-8}$ Nm [Shimoyama 1995]
  $F =$ weight of $1\ \text{mm}^3$, $r = 1$ mm leg

- Electrostatic force:
  $F \propto L^0$
  $\tau \propto L^1$

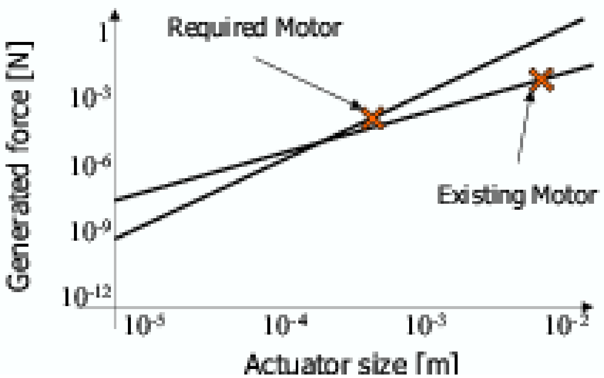




Microrobotic Ant

- Magnetic force on moving permanent magnet:
- I = 300 mA, coil diameter 5.8 mm, … F = 0.68 mN $\propto L^2$

- Ant needs $F = 1.6\ 10^{-6}\ 9.81 / 3$ N = 5.2 μN to support its body on 3 legs, and $F \propto L^3$

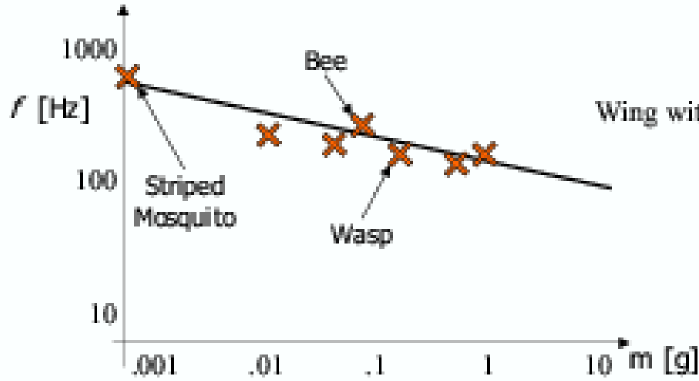


Scale Effects in Flight

Drag force: $F_d = ½\, c_d\, \rho\, v^2 A \propto L^2$, c_d drag coefficient

Gravity: $F_g = mg \propto L^3$

hence $v \propto L^{½}$



Wing with length l and flapping angle θ_0:

$v = l\, \theta_0\, \omega$

so $\omega = v / l\, \theta_0 \propto L^{-½} \propto m^{-1/6}$

Power: $P = F_d \times v = ½\, c_d\, \rho\, v^2 A \times v \propto L^{7/2}$