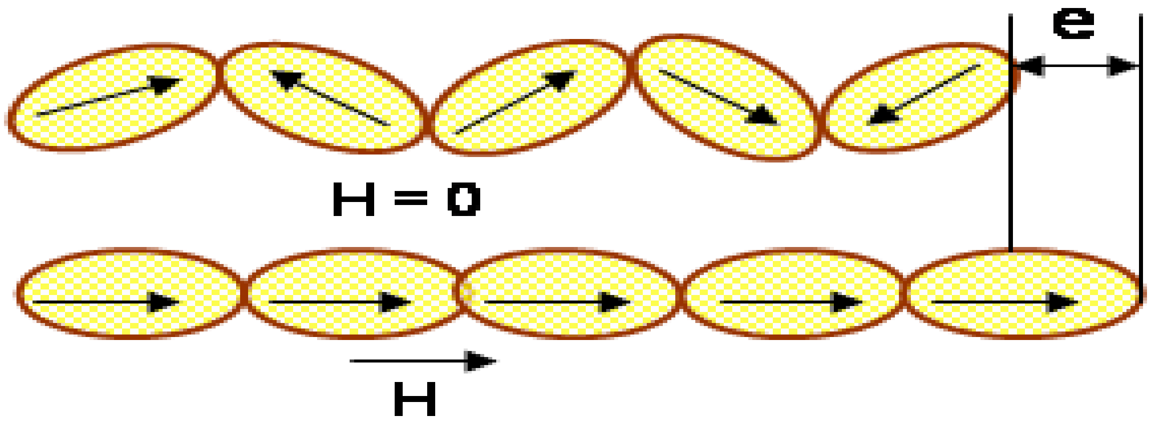
Magnetostrictive and MEMS Sensors

What is Magnetostriction?



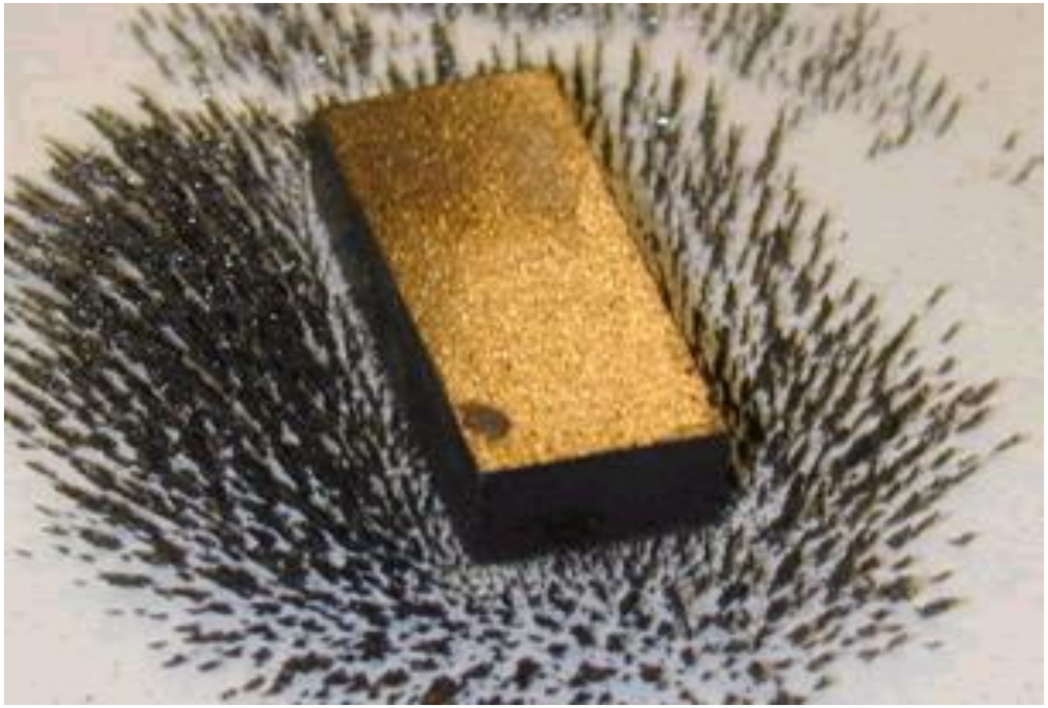
Magnetostriction (e) in materials due to domain migration and reorientation under applied magnetic field H

- If a crystal of ferromagnetic material is initially at a compressed state, the effect of Magnetostriction becomes more pronounced.
- All ferromagnetic elements show Magnetostriction to different degree.
- It is observed that the maximum one can achieve is for Cobalt which saturates around 50 μstrain (ppm).

Some Magnetostrictive Materials

Material	Magnetostriction (ppm)	Curie Temp (K)
Fe	14	633
Ni	-33	1043
Co	50	350
Permalloy	27	713
$DyFe_2$	650	635
$TbFe_2$	2630	703
$Tb_{.3}Dy_{.7}Fe_{1.9}$	2400	653

Terfenol-D: A Magnetostrictive Smart Material



Terbium – Iron (Fe) – Naval Ordinance Laboratory - Dysprosium (Is TerFeNOL-D explosive?)

Table 1, Technology features overview [1, 2, 8, 9, 10 and 11]

Typical features	**PZT**	**Terfenol-D**	**SMA**
Actuation mechanism	Piezoelectric material	Magnetostrictive material	Shape memory alloys
Elongation	0.1%	0.2 %	5%
Energy density	2.5 J/m³	20 J/m³	1 J/m³ *
Bandwidth	100 kHz	10 kHz	0.5 kHz
Hysteresis	10%	2%	30%
Costs as reference	200 $ / cm³	400 $ / cm³	200 $ / cm³

Magnetostrictive Effects for Actuation

Reverse Effects
Joule Effect: Magnetostriction: Change in Sample Dimension in the magnetic field
Wiedemann effect: Torque induced by helical magnetic field
Magnetovolume effect: Volume change due to magnetostriction also known as Barret Effect

Direct Effects for Sensing
Villari Effect: Change in Magnetisation due to Applied Stress
Matteuci Effect: Helical anisotropy and EMF induced by a Torque
Nagoka-Honda Effect: Change in the magnetic state due to change in the volume

Const. Eqn. of Magnetostrictive Material

Joule Effect: $S_1 = \sigma_1/E_m + d_m H$

Villary Effect: $B = d_m \sigma_1 + \mu H$

σ-stress,

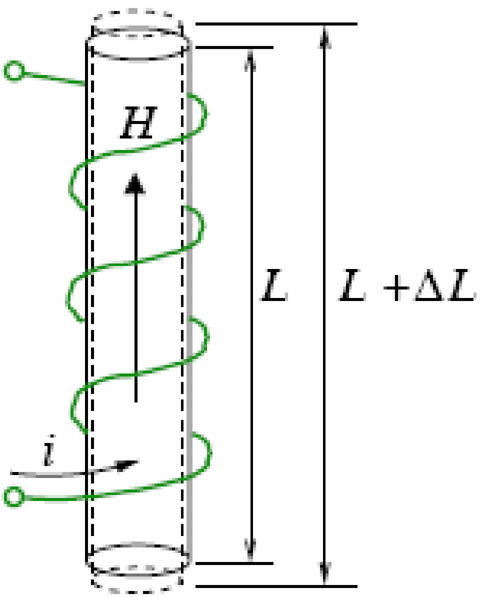
S-strain,

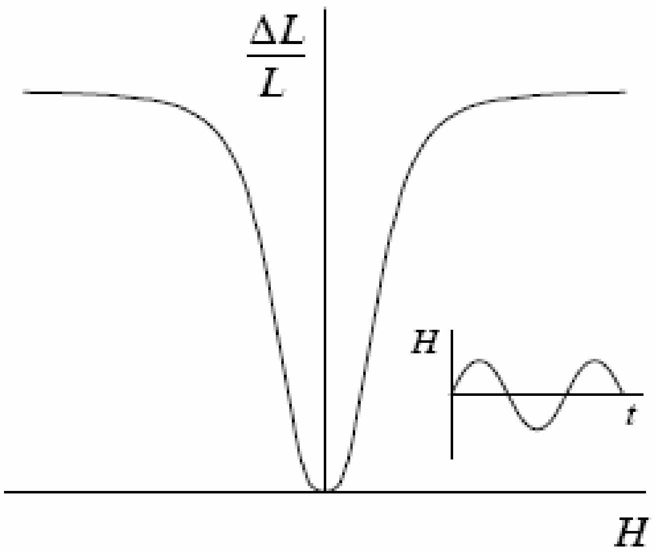
B - magnetic displacement/flux density,

μ - permeability,

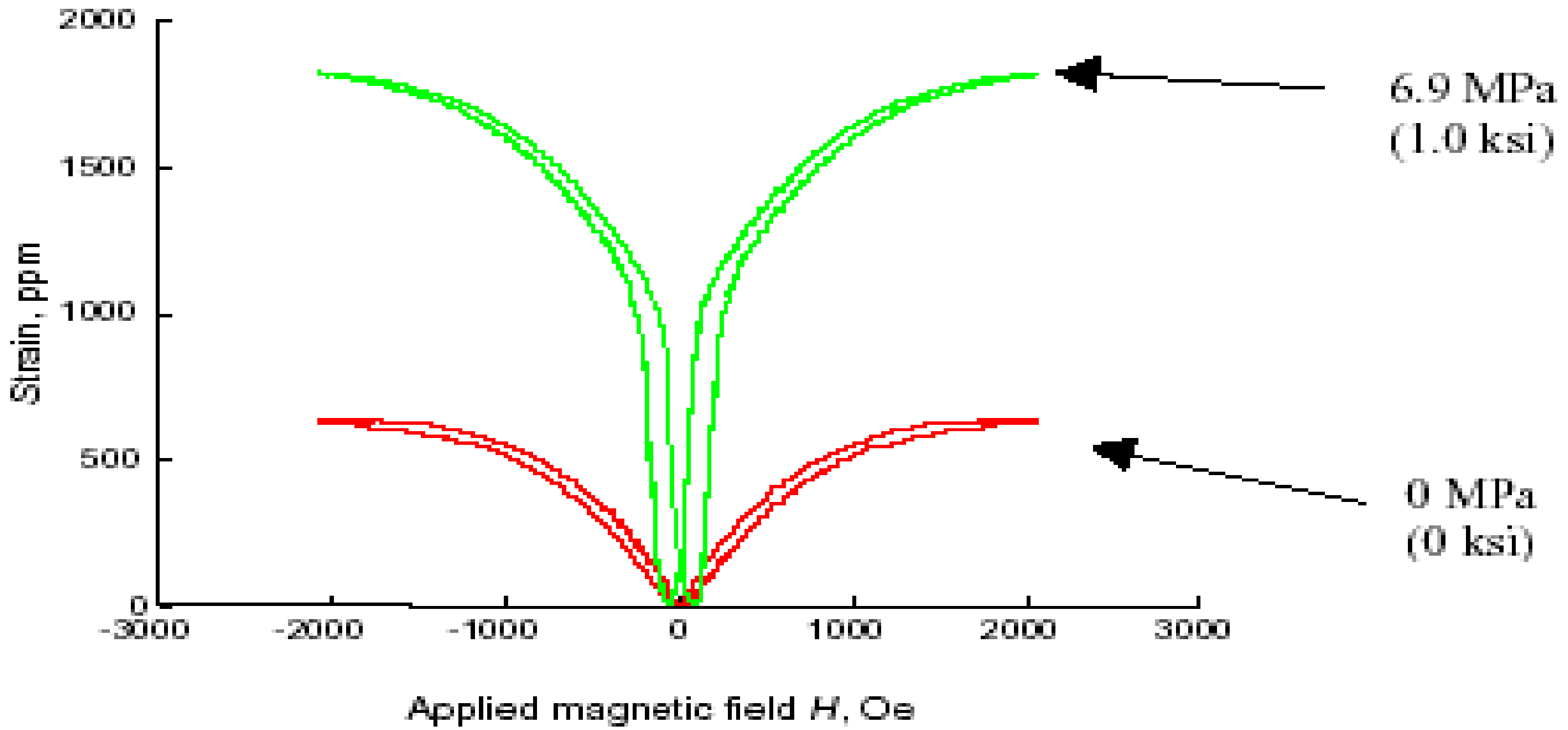
d_m- magnetostrictive constant

Magnetostriction in Solid Rod





Butterfly curve for TerFeNOL~D



Expansion of the Villary Effect

For a long, thin solenoid of number of turns, Nc, and length, Lc, a simple expression for Magnetic Field Intensity is:

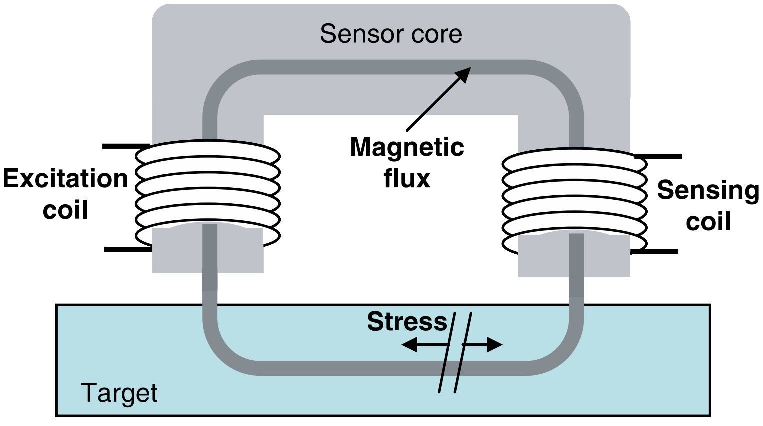
$$H = \frac{N_c I}{L_c}.$$

Also, following the Faraday – Lenz law, the voltage induced by Magnetic field potential on a solenoid of area A_c is:

$$V = -N_c \frac{\mathrm{d}\varphi}{\mathrm{d}t} = -N_c A_c \frac{\mathrm{d}B}{\mathrm{d}t},$$

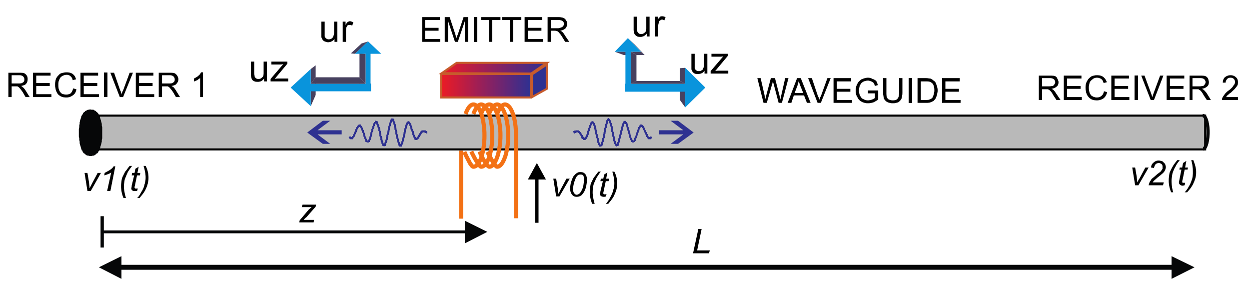
Magnetostrictive Torque Sensor

The basic principle of the sensor configuration is:
As a shaft is torqued, stress will develop at $\pm\ 45^0$from the shaft axis. For a magnetostrictive patch, this will induce a change in magnetic flux intensity (eqv. change in μ)



The C shaped ferromagnetic core supports an excitation and a detection coil. The change in stress will cause a change in permeability, which will be picked up by the sensing coil.

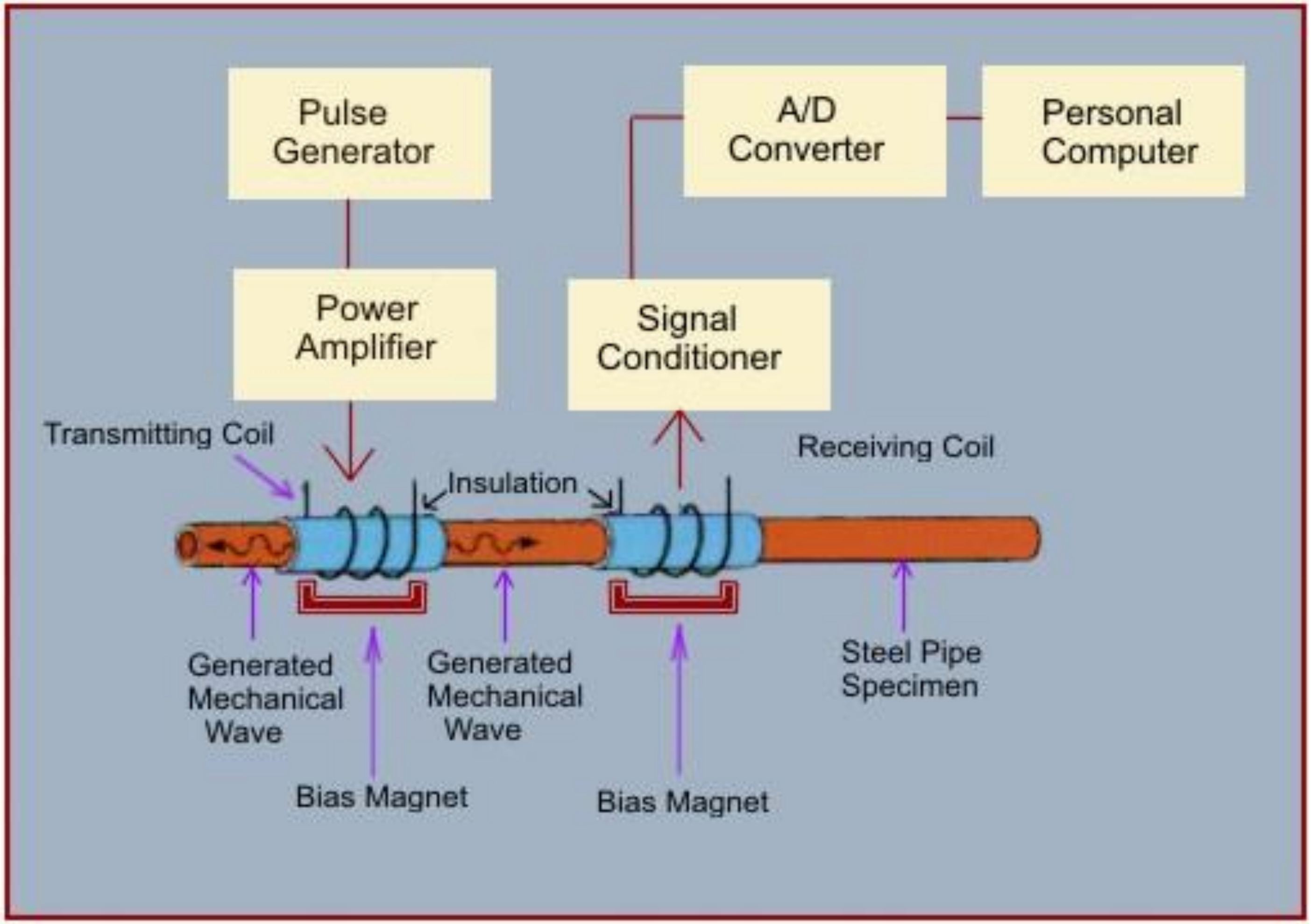
Magnetostrictive Position Sensor



Three signals are available for estimation of the cursor position in the sensor: the current in the generating coil, $v_0(t)$, and the ultra- sonic signals received at the left and right piezoelectric transducers, $v_1(t)$ and $v_2(t)$. It is readily proved that a linear relationship holds between the cursor position z and any of the three measurable time delays D_{ij} between signals $v_i(t)$ and $v_j(t)$.

$$\hat{z} = \frac{1}{2}(L - c\widehat{D}_{12}),$$

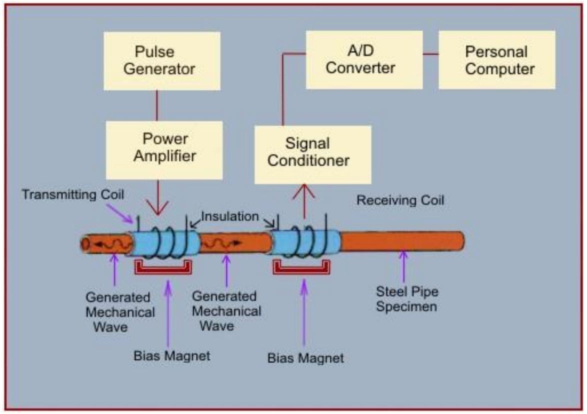
Magnetostrictive Delay Line (MDL) Sensor



Constitutive Relationship

$$H(x,t) = f(x)\, I(t) = 1/(\sqrt{(a^2 + x^2)}\;\; I(t)$$

$$\lambda(H) = \lambda_s\,(1\text{-}e^{-\alpha H^2}),\;\; \alpha>0$$



H – applied pulsed magnetic field,

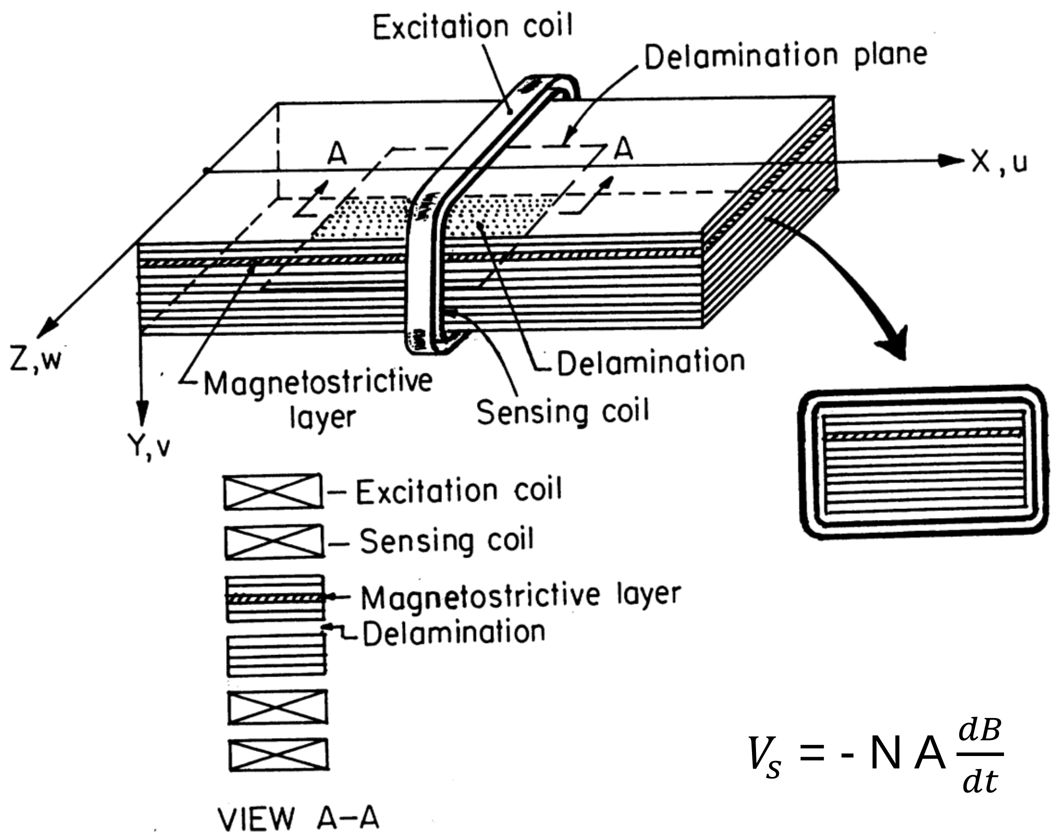
I(t) - applied current,

a^2- distance between the pulsed conductor and MDL,

λ_s - saturation magnetostriction,

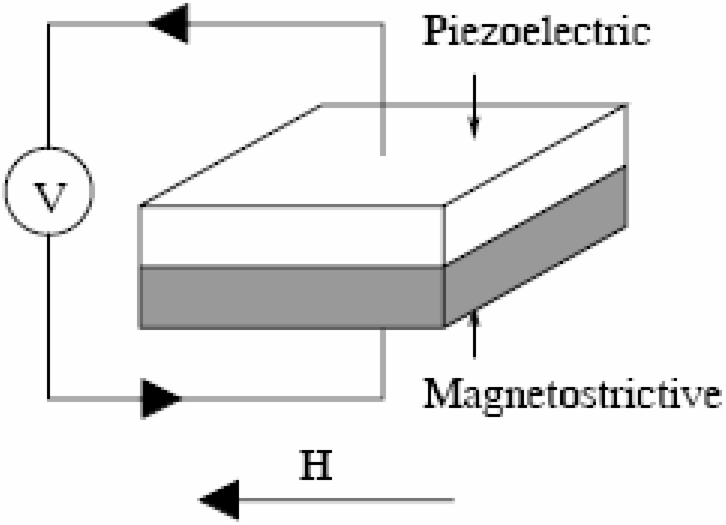
α - a material parameter

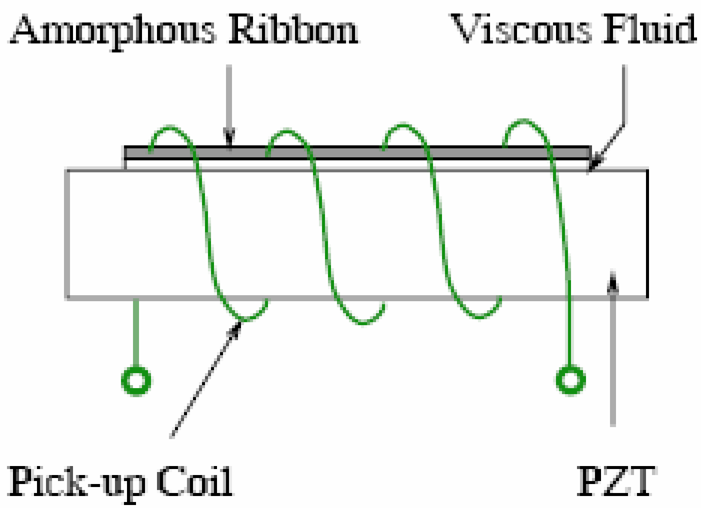
Delamination Sensing



$$V_s = -\,N\,A\,\frac{dB}{dt}$$

Hybrid Sensors





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MEMS Sensors
(Micro Electro Mechanical Systems

Why MEMS based systems?

MEMS, as the name suggests refers to micro-scaled electromechanical systems.
The **advantage of MEMS systems** over macro systems are:

- low power consumption,
- high sensitivity, easy to integrate/communicate
- low noise, high machine precision
- decreased cost (due to removal of manual assembly and substitution by batch fabrication)

Earliest MEMS products:

- Accelerometers based on Capacitive Sensing, Piezoresistivity, Piezoelectricity, Optical Interferometry, thermal expansion
- First micro-machined accelerometers are developed at Stanford in 1979!
- Gyroscopes like Inertial Measurement Units (IMUs)
- Digital Micro Mirrors (DMMs)

MEMS Development

- **There are broadly three issues related to MEMS development:**
  (a) System Level Development including signal processing, networking, packaging, design and simulation.
  (b) Micro-engineering including Layering, Micromechanics, Micro-electronics, Photonics and Micro-molding.
  (c) Materials and effects including smart materials.

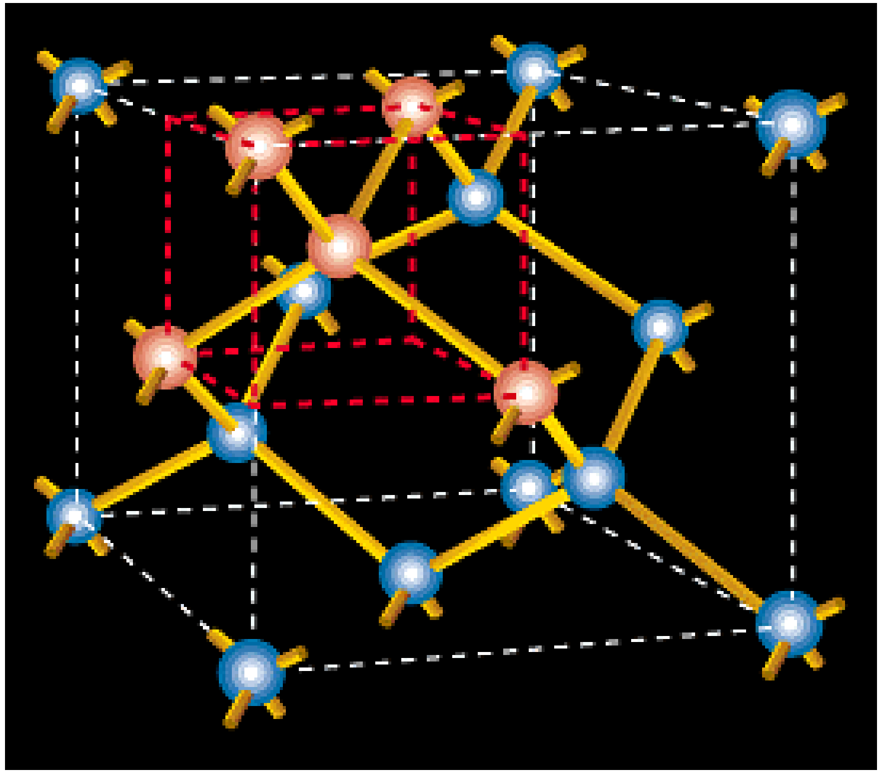
- **Foundation Materials for MEMS:**
  - Inorganic- Silica, Silicon, Quartz, Glass, Gallium Arsenide, Polydimethylsiloxane (PDMS)
  - Metallic- Gold, Aluminum, Platinum and Palladium.
  - Organic- Polyamides, PMMA

Why Silicon first and best choice?

- Excellent mechanical property.
  - 3 times Young’s Modulus of Steel about 700GPa, but as light as Aluminum- 2500Kg/m^3
- It is mechanically stable and can be easily developed by using micro-fabrication technology.
- For signal transductions, ‘p’ or ‘n’ type semiconductors can be readily integrated with the Si substrate.
- Melting point around 1400^0 C- makes it thermally stable.
- Very low thermal expansion coefficient-10 times lesser than Aluminium
- No Mechanical Hysteresis
- Very flat for coating

Crystal Structure

- Silicon Crystal Structure is basically FCC in nature.
- An FCC structure has 8+6=14 atoms
- However, Si has four extra atoms inside, making it of 18 atoms and partly anisotropic in nature. The weakest being the 100 plane and the strongest the 111 plane.



•**Number of atoms in a unit cell:**

- 4 atoms completely inside cell
- Each of the 8 atoms on corners are shared among cells → count as 1 atom inside cell
- Each of the 6 atoms on the faces are shared among 2 cells → count as 3 atoms inside cell

⇒ Total number inside the cell = 4 + 1 + 3 = **8**

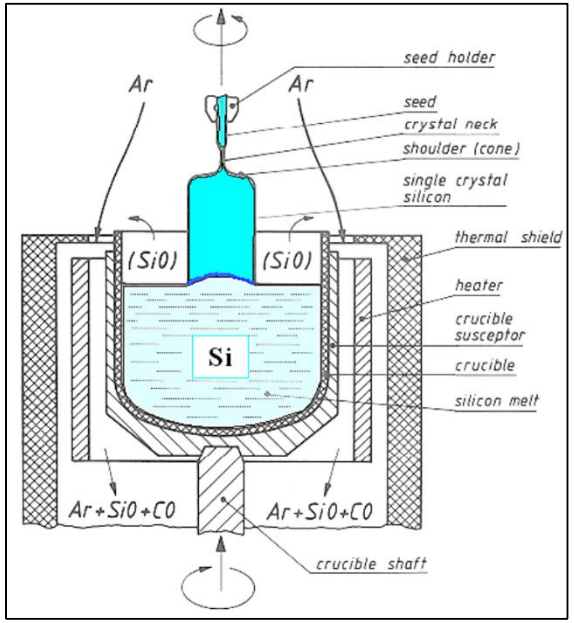
Ref: Berkley.edu

Property Set

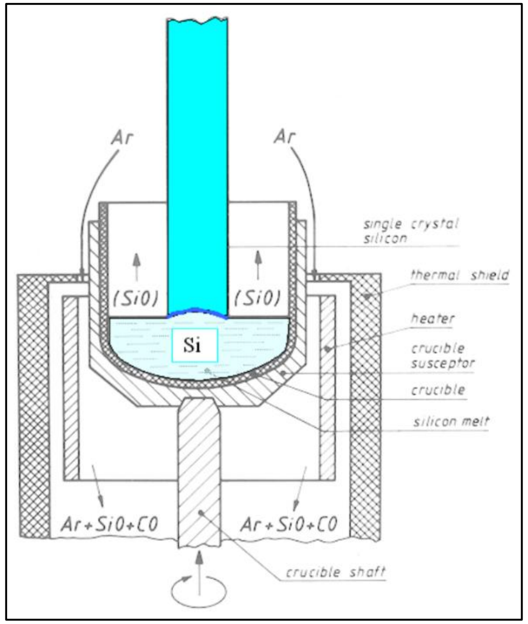
	σ_y (10^9 N/m^2)	E (10^{11} N/m^2)	ρ (g/cm^3)	C (J/g-^{o}C)	k (W/cm-^{o}C)	α (10^{-6}/^{o}C)	T_M (^{o}C)
Si	7.00	1.90	2.30	0.70	1.57	2.33	1400
SiC	21.00	7.00	3.20	0.67	3.50	3.30	2300
Si_3N_4	14.00	3.85	3.10	0.69	0.19	0.80	1930
SiO_2	8.40	0.73	2.27	1.00	0.014	0.50	1700
Aluminum	0.17	0.70	2.70	0.942	2.36	25	660
Stainless Steel	2.10	2.00	7.90	0.47	0.329	17.30	1500
Copper	0.07	0.11	8.9	0.386	3.93	16.56	1080
GaAs	2.70	0.75	5.30	0.35	0.50	6.86	1238
Ge		1.03	5.32	0.31	0.60	5.80	937
Quartz	0.5-0.7	0.76-0.97	2.66	0.82-1.20	0.067-0.12	7.10	1710

Czochralski Crystal Growth Process

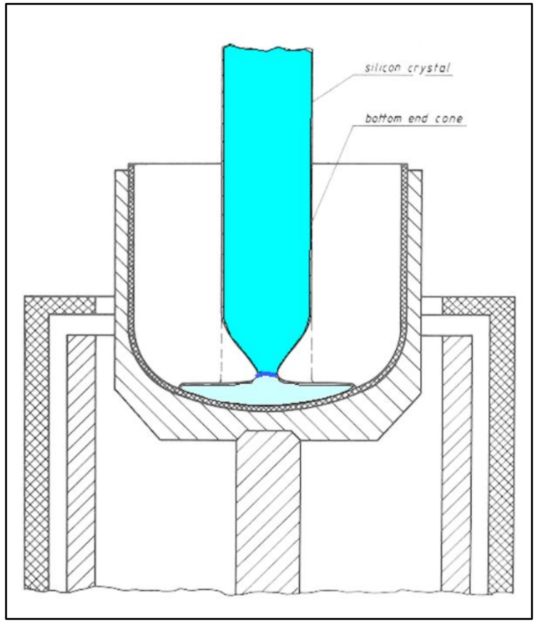
Raw Silica (Quatzite) is molten in a chamber. The crystal formation process is initiated with a seed crystal which is gradually pulled to get the complete bigger crystal.



Beginning of Crystal Growth



Advanced Stage



Final Stage

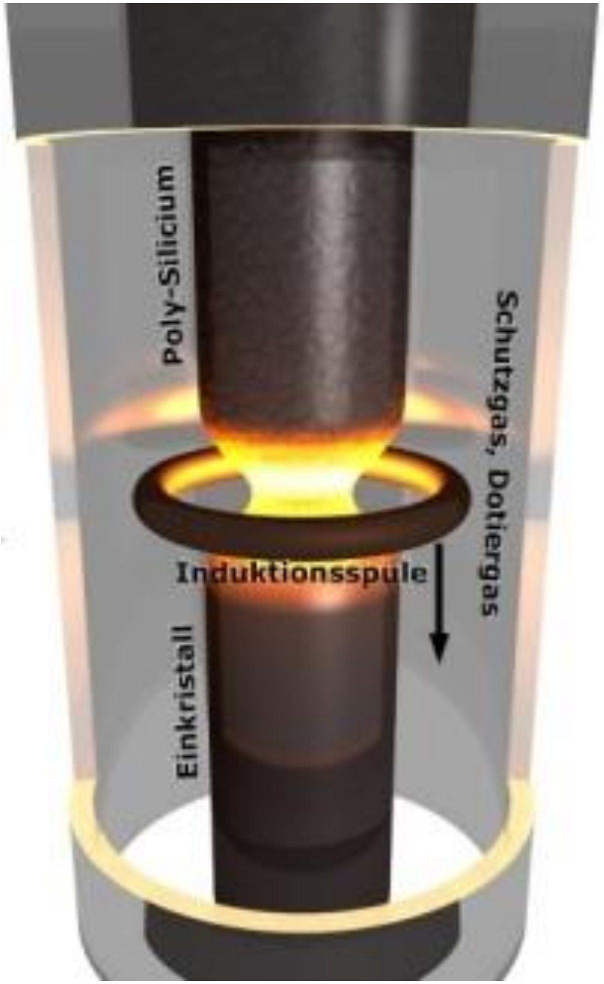
$$SiC + SiO_2 \rightarrow Si + SiO(gas) + CO(gas)$$

Pulling Rate: mm/min

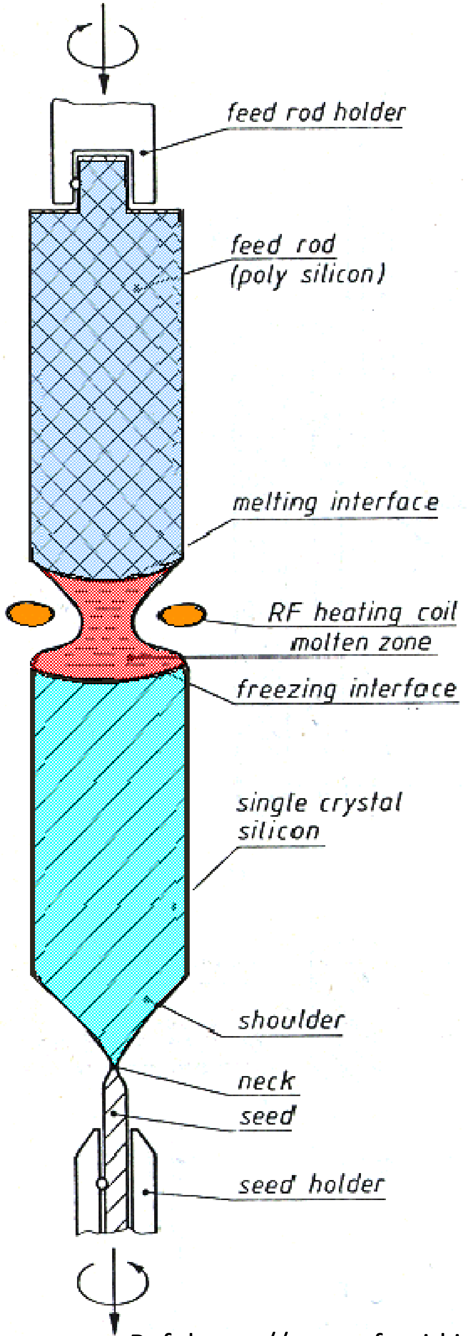
Oxygen can work as impurity and create n-type dopant which reduces the resistivity.

Ref: https://www.tf.uni-kiel.de

Float Zone Crystal Growth Process



- The float Zone (FZ) method is based on the zone-melting principle and was invented by Theuerer in 1962.
- The production takes place under vacuum or in an inert gaseous atmosphere.
- The process starts with a high-purity polycrystalline rod and a monocrystalline seed crystal that are held face to face in a vertical position and are rotated.
- With a radio frequency field both are partially melted.
- The seed is brought up from below to make contact with the drop of melt formed at the tip of the poly rod.
- A necking process is carried out to establish a dislocation free crystal before the neck is allowed to increase in diameter to form a taper and reach the desired diameter for steady-state growth.
- As the molten zone is moved along the polysilicon rod, the molten silicon solidifies into a single Crystal and, simultaneously, the material is purified.



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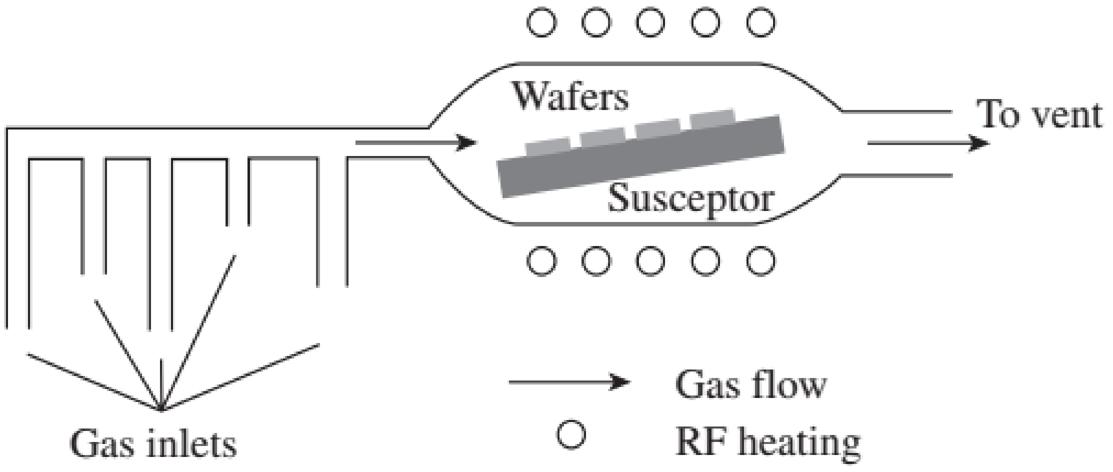
Vapour Phase Epitaxy

Epitaxy is the regularly oriented growth of a crystalline material on a crystalline substrate. The epitaxial layer builds up on the substrate with the same crystallographic orientation, the substrate acting as a seed for the growth



$$SiCl_4(gas) + 2H_2(gas) \rightarrow Si(solid) + 4HCl\ (gas)$$

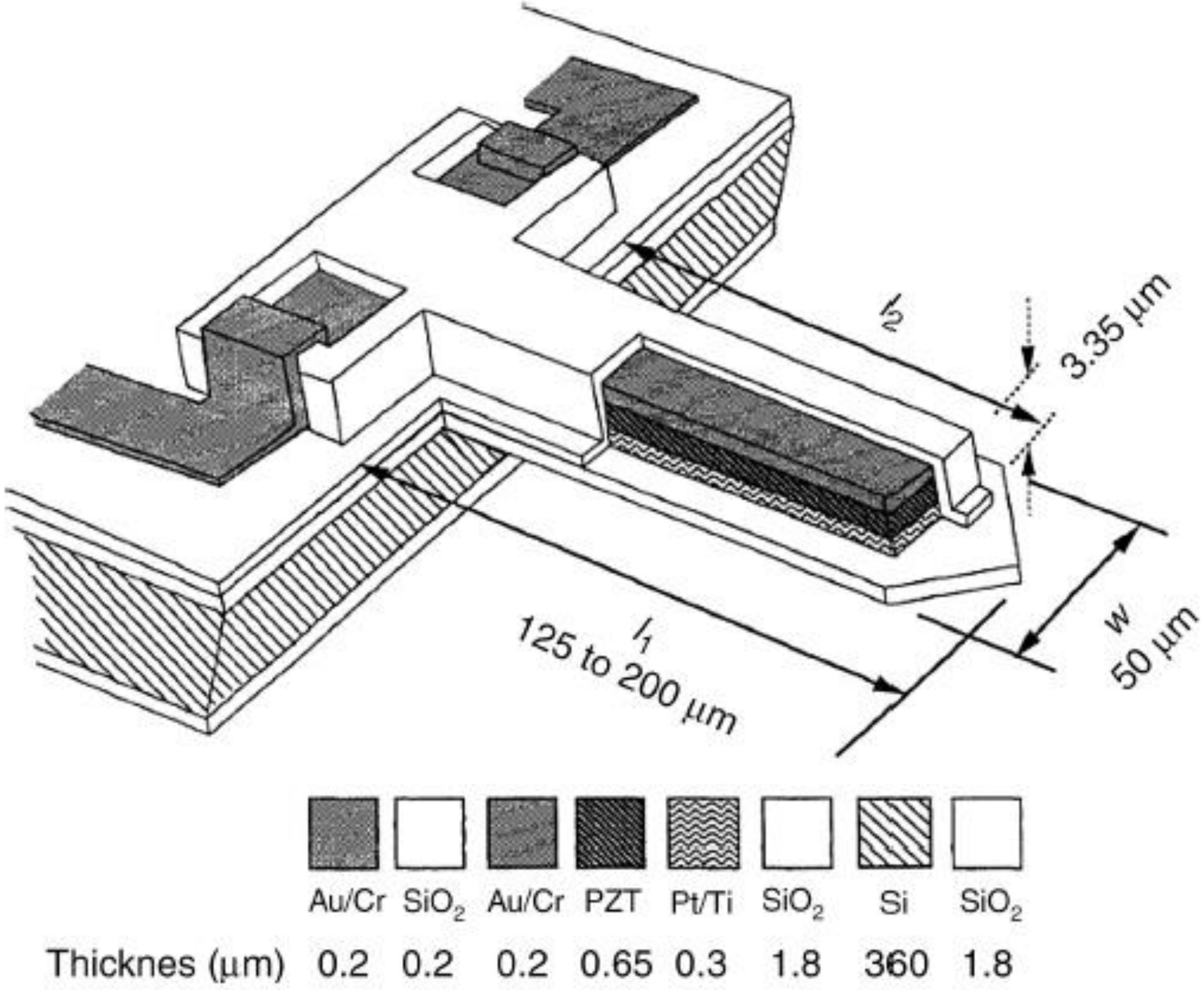
A competing reaction which occurs simultaneously is:

$$SiCl_4(gas) + Si\ (solid) \rightarrow 2SiCl_2(gas)$$

MEMS Fabrication

- **Bulk Micromachining** – removal of materials from bulk substrates – either by isotropic or anisotropic wet etching
- **Dry etching** – by corrosive gases
- **Wafer bonding** - using precisely aligned wafers
- **Surface micromachining** by thin film fabrication

Final Product



Polymer Processing Techniques

- Polymer processing techniques include Photopolymerization,
  - Electrochemical polymerization and
  - Vacuum polymerization, either stimulated by electron bombardment or initiated by ultraviolet irradiation, or microwave assisted polymerization.

Photopolymerization

When polymerizations are initiated by light then we can call that process to be Photopolymerization.

$$PI + h\nu \rightarrow R^{\circ}$$

$$R^{\circ} + M \xrightarrow{k_i} RM_1^{\circ}$$ ....Photoinitiation

$$RM_1^{\circ} + M \xrightarrow{k_p} RM_2^{\circ}$$ ....Propagation

$$RM_{n-1}^{\circ} + M \xrightarrow{k_p} RM_n^{\circ}$$ ....Propagation

$$RM_n^{\circ} + RM_m^{\circ} \xrightarrow{k_t} RM_{m+n}$$ ....Termination

- Two types of polymers are employed for micromachining polymeric MEMS devices: **structural polymers** and **sacrificial polymers**.
- The **structural polymer** is usually a UV-curable polymer with a urethane acrylate, epoxy acrylate or acryloxysilane as the main ingredient.
- The **structural polymer** may be used as a backbone structure for building the multifunctional polymer.

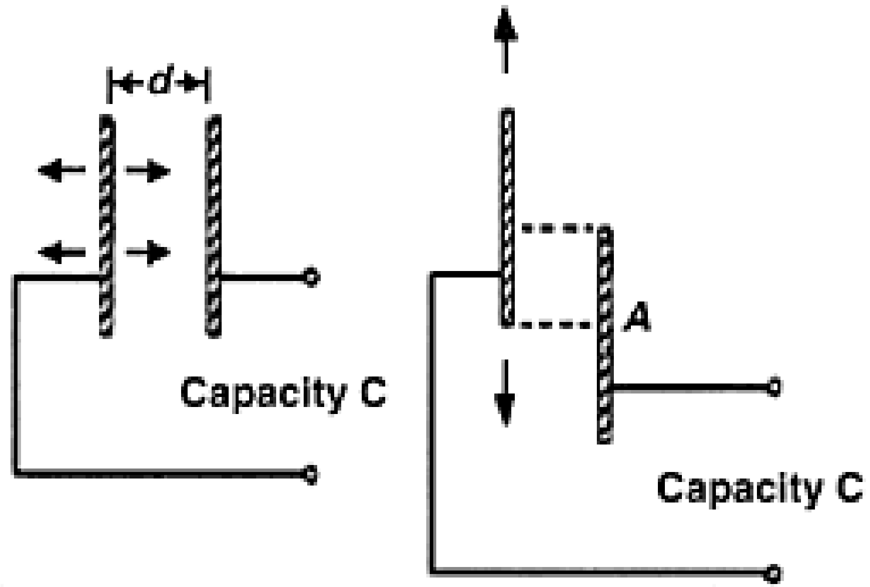
Photopolymerization

- The **sacrificial polymer** is an acrylic resin containing 50 % silica and is modified by adding crystal violet.
- This composition is UV-curable and can be dissolved with 2 mol/l of caustic soda at 80 ^{o}C.
- In principle, this process is similar to the surface micromachining technique used for silicon devices. However, the process yields 3D structures.

Polymer based MEMS

Polymer	Functional property	Application
PVDF	Piezoelectricity	Sensor/actuator
Polypyrrole	Conductivity	Sensor/actuator/ electric/connection
Fluorosilicone	Electrostrictivity	Actuator [40]
Silicone	Electrostrictivity	Actuator [40]
Polyurethane	Electrostrictivity	Actuator [40]

MEMS Accelerometers: Fact Sheet



Consider two parallel steel plates with a gap between them. When a voltage is applied to one of the plates, the difference between the charges stored on the surfaces of the plates will cause an electric field to exist between them.

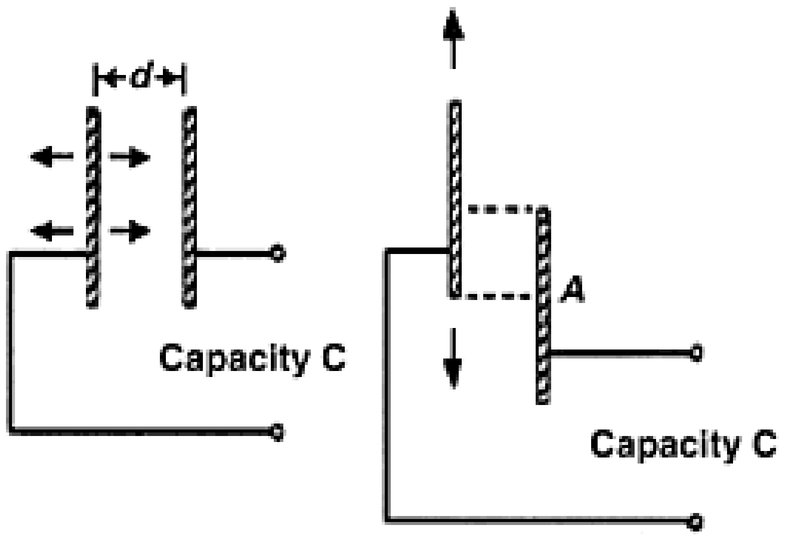
$$C = \frac{\epsilon_o \epsilon_r A}{d}$$

ϵ_o = absolute permittivity of free space ($8.85 * 10^{-12}$)
ϵ_r = relative permittivity (dielectric constant) of medium in gap between plates
A = plate common surface area
d = plate separation (displacement)

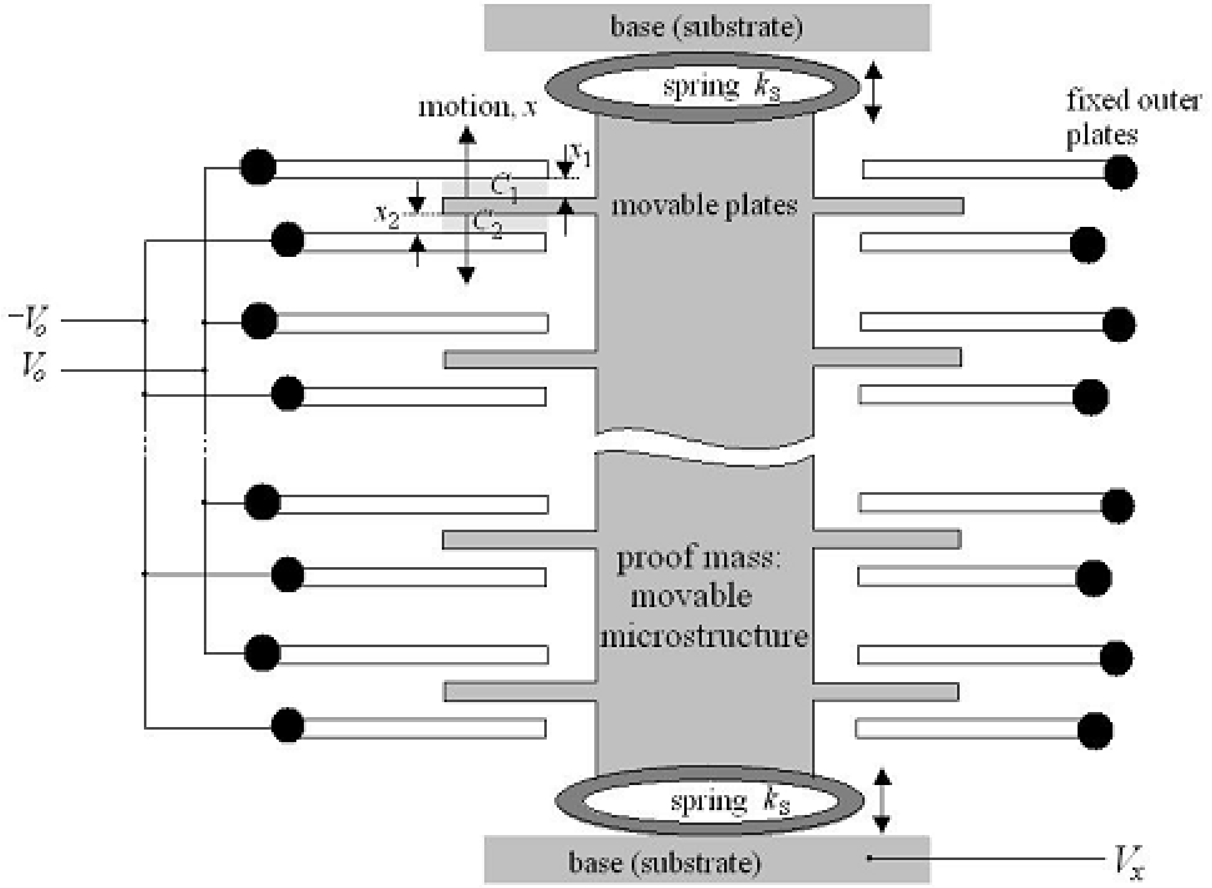
MEMS Accelerometers: Fact Sheet

There are three ways to change the capacitance of the parallel-plate system:

Variation of the distance between the plates (d)
Variation of the shared area of the plates (A)
Variation of the dielectric constant (ε_r)



MEMS Accelerometers based on capacitance change

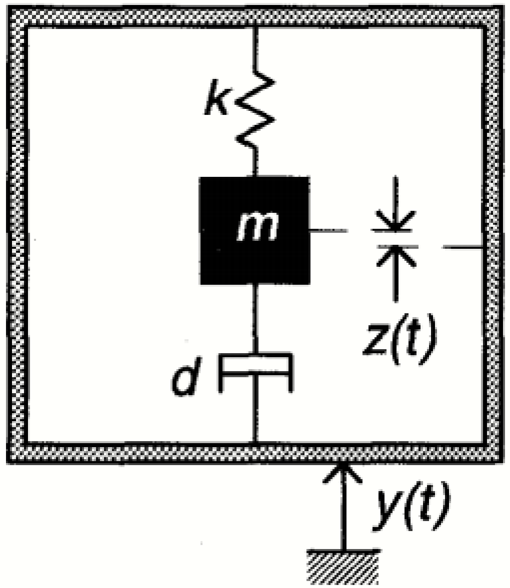


$$C_2 - C_1 = 2\Delta C = 2\epsilon \frac{x}{d^2 - x_2}$$

Ref: Matej Andrejasic (Uni. of Ljubljana)

MEMS Accelerometer: Energy conversion with linear model

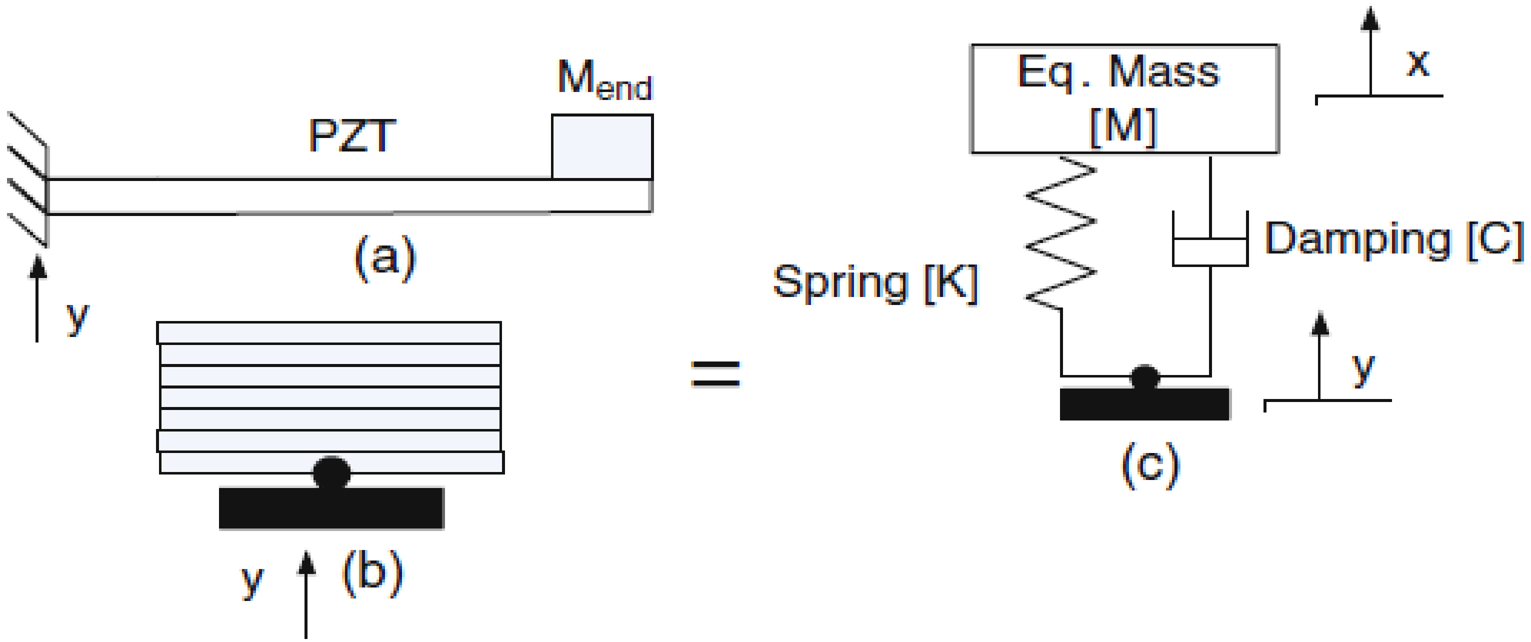
- Generally, a single degree of freedom lumped spring mass system is utilized to study the dynamic characteristics of a vibrating body associated with energy harvesting.



Schematic Diagram of Energy Transducer

Ref: C.B. Williams et.al. International Conference on Solid-state Sensors and Actuator ,1996

Concept of a Basic EH System



(**a**) Cantilever beam with tip mass, (**b**) multilayer PZT subjected to transverse vibration excited at the base, and (**c**) equivalent lumped spring mass system of a vibrating rigid body

Ref: Priya Shashank, Energy Harvesting Technologies

Mechanical Governing Equations

- The governing equation of motion for the system shown in Fig.1(c) can be obtained from D'alembert's principle

$$M\ddot{z} + C\dot{z} + Kz = -M\ddot{y}$$

Where z = x- y is the net displacement of mass.

- Above equation can be written in terms of damping factor and natural frequency where

$$\zeta = \frac{c}{c_c} = \frac{c}{2\sqrt{MK}} \qquad \omega_n = \sqrt{\frac{K}{M}}$$

$$\ddot{z} + 2\zeta\omega_n\dot{z} + \omega_n^2 z = -\ddot{y}$$

Mechanical Governing Equations contd…

- The transfer function in the frequency domain can be deduced as

$$\left|\frac{Z(s)}{Y(s)}\right| = \frac{s^2}{s^2 + 2\zeta\omega_n s + \omega^2{}_n}$$

- The time domain of the response assuming that the external base excitation is sinusoidal

$$z(t) = \frac{\left(\frac{\omega}{\omega_n}\right)^2}{\sqrt{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2}} Y\sin(\omega t - \phi)$$

- The phase angle between output and input can be expressed as

$$\phi = \tan^{-1}\left(\frac{c\omega}{K - \omega^2 M}\right)$$

Mechanical Power Generation

- The approximate mechanical power of a piezoelectric transducer vibrating under the above mentioned condition can be obtained from the product of velocity and force on the mass as

$$P(t) = \frac{M\zeta Y^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta \frac{\omega}{\omega_n}\right)^2}$$

- The maximum power can be obtained by setting operating frequency as natural frequency

$$P_{\max} = \frac{MY^2\omega_n^3}{4\zeta}$$

- It can be seen that power can be maximized by lowering damping, increasing natural frequency, mass and amplitude of excitation.

Now for the Piezoelectric System

- Consider Euler-Bernoulli Beam Equation (with λ_m as the linear mass density):

$$EI\frac{\partial^4 w(x,t)}{\partial x^4} = -\lambda_m \frac{\partial^2 w(x,t)}{\partial t^2}$$

- Boundary Conditions:

$$w(0,t) = \frac{\partial w}{\partial x}(0,t) = 0$$

$$\frac{\partial^2 w}{\partial x^2}(L,t) = 0$$

$$EI\frac{\partial^3 w}{\partial x^3}(L,t) = M\frac{\partial^2 w}{\partial x^2}(L,t)$$

System Response

- General Solution for governing equation using separation of variables method :

$$\omega_i(x,t) = \phi(x) * q(t)$$

$$\phi(x) = C_1 cos\lambda \frac{x}{L} + C_2 sin\lambda \frac{x}{L} + C_3 cosh\lambda \frac{x}{L} + C_4 sinh\lambda \frac{x}{L}$$

- Complete Solution:

$$\omega_i(x,t) = \phi(x) q(t) = \omega^2 \sum_{r=1}^{\infty} \frac{\phi(x)(\psi)}{\omega_r^2 - \omega^2 + i2\zeta\omega_r\omega}$$

System Response Contd...

Where :

$$\phi(x) = C_r\left\{\cos\frac{\lambda x}{L} - \cosh\frac{\lambda x}{L} - \beta\left[\sin\frac{\lambda x}{L} - \sinh\frac{\lambda x}{L}\right]\right\}$$

$$\beta = \frac{mL(\sin\lambda - \sinh\lambda) + \lambda M\left(\cos\lambda - \cosh\lambda\right)}{mL(\sin\lambda + \cosh\lambda) - \lambda M\left(\sin\lambda - \sinh\lambda\right)}$$

$$q(t) = \frac{\psi\omega^2}{\omega_r^2 - \omega^2 + i2\zeta\omega\omega_r}\, y_\circ e^{j\omega t}$$

$$\psi = -m\int_0^L \phi(x)\,dx + M\phi(L)$$

Strain at a Point and Output Voltage

- Strain:

$$\varepsilon(x) = -y\frac{\partial^2 \omega}{\partial x^2}$$

- Output Voltage:

$$V\left(\frac{x}{L}\right) = g_{31}E\varepsilon\left(\frac{x}{L}\right)L_b$$

- Power:

$$P = \frac{v^2}{R_L} = \frac{1}{R_L}\left\{g_{31}E\varepsilon\left(\frac{x}{L}\right)L_b\right\}^2$$

A Real-life System

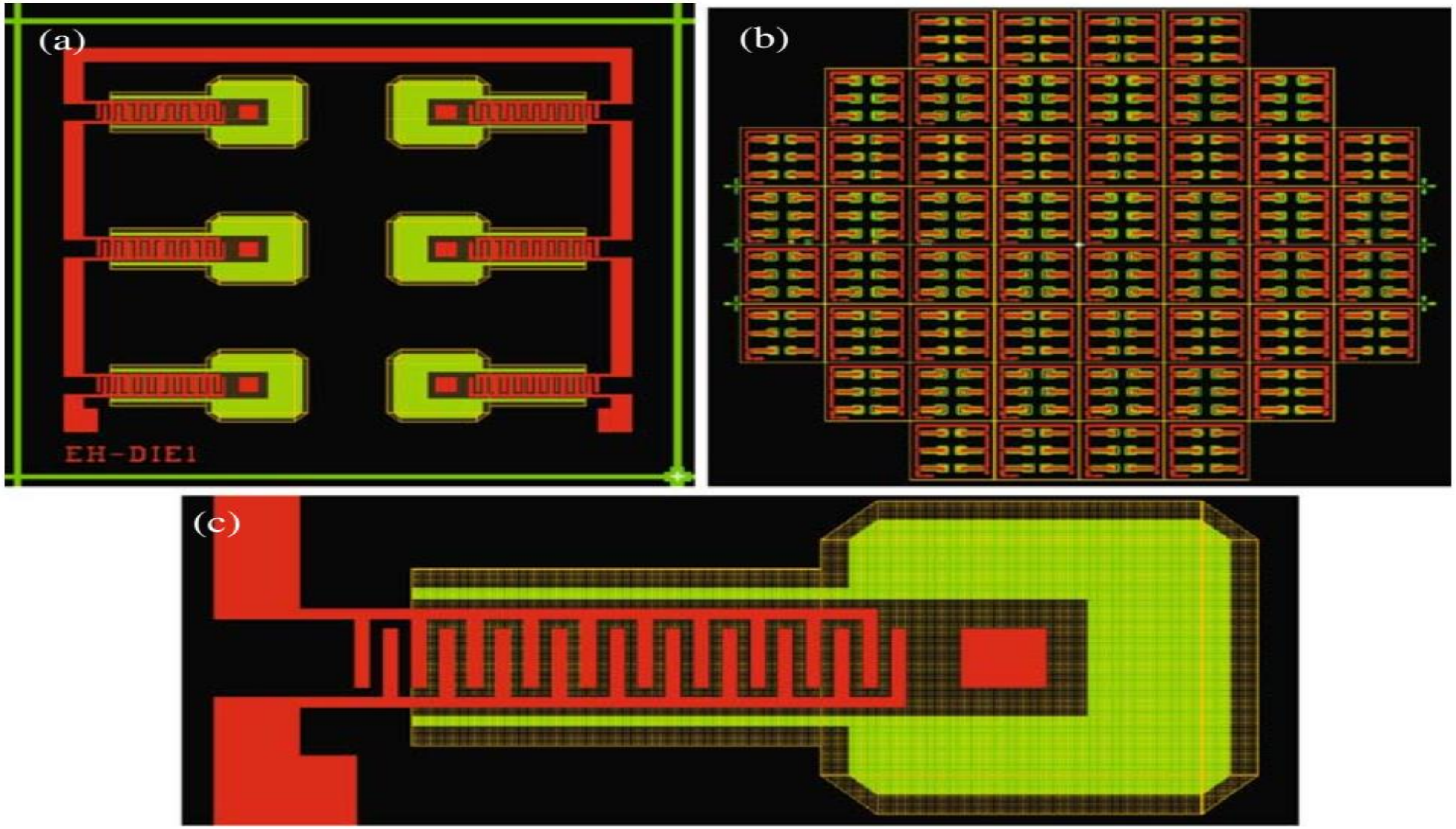


Fig: (a) Layout of six micro cantilever energy harvesting beams,(b) Layout of mask for 4” wafer, and (c) close up a d_{33} - mode cantilever beam