SENSORS and TRANSDUCERS

Klas Hjort, Materialvetenskap

- Micromechanics
  - Micromechanics - simple mechanics
  - Principles of detection: piezoresistive
    piezoelectric
    capacitive
  - Micromechanical properties
  - Micromechanical sensors

MICROMECHANICS

- Micromechanics is simple mechanics:
  - Mechanics like of the middle ages, but miniaturized:
  - Cantilever beams, bridges, plates, and diaphragmas
  - Only designs of low relative tolerances!
  - We detect changes in stress, position, or frequency.

MICROMECHANICS

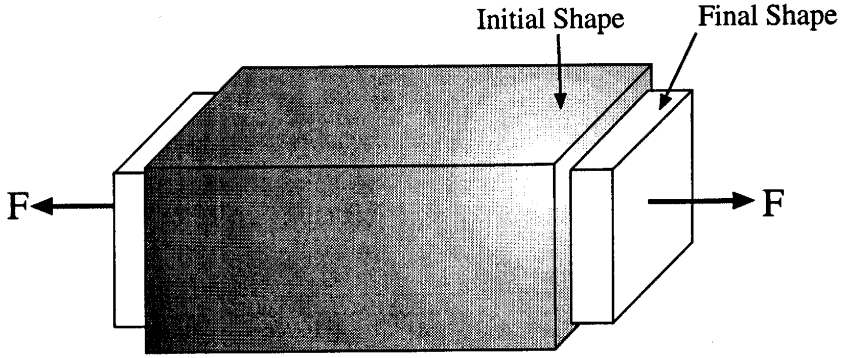
- Basic mechanics:

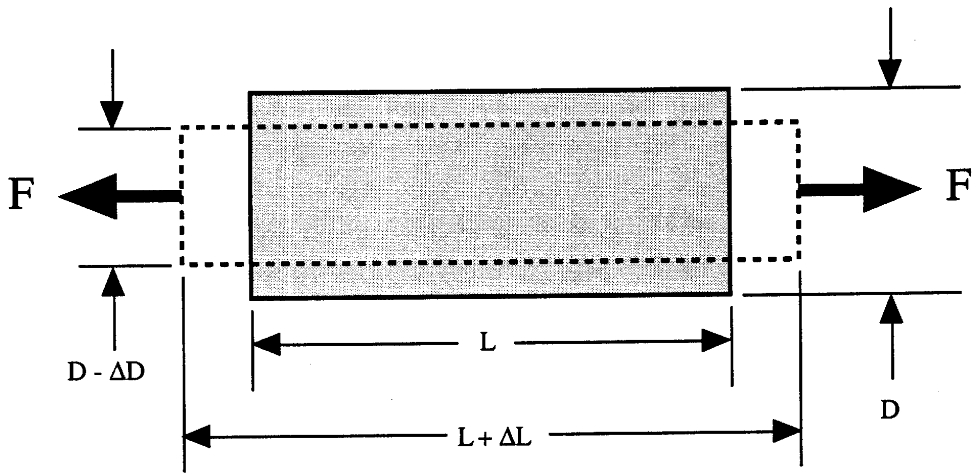
$$s = \frac{F}{A}$$

$$e = \frac{\Delta L}{L}$$

$$s = E e$$

$$n = \frac{\frac{\Delta D}{D}}{\frac{\Delta L}{L}}$$



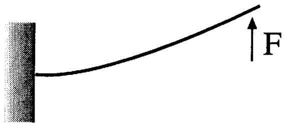


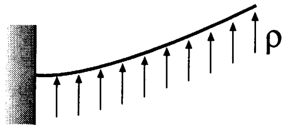
MICROMECHANICS

- Simple mechanics:

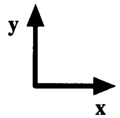
	Point Load	Distributed Load

Beam:





$$y(x) = \frac{F}{6EI}\left(3x^2L - x^3\right)$$



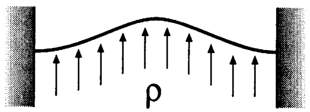
$$y(x) = \frac{\rho x^2}{24EI}\left(6L^2 - 4Lx + x^2\right)$$

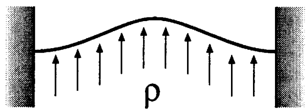
$$\sigma_{max} = \frac{FLt}{2I}$$

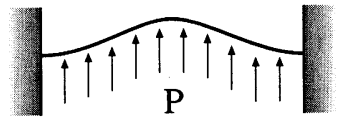
$$\sigma_{MAX} = \frac{\rho L^2 t}{4I}$$

Membrane:

Bridge:





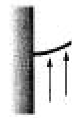


$$y(x) = \frac{Fx}{48EI}\left(3Lx - 4x^2\right)$$

{for $x \leq L/2$ away from a support}

$$y(x) = \frac{\rho x^2}{24EI}(L - x)^2$$

$$\delta_{max} = \delta_{center} = \frac{3Pr^4(1-\nu^2)}{16Et^3}$$



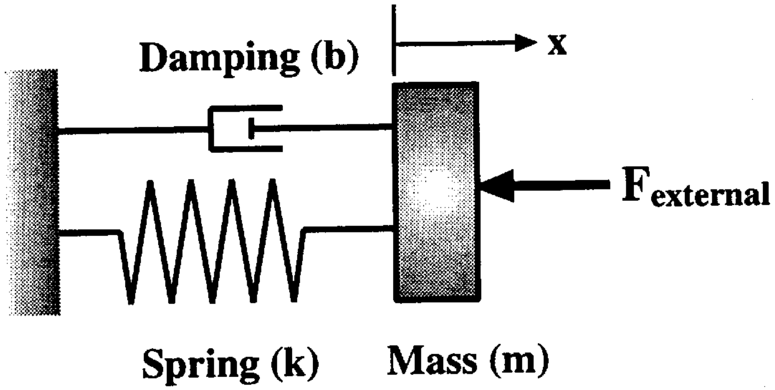
$$\sigma_{MAX} = \frac{FLt}{8I}$$

$$\sigma_{MAX} = \frac{\rho L^2 t}{12I}$$

MICROMECHANICS

- Simple dynamics:

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F_{external}$$



where,

m = mass, in kg

b = damping coefficient, in (N•s)/m

k = spring constant, in N/m

$F_{external}$ = applied force, in N = (kg•m)/s^2

MICROMECHANICS

- Scaling mechanics:

Table 7.6 Geometric scaling factors of a cantilever beam (constant stress).

Parameter	Symbol	Factor
Beam force	F	K^2
Spring constant	k_m	K
Deflection	y	K
Beam stress	σ_m	1
Mass	m	K^3
Natural frequency	ω_o	K^{-1}

Damping: viscous (K^2), surface adhesion (K^2)

MICROMECHANICS

- Mechanical properties of silicon

  - Brittle
  - Anisotropic
  - Low ageing

Property	*Value*
Yield Strength	7 GPa
Hardness	10 GPa
Young's modulus	166 GPa
Density	2.33 g/cm^3
Thermal conductivity	1.57 W/cmK
Thermal expansion	2.6 ppm/K

MICROMECHANICS

- Sensor mechanisms

Mechanism	Parameter Sensed	Needs Local Circuits?	DC Response?	Complex System?	Linearity	Issues
Metal Strain Sensor	strain	NO	YES	+	+++	• low sensitivity • very simple
Piezoresistive Strain Sensor	strain	NO	YES	+	+++	• temperature effects can be significant • easy to integrate
Piezoelectric	force	NO	NO	++	++	• high sensitivity • fabrication can be complex
Capacitive	displacement	YES	YES	++	poor	• very simple • extremely low temperature coefficients
Tunneling	displacement	YES	YES	+++	poor	• sensitive to surface states • drift performance not yet proven
Optical	displacement	NO	YES	+++	+++	• rarely employed in mechanical microsensors

MICROMECHANICS

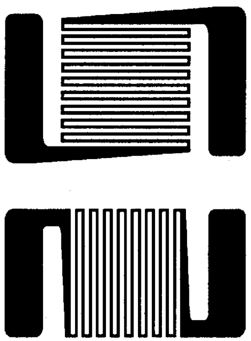
- Scaling sensor mechanisms:

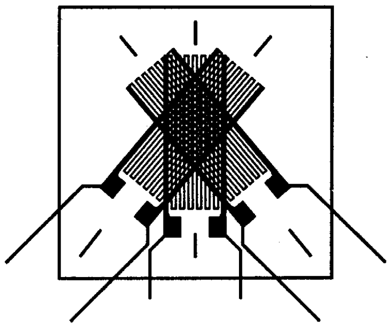
Table 7.7 Dimensions of physical sensing parameters.

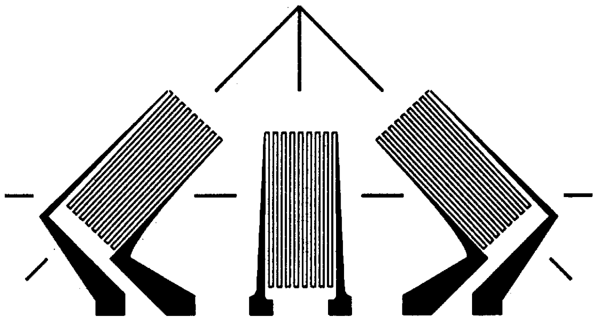
Physical parameter	Electromagnetics	Electrostatics
Capacitance	$L^{-1} T^{2} \mu^{B-1}$	$L \varepsilon$
Inductance	$L \mu$	$L^{-1} T^{2} \varepsilon$
Resistance	$L T^{-1} \mu^{B}$	$L^{-1} T^{-1}$
Electric current	$M^{1/2} L^{1/2} T^{-1} \mu^{B-1/2}$	$M^{1/2} L^{3/2} T^{-2} \varepsilon^{1/2}$
Potential difference	$M^{1/2} L^{3/2} T^{-2} \mu^{B-1/2}$	$M^{1/2} L^{1/2} T^{-1} \varepsilon^{1/2}$

MICROMECHANICS

- Strain gauges







Gauge factor: $GF = \frac{\Delta R}{\varepsilon R}$

$$GF_{met} = (1 + 2\nu) + \frac{\frac{d\rho}{\rho}}{\varepsilon} \approx 2$$

$$GF_{SC} = 80 - 200$$

MICROMECHANICS

- Semiconductor bandgap

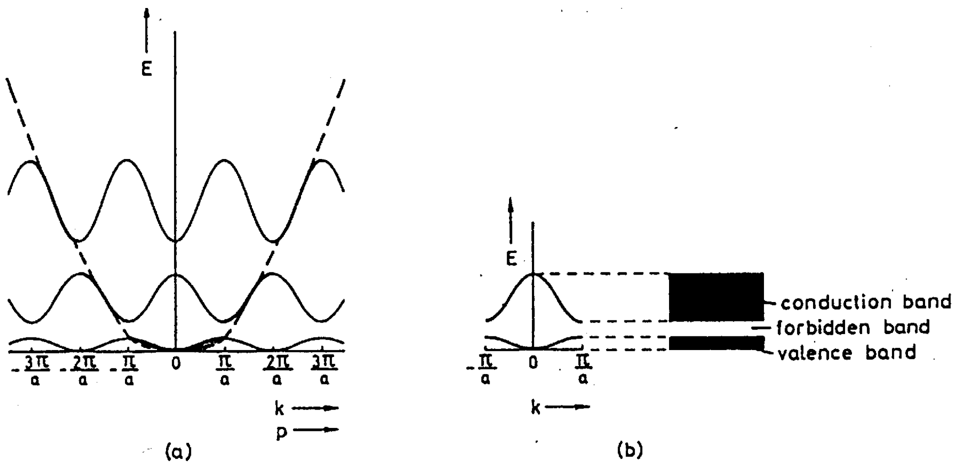


Fig. 3.2 (*a*) Energy E as a function of the momentum p for a classical particle (dashed line) and as a function of the wave number k for a particle with wavelike nature in interaction with a periodic crystal lattice (solid thick and thin lines), (*b*) part of the possible solutions indicating the conduction, the forbidden and the valence band.

MICROMECHANICS

- Semiconductor bandgap in space

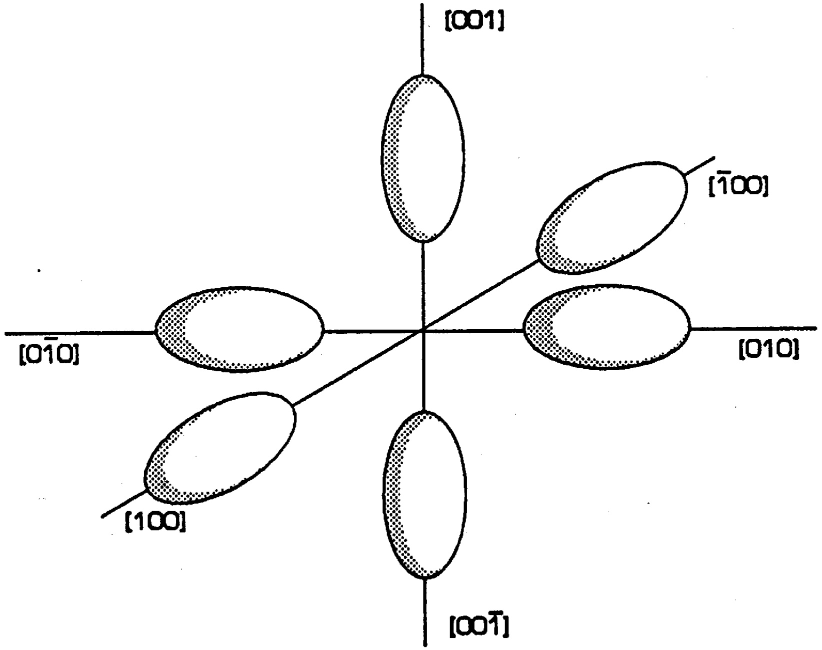


Fig. 3.4 Constant energy ellipsoids in k-space near the energy minimum in the conduction band of silicon.

MICROMECHANICS

- Piezoresistive mechanism for silicon:

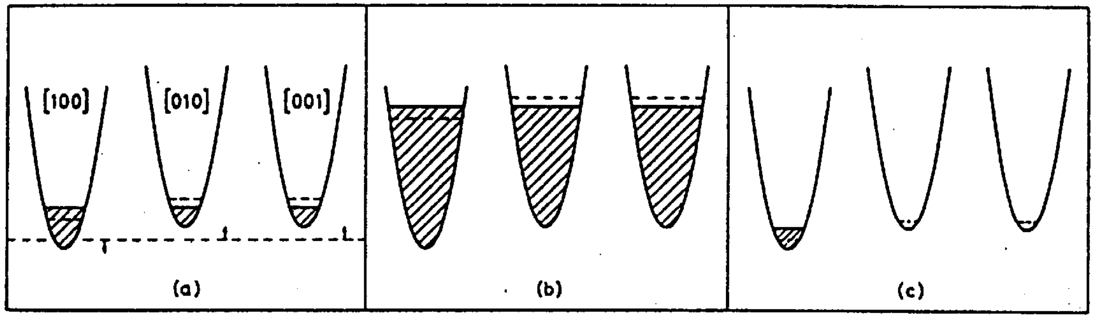
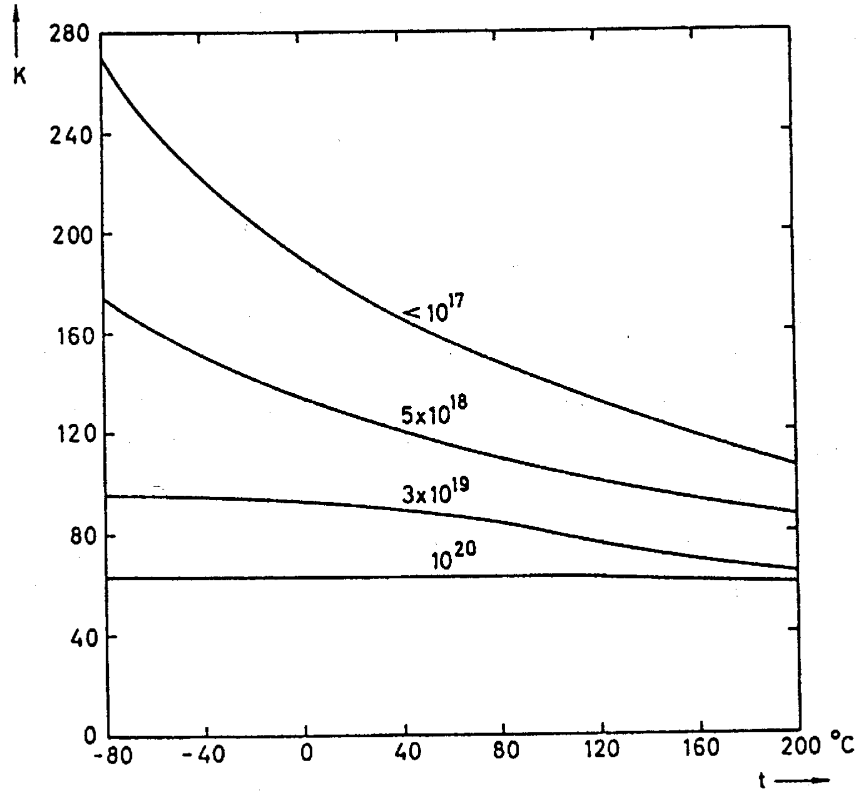


Fig. 3.5 (*a*) Upon compression in the [100] direction, the [100] energy minimum is lowered and the [010] and [001] minima are raised. Electrons flow from the [010] and [001] minima to the [100] minimum, (*b*) and (*c*) show the influence of the electron occupancy of the conduction band on the flow of electrons for high and low impurity concentration.

MICROMECHANICS

- Piezoresistive respons to dopants and temperature

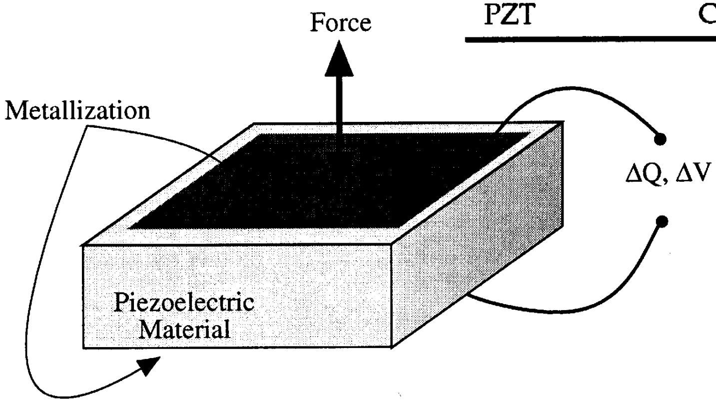


MICROMECHANICS

- Piezoelectric sensing

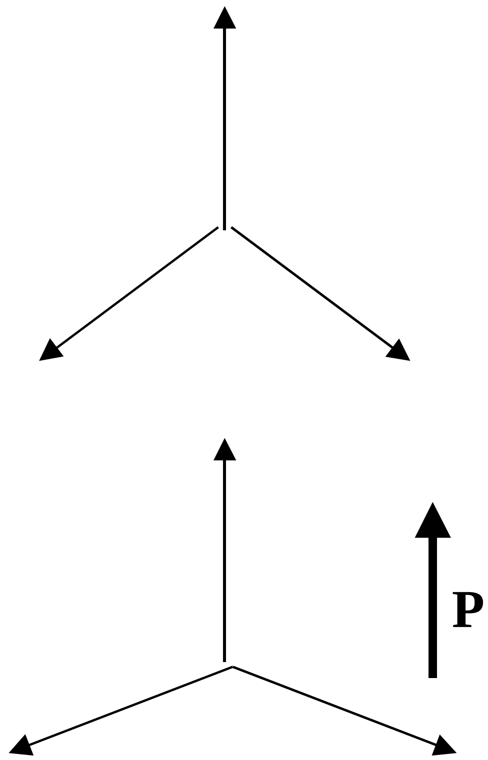
Table 7.14 Piezoelectric coefficients of materials at 300 K.

Material	Type	Form	Coefficient, Ξ_{33} (pC/N)	Permittivity, ε_r
Quartz (X-cut)	Glass	Bulk	2.33	4.0
PVDF	Polymer	Film	1.59	-
P(VDF-TrFE)	Polymer	Film	18.0	6.2
ZnO	Ceramic	Bulk	11.7	9.0
ZnO	Ceramic	Film	12.4	10.3
$BaTiO_3$	Ceramic	Bulk	190	4,100
PZT	Ceramic	Bulk	370	300- 3,000



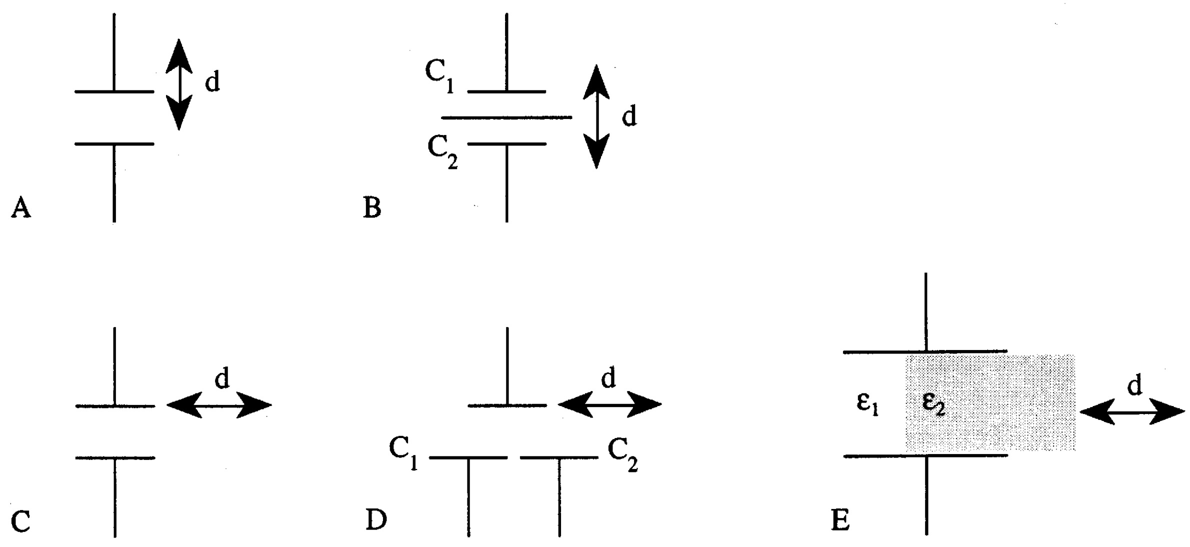
MICROMECHANICS

- Piezoelectric mechanism
  - Charge generation due to polarization to an applied force.
  - With two conductors to the piezoelectric dielectric a capacitor is created, and we may meassure a voltage difference.



MICROMECHANICS

- Capacitive sensing



MICROMECHANICS

- Micromechanical sensors:
  - Strain gauges
  - Accelerometers
  - Gyroscopes
  - Pressure sensors
  - Microphones
  - Tactile sensors
  - Position sensors
  - Flow sensors

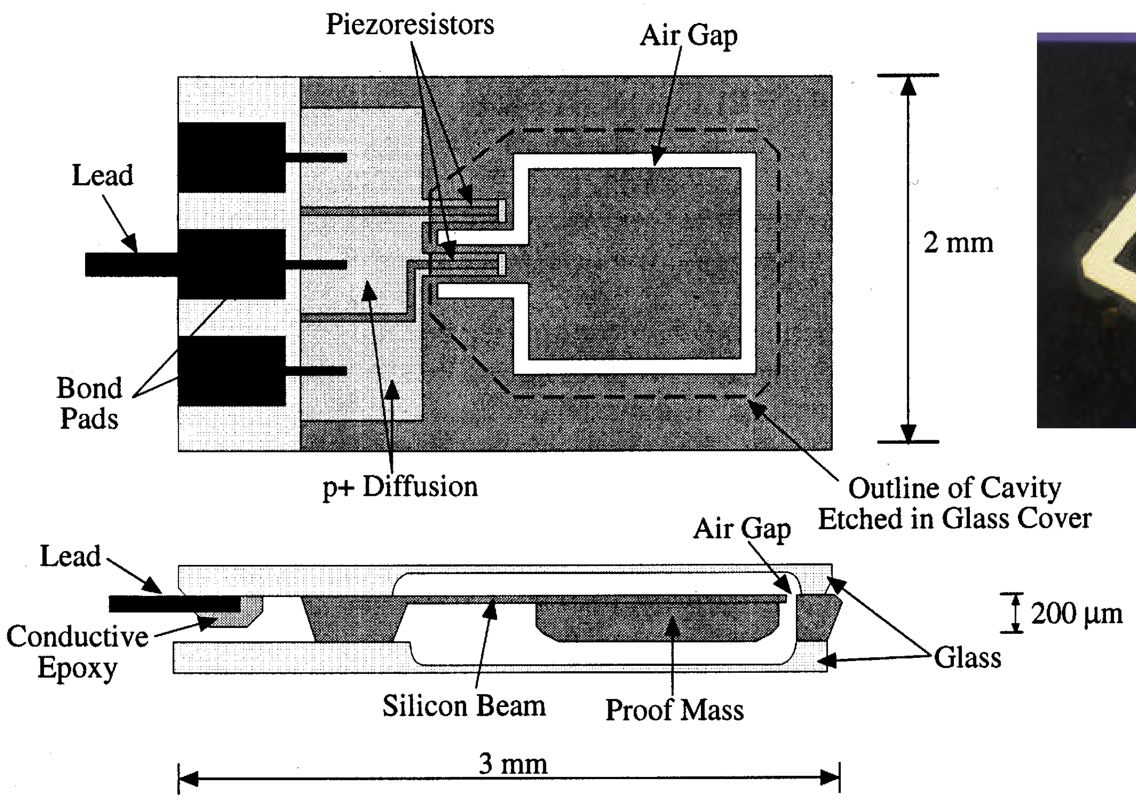
MICROMECHANICS

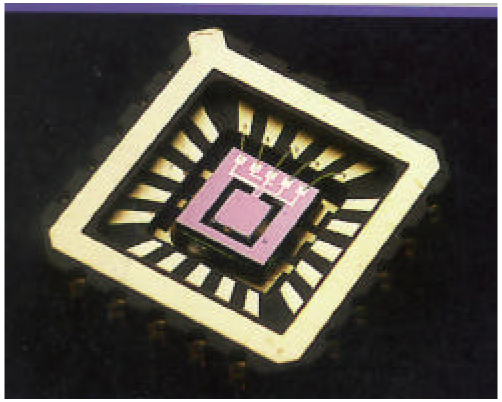
- Accelerometer ranges and applications

Range	± 1 g	antilock braking (ABS)/traction control system (TCS)
	± 2 g	vertical body motion
	± 40 g	wheel motion
	± 50 g	air bag deployment
	± 100°/s	steering feedback
Accuracy	± 2 %	5% at temperature extremes
Cross-Axis Sensitivity	< 1 to 3 %	all applications
Shock Survivability	> 500 g	1 m drop onto concrete
Frequency Response	0 to 5 Hz	vertical motion
	0.5 to 50 Hz	horizontal motion (up to 1 kHz for air bags)
Temperature Range	-40 to 85°C	most applications
	-40 to 125°C	under hood

MICROMECHANICS

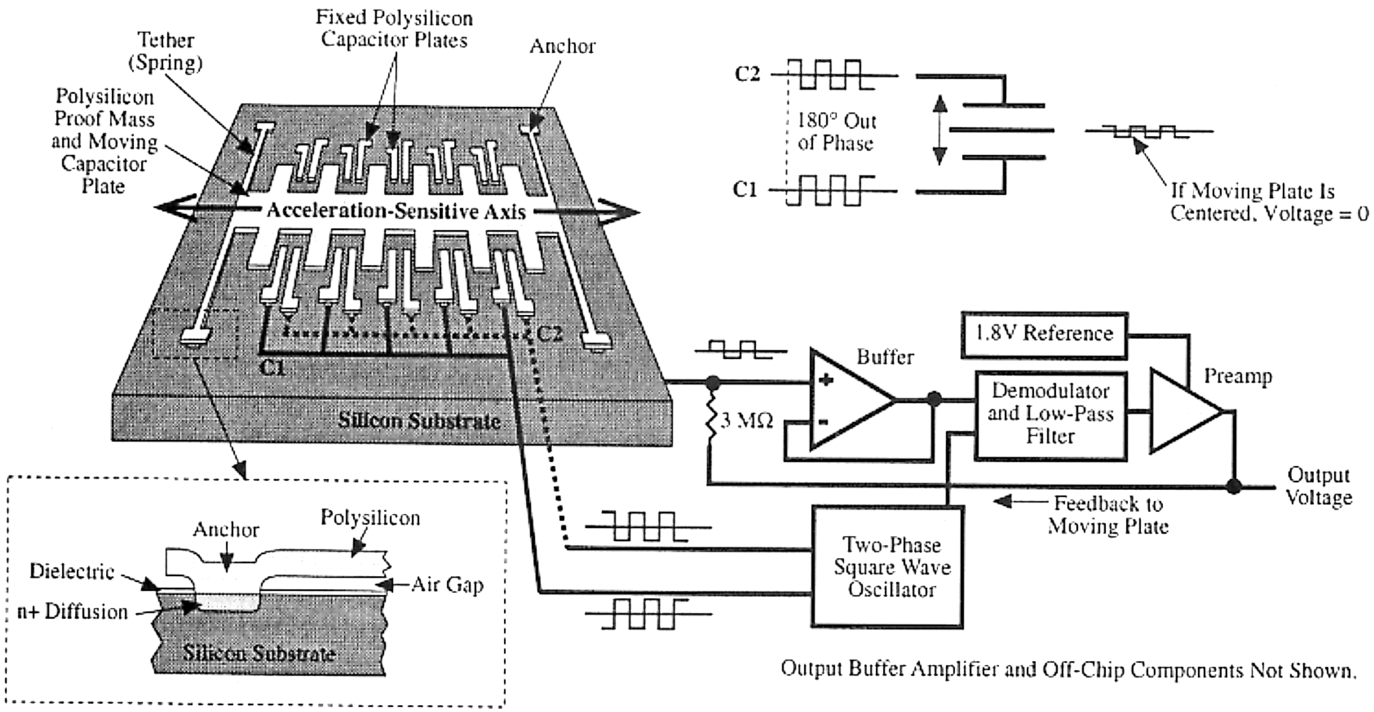
- Bulk micromachined accelerometer





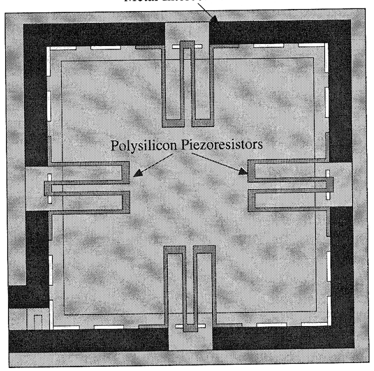
MICROMECHANICS

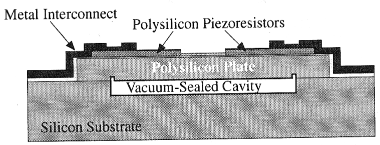
- Surface micromachined accelerometer (AD):

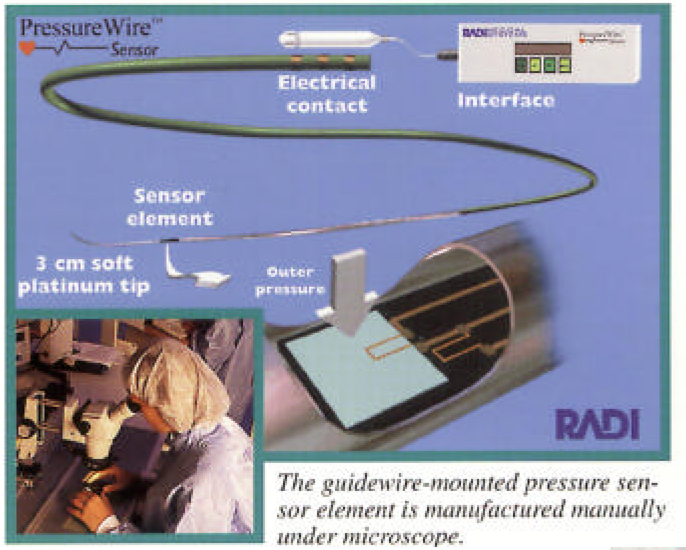


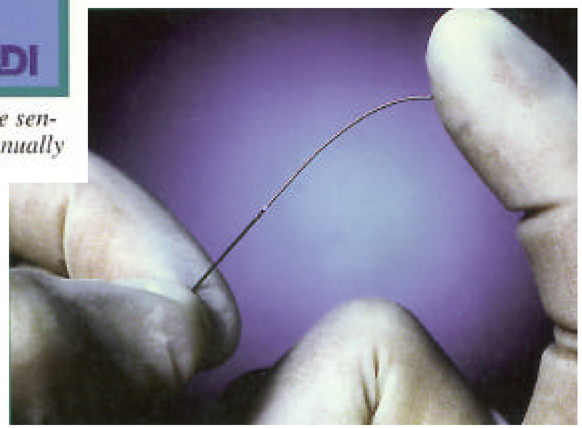
MICROMECHANICS

- Pressure sensor (Radi Medical Systems AB)



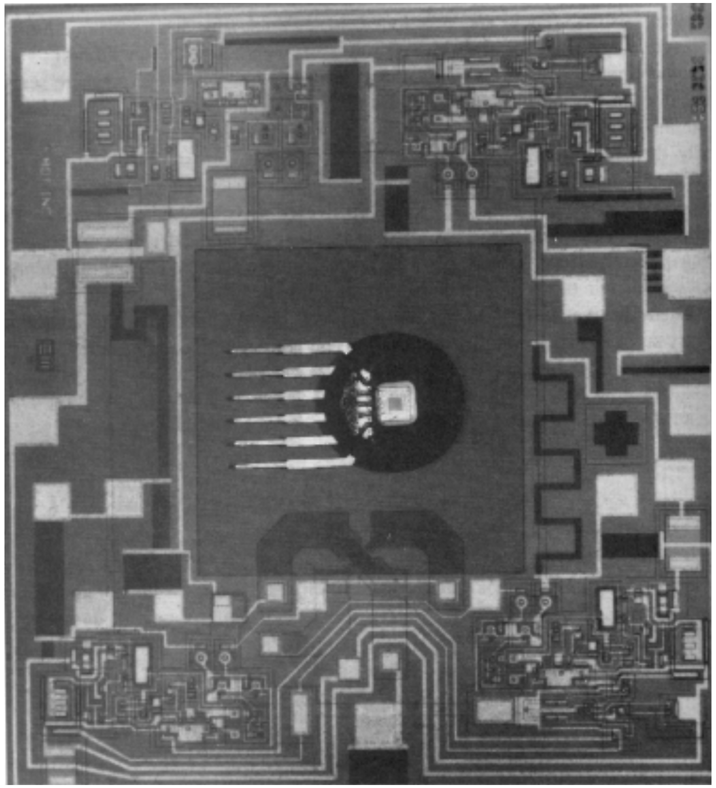






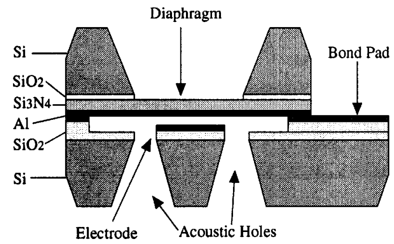
MICROMECHANICS

- Smart pressure sensor chip

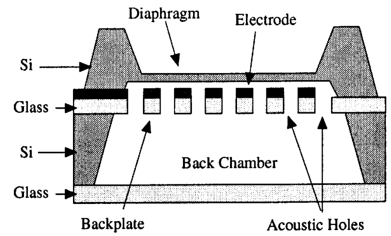


MICROMECHANICS

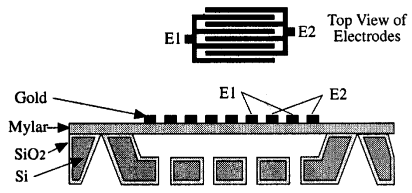
- Micromachined microphones



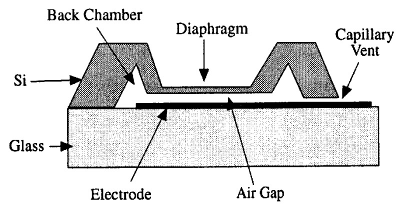
After Hohm (1986)



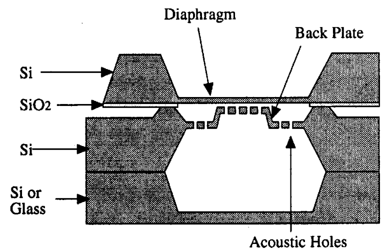
After Bergqvist and Rudolf (1990)



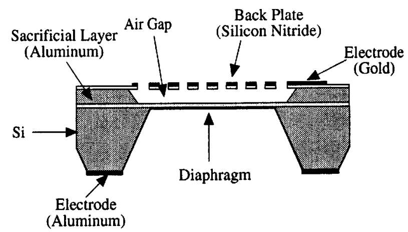
After van der Donk (1992)



After Bourouina, et al. (1992)



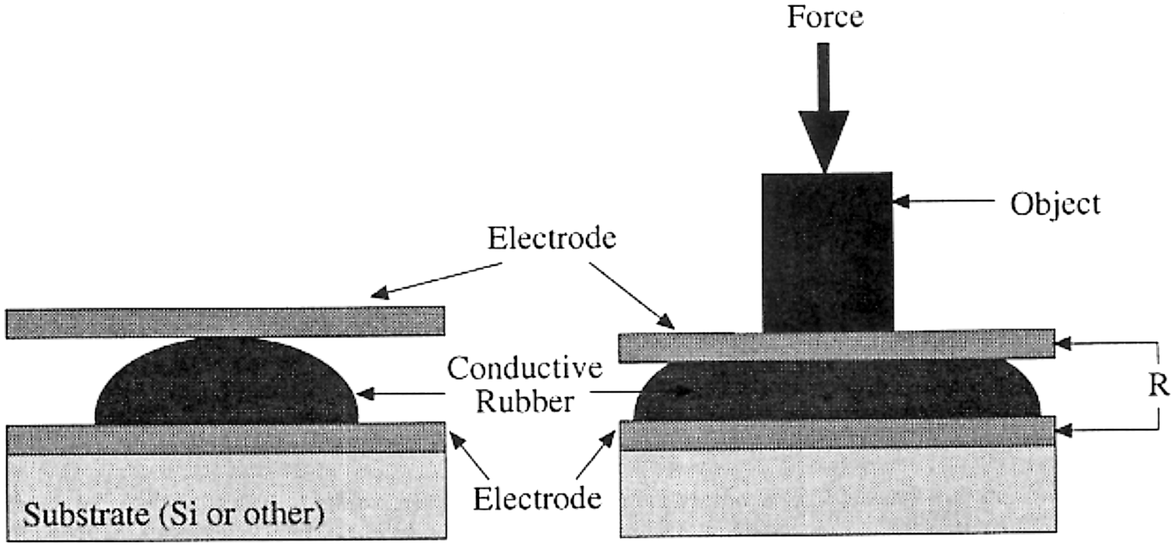
After Bergqvist, et al. (1991)



After Scheeper, et al. (1992)

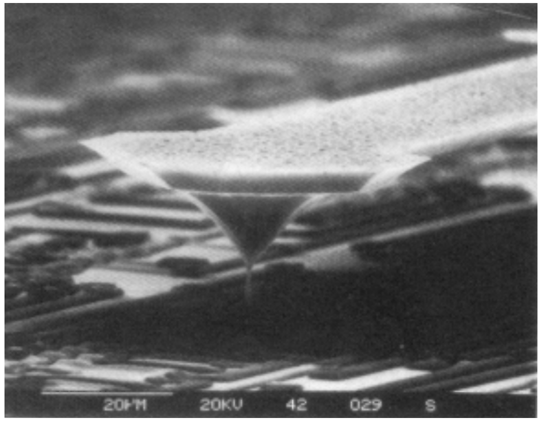
MICROMECHANICS

- Tactile sensor



MICROMECHANICS

- Tunneling



$$I = I_o e^{(-\beta\sqrt{\phi}z)}$$

where,

I_o = scaling factor, dependent on materials, tip shape, etc.

β = conversion factor, typical value = 10.25 $eV^{-1/2}$/nm

ϕ = tunnel barrier height in electronvolts (eV), typical value = 0.5 eV

z = tip/surface separation in nanometers (nm), typical value = 1 nm

SENSORS and TRANSDUCERS

Klas Hjort, Materialvetenskap

- Micromechanics, more...
  - Principle of detection: resonant
  - Micromechanical resonant sensors: gyroscopes
  - Micromechanic actuators

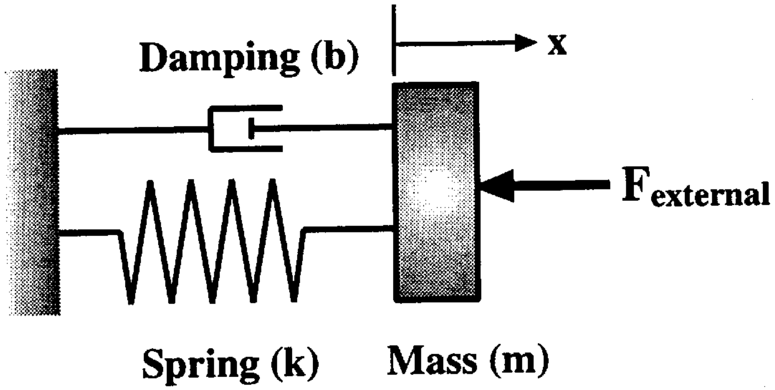
MICROMECHANICS

- Resonators - applications
  - Mechanical sensors, meassuring strain
  - Microbalances, meassuring mass
  - Chemical or biological sensors, meassuring mass
  - High-Q electrical filters

MICROMECHANICS

- Simple dynamics:

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F_{external}$$



where,

m = mass, in kg

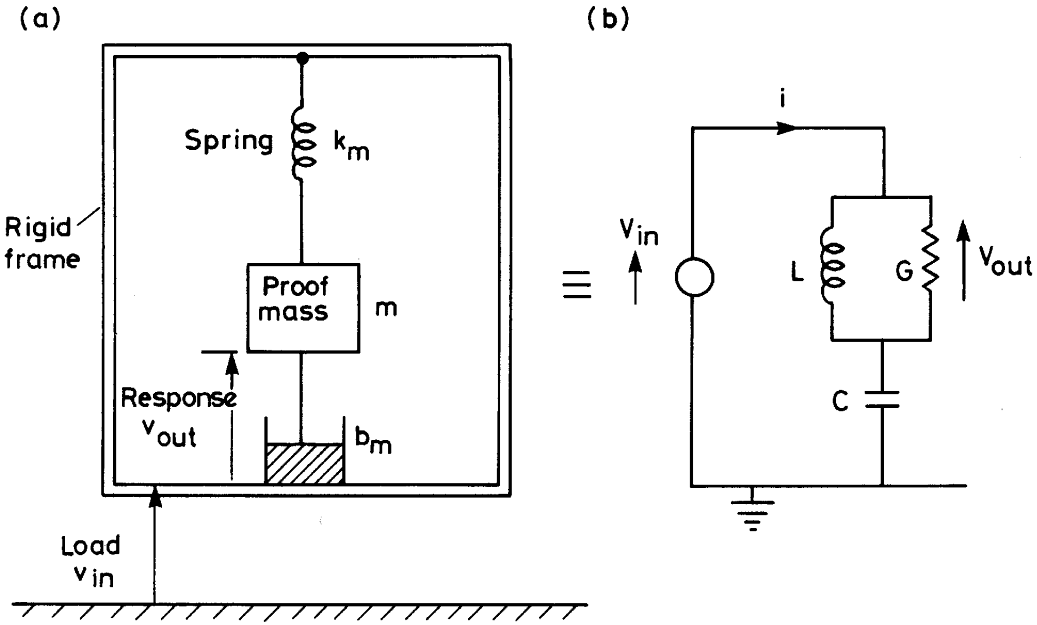
b = damping coefficient, in (N•s)/m

k = spring constant, in N/m

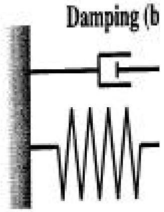
$F_{external}$ = applied force, in N = (kg•m)/s^2

MICROMECHANICS

- Dynamics in mechanics and electronics (1)



$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F_{external}$$

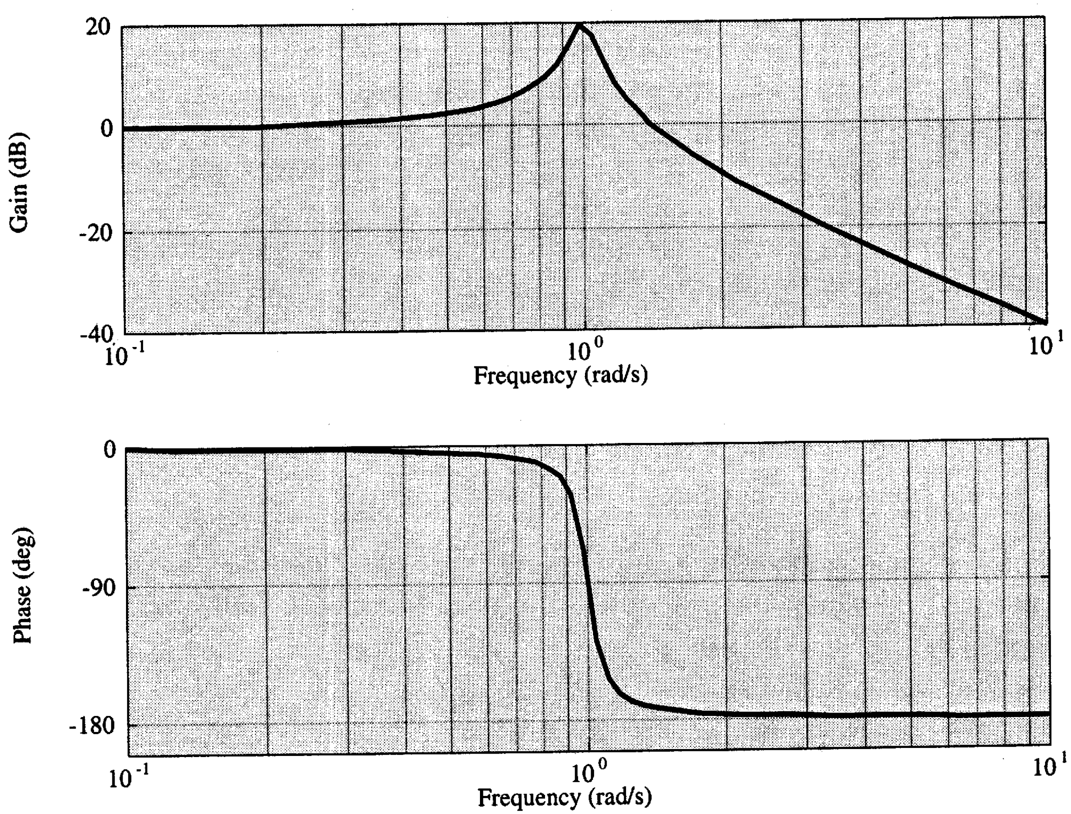


$$H(s) = \frac{\frac{1}{m}}{s^2 + \left(\frac{b}{m}\right)s + \frac{k}{m}}$$

$$H(S) = \frac{v_o}{v_i} = \frac{\frac{1}{LC}}{s^2 + \left(\frac{1}{RC}\right)s + \frac{1}{LC}} = \frac{\omega_o^2}{s^2 + \frac{\omega_o}{Q}s + \omega_o^2}$$

MICROMECHANICS

- Dynamics in mechanics and electronics (2)



MICROMECHANICS

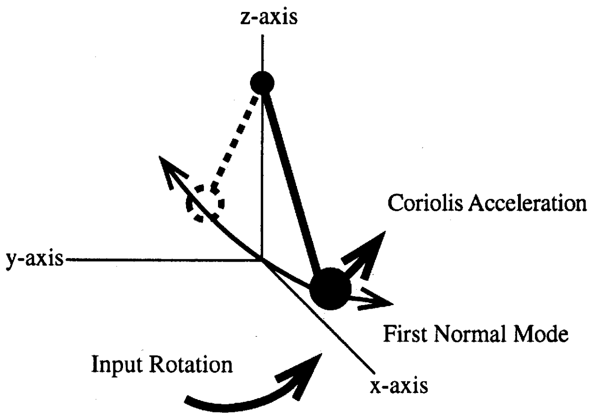
- Dynamics in mechanics and electronics (3)

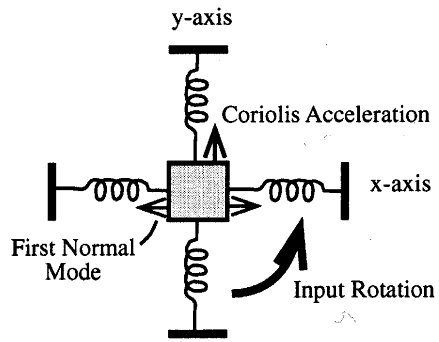
$$Q = \frac{\text{energy stored per cycle}}{\text{energy lost per cycle}} = \omega_o RC \quad \text{where} \quad \omega_o = \frac{1}{\sqrt{LC}}$$

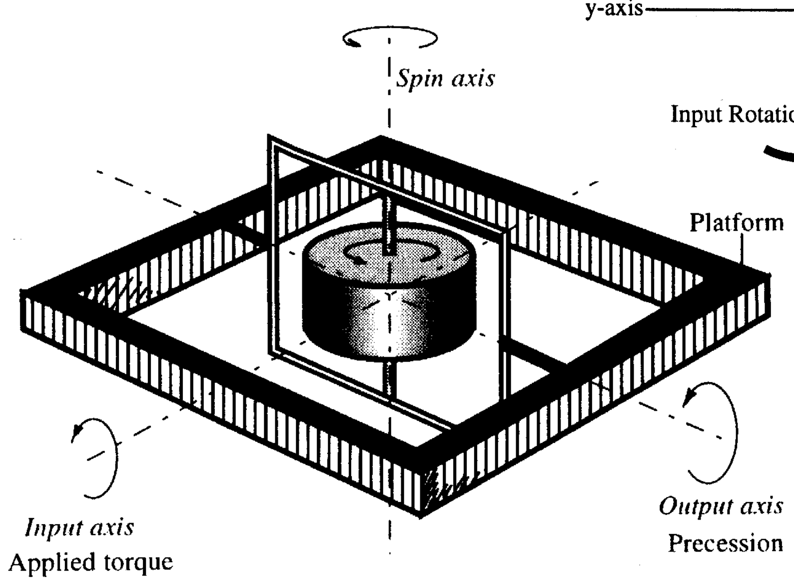
Parameter	Mechanical System	Electrical System
DC Gain	$\frac{1}{k}$	1
Natural Frequency, ω_o	$\sqrt{\frac{k}{m}}$	$\frac{1}{\sqrt{LC}}$
Quality Factor, Q	$\omega_o \frac{m}{b} = \sqrt{\frac{km}{b^2}}$	$\sqrt{\frac{R^2C}{L}}$

MICROMECHANICS

- Gyroscopes







MICROMECHANICS

† Applications of micromechanical gyroscopes

Automotive safety reliable, inexpensive, lifetime, rough environment	• improved controls for airbags • anti-collision systems • active suspension • anti-skid	50g, 200°/s 100°/s 50°/s 100°/s	500mg, 10°/s 1°/s 2°/s 1°/s
Consumer inexpensive, small, lifetime, low-power	• free-space pointers (small computers) • remote control devices (TV-controls) • video camera (anti-jitter compensation) • navigation (complement to GPS) • toys and sports equipment	100°/s 100°/s 50°/s 50°/s varies	1°/s 2°/s 0.5°/s 0.5°/s varies
Industrial reliable, small, rough environment	• machine control • angular vibration measurements • attitude control of flying objects • automatic guided vehicles • stabilised platforms • robotics	10°/s varies 20°/s 50°/s 20°/s 10°/s	0.01°/s varies 0.02°/s 0.2°/s 0.2°/s 0.01°/s
Medical reliable, small, low-power	• monitoring of body-movement • vibration diagnostics • controls for paralysed patients • surgical instruments • wheel-chairs	10g, 100°/s 0.1g, 50°/s 2g, 100°/s 20°/s 2g, 50°/s	100mg, 1°/s 1mg, 0.5°/s 20mg, 2°/s 0.1°/s 20mg, 0.2°/s
Military reliable, small, rough environment	• new weapon systems • smart ammunition	- -	- -

MICROMECHANICS

- Gyroscope for automotive applications (TEMIC/Colibri)